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A Systematic Review of Challenges and Opportunities in Achieving Cost-Effective Hybrid Solar Systems for Off-Grid Applications

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ABSTRACT

This study reviews the challenges and prospects for low-cost Hybrid Solar Systems (HSS) for off-grid applications, focusing on energy optimization and storage technology. Accordingly, HSS can deliver clean energy and reduce operating costs. However, it is highly dependent on diesel-generated power and has high energy storage costs. This study aims to identify solutions to mitigate diesel power generation dependency and to evaluate challenges and opportunities for enhancing the cost minimization and efficiency of Energy Storage Systems (ESS). In the approach known as Systematic Literature Review (SLR), we retrieved 54 articles published from 2019 to 2024 on optimization technologies, energy storage, and reducing diesel consumption in Hybrid Energy Systems (HES). The main findings reveal that using stochastic programming and Social Spider Optimization (SSO) approaches has improved the performance of energy consumption management. In contrast, Hybrid Energy Storage Systems (HESS) and hydrogen energy storage technologies offer promising potential for reducing storage costs and enhancing the system's efficiency. Although diesel generators are still necessary in some cases, the study indicates that innovative energy management technologies reduce dependence on diesel consumption, ultimately cutting costs and carbon emissions. Moreover, the proposed HSS Optimization Framework integrates data acquisition, optimization algorithms, and decision-making layers to holistically manage power generation, storage, and dispatch. Through this framework, the hybrid system achieves an optimal balance between energy production, storage utilization, and reliability. Ultimately, the findings could serve as a reference model to enhance the operation of HSS and minimize environmental impacts through technological innovation and enhanced optimization strategies.

Keywords: Diesel generator; energy optimization; energy storage; green technology; solar hybrid system; rural electrification

INTRODUCTION

Hybrid Solar Systems (HSS) are considered one of the most promising alternatives for rural areas not accessible to the grid electricity infrastructure (Ismail et al. 2023; Natividad & Benalcazar, 2023). These hybrids integrate solar with storage and diesel generators as a backup power source (Ali Sadat & Pearce 2024; Izumida Martins et al. 2022). Although HSS can decrease the need for conventional energy that relies on fossil fuels, dependence on diesel generators is a significant issue (Giwa et al. 2019). According to Giwa et al. (2019), diesel generators increase the system's operating costs, increase Carbon Dioxide (CO_2) emissions, and reduce the overall cost-effectiveness, affecting HSS's sustainability and effectiveness. Furthermore, Energy Storage Systems (ESS) such as batteries, which are widely adopted in HSS, also face severe problems. In line with this, high capital costs for energy storage and low storage efficiency are often major obstacles to achieving optimal cost-effectiveness (Amiruddin et al. 2024; Shamsuddin et al. 2025). This inefficient energy storage becomes a bigger issue when relying on uncertain renewable energy sources such as solar and wind, as it requires better storage solutions to provide a constant and stable energy supply.

Nonetheless, while there are remarkable developments in solar and energy storage technologies, research gaps remain in finding ways to achieve this more efficiently and cost-effectively by reducing reliance on diesel generators and improving energy storage efficiency and cost in HSS. In addition, further reliance on diesel generators increases economic and environmental costs, while inefficient energy storage leads to resource waste and the uneconomical use of diesel as a backup. According to Tooryan et al. (2020), the optimal configuration of renewable energy resources and battery ESS can reduce operating costs and CO_2 emissions by approximately 35%. This significant cost and environmental impact highlight the necessity of exploring ways to reduce diesel fuel consumption and improve alternative, more sustainable, and economical storage technologies.

The primary goal of this work is to propose solutions that can decrease the dependence on diesel generators in HSS, particularly by utilizing more efficient storage devices and energy optimization algorithms. This study also seeks to explore challenges and opportunities to reduce the cost and performance of ESS, especially in the context of HSS for off-grid applications. Additionally, the findings of this study will be crucial to the government, industry, and communities, as they require more economical and sustainable HSS.

Furthermore, this study promotes the development of clean energy in rural areas, proposes solutions to lower storage costs, and optimizes the utilization of renewable energy. This contribution benefits the government by helping to set more sustainable energy policies and aids the rural community by reducing energy costs and distributing energy, offering a cheaper and more environmentally friendly energy source. Similarly, this work benefits the evolution of the energy industry by providing updated information, related energy storage technologies, enhanced energy management approaches, and enriched available literature in this field.

This work will include analyzing 54 articles, covering topics such as hybrid solar technology, optimal energy utilization, and energy management in HSS. Consequently, this article will discuss the challenges and opportunities of minimizing reliance on diesel generators and enhancing the cost-effectiveness of energy storage, as these are critical issues to address in the context of HSS applications in off-grid regions. Figure 1 depicts the flowchart for the prospective procedure of the article review.

The novelty of this review article provides insights into the optimization methods and specific technological advancements for reducing costs and improving the performance of ESS in HSS. Unlike previous works that focused on isolated optimization or single-parameter analyses, the HSS optimization framework established in this study incorporates an algorithm-driven approach. This represents a significant methodological advancement toward achieving sustainable, cost-effective, and intelligent hybrid solar energy systems.

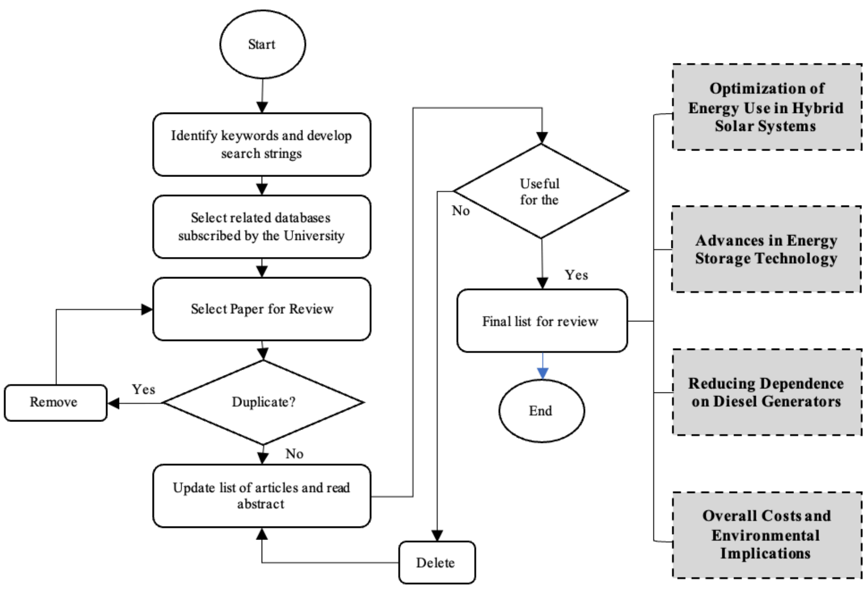

FIGURE 1. Methodology for reviewing process

METHODOLOGY

This study employed the Systematic Literature Review (SLR) approach to review and analyze the relevant articles on HSS and optimization in off-grid applications. Notably, SLR is a structured and methodical method of gathering, analyzing, and appraising available evidence from previous studies to make comprehensive and reliable conclusions (Mohamed Shaffril et al. 2021). Moreover, it allows objective and consistent selection of articles and minimizes bias during the study process. This research aligns with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol for well-organized and transparent systematic reviews (Page et al. 2021). Additionally, this study searched for refereed articles on the topic from major databases. Accordingly, the databases used in this study were IEEE Xplore, Scopus, and Web of Science (WoS) since all three contain relevant academic articles on energy engineering, microgrids, and renewable energy systems, and are subscribed to by the university. The search was conducted using specific keywords to ensure that the selected articles were relevant to the objectives of this study.

Furthermore, the terms were combined using Boolean operators (AND and OR) to extend the search. Wildcard and truncation were used for terms such as technology* to retrieve "technology," "technologies," and "technological." To suit the search method in each database, the specified keywords were modified to reflect the closest meaning, aiming to obtain a more comprehensive and significant number of articles. A publication period from 2019 to 2024 was selected for this study to review recent and relevant studies reflecting new developments in HSS technology and optimization. Table 1 summarizes the keyword searches used in the mentioned databases and the articles generated by each search, providing a complete overview of the search strategy in this study.

TABLE 1. Database search strategy (keywords, Boolean operators)

	Search String	Operator Boolean	Database	Result
1.	("Solar" OR "Photovoltaic" OR "PV") AND ("Cost Optimization" OR "Cost Efficiency") AND ("Off-Grid " OR "standalone" OR "Independent" OR "Rural") AND ("Programming" OR "Algorithm")	AND, OR	IEEE	18
2.	("Solar" OR "Photovoltaic" OR "PV") AND ("Cost Optimization" OR "Cost Efficiency") AND ("Off-Grid " OR "microgrid" OR "Independent") AND ("Linear Programming" OR "LP")	AND, OR	Scopus	17
3.	("standalone" OR "off-grid") AND ("solar photovoltaic" OR "solar PV") AND ("diesel generator" OR "backup generator") AND ("battery" OR "energy storage") AND ("energy management" OR "cost optimization" OR "economic analysis")	AND, OR	WoS	19

Potential articles included in this review must satisfy some inclusion criteria. In particular, the first criterion is that the selected papers must be on topics relevant to "hybrid energy systems," "energy optimization," and "energy storage." Secondly, the included articles must be published in refereed journals and open for full access. It is also desirable for articles to be in full text to enable a more detailed review. Following this, exclusion criteria include articles unrelated to the study aims or those published in languages other than English.

Article inclusion was also performed according to the PRISMA protocol. The first 54 articles obtained from the search were filtered to remove duplication. A total of eight articles unrelated to the study objectives were then excluded after screening titles and abstracts. The whole text filter proceeded with items relevant to the study's overall narrative and form. At the end of the process, 25 articles were selected in this study for further examination. The PRISMA flowchart employed for the present study is represented in Figure 2 for better clarification of the article selection process and the screening of articles according to the inclusion and exclusion criteria. This PRISMA flowchart illustrates how articles that were included met study eligibility.

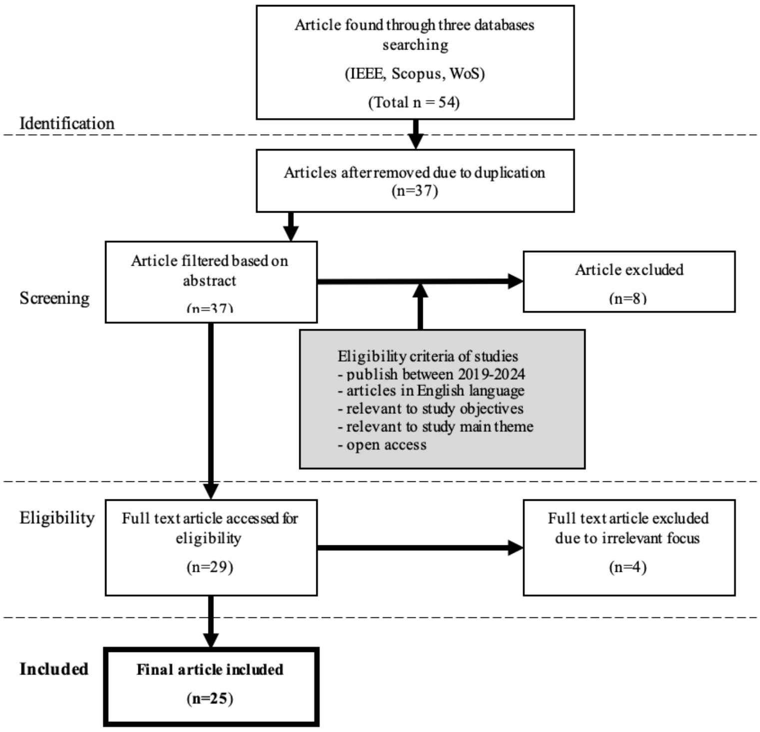

FIGURE 2. The SLR process flow

The next step of this review was to analyze and select the relevant articles, grouping them according to the previously identified main themes (Table 2). These themes involved energy use optimization, advances in energy storage technology, reducing dependence on diesel generators, and cost and environmental impacts. Accordingly, each article was analyzed to identify key findings related to these themes.

Furthermore, the methodological quality of the included articles was also evaluated. Criteria considered during the evaluation were clarity of study purpose, relevance to the proposed objectives, methodology, and comparison with related studies. At the same time, a quality check was performed to ensure that only high-standard articles were included in this study. Average scores are reported alongside percentages, and standard deviation values were calculated to reflect assessment variability (Table 3). The standard deviations, ranging from 0.47 to 0.57, indicate a moderate and acceptable level of variability in the scores. This method improves the reliability and transparency of the quality evaluation for the included studies.

An Article Summary Table is also provided to summarize the crucial details of each selected article, including the author, year of publication, research focus, and method relevant to the study theme (Table 4).

Subsequently, this Materials and Methods section explains how the complete and systematic SLR study was conducted. The methodologies adopted are intended to set this study on the path for sound discussion and analysis, ensuring relevance, objectivity, and quality article inclusion.

TABLE 2. Categorization of studies by themes and timeline

Theme	Year Published						Total Article
	2019	2020	2021	2022	2023	2024	
Optimization of Energy Use in Hybrid Energy Systems	Ignat et al.	Chatterji & Bazilian, Fathy et al., Liaquat et al.	Kharrich et al.	Espin-Sarzosa et al., Sorour et al.		Sarbu et al.	8

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Advances in Energy Storage Technology		Muqeet & Ahmad	Pandey et al.		Szilagyi et al., Almehizia & Al-Ismail	Ramos et al., Viole et al.	6
Reducing Dependence on Diesel Generators				Benti et al.	Rangel et al.	Dumas & Gosselin, Gil-González et al.	4
Overall Costs and Environmental Implications	Ahmad et al.	Liu et al.	Cosic et al.	Cetinbas et al., Ouederni et al.		Mahdi et al., Ali Sadat & Pearce	7
Total Article	2	5	3	5	3	7	25

TABLE 3. Quality assessment of studies

Quality Assessment (QA) Criteria	Average Score (25 articles)	Percentage (%)	Standard Deviation (SD)
QA1: Is the research objective clearly stated?	4.3	86%	0.47
QA2: Is the study relevant to the research objectives?	4.5	90%	0.51
QA3: Is the methodology explained clearly and adequately?	4.4	88%	0.51
QA4: Does the study compare its findings with existing studies?	4.1	82%	0.53
QA5: Are the limitations of the study clearly stated?	4.2	84%	0.57
QA6: Are the results and conclusions well-supported by evidence?	4.3	86%	0.48

RESULT

In the following section of this paper, the study findings, based on the themes provided in Table 2, will be described in detail. For each theme, a combination of narrative and visual synthesis is used to illustrate the main findings contained in the reviewed articles. It will also link this text to Figure 2, Table 3, and Table 4 to demonstrate how these articles were chosen and assessed. Each topic will be detailed, with studies that have influenced the objectives of this review.

This study includes an analysis of the 25 articles included in Table 4, which involve different methods of developing and innovating with the HSS technology. Every referenced article presents different aspects of the challenges and opportunities in HSS, particularly in the context of energy utilization optimization, advances in energy storage technology, and reduced dependence on diesel generators.

TABLE 4. Optimization approaches and technological advances in hybrid energy systems: a comprehensive review of recent trends in microgrids and off-grid solar solutions

Article	Research Focus			Optimization Methods and Technological Developments
	Solar Hybrid System	Energy Management/ Optimization	Reducing diesel generator operation	
(Ignat et al. 2019)	√	√	√	Day-ahead scheduling using stochastic programming.
(Ahmad et al. 2019)	√	√	√	Load requirement analysis using HOMER software.
(Chatterji & Bazilian, 2020)	√	√	√	Stochastic programming for system optimization.
(Fathy et al. 2020)	√	√	√	Social Spider Optimization (SSO) to optimize hybrid renewable energy systems and reduce the Cost of Energy (COE).

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(Liaquat et al. 2020)	√	√	X	Accelerated Particle Swarm Optimization (APSO) and Firefly algorithms for scheduling Hybrid Energy Systems (HES), Photovoltaic (PV)/hydro/ thermal.
(Liu et al. 2020)	√	√	√	Search Algorithm Referencing Adjacent Points (SARAP) algorithm to optimize the microgrid design for wind/solar/diesel/battery.
(Muqeet & Ahmad, 2020a)	√	√	√	Energy Management System (EMS) to reduce grid electricity costs and carbon emissions.
(Cosic et al. 2021)	√	√	X	Mixed-Integer Linear Programming (MILP) for optimal selection of the energy technologies.
(Kharrich et al. 2021)	√	√	√	The Equilibrium Optimizer (EO) to minimize Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) in PV/Wind/Diesel/Battery system design.
(Pandey et al. 2021)	√	√	√	Multi-criteria decision-making and robust optimization methodology to optimize design and minimize the gap between load and demand
(Cetinbas et al. 2022)	√	√	√	The Hybrid Harris Hawks Optimizer-Arithmetic Optimization (HHO-AOA) algorithm to optimize microgrid design.
(Espin-Sarzosa et al. 2022)	√	√	√	Integration of Small Productive Processes (SPP) into EMS to improve performance and reduce operating costs.
(Ouederni et al. 2022)	√	√	X	HOMER software to analyze the optimal combination of hybrid renewable resources.
(Sorour et al. 2022)	√	√	X	The MILP-EMS reduces operating costs and energy bills by increasing PV self-consumption.
(Benti et al. 2022)	√	√	√	Techno-economic analysis using the HOMER software to optimize a hybrid PV/diesel/battery system.
(Almehizia & Al-Ismail, 2023)	√	√	X	Stochastic Mixed Integer Nonlinear Programming (MINLP) Optimization model to upgrade the electrical distribution feeder.
(Rangel et al. 2023a)	√	√	√	The cost optimization model addressed the generator's performance.
(Szilagyi et al. 2023)	√	√	X	The Stochastic Dynamic Programming (SDP) optimizes the energy management and battery life.
(Ali Sadat & Pearce, 2024)	√	√	√	Evaluate 18 case studies to analyze the economics and realistic potential of grid defection.
(Dumas & Gosselin, 2024)	√	√	√	PV system optimization to reduce carbon emissions and provide a feasible renewable solution.
(Gil-González et al. 2024)	√	√	√	The Semi-Definite Programming (SDP) model minimizes energy losses and carbon emissions.
(Mahdi et al. 2024)	√	√	√	The Non-dominated Sorted Genetic Algorithm (NSGA-II) optimization model is used to optimize operating costs, energy consumption, and carbon emissions.
(Ramos et al. 2024)	√	√	√	The integration of pumped storage hydropower with solar and wind can reduce operational costs and carbon emissions.
(Sarbu et al. 2024b)	√	√	√	The two-stage optimization framework improves energy management, minimizes solar forecasting errors, and enhances operational efficiency.
(Viole et al. 2024)	√	√	√	Life Cycle Assessment (LCA) to optimize the energy system.

According to the analyses, the results of the studies cited can be classified into four themes. These themes cover system optimization, advancement of energy storage technology, less reliance on diesel generators, and cost and environmental impact analysis. Table 2 outlines the main themes and the studies associated with each theme that this analysis has addressed. Notably, optimization methods in HSS are essential for improving the effectiveness of energy extraction from renewable sources such as solar and wind, while also reducing dependency on backup energy sources. Several important studies have been conducted with regard to the energy performance of HSS using optimization algorithms, including stochastic programming and linear programming. Research by Ignat et al. (2019) optimized energy usage scheduling under stochastic programming, enhancing effectiveness by addressing uncertainties in renewable energy source predictions. In addition, the work in Chatterji and Bazilian (2020) proved that the application of Monte Carlo Simulation in energy planning decreases diesel dependence and enhances the reliability of solar systems against power outages. In addition, the work of Fathy et al. (2020) utilized a sensitivity analysis to optimize the configuration of HES optimally with energy storage components to minimize costs and diesel consumption.

In HSS, ESS is one of the main problems in terms of cost and efficiency. A critical requirement is for more efficient and cheaper storage technologies to lessen reliance on diesel generators. However, the cost of batteries to store the energy generated is a significant barrier to making these systems less expensive. According to Viole et al. (2024), hydrogen energy storage could be a potential solution for mitigating the cost of storage and the efficacy of HSS. However, Pandey et al. (2021) argued that better storage technologies and intelligent Energy Management Systems (EMS) would reduce reliance on diesel generators, lowering the total operation cost.

Reliance on a diesel generator remains a significant issue in HSS, particularly regarding cost-effectiveness and environmental friendliness. Research by Rangel et al. (2023b) implemented solar Photovoltaic (PV)-diesel-battery hybrid systems for rural schools in Ethiopia. They reported that even though diesel is still required in some instances, controlling the energy storage (storage capacity and discharging) leads to decreased diesel dependency (Rangel et al. 2023b). At the same time, Rangel et al. (2023b) analyzed how price-based demand response can be used to reduce diesel consumption by further maximizing the use of solar energy during the daytime. This study demonstrated that reliance on diesel generators, economic costs, and environmental footprints could be reduced with a more optimized EMS.

Cost-effectiveness and environmental considerations are crucial when assessing the potential benefits of HSS. According to Mahdi et al. (2024), although the initial cost of HSS remains high, using more efficient ESS can reduce overall operating costs and carbon emissions. Additionally, Cosic et al. (2021) assessed the environmental impact of using a Hybrid Energy System (HES) in remote areas. They discovered that using renewable energy sources can significantly reduce the carbon footprint. Furthermore, Viole et al. (2024) outlined that a Life Cycle Assessment (LCA) analysis for HSS can provide a clearer view of the costs and environmental impacts of the system. This, in turn, helps with better decision-making when designing and implementing HSS.

This analysis reveals that the principal barriers to hybrid power systems are reliance on diesel generation and the cost of electricity power storage. Note that the first theme (optimizing energy use) and the second theme (advancing energy storage technology) are related since more efficient energy storage can help optimize energy use. Meanwhile, the third theme describes the need for improved energy storage and more effective energy management to decrease reliance on diesel generators. Lastly, the fourth theme related to costs and environmental impacts contrasts the high HSS installation costs with suggestions of long-term cost savings through more effective energy management and storage technology, and provides significant environmental benefits.

This research will benefit from more cost-effective, sustainable HSS design. In particular, combining improved optimization algorithms, advances in energy storage technology, and more efficient energy management will reduce the dependence on diesel and the associated operating costs. Thus, the future direction is to pursue research on more sustainable energy storage technologies, such as thermal energy and hydrogen, and implement more sophisticated, innovative EMS to enhance the overall HSS performance.

OPTIMIZATION OF ENERGY USE IN HYBRID SOLAR SYSTEMS

The first topic highlighted in this work is HSS energy optimization. The most notable problem in HSS is managing the uncertain amount of available solar energy used to generate power. It also involves ensuring efficient energy consumption even during hours with insufficient solar radiation, minimizing consumption from backup energy sources (usually diesel generators).

Several studies have indicated that better optimization approaches can reduce operating costs and improve energy consumption for hybrid systems. According to Almehizia and Al-Ismail (2023), optimizing the microgrid energy system's daily schedule using Mixed-Integer Linear Programming (MILP) reveals that this method enhances energy management, reducing diesel consumption and ensuring optimal sustainable energy conditions. This method is crucial in addressing the uncertainty of energy generation from sources such as solar energy, where proper management can prevent waste and reduce running costs.

Chatterji and Bazilian (2020) also addressed the Monte Carlo approximation to optimize the home's ESS based on solar energy and batteries. The findings indicated that with the optimal exploitation of stored battery energy, reliance on diesel generators can be significantly reduced (Chatterji & Bazilian, 2020). This lowers operating expenses and makes the system less vulnerable to power outages. Building on this, Fathy et al. (2020) implemented SSO to optimize a hybrid system combining a diesel generator and energy storage, proving that this algorithm can locate the best configuration to minimize the cost and maximize the efficiency. The schematic diagram of an HSS with EMS is illustrated in Figure 3. Accordingly, power is supplied to the load (P_{Load}) through renewable energy sources obtained from the DC bus, which combines power from solar PV (P_{PV}) and batteries (P_{Batt}), then converts to AC power using an AC/DC inverter. Note that the diesel generator is directly connected to the AC bus to provide power (P_{Gen}) to the load when renewable energy is not available. All equipment is connected to an EMS to monitor power flow and maximize energy efficiency.

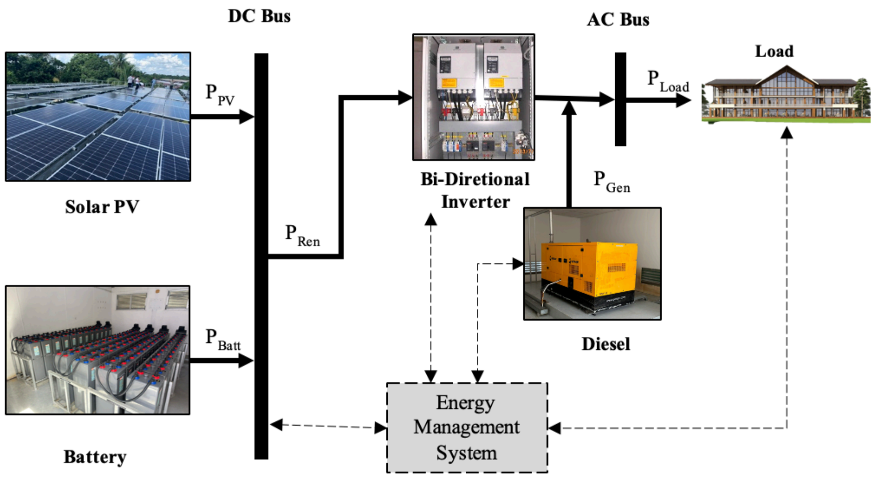

FIGURE 3. Schematic diagram for HSS with energy management system

ADVANCES IN ENERGY STORAGE TECHNOLOGY

Energy storage performance is one of the most important factors in the HSS. Storage technology is the basis of stable and continuous utilization of renewable energies, especially when solar or wind energy sources are not available. However, current ESS, such as lithium-ion batteries, still present serious limitations, particularly when it comes to cost and longevity.

Szilagyi et al. (2023) proposed Stochastic Dynamic Programming (SDP) to enhance the efficiency of ESS in hybrid systems. It was observed that the application of SD leads to cost reduction through productivity improvement and the extension of the life cycle of energy storage. This contributes to reducing the reliance on diesel generators and enhancing the stability of the power supply. Viole et al. (2024) also investigated hydrogen energy storage, which can replace the widely used battery in HSS. They concluded that Lithium Iron Phosphate (LFP) or hydrogen storage technology has strong potential to minimize the cost and improve the efficiency of hybrid systems (for off-grid systems with long-term storage requirements).

REDUCING DEPENDENCE ON DIESEL GENERATORS

One of the major challenges is minimizing the use of diesel generators to ensure a cost-effective and clean HES. Although diesel generators are essential backup power sources, their operating costs and CO_2 emissions rise in HES. Thus, several works have proposed different options for minimizing diesel dependence in this system.

The HSS used with hybrid solar power systems in rural schools in Ethiopia was presented in Rangel et al. (2023a). Notably, they were reported to be more economical for reducing operating costs on conventional grid electricity. However, in some cases, diesel generators were also utilized for backup power. A study by Benti et al.

(2022) discovered that the reliance on diesel can be significantly mitigated by optimizing energy storage and solar energy. Moreover, Muqeet and Ahmad (2020a) studied the use of price-based demand response in an HES by shifting diesel load to solar load during daytime hours. Collectively, the findings indicate that operational costs can be alleviated through better energy management and innovative technologies, reducing reliance on diesel.

OVERALL COSTS AND ENVIRONMENTAL IMPLICATIONS

While HSS has significant potential to reduce energy costs and mitigate the environmental impacts of carbon emissions, high initial investment and energy storage costs pose significant barriers. A number of studies have demonstrated that the initial cost of HSS is higher than grid electricity. However, due to low running costs and net savings of carbon emissions, it can be perceived as more sustainable in the long run.

According to Viole et al. (2024), their study on LCA for HSS suggested that, although the initial investment is expensive, the application of solar energy and ESS can reduce carbon emissions and positively impact the environment in the long term. This research emphasizes that a well-functioning HSS can reduce environmental impacts and improve operational costs. Consistent with this, Cosic et al. (2021) also studied the impacts of HES in rural areas concerning fossil energy source dependency and carbon footprint reduction. Thus, introducing green technologies into hybrid systems would be crucial for sustainable energy development.

CROSS-THEMATIC ANALYSIS AND COMPARISON OF FINDINGS

By comparing them, findings can be mapped to present a more comprehensive picture of the challenges and opportunities of HSS (FIGURE 4). In particular, two themes, energy efficiency and new energy storage solutions, are strongly interconnected. As such, better energy storage leads to better energy optimization and less dependence on diesel fuel. Meanwhile, themes three and four indicate that reducing diesel use will require better energy storage technology and more efficient use of renewable energy.

This study overviews the difficulties and possibilities of reaching a cost-effective and environmentally friendly HSS. Correspondingly, optimization technology, improved energy storage, and better energy management are crucial in achieving cost-effectiveness and reducing dependence on diesel generators. Notwithstanding such challenges, new storage technologies and advances in energy-storage solutions generally demonstrate potential for increasing the cost-effectiveness and sustainability of HSS.

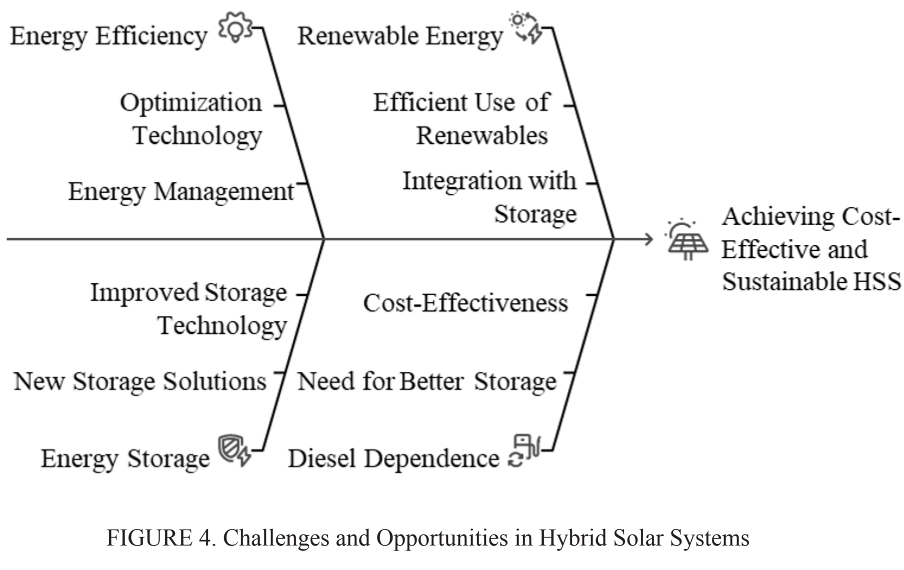

FIGURE 4. Challenges and Opportunities in Hybrid Solar Systems

DISCUSSION

This study aims to review the optimization techniques and technological developments in HES, focusing on HSS for off-grid applications. Several general findings can be drawn from examining the 25 articles in this review (as summarized in Table 4). The first noticeable result is that smart energy utilization in HSS, based on algorithms such as stochastic programming and SSO, can minimize reliance on diesel generators and promote higher solar and wind power integration. These methods make HES operate better, even with the uncertainties of solar and wind energy. Although previous studies have demonstrated that the optimization algorithm can improve the energy performance of HSS and reduce operational costs, this effectiveness has only been confirmed through simulations that do not reflect real-world conditions. Essentially, adjustments to the optimization algorithm might be required when applied in actual situations.

The second observation is the progress of energy storage technology. SDP can also be considered to increase a storage system's efficiency and lifetime. This opens the door for cost savings and minimizing dependence on backup diesel generators. Storage alternatives such as hydrogen energy also present great potential in reducing costs and increasing the effectiveness of HES. Whilst this storage still needs additional development work, it is a promising future alternative.

The third finding concerns the decrease in dependence on diesel generators. The optimal use of solar energy and improved energy storage technologies could decrease the dependence on diesel and the system's operational costs. While this indicates that diesel generators are still required to maintain system strength in some conditions, substantial reductions in their utilization are possible using more efficient technologies. However, while some of these studies might focus on only a single aspect, such as storage technology or optimization, this study takes a more holistic approach by combining all crucial aspects of HSS and demonstrating the relationship between energy storage, energy optimization, and reducing dependence on diesel.

Considering the challenges displayed in Figure 4, the systematic workflow in Figure 5 offers the hybrid solar power optimization framework that links energy sources, storage components, and optimization algorithms. It starts with data collection, where solar radiation, load demand, and meteorological parameters are gathered. The inputs related to solar radiation and load demand are then fed into the optimization engine, which uses various algorithms such as SSO and SDP to determine the best configuration and operational strategy. Through this framework, HSS will optimize renewable energy sources by charging the battery () with excess solar energy and will only discharge () the battery when solar energy cannot meet the load demand. Note that diesel generators will operate only when renewable sources cannot satisfy the load and the battery State of Charge () at minimum level (). The energy capacity of diesel generators will be optimized for electricity supply and battery charging within the maximum limit ().

The main goal of optimization is to balance energy supply and demand by managing power flow between PV panels, diesel generators, and ESS. Key performance indicators such as Cost of Energy (COE), Levelized Cost of Energy (LCOE), and Loss of Power Supply Probability (LPSP) are evaluated to measure system efficiency and affordability. In addition, this EMS diagram highlights the closed-loop analysis process, where the optimization results are fed back into data models for ongoing system improvement, providing a comprehensive view of hybrid solar power system analysis and optimization. This also offers a broader overview of the functioning of hybrid power systems within an off-grid scenario.

The findings reported in this paper offer valuable theoretical insights into the optimization problem in HES. For example, the methodologies of stochastic programming and SSO used in this paper provide new techniques to enhance the operation of energy systems with uncertain resources. The results also yield additional insights into energy storage theory, addressing alternative technologies such as LFP and hydrogen storage, which might offer more sustainable and cost-efficient alternatives to diesel. This, ultimately, creates a research niche in this context and adds to the current literature on HES optimization.

From a practical perspective, the results of this study offer useful references for policymakers to design and operate HES in rural/remote regions. Through more advanced use and storage of energy, HES can operate more cost-effectively and is more environmentally friendly. This benefits local authorities, energy system operators, and technology providers involved in developing renewable energy systems in off-grid areas. Furthermore, this study discusses the feasibility of demand response solutions in managing energy consumption and reducing diesel dependency, which can significantly improve system resiliency and save operating costs.

From the policy perspective, the study offers strong evidence for designing policies that encourage HES, such as support measures, incentives, or subsidies to support the most efficient energy storage technologies. For countries developing renewable energy infrastructure, especially off-grid systems, the results of this study can be used to determine policies that promote research into capturing, storing, and utilizing energy storage devices, as well as optimizing systems. Additionally, policies that concentrate on lowering the price of energy storage can promote the job of HSS and be environmentally sensitive.

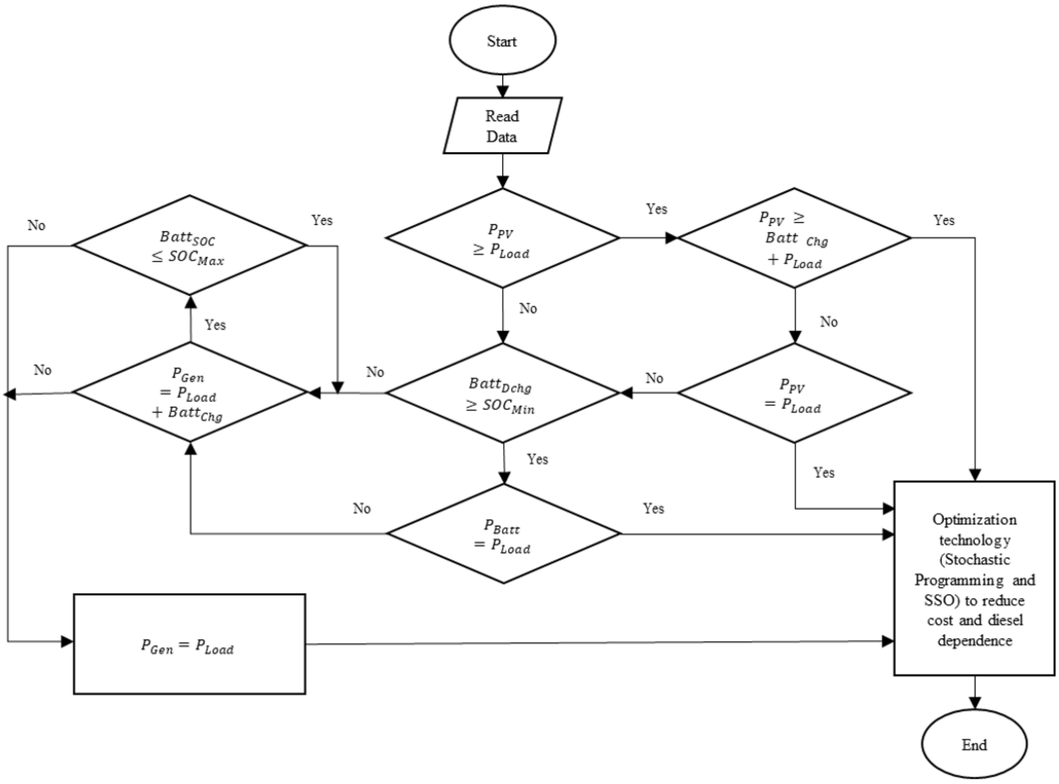

FIGURE 5. Hybrid solar system optimization framework

LIMITATION

Although this review details the optimization techniques and technological development of hybrid energy power systems, some limitations should be mentioned. One of the main limitations is that we only included articles published between 2019 and 2024, and there may be older studies that contribute important insights into the development of this technology. This review also included only articles in English, which may exclude related studies in other languages. In addition, this study did not fully evaluate the operational use of the technologies studied in the field, which might require more case studies to capture the actual challenges of technology implementation.

CONCLUSION

This review deepens the challenges and opportunities for realizing cost-effective HSS, particularly for off-grid applications. Several key insights have been obtained from the findings of the various articles reviewed. First, the use of optimization algorithms, like SSO and stochastic programming, has been verified to enhance energy utilization performance in HSS. This reduces the use of diesel generators and further enhances the system's cost-effectiveness in tackling uncertainties from intermittent renewable energy generation, such as solar and wind. Second, energy storage can also be a very effective tool to significantly reduce the reliance on diesel and achieve a more consistent energy supply. For instance, lithium-ion batteries are the preferred technology option throughout most of the HSS today. However, other storage technologies, such as LFP and hydrogen energy, are promising to become cost-effective and decrease storage costs in the long term.

Furthermore, the study emphasizes that although diesel generators are still required in some situations, advancements in more innovative and effective EMS can significantly reduce diesel energy consumption, resulting in fewer carbon emissions and lower costs. Building on this, the demand response techniques in energy usage management are also an integral part of enhancing the performance of HES. Previous studies have demonstrated, and this study's results confirm, that more advanced technology and better system integration can reduce reliance on non-renewable energy sources such as diesel. It also promotes the adoption of cleaner, environmentally friendlier options.

This study provides opportunities in the following domains regarding future research recommendations. First, further research is required to determine the practical application of energy optimization and storage technologies at the implementation level in the real world, particularly to address the challenges and opportunities in rural and remote areas.

In line with this, future research should also focus on developing techno-economic decision-support tools that integrate life-cycle cost analysis, carbon footprint evaluation, and financial feasibility to guide policymakers and investors. Additionally, further exploration of sustainable and low-cost energy storage options, including hydrogen, thermal, and hybrid technologies, is essential to reduce storage costs and improve long-term energy efficiency.

Beyond technological innovation, comprehensive studies examining policy frameworks, regulatory incentives, and government support mechanisms are required to understand their influence on HES adoption, particularly in developing regions. Thus, integrating innovative grid technologies and Internet of Things (IoT)-based monitoring systems will enhance system flexibility, load management, and energy efficiency.

While numerous studies have demonstrated the effectiveness of HES through simulation and modeling, there remains a significant gap between theoretical optimization and real-world implementation. Hence, empirical validation through pilot-scale and field-based studies is critically needed to assess the operational reliability, maintenance requirements, and socio-economic challenges of HES in real off-grid environments. Moreover, the literature lacks data-driven optimization frameworks that leverage machine learning and predictive analytics to enhance real-time decision-making, load forecasting, and cost optimization under uncertain environmental conditions.

Ultimately, this study provides a strong foundation for advancing HSS optimization research, while emphasizing the need for real-world validation, data-driven optimization, and integrated techno-economic assessment tools to accelerate sustainable off-grid energy solutions globally.

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DECLARATION OF COMPETING INTEREST

None.

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