

Evaluating Environmental and Economic Perspectives of Hybrid Energy Storage Systems: A Review

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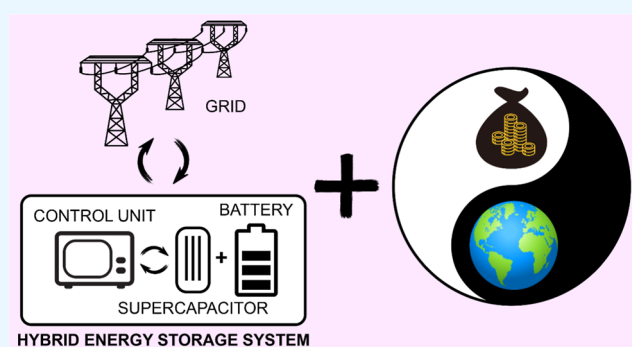
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ABSTRACT: The escalating global challenges have driven significant shifts toward cleaner energy solutions, many of which rely on energy storage technologies. However, there is currently no single energy storage technology that meets all of the application requirements. To address this, hybrid energy storage systems, which combine two or more types of storage devices, have emerged as a promising solution. To support the sustainable implementation of hybrid energy storage systems, this work provides a comprehensive overview of metrics and factors that influence their financial and environmental impacts. In addition, the article discusses the challenges, recommendations, and future directions in conducting sustainability analyses.



1. INTRODUCTION

Climate change, global warming, and energy crises are among the major challenges facing the world today.^{1,2} As a result of rapid consumption of fossil fuels, which are considered the primary origin of global warming due to the greenhouse effect and rising concentration of greenhouse gases (GHGs) in the atmosphere, a new energy revolution is coming, accompanied by the intensive development and use of renewable energy sources (RESs) and rapid development of new energy vehicles.^{3–7} One of the advantages of renewable energy is the possibility to produce it in an environmentally friendly way, for example, using solar and wind energies.^{4,8–10}

According to current research, clean energy production from renewable sources could reduce CO₂ emissions by 72% compared to production without the use of renewable power.¹ In addition, the transport sector currently causes about 14% of world's GHG emissions.¹¹ Thus, the widespread use of RESs in the power system and utilization of green transportation systems will reduce the negative consequences of climate change.^{9,11–15} In this regard, various RESs, such as solar, wind, hydro, wave, geothermal, and bioenergy, are used in many countries around the world to minimize fossil fuel depletion for electricity generation.^{2,3,5,13} In addition to RESs, modern energy systems now commonly use microresources such as fuel cells and microturbines.¹⁶ These sources are constantly evolving and expanding due to high energy demands and the rapid development of electrical technologies in recent decades.^{13,16}

A further reduction in CO₂ emissions could be achieved by using energy storage technology.¹⁷ So, the combination of

renewable energy and energy storage device (ESD) represents an effective way to achieve deep decarbonization in generation of power.^{8,17} The use of ESDs is inevitable due to the sporadic nature and seasonal variations of RESs.^{2,10,18} The volatility of RESs, e.g., wind and solar energies, adversely affects the production of electricity and thus causes fluctuations in the power supply to the customer.^{3,7,10,13} ESDs, which are required to provide economic feasibility as well as efficient conversion and safe storage of energy, are essential in electric, hybrid electric, and plug-in hybrid electric vehicles and could also address some of the issues associated with RESs.^{3,4,6,9,13,14,19–21}

Energy storage makes it possible to store excess energy at times of high production for later use and thereby balance energy demand and supply at both the grid and smaller scales, thus minimizing system fluctuations and ensuring energy security.^{22,23} Several energy storage techniques based on mechanical, chemical, thermal, and electrical energy storage principles were proposed with quite different operating characteristics and technical parameters (Figure 1).^{5,24} However, a single energy storage technology has various limitations regarding efficiency, life cycle, cost, energy and

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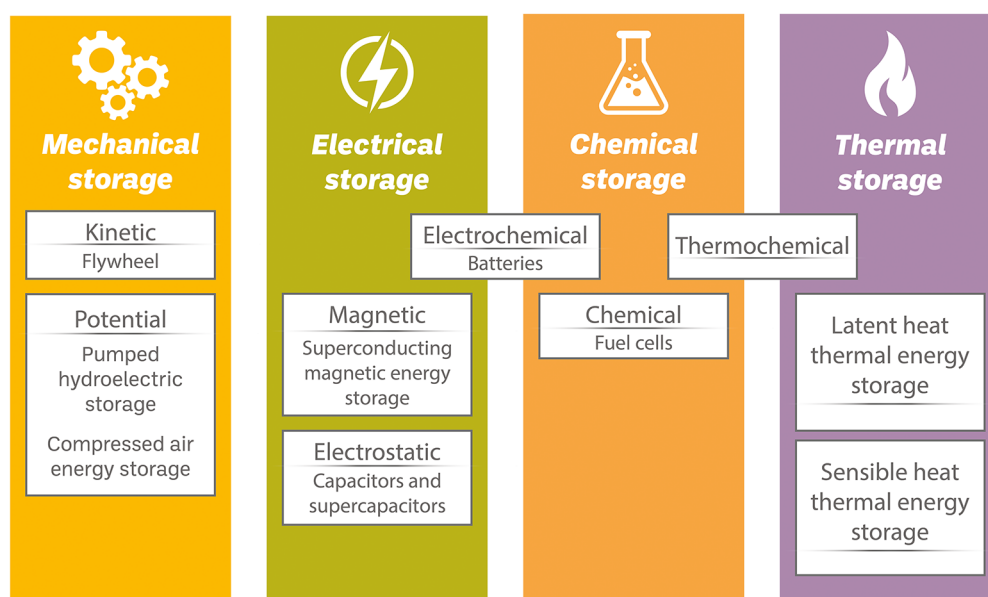


Figure 1. Classification of energy storage techniques based on the form of stored energy.^{24,26}

power density, and dynamic response and cannot perform all required operations or solve all problems of RESs.^{13,25}

The basic characteristics of energy storage technology are power and energy density. Energy density corresponds to the total energy that a system can store for a given mass or volume. Power density expresses how quickly the device can deliver energy.¹⁰ Accordingly, ESDs can be grouped as high power density (HPD) and high energy density (HED) devices. ESDs with HPD, such as supercapacitors (SCs), superconductors, and flywheels, exhibit long lifetimes and fast response speed to high power demands, which are suitable for small-scale applications where fast charging and discharging are required.^{3,11,21,23,27} However, they have limited energy density.^{3,23} ESDs with HED such as batteries and pumped-storage hydro plants usually have a relatively larger storage capacity but lower lifecycle, slow response speed, and limited power density.^{3,21,23,28}

Energy storage applications can broadly be divided into power quality applications (short term), bridging power applications (medium term), and energy management applications (long term).⁶ Due to the different characteristics and performance of each technology, there is no single energy storage technology that fully satisfies the multiple requirements of various applications.^{3,6,21,25,27} An ideal application requires both HPD and HED. In order to ensure technical complementarity, a hybrid energy storage system (HESS) has been proposed.^{3,6,10,13,21,27} The HESSs integrate two or more kinds of ESDs with supplementary operating characteristics: one ESD exhibits HED, e.g., batteries or fuel cells, and the other ESD possess HPD, e.g., SCs or flywheels.^{2–6,9,10,13,21} Thus, HESSs effectively combine complementary advantages of both high-energy storage, which meets the long-term energy demand and high-power storage, which provides the peak powers.^{7,8,10,12,16,19,25,29–31} As a result, HESS can deliver improved technical performance and environmental sustainability, increased efficiency and reliability, longer lifetime, reduced costs, and more appropriate design and sizing compared to a single storage system.^{2,5,8,13,22,25,32,33}

Recently, several promising HESS applications have been widely studied, e.g., microgrids, wind/photovoltaic power

generation systems, electric vehicles, railway, and maritime applications, as well as in the field of portable electronics and other fields.^{3,5,16,29,30,34,35} The most common HESS consists of batteries and supercapacitors.^{3,4,7,8,11,18,28,29,31,32,36} But increased attention has also been paid to hydrogen-battery HESS.^{37–45}

Although hybrid energy storage systems offer a promising solution toward achieving a sustainable future,^{6,45,46} their implementation does not automatically guarantee improved environmental performance or reduced costs. For example, Jiao and Månsson²¹ demonstrated that while adding a supercapacitor to a battery in wind-power system extended battery lifetime by 18% or 28%, depending on the battery chemistry, it also increased the total cost of the energy storage system over a 30 year project horizon by 674 EUR and 7425 EUR, respectively, relative to a battery-only wind power system. On the contrary, Bionaz et al.⁴⁰ found that the HESS-based system was the most cost-effective option for supplying electricity to an insular community, but the sea cable scenario proved more advantageous from an environmental perspective. These examples highlight the critical need for comprehensive economic and environmental assessments to determine the actual benefits of HESS integration. Such analyses allow for the identification of the most suitable solutions, the pinpointing of high-impact sources, and assessments of the effects of changes, guiding improvements and enabling stakeholders to make informed decisions.^{22,40,43,47,48}

Numerous review articles on HESS have been published in recent years.^{49–60} Yet, none provides a systematic overview of sustainability assessment approaches for HESS. Prior works primarily focus on technical and operational aspects of HESS, while economic/environmental analyses are treated narrowly (see Table S1 in the Supporting Information). For instance, Hajiaghahi et al.⁵⁰ and Lencwe et al.⁵⁸ discuss selected economic studies only within their sections on capacity-sizing methods. They do not address economic studies with other objectives or assess those analyses in detail. Similarly, Reveles-Miranda et al.⁵⁹ only identify cases where HESS implementation yielded financial or environmental benefits (e.g., cost and/or CO₂ emission reductions) but do not analyze the underlying

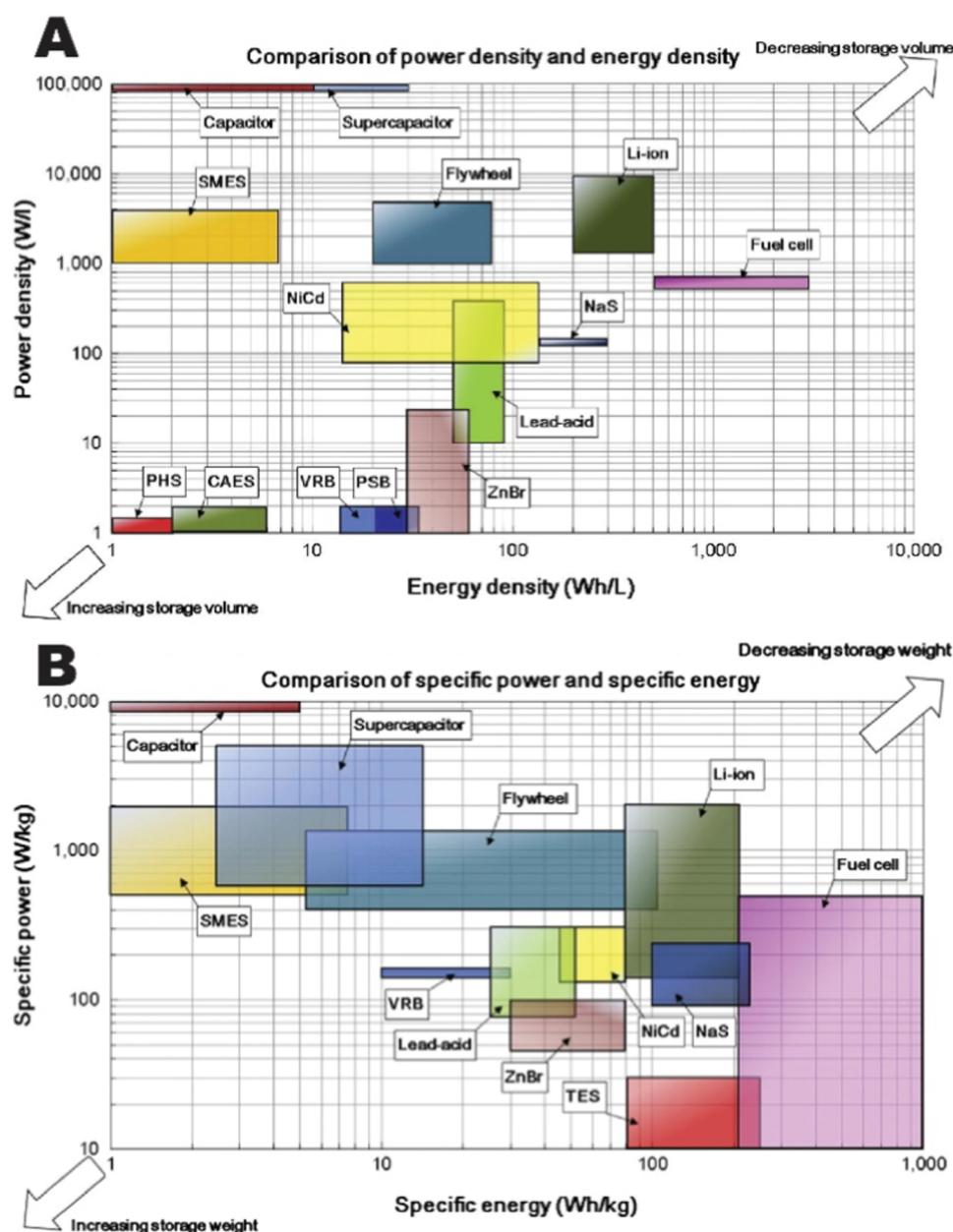


Figure 2. Comparison of different ESDs in terms of (A) volumetric and (B) gravimetric energy and power densities. Reprinted from ref 67 under the terms of the Creative Commons Attribution 3.0 Unported (CC-BY 3.0) license (<https://creativecommons.org/licenses/by/3.0/>); CAES—compressed air energy storage, Li-ion—lithium-ion battery, NaS—sodium–sulfur battery, NiCd—nickel–cadmium battery, PHS—pumped hydroelectric storage, PSB—polysulfide bromine flow battery, SMES—superconducting magnetic energy storage, TES—thermal energy storage, VRB—vanadium redox flow battery, ZnBr—zinc bromine flow battery.

assessments in depth or consider additional metrics. This paper fills that gap by (i) synthesizing the metrics used to evaluate economic and environmental performance and the factors that influence these outcomes and (ii) discussing challenges, recommendations, and future directions for sustainability analyses. Because a solid grasp of HESS fundamentals underpins effective system design, this review begins with an overview of HESS composition, structure, and operation, with design considerations integrated into each section.

2. COMPOSITION OF HESS

The main components of a HESS are ESDs. Generally, HESS consists of at least two electrically connected separate ESDs that are combined to create a system with enhanced

features.^{51,61,62} Typically, two ESDs are employed: whereas one of these devices has HED and meets long-term energy requirements, the other one has HPD and meets short-term power demands.^{57,63} Figure 2 shows a comparison of different ESDs in terms of volumetric energy and power densities (Figure 2A), and gravimetric energy and power densities (Figure 2B). An overview of the properties of different ESDs can be found in ref 24, 26, and 54.

As a wide variety of ESDs with distinct features exist, many different HESS can be assembled.^{50,53,54,57,61,62} In the process of selecting the most appropriate ESDs combination for a particular application, several factors must be considered. First of all, the chosen ESD combination should be able to fulfill energy storage needs related to a particular use

case.^{6,50,51,53,54,61,62,64} Besides, other aspects concerning ESDs such as their energy efficiencies,^{53,54,61} impacts on the environment,^{6,51,61,64} sizes,^{50,54,62,65} lifespans,^{51,53,54,61,64} storage expenditures,^{50,53,54,61,62,64} technical maturity,^{53,62} and safety^{51,54,61,64} should be considered. Considering the type of application for which HESS is being designed, additional factors such as geographical location of the planned energy storage facility,^{50,57,62,66} weight of ESDs^{5,4,57,65} or the complexity of system installation and maintenance necessary to ensure its proper operation⁵³ may also be relevant. Depending on the significance of particular characteristic to the intended utilization, some factors may be prioritized in the decision-making process.^{53,61,64}

Moreover, safety components need to be integrated into HESS to protect it from various potential risks, such as overheating, overcharging, overcurrent, short-circuit, and other situations that could lead to damage to system components or pose safety risks.^{42,51,63,68,69} Apart from that, additional components, such as power converters, diodes, switches, and other elements of control system can be part of HESS.^{50,55,56,63,69,70}

3. STRUCTURE OF HESS

The choice of the suitable HESS structure is a highly significant aspect when designing HESS. The way the ESDs are connected in HESS directly impacts its operation, performance, control complexity, flexibility, energy efficiency, size, and weight as well as lifespan of ESDs and cost of the whole system. Therefore, these parameters in context of particular application should be considered when selecting the most appropriate structure.^{49,51,54,56,71,72}

The connection of ESDs to the common bus can be established either directly or via power converters that are employed to regulate the power exchange,^{22,30,49} while HESS can interface with either the AC or DC bus.^{22,49} Three types of HESS structures (passive HESS, semipassive/semiactive HESS, and active HESS) are typically distinguished based on the method of interconnecting two ESDs to the common bus.^{31,55,56} Their description is provided in the [Supporting Information](#). When more than two separate ESDs are integrated into a single HESS, additional arrangement options such as parallel configurations become possible. However, HESS configurations involving more than two ESDs are relatively scarce^{6,22,31,57,69,73–75} and such topologies can basically be regarded as extensions and/or combinations of HESS designs with two ESDs.^{31,69,73–75}

4. OPERATION OF HESS

Since the fundamental purpose of a HESS is to store and provide energy, the operation of any HESS includes both charging and discharging phases. However, various systems may differ in their operation strategies, which dictate the allocation of the power between the ESDs and, thus, determine their utilization rate. As stated in the HESS structure section in the [Supporting Information](#), the distribution of power in semiactive and active HESS is actively managed. This is done by control strategies, which aim to maximize the advantages of HESS.^{54,55,65,72,76} To date, a significant number of control methods have been proposed.^{50,54,55,65,77} Based on their applicability for real-time control, these algorithms can be categorized as either online or off-line ([Figure 3](#)).^{63,78,79}

Detailed descriptions of these methods and the challenges encountered are provided in the [Supporting Information](#).

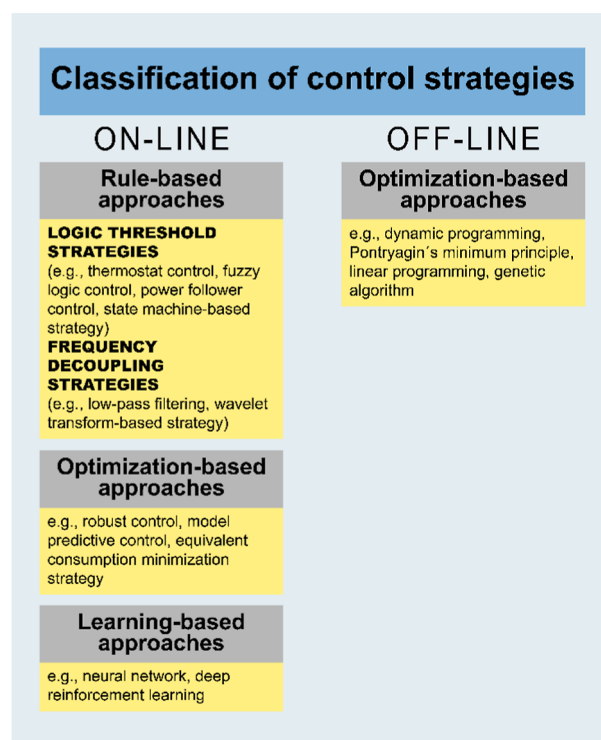


Figure 3. Classification of control strategies employed in hybrid energy storage systems based on their applicability for real-time control.^{50,54}

When designing or choosing the suitable control method, there are several aspects to consider, such as the objective of employing HESS,^{50,72,77,80} the kind of system that HESS will be part of,^{50,51,55,72,80} the response time of the control method^{50,51,74} and its complexity,⁵¹ its cost,⁵⁰ the selected ESD combination,^{50,81} and the structure of HESS.^{50,55,56,72,74,77}

5. ECONOMIC ASSESSMENTS: METRICS AND INFLUENCING FACTORS

Given the critical role of pricing in industrial applications, the financial viability of HESS alone, as well as systems integrating HESS, has been extensively investigated. The results of these evaluations have been used to identify the most suitable solution and/or to analyze how different factors affect economic feasibility.^{9,18,21,39,40,42,44,47} Despite extensive research, methodological differences in HESS-related economic evaluations make cross-study comparisons difficult and may lead to divergent economic conclusions.

To address these methodological disparities, the following subsections review the main approaches used in HESS-related economic assessments, focusing first on metrics commonly employed to evaluate financial viability and then on factors influencing the overall system cost.

5.1. Metrics Employed in Economic Analyses

A wide range of economic metrics has been employed to assess the economic performance of HESS and power systems containing HESS. These metrics differ considerably in their definitions, scope, and comprehensiveness, reflecting the

Table 1. Comparison of the Major Net Cost Metrics Used in HESS-Related Economic Assessments

economic metric	cost components	definition and application	strengths	limitations	references (examples)
capital costs	initial capital investment	initial investment cost of HESS or systems containing HESS	simple; enables straightforward comparison across technologies	ignores operational, replacement, and other life cycle costs—may not lead to an optimal long-term economic decision	11,82,83
operational costs	electricity, ESD degradation, operation and maintenance (O&M) or other costs (e.g., diesel costs, demand charge)	operational expenditure of HESS or systems containing HESS over a defined period	simple	lacks full life cycle context	79,83–86
life cycle cost ^{9,14,36,87–89} / overall cost ^{1,21,47} / total cost of ownership ^{90–92}	capital, often O&M, sometimes replacement, ESD degradation, or other costs (e.g., waste treatment, salvage)	total cost of system over project lifetime; applied to both HESS and systems containing HESS	flexible—allows inclusion of various cost components as needed	sensitive to project lifetime; formulas vary; incomplete cost inclusion, including end-of-life costs, can bias results	9,11,14,21,36,47,87–92
net present cost (NPC)	initial investment, O&M, replacement, often salvage, sometimes additional costs	present value of the total system cost over the project lifetime; applied to systems containing HESS	flexible	sensitive to project lifetime and discount/interest rate assumptions; incomplete life cycle cost inclusion may affect results	40,41,46,81,93–95
total annual cost ^{39,43,96,97} / equivalent annual cost ⁶⁸ / annual system cost ⁹²	capital, O&M, often replacement, sometimes salvage or other costs (e.g., environmental penalties, trading profit)	average yearly cost of system over project or system lifetime; applied to both HESS and systems containing HESS	flexible; facilitates yearly cost comparison	incomplete life cycle cost inclusion may bias results	39,43,64,92,96,97
daily cost	capital, maintenance, and sometimes operation cost	average daily cost of system over project or system lifetime; applied to HESS only	flexible; facilitates daily cost comparison	sensitive to discount rate assumptions; omits several life cycle costs	34,98–100
levelized cost of energy (LCOE) / COE	capital, O&M, replacement, sometimes salvage or other costs (e.g., fuel costs, grid sellback price or costs of maintaining self-discharging ESDs charged)	minimum unit price at which energy must be sold to cover all expenditures over the project lifetime; applied to energy producing technologies in general, including power systems with HESS	widely accepted; flexible; highly suitable for cross-study comparison	sensitive to project lifetime and discount rate assumptions; varying cost components across studies complicate comparison; excludes end-of-life and sometimes salvage cost, which may bias results	40–44,46,66,83,94,95,101–103
levelized cost of storage ¹⁰⁴ (LCOS, LCOHES) ⁶²	capital, O&M, replacement costs	discounted cost of storage system per unit of discharged energy over the project lifetime; LCOS applies to energy storage systems in general, LCOHES to HESS only	flexible; highly suitable for cross-study comparison	sensitive to project lifetime and discount rate; omits salvage and end-of-life costs, which might bias results; limited adoption in HESS studies	62,104
normalized HESS cost	capital, O&M, power converter costs	HESS life cycle expense for the hourly dispatching renewable power	enables cross-study comparison without assuming project lifetime; flexible; directly incorporates ESD degradation effects	omits end-of-life costs; limited to specific HESS studies; calculation formulas vary across studies	33,105,106

diverse approaches used to evaluate the cost-effectiveness of HESS. Economic metrics used in HESS studies can be grouped into four conceptual categories, each representing a distinct perspective on system economics:

- (i) simple cost metrics (capital, operational),
- (ii) life cycle-based metrics (life cycle cost, total annual cost, daily cost, net present cost),
- (iii) levelized metrics (levelized cost of energy, levelized cost of storage, normalized HESS cost), and
- (iv) profitability metrics (net present value, annual profit, return on investment, (simple) payback period, internal rate of return).

Tables 1 and 2 summarize the principal net cost economic metrics and profitability metrics, respectively, used in HESS-related assessments, outlining their cost components, definitions, applications, strengths, and limitations.

As shown in Table 1, several economic metrics share similar definitions but appear under different names across studies, reflecting a lack of standardized terminology in HESS-related economic analyses. Despite partial overlap among terms such as life cycle cost, overall cost, and total cost of ownership, their underlying formulations differ across studies, underscoring the need for standardized terminology. This overlap creates ambiguity and complicates the cross-study comparison. Beyond terminology, substantial variation also exists in how cost components are defined and included. Even for widely used approaches such as levelized cost metrics (LCOE/COE) and life cycle-based metrics, cost boundaries remain inconsistent across studies, hindering comparability. Consistent comparison is, by contrast, enabled by capital costs; however, because they omit essential life cycle costs, conclusions derived from such analyses may differ from those based on more comprehensive metrics. For instance, in⁹¹ a battery–super-capacitor–flywheel solution required a 2.6% higher initial investment than a battery-only microgrid design yet achieved a 1.96% lower overall cost over its lifetime. Profitability-oriented metrics such as net present value (NPV) or internal rate of return (IRR) provide complementary insights into investment attractiveness; however, their scope also varies across studies (Table 2). Collectively, the identified inconsistencies point to the need for unified methodological standards to strengthen the validity and comparability of future HESS-related economic evaluations.

5.2. Factors Influencing the Cost of HESS

As discussed in the preceding section, a diverse range of economic metrics have been employed to evaluate the cost-effectiveness of HESS technologies. While these metrics differ in formulation and scope, their reliability ultimately depends on how cost components are defined, quantified, and integrated into the underlying economic models. As shown in Tables 1 and 2, capital investment and operation and maintenance (O&M) expenses represent the cost elements most frequently included across various metrics used to assess the financial viability of HESS, whether alone or as part of power system. Several studies, however, extend this baseline by incorporating additional expenditures such as replacement, salvage value, or life cycle-related expenditures, thereby providing a more comprehensive but not necessarily consistent representation of HESS economics.

The total cost of a HESS is highly sensitive to the selection of ESDs, as some technologies differ markedly in their expenditures (Figure 4).^{21,47,57,62,83,93,116} Comparative studies

Table 2. Comparison of the Profitability Metrics Used in HESS-Related Economic Assessments

economic metric	cost components	definition and application	strengths	limitations	references (examples)
net present value (NPV)	investment and other costs (e.g., O&M, replacement, repair cost) and cash inflows	sum of discounted cash flows over the project lifetime; applied to HESS or systems containing HESS	when revenues are included, provides intuitive profitability measure; flexible; widely used	sensitive to project lifetime and discount rate assumptions; incomplete life cycle cost inclusion may bias results	22,42,95,102,103,107,108
annual profit	capital, revenue, often operating, sometimes maintenance or other costs (e.g., disposal, replacement, carbon-trading)	average yearly profit of the system over its or the project lifetime; applied to HESS or systems containing HESS	simple measure of yearly economic performance	incomplete life cycle cost inclusion may affect results	18,109–114
return on investment	capital, replacement, O&M, sometimes other cost	the ratio of yearly cost savings (relative to the baseline) to the initial investment; applied to systems containing HESS	simple and intuitive profitability measure	typically, it does not consider cash-flow timing or discount rate (less reliable for long-lifetime projects); incomplete life cycle cost inclusion may distort results	46,66,95,102,103
(simple) payback period	capital and annual net savings or capital and other cash flows	time required to recover the initial investment through annual savings, or to offset the difference in investment cost between the evaluated system and the baseline; applied to systems containing HESS	intuitive; provides a quick indication of investment recovery; widely used	ignores time value of money and post-payback profitability	46,83,95,102,103,107,115
internal rate of return (IRR)	investment, O&M, replacement, sometimes salvage value, or other cash inflows (e.g., grid sellback price)	discount rate at which the net present value of an investment equals zero; applied to systems containing HESS	considers time value of money; provides an intuitive percentage measure of investment profitability	sensitive to cash-flow pattern and lifetime assumptions; incomplete cost inclusion may affect accuracy	42,46,95,102,103

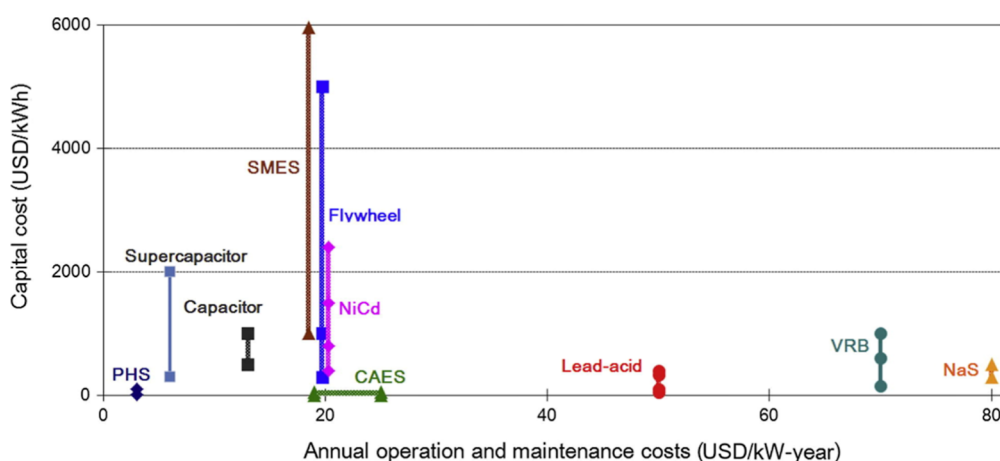


Figure 4. Comparison of various ESDs in terms of annual operation and maintenance costs and capital cost. Reprinted from ref ⁶⁷ under the terms of the Creative Commons Attribution 3.0 Unported (CC-BY 3.0) license (<https://creativecommons.org/licenses/by/3.0/>); CAES—compressed air energy storage, NaS—sodium–sulfur battery, NiCd—nickel–cadmium battery, PHS—pumped hydroelectric storage, SMES—superconducting magnetic energy storage, VRB—vanadium redox flow battery.

of Gbadegesin et al.^{62,84} and Torkashvand et al.³⁶ indicate that supercapacitor–lithium-ion battery HESS are generally more economic than supercapacitor–lead acid battery systems. However, the magnitude of this advantage differs not only among studies but also within the same analysis when key economic or technical assumptions are modified, which underscores the high sensitivity of HESS cost assessments to modeling assumptions and methodological frameworks.

Beyond technology selection, the total HESS expenditure is strongly influenced by the sizing of individual ESD components.^{42–44,93,97,101,104,106,116} Reported sizing methods range from simple analytical estimates based on energy and power requirements to optimization-based approaches that determine component capacities by optimizing one or several objective functions. These strategies typically aim to reduce value of some cost metric, energy consumption, or ESD degradation while satisfying technical and operational requirements.^{21,47,50,54,79,87,89,106,117,118} Commonly applied algorithms include genetic algorithms, particle swarm optimization (PSO), and multiobjective evolutionary techniques such as the nondominated sorting genetic algorithm II, which enable trade-off analysis between conflicting objectives such as cost and battery degradation.^{54,97,118} While optimization-based approaches provide a systematic framework for exploring the design space, their results are not always consistent. For instance, Wang et al.¹⁰⁰ reported that quantum-behaved PSO achieved smaller optimal ESD capacities (7807.84 kWh for batteries and 1985.16 kWh for ultracapacitors) and a lower daily cost (5902.36 USD) than traditional PSO (9084.26, 2196.52, and 6708.83 USD). In contrast, Qu and Yuan³⁴ obtained nearly identical outcomes using PSO and the mixed integer linear programming. These contrasting findings indicate that optimization-derived sizing is highly sensitive to algorithm type, underscoring the need for standardized and validated optimization frameworks in HESS economic analyses.

The capacities of ESDs are also affected by system-level parameters such as the combination of storage technologies,^{6,21,33,93} system architecture,^{47,79} and control strategy.^{18,21,104,106,117} Since HESS sizing and control are interdependent, many studies employ co-optimization frameworks that jointly determine both sets of variables to achieve

overall system optimality.^{47,54,58,104} The combined optimization problem can be generally expressed as

$$\underset{X_s, U_c}{\text{minimize}} J_{s,c}(X_s, U_c(t), \xi(t), t) \quad (1)$$

subject to

$$h_{e,i}(X_s, U_c(t), \xi(t)) = 0, i = 1, 2, 3, \dots m \quad (2)$$

$$g_{ine,j}(X_s, U_c(t), \xi(t)) \leq 0, j = 1, 2, 3, \dots n \quad (3)$$

where $J_{s,c}$ is the joint objective function for sizing and control optimization, X_s and U_c represent the set of the sizing and control variables, respectively, and ξ denotes the set of input parameters. The functions $h_{e,i}$ and $g_{ine,i}$ define the i th equality and j th inequality constraint, respectively, while m and n are the corresponding numbers of constraints. This generalized formulation is highly flexible and can accommodate various objective functions depending on the intended optimization goals and system requirements.^{54,119} However, the lack of standardized objective functions and constraint formulations across studies limits the comparability of the reported results.

Beyond sizing, the interconnection topology of ESDs also has a substantial impact on overall HESS cost.^{51,56,72,79} In systems incorporating power converters, the converter type, required input-to-output voltage ratio, and peak power throughput are key determinants of converter-related cost.^{20,47,61,79,90} However, these expenses are frequently treated simplistically or omitted entirely from cost models.^{14,40–42,46,89,105,106} Such omissions may lead to systematic underestimation of total system expenditure, particularly in configurations that employ multiple converters or operate under a high power demand.

Operational duration also exerts a significant influence on total HESS expenditure. As the operational period increases, cumulative O&M costs rise correspondingly.^{40,62,66,83,94,106} Moreover, the service lifetimes of individual ESDs in hybrid energy storage systems play a critical role in determining the total system cost, as replacement frequency and degradation dynamics directly affect life cycle expenditures. However, the approaches used to incorporate lifespan into economic metrics vary across studies, reflecting a lack of methodological consensus. Some analyses consider only the lifetimes of

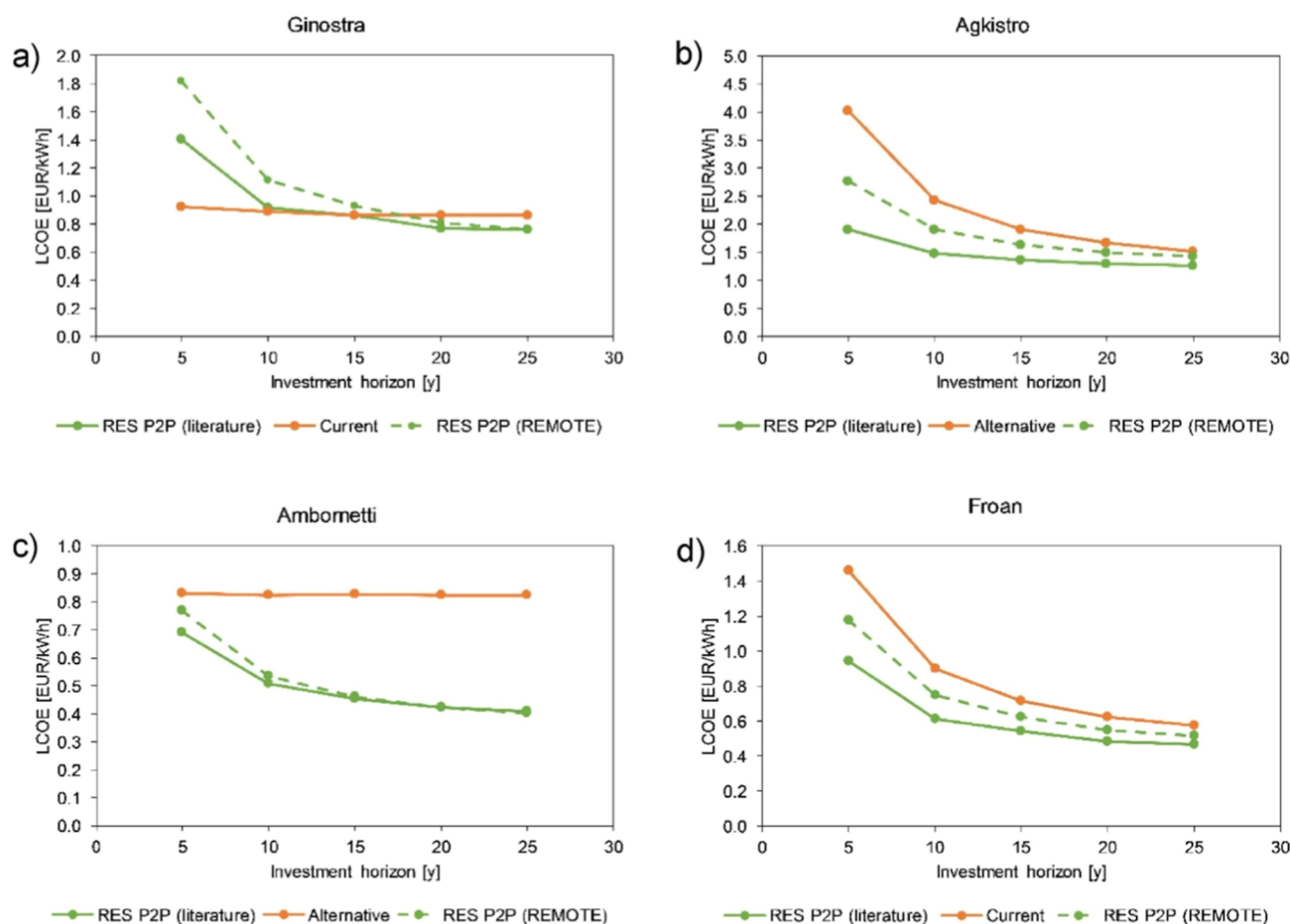


Figure 5. Comparison of LCOE values for various systems integrating renewable energy sources and hydrogen-battery energy storage system, calculated using cost inputs from the literature and REMOTE project (green), across four different demonstration sites: (A) Ginostra, (B) Agkistro, (C) Ambornetti, and (D) Froan over different time horizons. Reprinted from ref 44 Copyright (2020), with permission from Elsevier; LCOE—levelized cost of energy, RES P2P—renewable energy sources coupled with power-to-power storage systems.

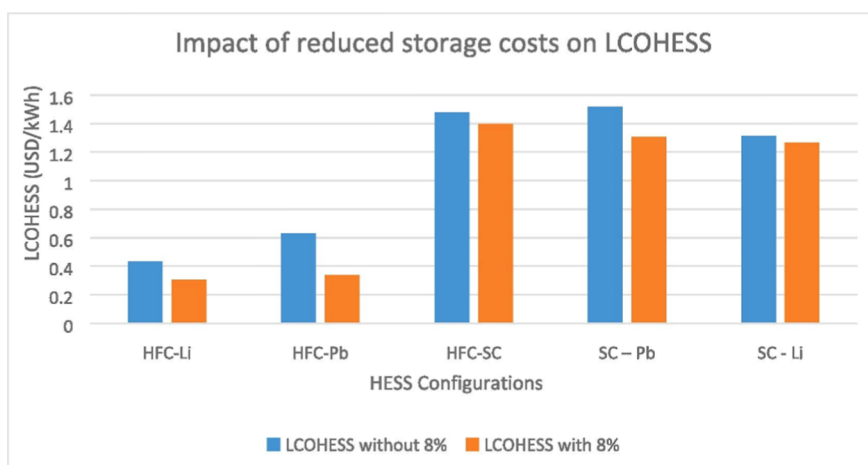


Figure 6. Impact of an annual 8% decrease in storage prices on LCOHESS. Reprinted from ref 62 Copyright (2019), with permission from Elsevier; HESS—hybrid energy storage system, HFC—hydrogen fuel cell, LCOHESS—levelized cost of hybrid energy storage systems, Li—lithium-ion battery, Pb—lead acid battery, SC—supercapacitor.

components shorter than the system's intended operational period,^{21,39,47,62,90,93,104} while others account for longer-lived components through salvage value estimation.^{41,43,46,81,94,104,120} A few works^{11,33,105,106} adopt a more integrated approach by embedding the lifespan of all ESDs directly into their economic formulations. Nevertheless, most

of these assessments rely on generalized lifetime values for all of the components. As illustrated by Roy et al.,³³ such assumptions may deviate from actual lifetimes under the specified operating conditions, producing substantial cost-estimation errors. Incorporating reliable lifetime-prediction models into cost assumptions is therefore essential.

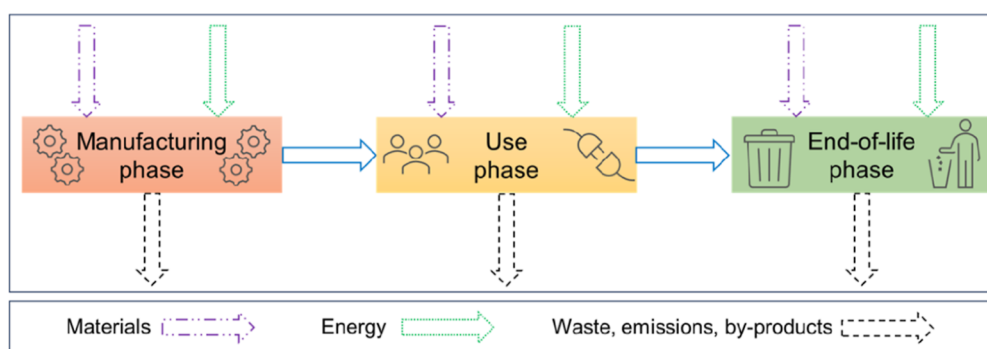


Figure 7. Overview of the main life cycle stages of system.

The service lives of ESDs within HESS depend on multiple interacting factors, including the type of ESDs,^{21,33,47,106,121} specific conditions of system use,^{31,33,73} sizes of ESDs,^{18,47,72,79,118} control strategy,^{18,72} and system architecture.¹¹⁸ When a power converter is included in the HESS structure, its conversion efficiency also affects the degradation rate of individual storage components.⁴⁷ These complex interdependencies highlight the need for integrated technoeconomic models that explicitly couple operational, structural, and control parameters with cost and lifetime projections. Such holistic modeling approaches are essential to accurately capture degradation dynamics and to improve the reliability of economic evaluations.

Besides, the outcomes of economic analyses may vary considerably depending on the data sources used (Figure 5), which is due to the high variability of production costs of emerging technologies and differences in technical and economic assumptions. Since financial analyses typically account for both current and future expenditures, variations in projected future costs can substantially influence the results (Figure 6). For instance, future expenditures associated with HESS may be influenced by fluctuations in electricity costs driven by carbon taxation or shifts in energy sources. Furthermore, variations in prices may result from increased production and usage, technological advancements, or tax rebate and incentives designed to promote these technologies.^{22,37,44,62,116}

6. ENVIRONMENTAL IMPACT ASSESSMENTS: METRICS AND INFLUENCING FACTORS

In order to choose the most appropriate solution for a specific use case, to gain a deeper understanding, and to examine the impact of implementing HESS into system or its environmental effect, several studies have analyzed environmental impacts associated with either HESS alone^{6,22,48,61,64,97} or with systems integrating HESS.^{6,38,40,45,46,66,83,94,96,108,115,121–123} In almost all of these studies, quantitative analyses were performed for these purposes. Within these studies, two different approaches for assessing the environmental impact of systems can be distinguished: indirect and direct. Analyses using the former approach estimated only the emissions arising from fossil fuel use^{46,66,94,96,108} and/or grid electricity^{96,121} while omitting device-level burdens. By contrast, the latter approach accounts for environmental impacts across the whole or partial life cycle of the system's components.^{6,22,38,40,45,48,64,83,97,108,115,122,123} While indirect methods are simpler, they can yield conclusions that diverge from component-inclusive evaluations. For instance, in 100%

renewable power systems analyzed by Jiao and Månsson,⁶ GHG emissions from renewable generation were similar across HESS configurations, yet the life cycle emissions of the electricity mix provided by these systems differed markedly due to differences in device manufacturing, their utilization, and operational losses. Likewise, Le et al.¹²² found that microgrids relying almost entirely on solar energy with HESS can be less environmentally friendly than systems that draw partially on grid electricity, even when the grid mix has a high share of fossil fuels.

While essential, component-inclusive HESS-related environmental assessments are performed inconsistently across studies. The following subsections therefore provide an overview of the metrics employed in these evaluations and the factors affecting the environmental outcomes.

6.1. Metrics for Assessing Environmental Impact

As with economic analyses, various metrics were employed for assessing the environmental impacts of HESS or power systems containing HESS. Across the literature, two families dominate: single-indicator climate metrics (e.g., total emissions,^{83,108} GHG emissions,⁶ or damage cost due to CO₂ emission⁹⁷) and multicategory life cycle assessment (LCA) metrics (e.g., human toxicity potential, global warming potential, fossil depletion potential, and marine and freshwater eutrophication potentials²²). An overview of these metrics with their general units is provided in the Supporting Information (Table S2). The selection of metrics in cited studies was driven by the motivation and goal of the analysis, the assessment tool selected for study, their global acceptance, utilization in other studies, recommendations, and relevance of the metric to the studied system.^{6,22,38,40,64,83,97,115,122,123}

Unlike cost metrics, in most environmental studies, outcomes are reported per application-specific functional unit. Vehicle studies typically use impact per kilometer traveled,⁴⁸ whereas stationary applications often report impact per kWh or MWh of delivered energy.^{6,22,38,40,45,115}

Across applications, conclusions may be highly sensitive to the choice of metrics. Diverse components and life cycle phases may contribute differently to each impact category,^{38,48,115,122,123} often yielding trade-offs rather than a single “best” option (see Table S3 in the Supporting Information). Normalized presentations of category results (e.g., values expressed relative to the largest footprint among scenarios) make such trade-offs explicit and aid comparison across configurations,¹²² but they are sensitive to the chosen reference and do not convey absolute magnitudes. Alternatively, technologies can be compared using a single score environmental index that aggregates multiple impact categories.⁴⁵

However, because such indices depend on the selected weightings, individual impact category results should be reported alongside any single score to maintain the transparency.

6.2. Factors Influencing Environmental Impact

As with the cost analysis, environmental outcomes reflect not only the technology but also the analytical choices behind it. Results depend on the quality and provenance of inventory data, the definition of system boundaries (i.e., which life cycle stages are considered), impact-metric selection, functional unit and the calculation tools, and their implementation in specific software–database combination.^{6,22,45,48,116,123,124} In HESS-related environmental assessments, these parameters vary widely across studies, hindering cross-study comparison and robust generalization. Even when the same environmental impacts (e.g., acidification, eutrophication, and climate change) are examined, studies often quantify them using different metrics (Table S2). System boundaries likewise differ: many studies include manufacturing, use, and end-of-life (EOL) phase (Figure 7),^{22,45,48,108,115,123} whereas others address the EOL stage only in a limited way or omit it entirely due to lack of data or high uncertainty.^{6,38,40,122} Even among those that include EOL, approaches diverge, several assume recycling,^{6,22,48} one landfill,¹¹⁵ and others a combination of both,^{40,45,123} which leads to different impact estimates. Despite this variability, none of these studies analyzed how alternative EOL scenarios would affect the results.

Component choice is another driver. Because materials and manufacturing routes differ across components, so do their environmental profiles. For example, Jiao and Månsson⁶ reported that producing 1 kWh of SC capacity releases more than ten times the GHG emissions associated with the production of a hydrogen technology. Context, however, can reverse apparent hierarchies. Gandiglio et al.³⁸ and Le et al.¹²² found hydrogen storage to be a significant contributor to ozone depletion and ecotoxicity in their system-integrated analyses, whereas Abualshawareb and Dehouche¹¹⁵ reported a minor contribution due to a relatively small hydrogen subsystem and the dominance of photovoltaic and grid electricity. Energy-related impacts are typically higher when processes are energy-intensive and/or when that energy comes from pollutant-intensive sources.^{6,40,115,122} Moreover, as discussed in Section 5.2, different sizing methods may yield different environmental outcomes, even for the same scenario.

Results further depend on the treatment of missing data and study assumptions. These choices must be explicitly reported to ensure reproducibility and made with care to avoid misleading conclusions. For instance, Le et al.¹²² replaced an electrolyzer bill of materials with a fuel cell proxy due to missing composition data, then scaled the proxy using a factor inferred from GHG emissions reported by Bionaz et al.,⁴⁰ and estimated the impact of this technology across 12 categories. However, analysis by Lotrič et al.¹²⁵ of both technologies indicates that scaling is category-specific rather than universal. This underscores the need to justify proxy selection, confine scaling to categories where it is defensible, and quantify the additional uncertainty introduced by such substitutions. In addition, several studies relied on assumed, generic fixed lifetimes for key components instead of modeling degradation under realistic duty cycles, which can misestimate replacement impacts and distort the overall environmental conclusions.^{38,40,83,115,122,123}

Finally, depending on how the environmental effect calculation is done, utilization rates of system devices may also significantly influence the results of environmental analyses. This is most visible for studies where the total impact is calculated per unit affiliated with energy discharged from system (e.g., km, kWh, MWh).^{6,40,48} However, even Venkateswaran et al.⁹⁷ considered energy discharged from ESDs in their calculations.

7. CHALLENGES, RECOMMENDATIONS, AND FUTURE PROSPECTS

Several challenges, recommendations, and future directions for HESS have been recently identified.^{51,52,54} Therefore, the following subsections address the challenges found through a review of HESS-related sustainability analyses and present recommendations and future prospects to enhance the credibility and reproducibility of subsequent assessments.

7.1. Economic Challenges

- Metric scope and terminology inconsistency: overlapping definitions and inconsistent inclusion of cost components hinder comparability.
- Sizing and control dependence: expenses are highly sensitive to the adopted sizing and control methods.
- Time horizon and replacements: longer operating horizons drive cumulative O&M and replacement costs, which are often treated superficially.
- Lifespan modeling and degradation: economic results hinge on component life assumptions. Generalized lifetimes can deviate from duty-specific realities and induce large errors.
- Input data and forward prices: outcomes vary with data sources and projected future costs.

7.2. Environmental Challenges

- Assessment approach inconsistency (indirect vs component-inclusive): omitting device-level burdens skews results and can reverse conclusions between configurations.
- Metric inconsistency: existence of various metrics for the same environmental impacts hinder cross-study comparability.
- System boundaries and EOL: inclusion of EOL is inconsistent and scenarios vary across studies.
- Inventory quality and proxies: data gaps lead to proxying and scaling that can be category-specific and add uncertainty.
- Lifetime modeling: generic lifetimes may misestimate replacements.
- Software–database dependence: results may vary significantly depending on the used software–database combination.

7.3. Recommendations and Future Prospects

To enhance credibility and reliability of sustainability assessments, sensitivity and uncertainty analyses should always be included.¹¹⁶ In sensitivity analysis, uncertain factors are typically varied one at a time, and the resulting changes in outcomes are evaluated. In cost analyses, dominant uncertainty sources reported across the literature include assumptions about battery lifetime,¹⁸ component cost volatility,^{43,62,66,81,93,110} component efficiency,⁴³ degradation-induced reductions in delivered energy,⁶² optimization algorithm

choices,¹¹⁰ and load demand variability.⁹³ In environmental analyses, key uncertainties include assumptions about HESS lifetime,⁶ HESS depth-of-discharge,⁶ end-of-life scenarios,³⁸ and variability in lead and rare metal consumption.¹²³

To improve transparency, detailed data inventories should be provided wherever possible, and the study's assumptions and scope should be clearly documented. To obtain reliable results and draw the most objective conclusions, financial and environmental contributions from all life cycle stages of the system should be included, and component lifespans should be estimated under specific use conditions. Because different metrics yield different insights, the evaluation of multiple metrics can provide complementary perspectives for decision-making. To support comparability, the community could create a comprehensive open database for both cost and environmental impacts and converge on a set of standard metrics.

Given the similarities in parameters across the economic and environmental assessments, a joint model could be developed in the future. Furthermore, as sustainability development goals encompass social impacts, future research should also aim to evaluate social effects alongside economic and environmental analyses.⁴⁶

8. CONCLUSION

This paper provides an in-depth overview of HESS composition, structure, operation, and the metrics and factors that influence their financial and environmental impacts, which is necessary for development of more sustainable solutions.

Hybrid energy storage systems typically incorporate at least two separate, electrically connected ESDs combined to create a system with enhanced features. The requirements of a particular application should guide the selection of the optimal combination of ESDs, system structure, and operation strategy.

Assessing the economic impact of HESS may involve evaluating various cost-effectiveness metrics, such as the levelized cost of energy/electricity for energy producing technologies that integrate HESS and normalized HESS cost, LCOS, or levelized cost of HESS for HESS alone. Profitability metrics such as NPV, the IRR, return on investment, and payback period, along with other financial viability metrics (e.g., net present cost, life cycle cost, etc.), may also be considered. Key factors influencing economic viability include HESS composition, structure, control strategies, ESD sizes, and specific conditions of system use. In addition, economic outcomes are highly sensitive to methodological choices; therefore, transparent reporting is essential.

HESS-related environmental evaluations typically use either single-indicator climate metrics or multicategory LCA metrics. Because different life cycle phases and components contribute differently to each impact category, multicategory metrics are generally preferable. As with the cost analysis, environmental outcomes reflect not only the technology itself but also the analytical choices behind the assessment. Consequently, inconsistencies across assessments can limit the cross-study comparability and hinder robust generalization. Clear reporting of assumptions, boundaries, and sensitivity analyses is therefore essential.

The similarities in parameters between economic and environmental assessments highlight the potential for a unified model. Future research should further incorporate social impact evaluations alongside economic and environmental

analyses to foster a holistic approach to advancing hybrid energy storage systems.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsomega.5c05912>.

Contribution of this paper in comparison to the recent works on HESS; detailed description of three predominant types of HESS structures; control strategies employed in HESS; overview of environmental metrics; and environmental impacts of HESS and systems integrating HESS across various applications (PDF)

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Notes

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■ ABBREVIATIONS

CAES	compressed air energy storage
COE	cost of energy
EOL	end-of-life
ESD	energy storage device
GHG	greenhouse gas
HED	high energy density
HESS	hybrid energy storage system
HPD	high power density

IRR	internal rate of return
Li ion	lithium-ion battery
LCA	life cycle assessment
LCOE	levelized cost of energy/electricity
LCOHESS	levelized cost of hybrid energy storage systems
LCOS	levelized cost of storage
NaS	sodium-sulfur battery
NiCd	nickel-cadmium battery
NPC	net present cost
NPV	net present value
O&M	operation and maintenance
PHS	pumped hydroelectric storage
PSB	polysulfide bromine flow battery
PSO	particle swarm optimization
RES P2P	renewable energy sources coupled with power-to-power storage systems
RESs	renewable energy sources
SC	supercapacitor
SMES	superconducting magnetic energy storage
TES	thermal energy storage
VRB	vanadium redox flow battery
ZnBr	zinc bromine flow battery

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