

Review

# Recent Advances in Hybrid Energy Storage System Integrated Renewable Power Generation: Configuration, Control, Applications, and Future Directions

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**Abstract:** The increased usage of renewable energy sources (RESs) and the intermittent nature of the power they provide lead to several issues related to stability, reliability, and power quality. In such instances, energy storage systems (ESSs) offer a promising solution to such related RES issues. Hence, several ESS techniques were proposed in the literature to solve these issues; however, a single ESS does not fulfill all the requirements for certain operations and has different tradeoffs for overall system performance. This is mainly due to the limited capability of a single ESS and the potency concerning cost, lifespan, power and energy density, and dynamic response. In order to overcome the tradeoff issue resulting from using a single ESS system, a hybrid energy storage system (HESS) consisting of two or more ESSs appears as an effective solution. Many studies have been considered lately to develop and propose different HESSs for different applications showing the great advantages of using multiple ESSs in one combined system. Although these individual methods have been well documented, a comprehensive review of HESS-integrated RE has not been fully investigated in the literature before. Thus, as a novel contribution to the literature, this study aims to review and analyze the importance and impact of HESSs in the presence of renewable energy towards sustainable development that will facilitate this newly emerging topic to researchers in this field. In this regard, the present scenario and recent trend of HESSs in RESs at the global level, including a comparison with main ESS features, are discussed and analyzed along with the concept, design, classifications, and a detailed comparison of HESSs. The emerging role of HESSs in terms of their benefits and applications has been analyzed. Recent control and optimization methods of HESSs associated with RESs and their advantages and disadvantages have been reviewed. Finally, open issues and new challenges toward more efficient, sustainable, and green energy have also been highlighted herein. All the highlighted insights of this review will hopefully lead to increased efforts toward the development of an advanced HESS for future renewable energy optimal operation.

**Keywords:** renewable energy; hybrid energy storage system; control and optimization; energy management; energy storage system; benefits and application; pros and cons; challenges; intermittent nature



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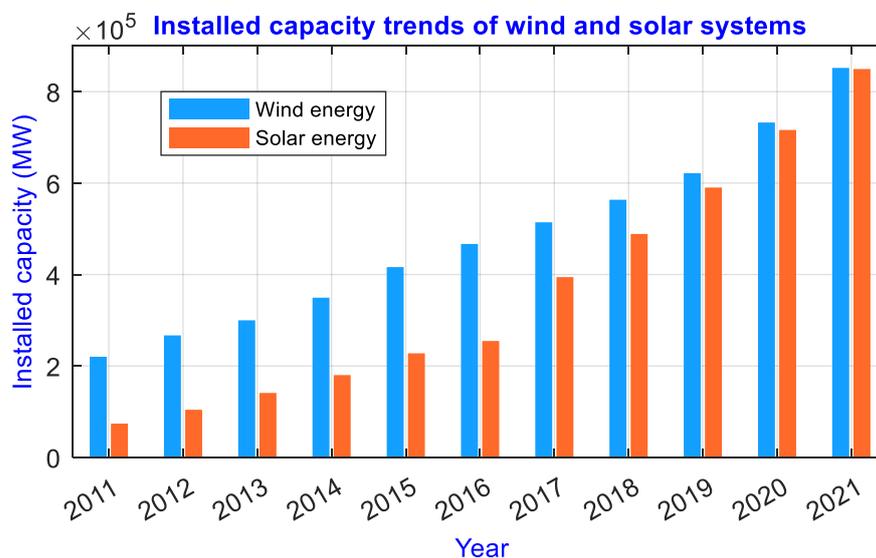


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## 1. Introduction

It is well known that environmental impacts, climate change, and the polluting nature of today's power systems have tremendously increased the use of renewable energy sources (RESs). In this regard, various RESs, including hydro, solar, wind, wave, bioenergy, and geothermal, have been considered and employed in many countries around the world [1,2]. These sources, due to the high demands of energy, are continuously evolving and expanding. For instance, the total installed capacity of RESs increased by 11% to reach approximately 3146 GW by the end of 2021. The increase of RES capacity scored a new

value of 315 gigawatts (GW) in 2021, representing a growth of 17% from the previous year. Among all renewable energy sources, solar photovoltaic (PV) and wind power have been the most successful forms of renewable energy (RE) development, contributing to 90% of all new RE additions [1,3]. Hence, solar PV and wind are the two most cutting-edge RESs that have also seen widespread deployment globally in the last ten years, as shown in Figure 1 [1].



**Figure 1.** Installed capacity of wind and solar energies during the last ten years (2011–2021).

Although PV and wind have been widely deployed in the last decade, the intermittent availability of these sources can cause power oscillations, affecting power systems' flexibility, stability, quality, and reliability, as proved by the authors in Ref. [4]. In light of this, the authors in [5] demonstrated that energy storage systems (ESSs) could address some of these RES problems. However, in [6], Matos et al. clarified that the various ESS technologies currently in use are insufficient to handle issues related to RE systems. Moreover, as proved by the study conducted in [7], the authors proved that single ESS technology has limited features and cannot carry out desired operations or fulfill all operational issues associated with RESs. In the same manner, the authors of [8] showed that each single ESS has constraints that limit its field of application because an ideal application requires both high energy density and high power density. However, a single ESS technology cannot fulfill the desired operation due to its limited capability and potency in terms of lifespan, cost, energy and power density, and dynamic response, as concluded by [9]. Thus, to overcome the operational limitations of a single ESS, a hybrid energy storage system (HESS) that consists of two or more ESSs is a promising solution for achieving optimal operation and integration of RESs.

An HESS is made up of two or more heterogeneous storage technologies that have sort of matching features. This is done in order to take advantage of the positive aspects of each individual ESS technology while restraining its disadvantages [10]. Hence, lower cost, increased system lifetime, and better system efficiency are the most probable benefits due to the hybridization's ability to perform more tasks and increase lifespan with less total storage capacity [11]. In an HESS, one storage is usually used for high dominant energy storage with a low self-discharge rate and lower energy-specific installation costs, and the other is used to handle high power demand, transients, and fast load swings. For instance, some battery types contain characteristics such as high specific energy, limited life cycle, low specific power, and low self-discharge units with a low cost per watt. On the other hand, supercapacitors (SC) display more specific power, less specific energy, longer lifetimes, faster charging, and a higher capacity for self-discharge [12,13]. Therefore, the hybrid deployment of having a battery–SC combined together in one unit can complement

each other and have the advantages of both as one combined hybrid solution. Due to its homologous operating concept, wide availability, and affordable initial cost, this combination has gained the high interest of researchers and developers in the industry [13,14]. To obtain the best performance of hybridization, efficient control and/or optimization strategies for energy management and other purposes are important for HESS [15]. However, the selection of control and optimization techniques and addressing their drawbacks are still challenging [15,16].

According to the literature, HESSs have been reviewed by various authors, especially for electric vehicle deployment [13,17–19]. In addition, a comprehensive review of the control and energy management of HESSs in electric vehicles has been previously investigated in [20–24]. Other review studies focused on HESS application for microgrids (MG) [15,25,26], standalone PV systems [27], buildings [28], and standalone RE power systems [29]. However, a comprehensive review of the recent hybridization of ESSs in renewable power systems has not been fully considered in the literature. In addition, all review studies considered the topics of applications, energy management, configuration, sizing, and converter topologies only. However, the recent advancement of HESS-integrated RES applications and benefits for RESs connected to the grid or standalone RESs are not sufficiently reviewed. Although, many research papers were conducted recently and proposed new forms of HESSs in RE systems that were not taken into consideration by the previous comprehensive review article. Furthermore, to enhance the operation and performance of HESSs in the presence of RE, new control and optimization methods were proposed; however, a critical analysis of these methods along with their pros and cons had not been fully addressed in earlier studies. Thus, this review provides a comprehensive review to completely address the issues mentioned above and the limitations of previous studies. The main contributions of this review can be summarized as follows:

- Reviews and discusses the present scenario and trend of energy storage-integrated RE along with a brief comparison.
- Studies the various operational and technical perspectives of HESSs in the area of renewable power generation and the presentation of a general and comprehensive outlook of state-of-the-art advances.
- Explores and presents the recent applications and main benefits of HESSs in RE systems.
- Provides a comprehensive review of recent control and optimization techniques applied to HESSs in the presence of RE systems along with each method's main findings, pros, and cons.
- Identifies the key issues and challenges of HESSs from different aspects based on the review results.
- Finally, delivers future prospects and recommendations for deploying and improving HESSs in various RE applications toward sustainable and green energy.

The remainder of the paper is arranged into eight sections. Section 2 narrates the process of surveying methods. An overview, the trends, and a comparison of ESS-integrated RE are outlined in Section 3. Classifications and the structure of HESSs are presented in Section 4. HESS benefits and applications in RE are covered in Section 5. Recent control and optimization methods of HESS-integrated RE systems are reviewed in Section 6. Key issues and challenges are explored in Section 7. Concluding remarks and future perspectives are highlighted in Section 8.

## 2. Reviewing Methodology

To attain the aims of this review, the survey method was performed on the basis of content analysis. The literature survey was conducted using different platforms, including Scopus, Web of Science, Science Direct, and Google Scholar databases, research gate, and international agencies of energy. In order to search for relevant publications within the scope of the research, the authors employed keywords such as *renewable energy*, *hybrid energy storage system*, *control and optimization*, *energy management*, *energy storage system*, *benefits and application*, *pros and cons*, *challenges*, and *intermittent nature*. Many articles were discovered

from our search. To search for the most recent advances on the topic, the assessment and screening were conducted for published articles between 2011 and 2022. Then, the relevant literature was chosen by analyzing the title, keywords, abstract, article content, and journal's main subject of interest. These selected references were read carefully in order to extract useful information related to recent advances in HESS-integrated RE in terms of configuration, control, and applications. The review process was divided into two phases which were employed to select a suitable number of previous studies, as shown in Figure 2 and summarized as follows:

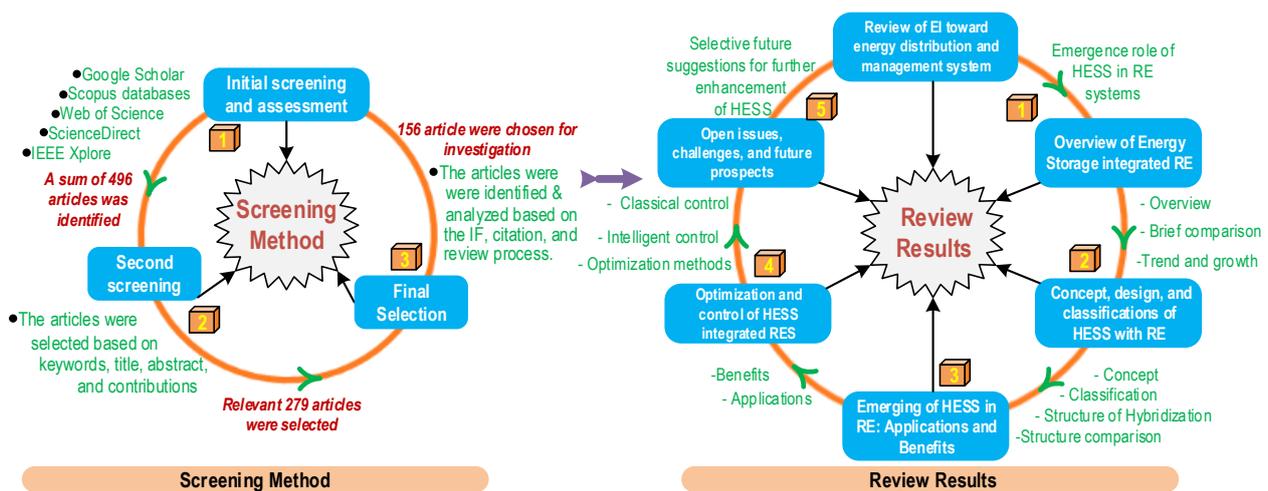


Figure 2. Schematic illustration of the reviewing methodology.

The screening and assessment phase was conducted through the search for a literature review using the different databases mentioned above. Subsequently, a total of 496 papers were identified after the first screening. Then, article selection through the assessment phase was performed using the essential keywords. In line with this, the title, abstract, subjects, and contributions were evaluated to explore relevant articles. Consequently, a total of 279 papers were found in this stage. The final selection of the article was carried out using the impact factor, citations, review process, and period. The authors explored notable journals, reports, books, and conference processing to search for appropriate papers and accordingly picked out 165 relevant articles. A review, analysis, and critical discussion related to HESS-incorporated RES, including an overview and comparison of the main ESS features, the trend of energy storage growth, design, structure, classifications, benefits, applications, control, and optimization methods in different applications along with issues and challenges, were conducted using the above-said 156 articles.

### 3. Overview of Energy Storage-Integrated RE

#### 3.1. Overview

In order to store electrical energy, especially the harvested energy from RE, ESS structures use several different storage technologies. The most common forms of energy storage used in renewable energy, power systems, and MGs are illustrated in Figure 3 [25]. The categorization of different electrical energy storages, the energy conversion process that those storages use, and the efficiency of those systems was investigated in [30]. It is commonly approved that batteries are among the most effective and crucial tools for maintaining the stability of electrical networks [31]. In terms of RE integration, the essential battery types used are lithium-ion (Li-ion) which dominates the market, zinc–bromine (ZnBr), lead acid, nickel–cadmium (Ni-Cd), and vanadium redox battery (VRB), as shown in Figure 3 [25,31]. In addition, flow batteries could be the perfect complement to lithium-ion batteries to back up the RE transition. Based on the review conducted in [32], the iron–chromium redox flow battery is considered the first true RFB and utilizes low-cost, abundant iron

and chromium chlorides as redox-active materials, making it one of the most cost-effective energy storage systems.

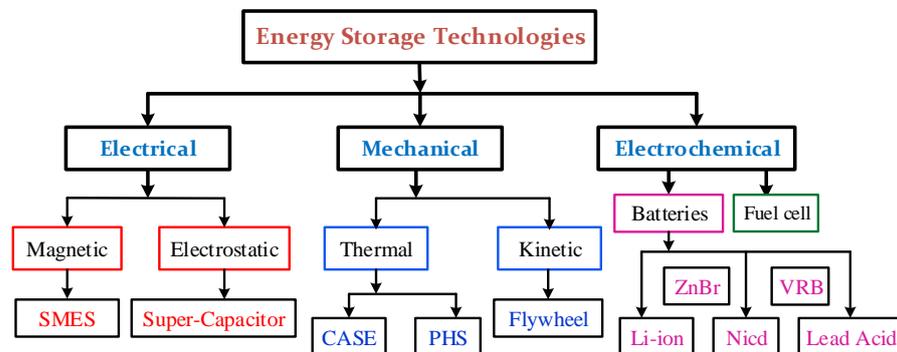


Figure 3. Classification of common forms of energy storage used in renewable energy.

Several storage techniques are considered in the literature depending on the type of energy source; for instance, electromechanical energy storage is provided by a flywheel energy storage system. Electrostatic storage with a high-power density and a high degree of recyclability are known as supercapacitors (SCs). One of the few direct electric energy storage techniques is superconducting magnetic energy storage (SMES). Compressed air energy storage (CAES) and pumped hydro storage (PHS) are thermal-based energy storage methods suitable for large-scale energy storage and support RE integration [33]. Fuel cells are electrochemical devices that convert the chemical energy stored in a gaseous or liquid fuel, e.g., hydrogen, methane, methanol, ethanol, and others, directly into working electrical energy (direct current electricity) [34].

3.2. Brief Comparison of Main ESS Features

The most significant factors that should be considered when selecting the required type of ESS and the related technology are the storage capacity, power and energy densities, operating life, efficiency, cost, response time, operational constraints, and systems for monitoring and control [35]. As mentioned earlier, energy storage methods are distinguished by several key features; two of the main factors are power density and energy density. Figure 4 displays and compares the power density in watts per liter (W/L) and the energy density of various types of energy storage in watt-hours per liter (Wh/L). As shown in Figure 4, none of the present storage solutions can simultaneously meet both energy and power density. Thus, because of current storage technology drawbacks, an HESS is frequently required to improve the operation of a storage system in RE applications.

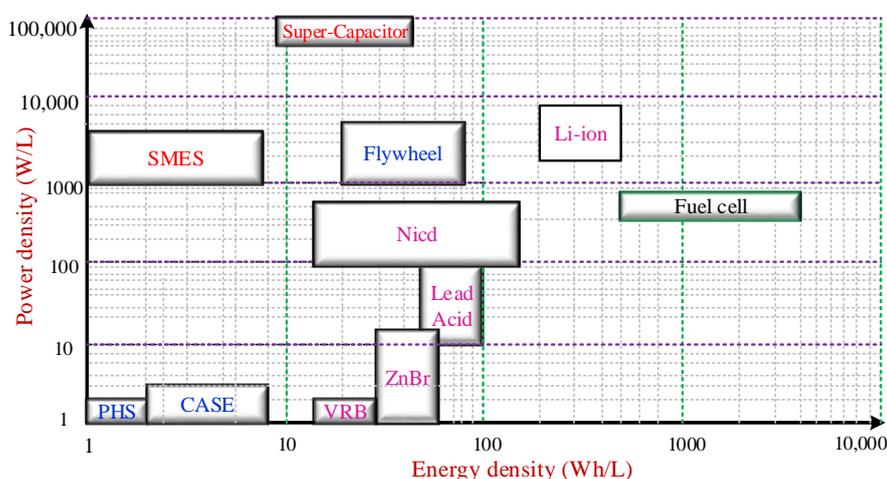
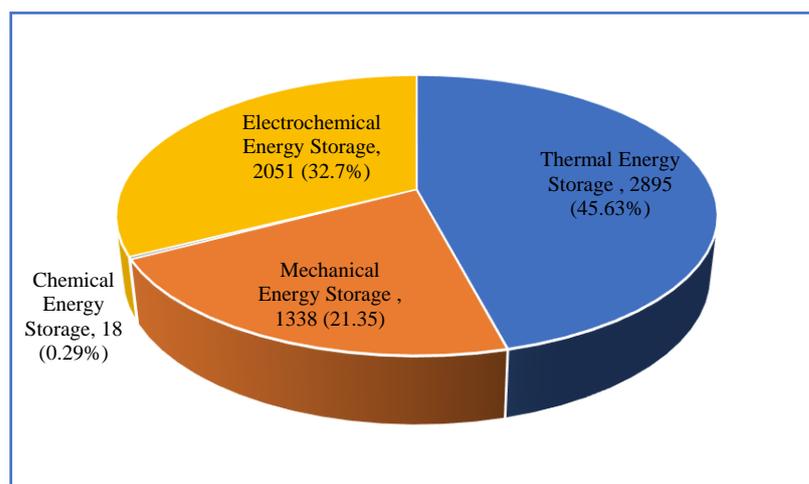


Figure 4. Classification of common forms of energy storage in terms of power and energy density.

At the moment, around 96% of the world's total installed ESS capacity is provided by pumped hydro energy storage (PHES), while the remaining 4% of the capacity is vested in other forms of energy technology. Figure 5 illustrates the capacity of several energy technologies other than PHES [35]. In this work, as much information as possible was taken from the literature about each main energy storage option utilized for RE integration in terms of energy density, efficiency, energy capacity, capital investment costs, run time, lifespan, response time in cycles and years, maturity, and self-discharge. This information is summarized in Table 1.



**Figure 5.** Capacity for the grid-connected operation of various types of energy storage systems.

A comparison of different features of the main ESS is provided in Table 1. It can be seen from the table that flywheels, SMESs, and SCs have the fastest response times and the highest maximum efficiency. However, because they have short operating times, they also have some of the highest capital costs in \$/kWh. By a wide margin, PHS systems offer the biggest capacity, but they are also among the available storage alternatives with the least energy density. PHS, underground compressed air energy storage (CAES), and fuel cells are the types of technologies capable of supplying a continuous source of electricity for at least 24 h. CAES and PHS have the lowest cost of delivered energy and the lowest investment risks in terms of the cost per kW/h of energy produced compared to combined cycle gas turbines (CCGT) [36]. However, they are costly to site and construct, take a long time to build, are appropriate for large scales only [37], have a low energy density [38], and often result in long power transmission distances [39]. Fuel cells are devices that directly convert chemical energy into electrical energy through the reaction of fuel and oxygen. The products of the reaction are electricity and water. Fuel cells have a high energy density. However, they have the highest initial cost and low energy conversion efficiency [40]. A detailed comparison of all ESSs is detailed in Table 1.

**Table 1.** Comparison of different features of the main ESS.

Category	Capacity (MW)	Efficiency (%)	Lifetime		Run Time (ms/s/m/h)	Energy Density (Wh/kg)	Self Discharge (Per Day)	Charge Time	Response Time	Envi. Impact	Refs.
			Cycle	Year							
SC	0.3	90–95	$>1 \times 10^5$	20+	ms–60 m	2.5–15	20–40%	Seconds	Very fast (<4 ms)	Small	[5,38,41–44]
Flywheels	0.25	93–95	$>1 \times 10^5$	$\approx 15$	ms–15 m	10–30	100%	Minutes	Very fast	Benign	[5,26,38,41–43]
PHS	100–5000	75–85	$>13 \times 10^3$	40–60	1–24+ h	0.5–1.5	Very small	Hours	Fast	None	[26,38,41–43,45]
CAES above ground	3–15	50	$>13 \times 10^3$	20–40	2–4 h	-	Small	Hours	Fast	Moderate	[36,38,42]
CAES under ground	5–400	70–88	$>13 \times 10^3$	20–40	1–24+ h	30–60	Small	Hours	Fast	Large	[38,44,45]
SMES	0.1–10	95–89	$>1 \times 10^5$	20+	ms–8 s	0.5–5	10–15%	Minutes to hours	(<3 ms) Very fast	Moderate	[38,41,42,44]
Fuel cells	0–50	20–50	$>1 \times 10^3$	5–15	8–24+ h	800–1000	$\approx 0$	Hours	(<1 s) Good	Small	[5,26,38,40,42,43,45]

Table 1. Cont.

Category	Capacity (MW)	Efficiency (%)	Lifetime		Run Time (ms/s/m/h)	Energy Density (Wh/kg)	Self Discharge (Per Day)	Charge Time	Response Time	Envi. Impact	Refs.
			Cycle	Year							
Li-ion	0.1	85–90	$4.5 \times 10^3$	5–15	m-h	75–200	0.1–0.3%	Hours (2–4)	Fast-ms	Moderate	[5,38,44,45]
Ni-Cd	0–40	60–65	$3 \times 10^3$	10–20	s-h	50–75	0.2–0.6%	Hours	Fast-ms	Moderate	[5,38,43,45]
Lead Acid	0–40	75	$2 \times 10^3$	5–15	s-h	30–50	0.1–0.3%	Hours	(<20 ms) Fast	Moderate	[5,26,38,41,43]
VRB	0.03–3	75–85	$>1 \times 10^4$	15–20	s-h	10–50	Small	Hours	Fast-ms	Low	[43–45]

### 3.3. Trend of Energy Storage Growth

The capacity of grid-connected energy storage for top countries all around the world is shown in Figure 6. According to the latest report of the international energy agency (IEA) [46], the adequate capacity of installed energy storage is expected to reach 450 GW in 2050 as opposed to 180 GW in 2018. This capacity is expected to mitigate global warming by 2 degrees Celsius. This figure shows that countries with the highest energy systems are likely to have a stable medium for generating energy. China's installed capacity currently exceeds that of any other country. Pumped hydro storage accounts for the majority of China's installed capacity [30].

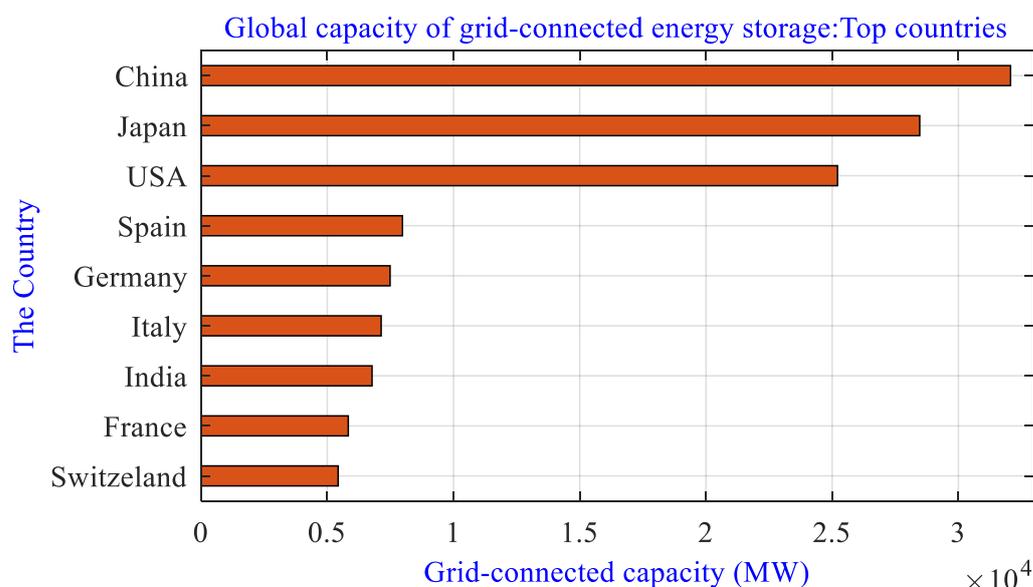


Figure 6. The capacity of grid-connected energy storage for top countries all around the world.

Based on the IEA's latest report, as of the end of 2020, the total installed battery storage capacity was roughly 17 GW. In 2020, compared to a disappointing 2019, installations increased by 50%. In the same year, 5 GW of storage capacity was added globally, with China and the United States leading the way with gigawatt-scale installations. Grid-connected-scale installations remain dominant in the industry and account for about two-thirds of the total capacity that has been added [46]. Figure 7 shows the yearly energy storage additions per country from 2015 to 2020. By 2026, installed storage capacity around the globe is expected to increase by 56% to over 270 GW [47]. The primary factor driving this market is the need to fully use and integrate bigger shares of various renewable energy sources (RESs) into power systems. As a result, there is a growing need worldwide for more system flexibility and storage capacity that HESSs can achieve.

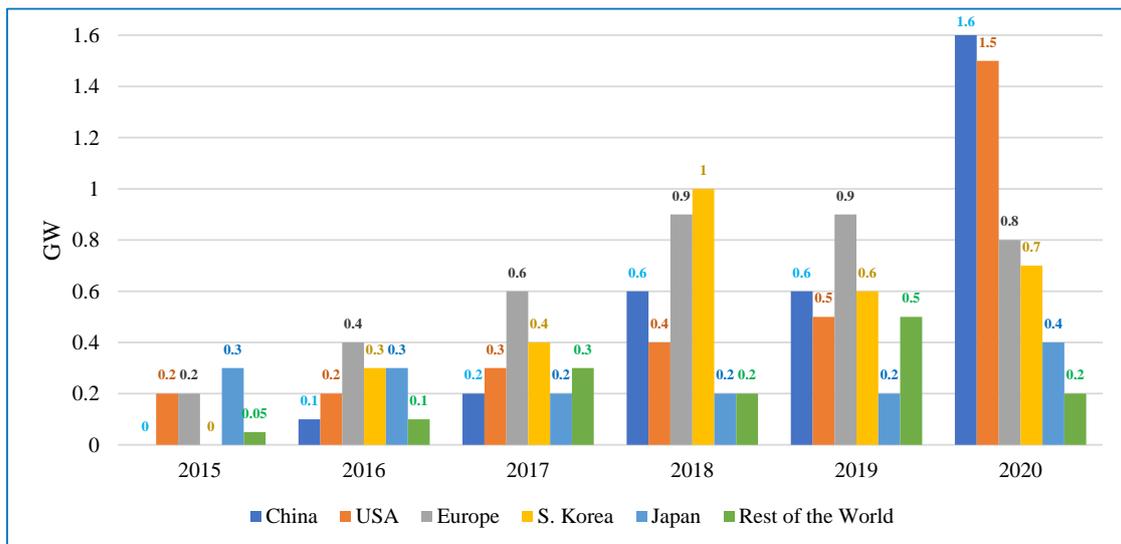


Figure 7. Energy storage additions per country from 2015 to 2020 [47].

#### 4. Hybrid Energy Storage: Design and Classifications

In general, an HESS is made up of two or more types of storage devices that work together to make it better than single-component energy storage technologies, such as batteries, supercapacitors (SCs), and flywheels. HESSs have recently garnered extensive application prospects in various contexts, including renewable energies, smart grids, MG, electric automobiles, and ships. Compared to single energy storage devices, the harmonic integration of hybrid energy storage technologies offers improved overall performance concerning efficiency, reliability, financial profitability, and lifespan. This is the case because the integration of multiple dynamic energy storage technologies improves overall performance, as proved by [25].

##### 4.1. Classification

Based on the objective of hybridization, various storage technologies could be employed as HESSs. In general, an HESS is made up of at least two components: high-energy storage (HES) and high-power storage (HPS). The HPS is responsible for delivering or absorbing peak and transient power whereas the HES is responsible for meeting long-term energy needs [48,49]. The typical structure of an HESS is shown in Figure 8. The HES is represented by energy storage one (ES1), and the HPS is represented by (ES2). Because ES1 is specifically designed to handle high power demand, transients, and rapid load variations, it has a quick response time, long cycle lifespan, and high efficiency. On the other hand, ES2 prefers to be the storage technology characterized by high storage energy, a low rate of self-discharge, and lower costs (Table 1).

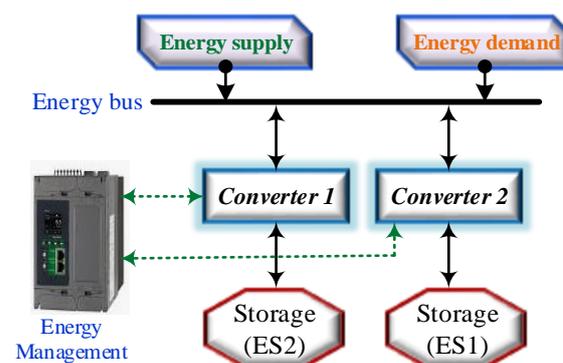
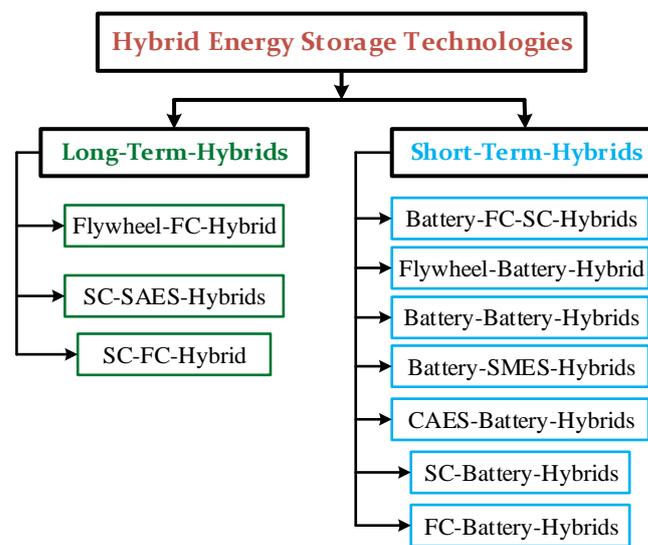


Figure 8. The basic architecture of HESS.

HESSs offer numerous advantages to RESs and MGs; among the most important ones are overall system efficiency improvement, system cost reduction, and increasing the ESS's lifespan [50]. As discussed in Section 2, because there are many different types of energy storage technologies, each of which has unique features, a wide variety of energy storage hybridizations are possible. Figure 9 illustrates how multiple storage systems can be combined to provide various functions in various RE applications [51]. Based on the studies conducted in [25,51–54], the SC/battery, battery/SMES, flywheel/battery, battery/FC, SC/FC, FC/flywheel, and CAES/battery are the types of hybrid energy storage systems that are most frequently used in RES applications. It is important to mention that choosing proper HESS combinations is contingent on a wide range of factors, such as the hybridization targets of the storage, the costs of the storage, the geolocation, and the availability of storage space.



**Figure 9.** Different methods for storage hybridization with RE systems.

#### 4.2. Design and Structure of Hybridization

The design of an HESS is one of the most important phases in renewable energy systems including an adopted hybridization structure. The hybridization structure has a significant impact not only on the energy management and control approach but also on a wide range of features, including efficiency, flexibility, modularity, and cost. As a result, as of now, the majority of the proposed hybridization structures have been altered in order to accommodate a certain control and energy management method [55,56]. Numerous structure designs have been proposed for hybridizing ESS technologies, ranging from straightforward and inexpensive to intricate and expensive. As depicted in Figure 10, the accessible data on the proposed structures were collected from the literature and grouped into three types: active parallel, cascade, and passive parallel. These structures enable an HESS to connect to RES via employing the combination of ES1 and ES2 (either HPS or HES). The following includes a description of these architectures along with their advantages and disadvantages [9,25,26,57,58]:

##### 4.2.1. Passive Structure

The passive parallel design, which is also known as direct parallel, is illustrated in Figure 10b. This structure is just to link the two ESS technologies that have the same voltage with no power electronic device in between them. The simplicity, ease of implementation, and absence of control or power electronic converters are advantages of this topology. These benefits combine together to form the so-called “lowest cost structure”. However, it has several flaws, which can be summarized as follows [25,26,57,59–61]:

- The structure is not protected against HPS or HES faults, so if one fails, it could affect the other one and bring the whole system down.
- The distribution of current between the HPS and HES is uncontrolled and is solely determined by voltage-dependent parameters.
- The nominal voltage selection of the ESSs is inflexible.
- Charge and discharge affect the output voltage of the system. The voltage fluctuation of one ESS restricts the amount of current that may be drawn from the other ESS.

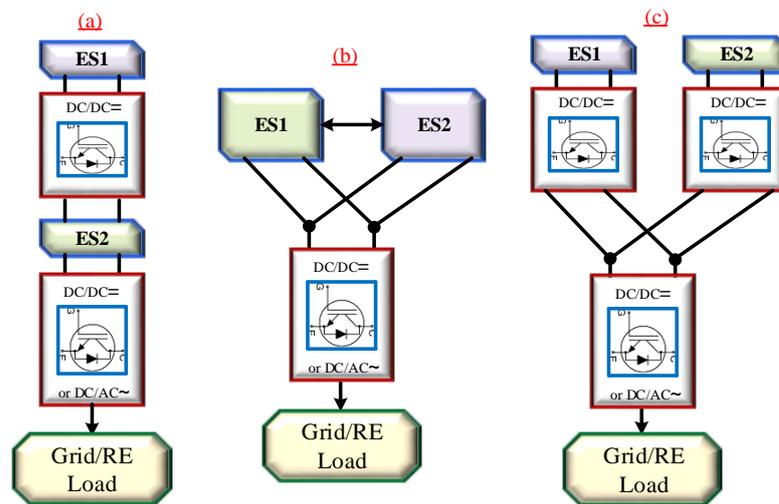


Figure 10. Structure of ES hybridization: (a) cascade, (b) passive (direct) parallel, and (c) active parallel.

#### 4.2.2. Cascade Structure

Placing a converter between the HPS and HES, as shown in Figure 10a, is more efficient but expensive. To pave the way for active energy management, the cascade structure (Figure 10a) offers decoupling of the ESSs. In this regard, the first power converter is responsible for controlling the power output of ES1, enabling its voltage to fluctuate, while ES2 is in charge of meeting the load's remaining power requirements [62]. In order to prolong the total system's lifespan, the ESS with more significant voltage variations and high sensitivity is typically designated as ES1 and the other as ES2. However, the cascade structure includes some drawbacks, such as [57,62,63]:

- The lack of flexibility in the control strategy is one of the most prominent downsides of this structure.
- As the number of power conversion steps rises, the cascade topology suffers from increased conversion losses, which limits its ability to scale.

#### 4.2.3. Active Structure

Finally, researchers have developed the active structure shown in Figure 10c. In this structure, each ESS is connected to its own power converter. Compared to the two structures discussed earlier, this topology demonstrates a level of flexibility that is definitely superior to the other two. Having a converter that is specifically designated for each ESS provides several benefits, including [9,57,58,64,65]:

- Each ESS is able to function at its own particular voltage, which enables the particular energy (for HES) and power (for HEP) to be optimized, making use of the most advanced technology that is now available.
- There is the potential to perform maximum power point tracking for each source.
- Because there are always two power conversion steps between every ESS and load, the scalability is higher, and there is no increase in the power conversion loss with increasing heterogeneity.

- Implementation options are available for a wide range of energy management and control systems.
- Because the failure of one source does not prevent the operation of the second source, the system's stability has also been strengthened.

It has been suggested to use multiple input converters [66,67] to reduce overall system costs. In contrast, the use of two independent power converters for each ESS can increase the cost. This is the only major disadvantage of this structure.

#### 4.2.4. Structure Comparison of HESS-Integrated RESs

To obtain an efficient hybridization between ESSs, the appropriate selection of the structure plays an important role in this regard. This is because the structure of the HESS has a direct impact on the energy management approach. The passive type lacks direct storage power control. In the cascade type, one storage's output power is uncontrollable, and the other's voltage should match the DC bus. The active topology manages the input or output power of both storages properly but at the expense of efficiency. Thus, efficiency, controllability, cost, complexity, and flexibility are the main factors that should guide topology selection. Based on the literature, a comparison between these operational factors of HESS structures is shown in Figure 11. It can be seen that the active structure has the highest flexibility and controllability, but it comes at a high cost and complexity, and it has low efficacy. The cascade structure has low controllability at a lesser cost. The passive structure is cost-effective and simple, but it is uncontrollable.

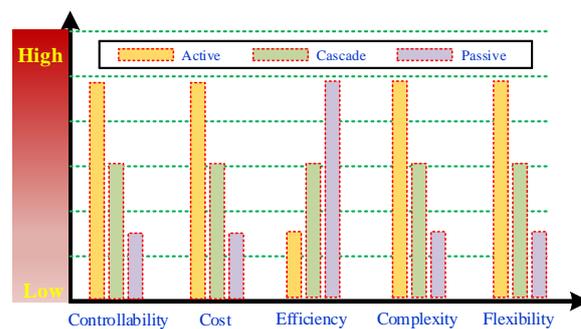


Figure 11. The comparison of various hybrid storage architectures.

## 5. Emerging of HESS in Renewable Energy Systems: Applications and Benefits

There has been a large growth in several countries worldwide in installing renewable energy sources, and this trend is anticipated to continue in the near future [4]. The annual capacity additions for RESs achieved a new high record in 2021, rising by 6% from the previous year. It is anticipated that the capacity of RESs will expand by more than 8% in 2022 [1]. Solar PV and wind are the most advanced RESs widely implemented in numerous regions worldwide [1,68]. RESs, including wind and solar energy, on the other hand, generally require ESSs due to their inconsistent availability. In addition, they have concerns, such as instability, poor power quality, imbalanced load, frequency control, and intermittent operation, among other problems. The ESS in a typical RE system goes through a charging and discharging pattern that is typically irregular and frequent. This pattern shortens the ESS's lifespan, which causes the cost of replacing the ESS to rise dramatically [69]. The use of HESSs is an appropriate solution to the problems that RESs present. In recent years, a considerable amount of research has been carried out with the objective of establishing the beneficial impact that HESSs have on RES, which can be summarized in the following subsections.

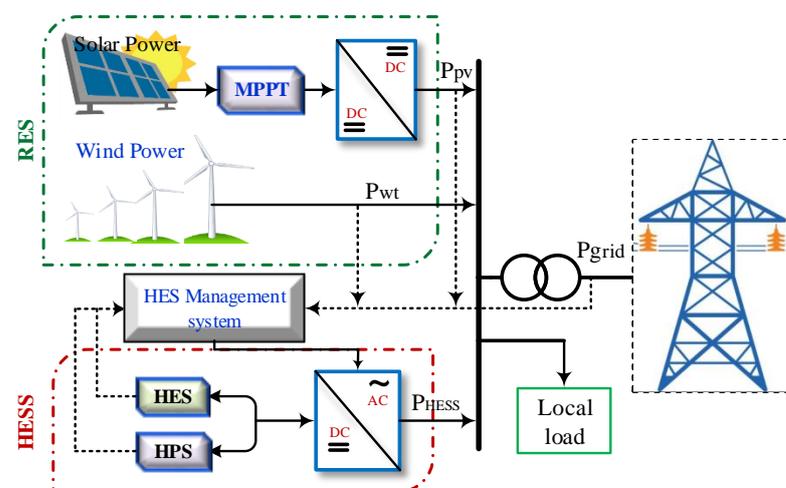
## 5.1. Benefits

### 5.1.1. Power Quality Improvement

Power quality (PQ) refers to the power system's ability to provide clean, stable power; constant power flow; high availability; and pure and noise-free sinusoidal within the acceptable frequency and voltage limits [70]. In this regard, ESS technologies can provide an improvement in PQ with a quick response time, high cyclability, and affordable cost. As each ES technology has its drawbacks, HESSs have gained great attention recently to improve PQ. All of the aforementioned features may be found by the compensation of SCs/flywheels/batteries [71], SMESs/batteries [72], SCs/FCs [73], FCs/batteries [74], fuel cells/batteries/hydrogen electrolyzers [75], and SCs/batteries [74]. Generally, a fast response that includes a discharge time of up to 10 min, transient stability, and millisecond responses are required to mitigate PQ issues using ESSs [45]. Based on [45,71,73,76], the typical power rating in this application is lower than 1 MW for CSs, between 1 kW and 10 MW for flywheels, up to 1 MW for SCESs, and from 1 MW to 10 MW for SMESs.

### 5.1.2. Intermittence Improvement of Renewable Systems

HESSs can be used to help solve some issues related to power fluctuation in different energy sources, such as wind or solar energy, as proved by different research [77–79]. Compared to a single ESS, the HESS provides better smoothing because it combines low- and high-speed responses. For instance, an HESS consisting of a CAES and flywheel was optimized in [79] to mitigate the power fluctuations of wind farms with an average capacity of 25.5 MW. The results show that the HESS could stabilize the wind power with variability within an average of 25.55 MW to a stable electrical power output of 24.18 MW. An HESS consisting of both a battery (VRB) and SC was presented by [80] to smooth the variable output power of a grid-connected 1 MW solar PV power plant. In [81], a control strategy for an HESS consisting of a battery/SC was applied to smoothen the PV power fluctuations. Simulation findings indicate that the applied control to the HESS could more effectively smooth out power fluctuations than using an HESS without a controller. Battery/SC hybridization was also used to tolerate power fluctuations in grid-connected RE microgrids [82] and in DC MGs [83]. An illustration of one possible application of HESSs for power fluctuation reduction in a grid-connected PV and wind system is provided in Figure 12. It can be seen that the HESS is made up of the HES and HPS, which smooth out power fluctuations at both high and low frequencies.



**Figure 12.** HESS for the improvement of the RES intermittent.

### 5.1.3. Frequency Regulation

The significant penetration of RESs into an electrical system would greatly lower the system's inertia—jeopardizing the power system frequency and making the potential for

system crashes and blackouts [84]. Thus, an HESS can be used to regulate the frequency, resulting in smooth RES integration. The authors in [85] have proposed a novel use of an HESS with an SMES/battery to control the frequency in the MG. The simulation findings reveal that the MG with the HESS performs superior frequency stabilization than the traditional MG and the battery-only MG. A battery/SMES was also proposed by [86], and the results proved that the HESS reduced the frequency deviation more effectively than the SMES alone. A fast frequency response control was achieved in [87] by an HESS consisting of an SC and BESS in low-inertia DC/AC systems. Enhancing the frequency response of 60 MW wind farms according to the UK grid code using HESS (VRFB battery/SC) was introduced in [88]. It was found that utilizing an HESS improved the frequency stability over using no storage or a single ESS. An SC/battery HESS was used in [89] for frequency control following fault occurrence. The proposed hybridization increased transient system stability after grid faults and primary frequency response under load fluctuation and generating interruption. A battery/SC hybridization was also used in [78] for the same purpose. It was concluded that the HESS improved the frequency fluctuations compared to using no storage or only one storage.

#### 5.1.4. Pulse Load

Pulse loads require a high instantaneous power with low average power. When a single energy source is applied to pulsed power loads, it can cause thermal and power disturbances [25]. Based on the studies conducted in [90–92], in the case of an ESS with high power density linked to the system, numerous advantages were realized, such as (a) lessening in the volume and weight of the system; (b) lessening the frequency fluctuation; (c) lessening the voltage deviation; and (d) removal of thermal concerns. In [93], an HESS (battery/SC) was employed with a real-time control method to improve an MG with high redundancy and significant pulse load. During transient periods, the SC bank was employed to supply the pulsed load and support the grid. The results reveal that by utilizing this control method, the generator's frequency fluctuation was prevented, and system performance was improved. In [91], lead-acid/li-ion/SC were utilized to supply multiple pulsed loads. The results reveal that this HESS provided a cost-effective method for managing different ES forms that serve multiple pulsed loads. The authors in [92] have concluded that the best HESS to serve under pulsed loads is a battery/SC. The results reveal that by utilizing this hybridization, the power loss was only 36% of what it was with the battery alone, the number of cycles went up by 70%, the battery's capacity loss was reduced by 60%, and its internal resistance was raised by 83%. However, the battery's service life is severely impacted by pulsed loads. The effect of pulsed demand on battery longevity was performed in [94].

#### 5.1.5. Peak Load Shaving

As the name suggests, peak shaving systems will shift the produced energy from the peak demand to off-peak hours. In other words, when RE production is abundant, the energy is stored and supplied to the grid when demand is high, as shown in Figure 13 [42]. The ESS must be scalable and capable of supplying energy for several minutes to several hours. However, using only one type of ESS may lead to some problems in terms of efficiency, stability, reliability, and cost [95]. Thus, to achieve optimal peak shaving, the HESS plays an important role in this regard [96]. PHS, CAES, flow batteries, electrochemical batteries, and hydrogen FC are currently the most suitable technologies [90]. Hybridization between an FC and battery is the most used HESS for load-shaving purposes [90].

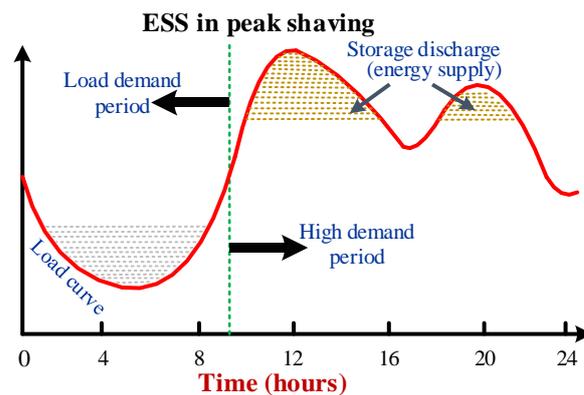


Figure 13. The load profile of energy storage used in peak shaving.

#### 5.1.6. Unbalanced Load and Harmonics

Unbalanced load and harmonics are severe issues that appear with RE power generation. In [97], an HESS with a battery/SC was proposed to enhance multiple RE generation performance under an imbalanced load. The results display that when the HESS was used under unbalanced load situations, it resulted in fast and accurate voltage regulation. An FC/battery was introduced in [98] to balance the load on grid-connected and off-grid states by intelligent battery discharging/charging and FC operation. The load of PV–wind DC microgrids was balanced under different scenarios of unbalanced load using a hybridization of battery/SMES [99]. In [100], CAES/flywheels were also used for the same purpose at various levels of wind power penetration and showed superior performance. RESs are typically equipped with multiple power electronic devices that generate harmonics in the system. However, there is no publication found that emphasizes the ability of an HESS to mitigate or limit harmonics generation.

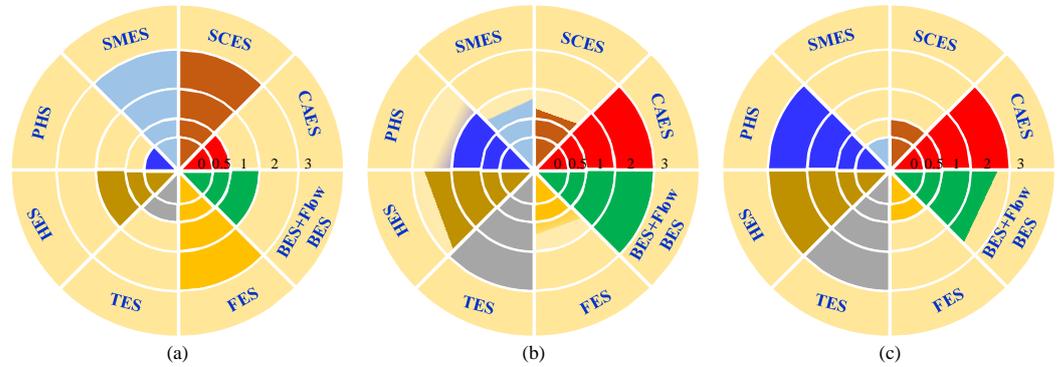
#### 5.2. Applications

Generally, an HESS is capable of providing all of the applications that a standard energy storage unit does. The exceptional features of HESSs enable them to be used widely compared to single ESS units. HESSs can improve multiple applications with a single ESS unit. They are ideal for transport and utility applications and can affect the acceptability of technology, such as vehicle-to-grid (V2G). HESSs are proposed and used as an energy source device in a variety of applications, such as grid-connected RE systems, standalone RE systems, MGs, rural electrification, water pumping, agriculture, water desalination, etc.

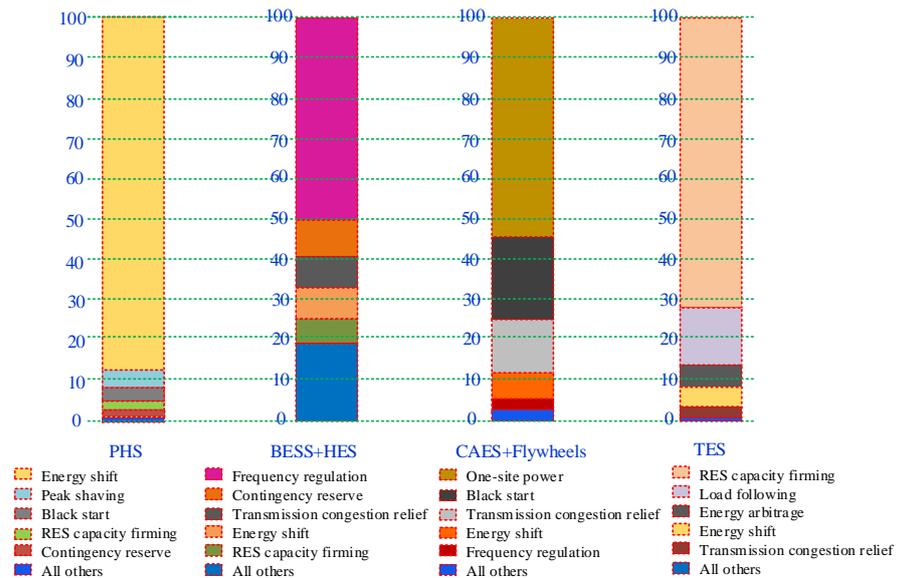
In grid-connected RE systems, it is vital to obtain a fixed amount of power injected into the grid. However, due to the intermittent nature of renewable energy, obtaining a constant value is almost impossible. Therefore, a combination between RESs and HESSs can solve this issue using RE capacity firming [49]. RE capacity firming entails using energy storage facilities to support RE production, so the total output is somewhat constant and firm. ESSs utilized in capacity firming of RESs must have a short discharge period and a power rating in the MW range. For RES capacity firming, the preferred alternatives are CAES, PHES, BESS, and thermal energy storage (TES) [35,49]. Electrochemical energy storage systems play an important role in diverse applications, such as electrified transportation and the integration of renewable energy with the electrical grid. In this regard, an overview of the current developments in mathematical models for lithium-ion batteries, lead–acid batteries, and SCs is presented in [101].

From the preceding explanation, it is evident that various ESSs are appropriate for various applications, and no single device can meet all the criteria of RESs integrated into the power system. Normally, the applications are frequently classified based on discharge length, energy management (long term), bridging power (mid-term), and power quality (short term). Figure 14 depicts the appropriateness of several ESSs according to their characteristics described in Section 2. In addition, the global power capacity share by type

and application of ESS is depicted in Figure 15 [102]. Further, the emerging applications of HESS for grid-connected RESs, standalone RES systems, MG, V2G, water desalination, and agriculture-based RE power are summarized in Table 2.



**Figure 14.** The ESSs’ suitability for various applications. The appropriateness level ranges between 0 (least suited) and 3 (most suited): (a) applications relating to power quality; (b) applications of bridging power; and (c) applications for energy management.



**Figure 15.** The global capacity of power shares by type and application of ESS by the end of 2021 (data come from previously conducted research [102,103]).

**Table 2.** Recent HESS application in renewable energy generation management.

Hybrid Storage Technology	Application	Energy System	Main Advantages/Findings	Year	Ref.
FC/SC	Power quality	MG including Hybrid PV HESS	The HESS provided a higher power response and offered energy balance during load transition, thus improving power quality and efficiency.	2020	[104]
Battery/SC	Techno-economic design	Standalone solar PV and wind	The HESS improved the dynamic system performance, kept the power balance between system parts, controlled the DC bus voltage, and kept the load voltage and frequency stable throughout various weather instabilities. SC/lead–acid batteries are more efficient than battery only.	2021	[105]

Table 2. Cont.

Hybrid Storage Technology	Application	Energy System	Main Advantages/Findings	Year	Ref.
Flywheel/Battery	Peak-shaving and dynamic behavior	Microgrid	This HESS reduces peak current by 58% and 30% less transient time. The flywheel offers peak-shaving functions for both the battery and the grid. Increased the lifespan of the battery.	2020	[106]
Battery/SMES	Pulse load	Grid-connected solar PV	The load pulses is mitigated. Regulates the DC voltage.	2019	[107]
Battery/SC/FC	Frequency control	Power grid-storage-ship	SC handled the high-frequency portion of the power load; battery life is extended. Stabilized the frequency.	2020	[108]
Battery/SMES	Stability during different events	PV-wind DC microgrids	Hybridization of SMES and battery has enhanced the MG stability during various events like wind fluctuation, shadow, and sudden outage of PV.	2021	[99]
Battery/SMES	Improve voltage profile	Grid-connected PV-wind system	The voltage fluctuations have been mitigated during symmetrical and asymmetrical faults. Secure and withstand the influence of grid-connected hybrid wind-PV power system voltage variations.	2022	[72]
SC/Battery/CAES	Frequency stability and optimal sizing	PV-wind in MG system	The CAES, Li-ion battery, and SC dealt with the source-load differential power's low, intermediate, and high frequencies. The cost of the PV-wind HESS was superior to the PV-wind-Li-ion battery system.	2022	[109]
Battery/FC/SC	Power quality and power-sharing	Microgrid	Regulated voltage and frequency, optimal power share during disturbances, and enhanced the dynamic response of the microgrid.	2021	[110]
CAES/Flywheel	Mitigate wind power fluctuations	Wind system-connected grid	The power fluctuation is mitigated, and the percentage of wind energy associated with the grid rises to 93.4%.	2018	[79]
FC/Flywheel	City transit buses efficiency improvement	Electric bus	The suggested hybrid power unit allows for overall power output for the FC stacks that more closely matches road power demands, improving system energy efficiency.	2020	[111]
Battery/FC	Optimal voltage of direct current coupling	Standalone PV system	It has been discovered that an on-off couple with a voltage range of 49–51 V presents the best transition period, indicating that the FC and the batteries are well harmonized.	2021	[112]
Battery/FC	Desalinate seawater	Standalone Hybrid PV HESS	The best configuration for desalinating seawater is PV/FC/BS. The best size is 30 kW FC, 235 kW PV array, and 144 batteries.	2020	[113]
Battery/FC	Electric vehicle energy management	PV-FC-battery hybrid EV	Under various solar radiations and battery states, the hybridization proposed performs admirably in terms of pushing the vehicle and managing power distribution.	2019	[114]
FC-battery/SCESS	Techno-economic hybridization /sizing	Grid-independent PV system	From an economic standpoint, the FC-SCESS configuration is preferable. FC-SCESS arrangement operates better by properly regulating the voltage and maintaining an active power balance between different constituents.	2020	[115]

Table 2. Cont.

Hybrid Storage Technology	Application	Energy System	Main Advantages/Findings	Year	Ref.
Battery/FC/Stored Hydrogen	Critical hospital load sharing and distribution with load shedding	Standalone Hybrid PVHES	The electrifying of ventilator loads via RE-based DC microgrids is technically feasible. The economic feasibility of the optimum optimal system architecture of this hybrid system supplying electricity for \$ 0.186.	2022	[116]
FC/Battery/SC	Fuel economy in hybrid EV	Hybrid EV	Hydrogen consumption is reduced by 8.7% as compared to the battery alone.	2022	[117]

## 6. Control and Optimization of HESS-Integrated RES

The control and optimization of an HESS are more complicated than that of a single ESS, and they involve a lot of different properties. A complex system management plan is required to extract the highest benefits from each ESS in the HESS. The HESS structure is the most important feature guiding the control method implementation and design [118]. Several researchers have developed different control, optimization, and energy management system (EMS) strategies for the optimal operation of HESSs [25,78,81,85,108,112,119,120]. Table 3 shows the recent HESS configurations developed and controlled. Each possible architecture (Table 3) has the ability to plan different control and management procedures, as stated in Section 3 above. The recent control and optimization methods to manage HESS-integrated RES with different objectives are described in the following subsections.

Table 3. Possible chart of HESS configurations [25,78,81,85,108,112,118–120].

Storage Devices with High Energy	Storage Devices with High Power
Fuel cell	✓ Flywheel
	✓ SMES
	✓ Battery
	✓ SC
Battery	✓ Flywheel
	✓ SMES
	✓ SC
	✓ FC
CAES	✓ Flywheel
	✓ Battery
	✓ SC
	✓ FC
PHS	✓ Flywheel
	✓ Battery
	✓ SC
	✓ SMES

### 6.1. Classical Control Approaches for HESS and RE System

In order for an HESS to maximize energy efficiency, the control approach is crucial. Due to the intermittent nature of the RESs and the several objectives that must be achieved, the control approach is typically complex and must operate continually. The performance and financial feasibility of the entire system can be increased with optimal HESS control and management [121]. In general, the main classical control methods for HESSs with an RE system are rule-based control (RBC) and filtration-based control (FBC).

### 6.1.1. Rule-Based Control

RBC is attained via the formulation of a sequence of empirical and predetermined rules of the control [122]. Some work has been done to investigate RBC for HESSs [105,123–127]. The authors in [123] suggested a novel hybrid EMS combined with PV, battery, SC, and FC for remote dwellings. The suggested EMS could control the system's power balance and define the power supply for every source considering the weather condition. Ref. [124] proposed a controller of a two-layers technique for an islanded hybrid energy system-based RE system. Wind turbines, FC, battery, and electrolyzer made up this hybrid system. The power regulation and management system were the top layer, which, based on wind and load circumstances, created reference dynamic operating points for the low-level control system. According to the reference dynamic operating point, the control in low-level modified the WT, battery, and FC output power. Ref. [125] proposed a controller for SC/battery in a DC microgrid, including PV and wind systems, to overcome RES intermittency and load variation. The controller achieved that under load variation and RES intermittency; the DC voltage level never exceeded the 5% limit. RBC was also used to reduce energy losses, battery life degradation, and the cost for the HESS in [126] and to regulate the power flow, ensure power balance, and reduce the system's power fluctuation in [127]. An evaluation of HESSs based on RBC is presented in Table 4.

**Table 4.** The review analysis of the common conventional control methods for HESS integrated RE system.

Hybrid Storage Technology	Control Method	Objective	RE Source	Main Findings	Limitations	Ref.
Battery/SC/FC	RBC	EMS include: weather condition fluctuations, power balance, and power sharing	Standalone PV system	The suggested EMS can control the system's power balance and govern the power supply of every source based on weather conditions. The power regulation and power management system is the top layer, which, based on wind and load circumstances, creates dynamic operating reference points (DORP) for the low-level control system. According to the DORP, the control of low-level modifies the battery, WT, and FC output power.	<ul style="list-style-type: none"> <li>- The state of charge of the battery and SC are disregarded.</li> <li>- Bus voltage will fluctuate.</li> </ul>	[123]
Battery/FC	RBC	Power regulation, load scheduling during unfavorable wind conditions	Hybrid PV/wind MG	The controller overcame RES intermittency and achieved that under load variation, and the DC voltage level never exceeded the 5% limit.	<ul style="list-style-type: none"> <li>- The battery's lifespan will be shortened due to the continuous release and soaking up of extra current.</li> </ul>	[124]
Battery/SC	RBC	Overcome RES intermittency and load variation	PV-wind in MG system	The control strategy obtained the optimal sizing, enhanced the dynamic response, the stability of the DC bus voltage, and the load frequency/voltage in various weather and load interruptions.	<ul style="list-style-type: none"> <li>- The DC bus voltage cannot be returned to its original level.</li> <li>- Inaccurate power allocation between the battery and the SC.</li> </ul>	[125]
Battery/SC	RBC	Optimal sizing and voltage/frequency control	Off-grid solar/wind hybrid		<ul style="list-style-type: none"> <li>- There is no consideration given to the SoC level of the battery and SC.</li> </ul>	[105]

Table 4. Cont.

Hybrid Storage Technology	Control Method	Objective	RE Source	Main Findings	Limitations	Ref.
UC/Battery	RBC	Regulate the power flow, ensure power balance, and reduce the system's power fluctuation	Offshore wind/marine /UC hybrid RES	The proposed control can regulate the flow of power between the UC and the battery and ensure power balance by reducing system power fluctuation.	- The suggested method fails to take into account the UC's SoC level, which could leave the UC without adequate power for the next use.	[127]
Battery/SC	FBC	Energy management and power-sharing	Grid-connected HESS	Perform power-sharing is achieved, DC bus voltage deviation is reduced, and the SoCs of the battery and SC kept within a safe range	- Delays and failures in communication will prevent the system from operating normally.	[128]
Battery/SC	FBC	Power flow control	Remote military microgrid	Power is distributed between the battery and the SC via an LPF. Using the SC's current management mechanism, the SoC level is adjusted. Additionally, the controller can result in cost savings for MG.	- Switching between the discharging and charging modes of the SC is heavily reliant on the current gain parameter setting.	[129]
Battery/SC	FBC	Reduce degradation of the storage devices	Standalone HESS	The controller showed the ability to avert the storage devices' early deterioration by addressing the overcharge in the case of SC, deep discharge, and rapid current variations in the batteries case.	- The approach can still result in a bus voltage variation.	[130]
Battery/SC	FBC	Improving battery lifetime	Small-scale wind energy	Extends battery life by 19% while decreasing current ripple and battery depth of discharge.	- When the SC's SoC is at 100%, RE energy may still charge it.	[131]
Battery/SC	FBC	Reduce fluctuation	Hybrid PV-wind system	Wavelet-based FBC separates components that have high and low frequencies. Keeps the DC voltage steady and ensures the batteries do not run out of power too quickly.	- SC has a slow dynamic response and cannot be utilized continually.	[132]

#### 6.1.2. Filtration-Based Control

Different studies have used FBC to manage and control HESSs [128–132]. The authors of [128] presented a control and energy management technique for a grid-connected HESS in various operational modes. The proposed control could effectively share power between energy storages, dynamically share power between the grid and battery based on the SoC, more quickly regulate the DC link voltage response to the generation and load disruptions, improve PQ features in the utility grid, and reduce the rate of discharging/charging of the battery current during transient power variation. In Ref. [129], the proposed controller could manage the current of the SC and overcome the overcharge of SCs to sustain the system when drained to the lower operating limit. FBC was introduced in [130] and showed an ability to avert the storage devices' early deterioration by addressing the overcharge in the case of the SC, deep discharge, and rapid current variations in the batteries. Ref. [131] demonstrated how a battery/SC HESS can extend battery life in a small-scale wind power system using a low-pass filter (LPF)-based FBC model. The findings demonstrate that in comparison to the system with a battery-only storage system, the suggested method significantly reduces the current ripple and depth of discharge of the battery and increases battery life by 19% [131]. Wavelet transformation-based FBC is also used for SC/battery-integrated wind–PV hybrid systems [132]. Table 4 includes a critical review of different

FBC-based HESS. It is worth mentioning that the LPF, wavelet transformation, and moving average filter (MAF) are typical FBC techniques. Nevertheless, these strategies are only applicable to a single HESS (SC and battery) and not multi-HESSs. This is due to the FBC method's inability to perform proportional power distribution between multi-HESS systems. These approaches also require a communication mechanism to acquire battery and SC data. Delays in communication and single points of failure will appear. An evaluation of HESSs based on FBC is presented in Table 4.

## 6.2. Intelligent Control Strategy

To overcome the constraints of classical control-based HESS-integrated RES management systems, intelligent control approaches, such as artificial neural networks (ANN) and fuzzy logic controllers (FLC), are implemented since they are more robust and effective than the classical control strategies [29]. However, they do not ensure the highest possible level of performance. The following subsections thoroughly discuss these main intelligent control approaches for HESS-integrated RE management.

### 6.2.1. Fuzzy Logic Control

FLC is usually employed to control an HESS for energy management and different purposes. Different studies have investigated FLC for HESS management [72,115,133–140]. The authors in [133] suggested a novel hybrid EMS combined with PV, FC, battery, and SC for tourist ships. The proposed EMS was capable of optimal distribution of output power, high-frequency absorption, and fluctuation reduction. Moreover, the EMS-based FLC method saved 14.39% of the hydrogen compared to RBC, improved hydrogen utilization, preserved battery SOC consistency, and promoted energy conservation and frequency stabilization. Ref. [134] proposes FLC to handle power demand fluctuation. The proposed FLC method achieved a flat charging/discharging for the batteries compared to FBC. It also extended the battery lifetime via fluctuation reduction. FLC was applied to an HESS consisting of a battery/SC-integrated wind–diesel system for active power management [135]. The suggested EMS-based FLC for the hybrid SC/BESS mitigated the peak impact of the BESS in the presence of load and wind speed fluctuations. In [136], EMS-based FLC was presented to decrease HESS current variations, power supply probability losses, and system operating costs in a hybrid power system containing a battery/SC/FC/PV/wind system. FLC for optimal sizing and economic and technical analysis of an HESS consisting of a FC–SCESS in a PV system independent of a grid was introduced in [115]. The study concluded that the FC/SCESS arrangement is superior from the economic and technical point of view to the FC/battery. Voltage level was controlled using FLC for a flywheel/battery-connected standalone PV system by [137]. According to the simulation results, the controller supplied the critical load during islanding while maintaining acceptable voltage and frequency levels in the direction of the critical load. Table 5 provides a critical review of HESSs based on FLC. However, there is a possibility that this method may experience communication delays as well as single points of failure. In addition, FLC relies on suitable parameters in the rule base and membership functions. Typically, these factors are established through trial and error, which takes more time.

### 6.2.2. Artificial Neural Network Control

ANNs are utilized in control systems because of their nonlinear and adaptive structure and generalization abilities, and their design does not depend on system parameters [141]. ANN-based control was developed by [142] to manage an FC/battery HESS-integrated off-grid PV/wind system. The proposed method could share the power and supply the load based on the RE weather condition and showed a fast response. Efficient power-sharing and management for battery/SC integrated PV systems using ANN were proposed in [143]. The results of this control demonstrated that the controller was able to rectify the demand-generation disparity, maintain the SOC within the predetermined parameters, and manage the DC bus voltage. The optimal sharing and management of the DC microgrid

with an SC/battery HESS using ANN were also used in [144]. An ANN was applied in [145] to limit battery degradation and power losses for ultracapacitors (UC) and battery HESSs. It was also used in [146] to increase battery lifespan in an off-grid PV power plant with Li-ion batteries and SC HESS as well as to reduce the cost for battery/FC in [147]. A critical analysis of ANN control-based HESSs is described in Table 5. However, the optimal performance of ANN-based control is contingent on the number of data sets utilized in ANN training.

**Table 5.** The analysis of the common Intelligent control methods for HESS integrated RE system.

Hybrid Storage Technology	Control Method	Objective	RE Source	Main Findings	Limitations	Ref.
FC/Battery/SC	FLC	EMS: Optimal output power distribution, high-frequency absorption, and fluctuation reduction	Solar PV for tourist ship	The EMS-based FLC can save 14.39% of the hydrogen as compared to RBC, improve hydrogen utilization, preserve battery SOC consistency, and promote energy conservation and frequency stabilization.	The weather conditions are not taken into consideration. The bus voltage is not taken into account by the approach.	[133]
Battery/CAES	FLC	Handle power demand fluctuation	Grid-connected HESS	A flat charging/discharging current for the batteries is achieved. Extend the battery lifetime via fluctuation reduction.	The high demand still appears.	[134]
Battery/SC	FLC	Active power management	Wind-diesel system	The suggest hybrid SC BESS's EMS-based FLC mitigated the peak impact of the BESS during fluctuations in wind speed and load.	The method overlooks optimal battery and SC power distribution.	[135]
Battery/SC/FC	FLC	Reduce current fluctuations and operating costs	PV-wind	EMS-based FLC is presented to minimize changes in HESS current, the costs of running the system, probability of power supply losses.	The controller is very complex. No consideration is given to either the battery's SoC or SC's SoC.	[136]
FC-SCESS	FLC	Optimum sizing, economic and technical analysis	Grid-independent PV system	FC-SCESS structure is superior from the economic and technical points of view to FC/battery.	The technique for restoring bus voltage is disregarded.	[115]
Flywheel/Battery	FLC	Voltage control	Standalone PV system	The controller supplies the critical load during islanding while maintaining acceptable voltage and frequency levels.	This strategy ignores hybrid ESS deterioration.	[137]
FC/Battery/SC	FLC	EMS to obtain a stable voltage and avoid rapid changes	Power sources connected to HESS	The SC and battery SOCs are kept close to their ideal levels. The DC bus voltage is regulated.	The FC starvation problem and battery lifetime are not taken into consideration.	[138]
Battery/SC	FLC	Minimize peak current and regulate the SoC	Standalone PV system	The controller decreased the battery's peak current demand while actively checking the SCs state of charge. Has better than RBC and FBC.	Lifetime and Soc for the battery are ignored	[139]
Battery-SMES	FLC	Enhancing the power quality during faults	Grid-connected PV-wind system	The controller compensated the reactive voltage during faults.	Complex control increases the operational cost, and dc bus fluctuation appears.	[72]
FC/Battery	FLC	Overcome RE intermittence	Hybrid PV-wind system	The controller-based HESS overcame the PV and wind intermittence and supported the load with the required power.	The approach does not take into account the level of hydrogen.	[140]

Table 5. Cont.

Hybrid Storage Technology	Control Method	Objective	RE Source	Main Findings	Limitations	Ref.
FC/Battery	ANN	Optimal power-sharing based on weather conditions	Off-grid PV/wind	The method can share the power and supply the load based on the RE weather condition and has a quick response time.	The optimality is determined by the number of data sets utilized to train the ANN.	[142]
Battery/SC	ANN	Efficient power-sharing and management	Standalone PV system	The controller can resolve the demand-generation discrepancy, keep SOC within limits, and regulate dc bus voltage The controller reduced peak current and current variations and thus limited the battery wear. The power loss was also reduced as compared to only battery ES.	Increase the complexity	[143]
UC and Li-ion Battery	ANN	Limit battery degradation and power losses in HESS	Microgrid-based HESS	Minimizing Li-ion battery dynamic stress and peak current increases battery longevity.	The controller's calculations are complex and slow.	[145]
SC/Battery	ANN	Increase battery lifespan	Off-grid PV system	The HESS costs 48% less than a hydrogen-alone system and only 9% less than a battery-only system.	The DC link voltage regulation is not taken into consideration	[146]
Battery/FC	ANN	Optimal performance and cost reduction	Standalone PV system		Power-sharing and distribution as well as DC bus regulation have been overlocked.	[147]

### 6.3. Optimization Approaches for HESS with RE System

Optimization approaches have been developed to overcome the limitations of an intelligent controller such as FLC, which depends on suitable variables in the rule base and membership functions. Moreover, ANNs depend on huge data sets in their training, which increases the error possibility, complexity, and time. Thus, various optimization-based control techniques have been used to manage HESSs effectively. For instance, the whale optimization algorithm was used in [108] for frequency control and optimal sizing of an HESS containing a battery/SC/FC system. The method increased efficiency, stabilized the frequency, reduced power fluctuation to 44.2%, and improved energy savings to 5.4% compared with other controllers [108]. Ref. [109] proposed a genetic algorithm (GA) for capacity allocation and cost reduction of an SC/Li-ion battery/CAES HESS-integrated PV/wind hybrid power system. The results indicate that the PV-wind HESS can meet customers' energy needs more efficiently and at a lower cost. The authors in [148] proposed particle swarm optimization (PSO) for off-grid PV-wind power along with an HESS (battery/PHS) for cost reduction and optimal allocation. According to the findings, the PV-wind-PHS configuration is the most cost-effective choice. However, its level of reliability is inferior to that of PV-wind-battery/PHS systems. Overall, PV-wind-battery-PHS systems are more flexible, ensure a 100% power supply at the lowest possible cost, and minimize energy curtailment. PV-wind-battery-PHS systems were also optimized using grey wolf optimization (GWO) for optimal sizing [149]. This hybridization was more flexible, decreased curtailment by 290%, and had electricity costs that were 3.5 times lower than solo storage. In [150], wind power fluctuations were kept to a moderate level using simulate anneal algorithm for an SMES/battery HESS with a grid-connected wind farm. An HESS (FC/battery) linked with a PV/wind/microturbine was optimized using adaptive modified PSO (AMPSO) for cost and emission reduction in [151]. This method had quick convergence and a short computational time. The AMPSO method reduced the operation cost by 42.45%, and the minimum emission was achieved with a FC/battery and only PV/wind hybridization. A hybrid PV-wind-integrated different energy storage (SC/battery, fly-wheel/battery, PHS /battery) was optimized using hybrid PSO-grasshopper optimization

algorithm (GOA) methods for emission and cost reduction [152]. The results indicated that the SC/battery system had cut GHG emissions by 42.48% and energy costs by 12.92%. A flywheel/battery HESS lowered costs by 44% while a PHS/battery hybridization reduced costs by 51%. Ref. [153] proposed a capacity optimization algorithm to enhance system reliability and reduce cost and emissions for SC/battery integrated wind/PV in an MG system. This method concluded that the PV/wind/battery/SC was the optimal choice to increase the system reliability, reduce cost, and minimize GHG emissions compared to PV/wind/battery or PV/wind/SC.

A critical review analysis of different HESS-integrated various RE systems based on different optimization methods is detailed in Table 6 below. Typically, these strategies can attain multiobjective optimization, such as energy consumption, optimal sizing/structure, operating improvement, cost, and emission reduction. Nonetheless, as the optimization objective increases, so do the constraint conditions; hence, the computing load of the controller increases. Moreover, these procedures necessitate the development of a precise mathematical model of the system. Else, the optimization findings will be less accurate.

**Table 6.** The critical review analysis of the recent optimization methods for HESS-integrated RE systems.

Hybrid Storage Technology	Optimization Method	Objective	RE Source	Main Findings	Ref.
Battery/SC	Genetic algorithm	Optimal sizing	Standalone wind/solar PV	The proposed PV/wind turbine design with HESS selected by the proposed algorithm is superior to all other scenarios.	[154]
Battery/SC/FC	Whale optimization algorithm	Optimization of sizing and frequency control	Fuel cell hybrid ship	Power fluctuation is suppressed, and energy savings is improved up to 44.2% and 5.4%, respectively, than the original ship.	[108]
SC/Li-ion battery/CAES	Genetic algorithm	Cost reduction	PV-wind in MG system	The cost of the PV-wind HESS was superior to the PV-wind-Lithium-ion battery system at various confidence levels. The wind-PV HESS can better meet users' power demands while still being economically viable.	[109]
Battery/FC/SC	Equivalent consumption minimization (ECM)	Fuel reduction in hybrid EV	Hybrid EV	Hydrogen consumption is reduced by 8.7% compared to the control without optimization.	[117]
FC/Battery/SC	Coyote optimization algorithm (COA)	Enhancing fuel economy	Hybrid electric power	COA reduced the amount of hydrogen used by 38.8% compared to the external energy maximization strategy method.	[155]
Battery/SC	Genetic algorithm	Efficiency improvement and stable operation	Grid-connected wind power system	The method improved the energy efficiency and attained stable operation of the wind farm-connected power grid via HESS's system parameters optimization to achieve optimal allocation	[156]
FC/Battery/SC	Levy whale optimization algorithm (LWOA) and modified crow search optimizer (MCSO)	Optimal power flow based on variations in the parameters of the source side and load side	On-grid PV system	The proposed method attained optimal power flow under balanced and unbalanced load conditions. Moreover, increased the amount of energy stored by utilizing various storage technologies.	[157]
Battery/PHS	Particle swarm optimization	Cost reduction and optimal allocation	Off-grid hybrid wind/PV	PV-wind-battery-PHS systems are more flexible and ensure a 100% power supply at the lowest possible cost.	[148]
Battery/PHS	Grey wolf optimization	Optimal sizing	Off-grid hybrid wind/PV	This method permits achieving high reliability at a cheaper cost in comparison to a system using a single storage technology.	[149]

Table 6. Cont.

Hybrid Storage Technology	Optimization Method	Objective	RE Source	Main Findings	Ref.
SMES/Battery	Simulate anneal algorithm	Smoothing wind power fluctuations	Grid-connected wind farm	The fluctuations in the amount of power are kept to a reasonable level. In addition, optimal power sharing is achieved.	[150]
FC/Battery	Adaptive modified particle swarm optimization algorithm PSO	Minimizing cost and emissions	Hybrid PV/wind/microturbine	The method reduced the operation cost by 42.45%, and minimum emission was achieved with FC/battery and only PV/wind hybridization	[151]
SC/Battery Flywheel/Battery PHS/Battery	Hybrid PSO—grasshopper optimization algorithm (PSO-GOA) methods	Emission and cost reduction	Hybrid PV/wind system	With SC/battery, the GHG emissions have been reduced by 42.48% while the levelized energy cost has been reduced by 12.92%. Flywheel/battery HESS reduced the cost by 44% while PHS/battery hybridization reduced the cost by 51%.	[152]
SC/Battery	Genetic algorithm	Reduction of cost and loss of power supply	Off-grid PV/wind	Lower cost and minimum loss of power supply have been achieved with wind/PV hybrid with SC/battery compared to without HESS or single ESS.	[154]
FC/Battery/SC	Grey wolf optimization	Reduce frequency deviation	PV/wind/diesel generator	The controller has stabilized the frequency deviation at a reasonable level.	[158]
Battery/FC/ultra-capacitor	Path-finder algorithm (PFA)	Stability and reliability improvement	Grid-connected PV system	The PFA method of HESS increases the PV system's reliability and overall stability during grid-connected, isolated operations, steady-state, and disturbance situations.	[159]
Battery/SC	Capacity optimization algorithm	Enhance system reliability, minimize the cost and GHG	Standalone PV/wind as MG system	PV/wind/battery/SC was the optimal choice to increase the system reliability, reduce cost, and minimize GHG emissions compared to PV/wind/battery or PV/wind/SC.	[153]

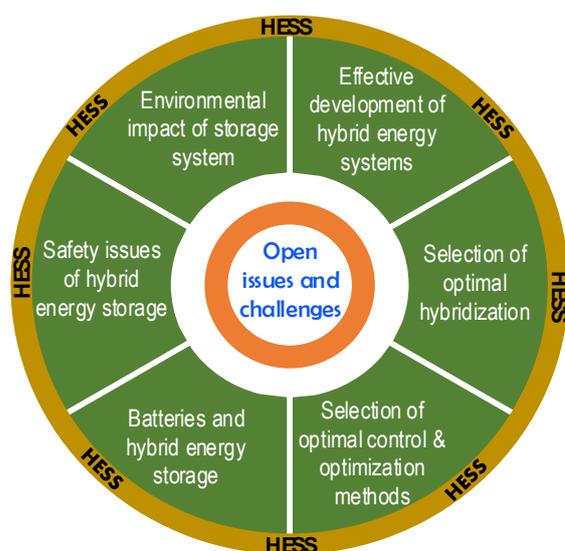
## 7. Open Issues and Challenges

Hybrid energy storage technology development can help reach 100% RE use in the future. However, it necessitates innovation and breakthroughs in long-lifespan, capacity, low-cost, low-emission, high-efficiency, and high-security ESSs. Moreover, research should focus on optimization in multiple applications to facilitate the implementation of HESSs in RE from a theoretical perspective. Additionally, to encourage the industrialization and commercialized development of HESSs, demonstration projects and rigorous evaluations should be prioritized. Standards for complete and stringent professional cohesiveness, transparency, openness, fair classification, and standards for ESS must be developed at the same time. The development of HESSs can address many of the single technologies' issues, such as efficiency, energy management, and storage capacity. The research focus is currently on efficiency, cost, safety, GHG emission reduction, and effective EMS. The subsequent sections provide a thorough summary of key issues along with recent challenges, which are summarized in Figure 16.

### 7.1. Effective Development of Hybrid Systems

Different ways can be used to build a hybrid system, but it is hard to build the most effective energy storage system. Moreover, engineers face several obstacles when working with hybrid systems, including system design, which calls for intricate modeling, simulations, and optimization to comprehend how the subsystems interact and create reliable control schemes. Thus, developing efficient, safe, environmentally friendly, and cost-effective hybridization is necessary. To minimize the system complexity and cost while providing adequate heat dissipation, parts should be integrated into predetermined

spaces; for instance, in the case of RE systems, DC–DC converters should be able to fit into the battery pack. In grid-connected RESs, electromagnetic compatibility, such as high-voltage AC cables, inverters, alternators, and controllers must be protected to guarantee low emissions. The operating condition should be considered for hybrid components to survive environmental conditions, such as moisture, dust, vibration, and temperatures. The performance of hybrid components should be equivalent to or even better than that of conventional applications to ensure dependability and resilience [112].



**Figure 16.** Main issues and challenges of HESS.

### 7.2. Selection of Optimal Hybridization

In recent years, different HESS forms have been used to enhance the overall performance of RE systems. However, due to the different properties of each energy storage device and RES, it is difficult to find a specific hybrid system for specific applications that need more investigation. Moreover, there are no standards and/or requirements for HESSs that regulate the hybridization in terms of efficiency, cost, and emissions similar to the standards applied for RE integration, for example. In addition, the sizing of each HESS combination is still governed by the efforts of researchers and engineers and has not reached the manufacturing stage. With their terrific elasticity and performance, SCs are able to store energy quickly for RE applications in difficult conditions, which batteries alone cannot do in many cases. For batteries, problems such as high cost, short life, and GHG emissions are still challenges of RE system-integrated HESSs including batteries. Thus, to overcome these limitations and provide adequate performance, supersized batteries should be developed. When hybrid applications make use of huge, expensive, and heavy battery systems, the cost will go up. For instance, in an SC/battery HESS, the SC can safely complete millions or even billions of charge and discharge cycles, thereby spanning the application's full life cycle [111]. Thus, the battery's short life is partially solved, but the cost and emissions still need treatment. In addition, the SC may suffer from the problem of self-discharge.

### 7.3. Selection of Optimal Control and Optimization Methods

As discussed in Section 6, many studies proposed different control and optimization methods to improve the benefits of HESSs, especially once integrated into RESs. These methods may include multiobjectives so that they can enhance the operation and management of HESS-incorporated RE from different aspects. However, some limitations and challenges for each method have been recorded, which need further investigation toward optimal HESS. In addition, most of these control and optimization methods are limited to simulation and experiments studies. In other words, they are still governed by the efforts

of researchers and engineers and have not reached the manufacturing stage. Therefore, concerted efforts must be made to implement these control and optimization methods to come up with a product and HESS growth in the market towards the optimal operation of both HESS and RE systems.

#### *7.4. Batteries and Hybrid Energy Storage*

It is abundantly obvious from the literature that batteries are the most often used storage devices for the majority of HESS. The short lifespan of these batteries necessitates ongoing maintenance and an increase in costs, as the batteries can only be used for a few years. According to different studies, the lifespan of batteries needs to be extended to a number of years before they can be utilized successfully in hybrid systems. In this regard, new battery technologies, such as lithium–air, aluminum, graphene, and sodium-ion, must be developed to replace present batteries with significant improvements in performance and lifespan [160]. In addition, BESSs can harm the environment. For instance, Li-ion batteries emit carbon dioxide and greenhouse gases during the production and disposal procedure [161]. Because there is a lack of standardization, every manufacturer makes its own batteries. This frequently poses challenges for RE projects that change over time because storage methods do not always meet those needs, and batteries occasionally need to be replaced.

#### *7.5. Environmental Impact*

Environmental impact studies have shown that when the amount of energy generated from RESs grows, GHG and other harmful pollutants decrease. During the manufacturing and disposal process, environmental risks arise from burning fossil fuels, magnetic fields, recyclable materials, or storage system chemicals. Therefore, the use of HESSs has reduced fuel usage and harmful emissions by integrating intermittent RESs into electrical systems. A hybrid system with FCs is a form of green technology since they emit no GHG and create hydrogen from water through electrolysis in a sustainable manner. If hydrogen generation is not dangerous to the environment, FCs are nonpolluting. However, in the case of hydrogen being created from sulfur-containing hydrocarbon gases, the chemical processes involved may harm the environment. Some of the chemical process' feeder and byproduct gases are also toxic. As a result, the usage of hydrogen in this situation is not environmentally friendly because hydrogen is produced using non-RES and still generates GHG [162]. Li-ion batteries release a significant amount of carbon dioxide and GHG during the manufacturing and disposal phases [163]. Additionally, researchers have discovered that those who work in battery manufacturing and production have a higher risk of contracting harmful respiratory and neurological disorders. These risks can be minimized by developing an appropriate battery recycling procedure to preserve virgin materials and by using less cobalt and nickel for the cathode electrodes [161]. The PHS system is favored for environmental sustainability since it has the least impact on ecosystem diversity, human health, and global warming. The lead–acid battery is the least desired system regarding human health and environmental diversity. The CAES system has a rather substantial impact on ecosystem diversity. In terms of ecosystem diversity, human health, and global warming, the PHES is the best followed by Li-ion and CAES while the lead–acid battery appears to be the least desired [164]. Therefore, a better hybridization should take all these environmental impacts into consideration, and research must be done to reduce them accordingly.

#### *7.6. Safety Issues*

For hybrid applications, energy storage system safety has become crucial. For safe and secure operations, various factors must be efficiently regulated, including the magnetic characteristics of the composites, life span, heat, short-circuit issue, over-discharging, and overcharging features of ESSs. Temperature control regulation mechanisms are required for batteries; SCs storage is plagued by a high rate of self-discharge; FCs necessitate corrosion

safety along with temperature management at low and high levels; CAES needs pressure relief valves implemented to reduce high pressure that may lead to explosions; flywheels have extremely high self-discharge rates and safety concerns about the high speed of the rotating machine, rotor failure, mechanical stress, and large rotating masses [165]; SMES requires safety concerns in terms of chemical, fire, and explosion hazards; lead–acid batteries need to be maintained on a regular basis when in use; and li-ion batteries need to be protected against over-charge and -discharge. As a result, new research can resolve these difficulties to make technology more user-friendly [31].

## 8. Conclusions and Future Direction

This study discussed the importance and the emerging role of using hybrid energy storage systems (HESSs) for renewable power towards fulfilling sustainable development objectives. The most recent studies on the application of HESS in renewable energy sources (RESs) were analyzed. In this regard, the present scenario and recent trend of HESS-integrated RESs at the global level, including the comparison of main energy storage systems' (ESSs) features, concept, design, and classifications of HESSs along with a detailed comparison, were critically reviewed, discussed, and analyzed. Moreover, the emerging role of HESSs in renewable energy (RE) systems in terms of their benefits and applications have been highlighted. The recent control and optimization methods of HESSs connected with RESs along with their pros and cons have been summarized. Finally, the open issues and the new challenges of HESS were highlighted to find the appropriate solutions toward green and sustainable energy. It can be concluded that the primary format of an HESS is the combined use of limited energy and power resources to meet RE needs. Prices for battery and SC technologies are fairly inexpensive now that they have reached relative maturity, and they are commercially available in various sizes. The battery/SC system is the most commonly used HESS, but battery/flywheel, battery/CAES, and FC/SC are less popular and need more investigation to produce thorough modeling. For standalone and grid-integrate RE systems, the battery/SC system is the most practical HESS to be used with RES from different aspects. Moreover, it is widely proposed to support PV plants with battery/SC, battery/FC, or battery/SC/FC HESSs. Additionally, the hybridization of wind–PV can be effectively supported by FC/battery HESSs. An HESS with FCs is a form of green technology because it emits no greenhouse gases and produces hydrogen from water using electrolysis. If hydrogen production is not harmful to the environment, then the FCs are clean without emissions.

The main benefits of using an HESS in terms of control and optimization in RE systems are the reduction of storage system cost, optimal power sharing, increased storage lifespan, intermittence improvement of RESs, response time reduction of RE dynamics, frequency and voltage regulation, power quality improvement, increased RE reliability, and pulse loads supply. According to the survey, storage lifespan improvement and sustainability compensation are receiving more attention, and the design technique is roughly clear. Nevertheless, the design of HESSs for power quality improvement and system stabilization is not fully addressed. There is a need for a multiobjective design strategy that sizes the HESS while taking various considerations into account. Different types of controls, classified into classical, intelligent, and optimized controllers, are used to coordinate HESSs and improve their operation with RESs. However, these methods have some drawbacks that may affect the operation of HESS and may result in instability.

In conclusion, the use of HESSs is anticipated to be a future-proof option for a variety of RE applications. However, additional development and research are required to demonstrate their viability and improve their functionality toward green energy and sustainable development. Thus, based on the review conducted, to enhance the effective improvement of HESS technologies, the following suggestions may be considered in future research:

- A novel combination of ESSs across different mediums (mechanical and thermal) will widen the options of HESSs for various applications. For instance, hybridization

of fast-responding high-power ESSs with high-energy ESSs such as CAES, thermal energy storage, and pumped hydro storage can be developed.

- An intelligent EMS controller with the superior performance of HESSs will facilitate the adoption of smart grids in the near future.
- In light of recent technological advances, universal standards for safe HESS selection and operation methods should be improved by standard-setting organizations.
- HESS technology research has slowed to a halt on a laboratory scale, focusing only on a theoretical perspective and necessitating the creation of efforts to advance the technology's commercialization and industrialization.
- The performance, dependability, and flexibility of HESS-based RE will be crucial in the novel internet of energy (IoE) strategy for future energy supply and distribution systems.
- The lifetime improvement, cost reduction, optimal sizing, mitigating power quality issues, control of the system, and peak load shifting of different HESS combinations are recommended to be compared to obtain the best combination of energy storages together.
- Novel optimization approaches can be applied in BESS sizing to achieve promising outcomes in terms of cost, capacity, power loss, power quality improvement, and carbon emission.
- Further research into the successful incorporation and operation of HESSs with different RES applications, such as water desalination, agriculture applications, artesian wells, heating, cooling, and transportation, with an appropriate optimization method is required.
- Among the various energy storage system categories, hydrogen energy storage systems appear to be the ones that can result in large changes to the current energy system. Several technological, economic, social, and political barriers need to be overcome before hydrogen technologies can be used in large-scale applications
- Developing a new control strategy for HESS using multiobjective optimization while considering economic and technological constraints remains an objective.
- In the future, the environmental constraints ought to be taken into consideration on a more regular basis, and the influence of HESSs in RE applications upon the environment ought to be measured with greater care.
- In the near future, an intelligent EMS controller would improve HESS performance. Moreover, IoE and machine learning will make it easier to use HESSs with RESs and facilitate overall system operation.
- Further research into the successful incorporation of HESSs with other current sources such as PV, wind, hydropower, and concentrated solar energy is required
- There has been insufficient study utilizing predictive controllers for HESS implementation; nevertheless, with the development of these approaches for HESSs, RE penetration may be boosted even further.
- Combining ESSs with different mediums (thermal and mechanical) in novel ways will give HESSs more options for different RE applications. For example, high-energy ESSs with fast-response high-power ESS can be combined, such as TES, PHS, and CAES.

As RESs and energy storage are expected to dominate the electricity market in the future, these suggestions may help to ensure the maturity of HESS-integrated RE systems. In addition, these suggestions may serve as a solid foundation for energy system operators, researchers, developers, and manufacturers in terms of the future development of HESSs toward optimal and cost-effective green energy.

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