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Journal of Energy Storage
Volume 114, Part A, 1 April 2025, 115634

Research papers

Optimization of grid-connected solar PV systems with Hybrid Energy Storage System: A case study of the Sri Lankan power system

H.C. Ganege [a] [b], D.P. Chandima [a], J.P. Karunadasa [a], Patrick Wheeler [c]

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https://doi.org/10.1016/j.est.2025.115634

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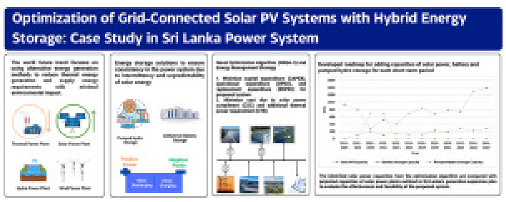
Highlights

- Focus on reducing greenhouse gas emissions by maximizing solar PV generation.
- Solar energy is stored in HESS consisting of batteries and pumped hydro storage.
- Optimal solar and storage capacities and timings are determined using the NSGA-II.
- A case study is conducted on the Sri Lankan power system with sensitivity analysis.
- The alignment of solar capacities with national needs is assessed for feasibility.

Abstract

Greenhouse gas emissions from fossil fuel-based electricity generation significantly contribute to climate change. This research aims to mitigate these emissions by reducing reliance on fossil fuels and maximizing solar photovoltaic (PV) energy generation. It is supported by a grid-connected Hybrid Energy Storage System (HESS) integrating lithium-ion Battery Storage (BS) and Pumped Hydro Storage (PHS). An optimization algorithm is employed to minimize total expenditures, including capital, operational, replacement costs, as well as costs associated with solar curtailment and supplemental thermal energy over the lifetime of the system. The Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to solve the multi-objective optimization problem through the open-source Python framework Pymoo (multi-objective optimization in Python). Optimal capacities for solar PV and BS are determined for short-term intervals, while PHS capacities are evaluated based on regional geological feasibility. A novel energy management strategy ensures an effective balance between energy generation and storage. Optimization results are visualized through Pareto optimal charts and supplemented by economic and environmental analyses to identify sustainable scenarios. Sensitivity analysis further refines the optimal capacities for solar PV, BS, and PHS. The proposed methodology is validated using the Sri Lankan power system. A detailed roadmap is developed to guide the incremental additions of solar PV, BS, and PHS capacities. Final results indicate minimal total cost variations, ranging from −14.05% to 56.69%, and an increase in solar PV generation between 2.19% and 5.13%, due to fluctuations in the interest rate of the country.

Graphical abstract



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Introduction

Since the 1800s, world temperatures and weather patterns have changed significantly, primarily due to human activities, especially the burning of fossil fuels such as coal, oil, and gas [1]. Greenhouse gases (GHGs), including carbon dioxide (CO_2) and methane, released from fossil fuel combustion have been major contributors to climate change. In 2019, global GHG emissions were distributed as follows: 6% from the building sector, 15% from transportation, 22% from agriculture, forest, and other land use, 24% from industry, and 34% from electricity and heat production. This data highlights that electricity and heat production is the largest contributor to GHG emissions [2]. Furthermore, global CO_2 emissions from the energy sector have been steadily rising, increasing by 1.1% in 2023 [3]. With population growth, industrialization, and rapid global development, electricity consumption is expected to continue increasing. While expanding electricity production is necessary to meet global demand, reducing dependence on thermal power plants is crucial for minimizing air pollution and mitigating climate change. The demand for renewable energy generation is growing worldwide, driven by technological advancements, cost reductions, lower maintenance requirements, and numerous environmental benefits. However, renewable energy sources face challenges such as intermittency, limited storage capabilities, and geographical constraints. Addressing these limitations has become a global priority, with a strong focus on advancing renewable energy technologies to ensure a sustainable future.

When considering renewable energy sources, solar and wind energy are the most popular globally due to their increasing maturity and affordability [4]. Among these, solar energy has emerged as the leading renewable energy technology in recent decades due to its ease of installation and low operating costs. Moreover, it is especially suitable for tropical countries like Sri Lanka, which benefit from abundant sunlight [5]. To maximize solar energy utilization, energy storage solutionsare critical in addressing challenges such as intermittency. Combining multiple technologies can further enhance the performance of energy storage systems, enabling the development of more efficient Hybrid Energy Storage system (HESS) solutions. Research in this field typically focuses on two categories of storage technologies: high-energy storage and high-power storage [6]. For high-energy storage, technologies such as batteries, hydrogen, or fuel cells are commonly explored. Conversely, high-power storage applications often investigate technologies like flywheels, super-capacitors, ultra-capacitors, and superconducting magnetic energy storage. Large-scale energy storage applications typically utilize Pumped Hydro Storage (PHS) and compressed air energy storage. However, these large-scale technologies face significant design challenges due to their geological and environmental complexities [7], [8]. This study proposes a grid-connected solar PV system integrated with large-scale HESS as a solution to these challenges, aiming to enhance efficiency and sustainability in renewable energy utilization.

For the HESS, PHS is chosen due to its low investment risk, mature and well-established technology, low power generation cost, and its ability to meet peak power demand without requiring ramp-up time [9]. Moreover, PHS can function as a 'black start' source in the event of a power outage [10]. On the other hand, battery technology is selected for its effectiveness in power balancing, fast response times, and economic advantages. Battery storage (BS) systems are among the most widely adopted energy storage technologies globally due to their high efficiency, low environmental impact, and decreasing manufacturing and installation costs driven by technological advancements. For renewable energy integration, several battery technologies are considered, including lithium-ion (Li-ion), lead–acid (Pb-acid), Sodium-sulfur (NaS) zinc-bromine (ZnBr), polysulfide-bromine (PSB), and vanadium redox flow batteries (VRFB) [11], [12]. Sodium-sulfur batteries are widely used for commercial energy storage applications due to their high energy density, energy efficiency, and long cycle life. However, they are associated with high operation costs and significant safety concerns. Among battery technologies, Li-ion and lead–acid batteries demonstrate superior performance in energy management [13]. Lead–acid batteries, despite their mature technology, low cost, and high reliability, have several limitations, including low efficiency, low energy density, short lifespan with high depth of discharge, and the need for periodic water maintenance [14]. Consequently, they are gradually being replaced by Li-ion batteries. Li-ion batteries offer numerous advantages, such as fast response times, high power and energy density, and greater round-trip efficiency. They also outperform other battery technologies in areas such as response times and energy-to-power ratios [15]. Considering these benefits, Li-ion batteries are selected for this study due to their high power, energy density, efficiency, and technological maturity. They are also identified as a promising solution for grid-scale HES, particularly when integrated with PHS [16], [17].

Optimization in renewable energy and energy storage has emerged as a important area of focus as global trends increasingly prioritize sustainable energy generation. Numerous studies have explored solutions for grid-connected solar photovoltaic (PV) systems, emphasizing the integration of diverse energy storage technologies to address the limitations of solar PV.

Research has been conducted to compare the effectiveness of using a single storage technology versus combining multiple technologies, highlighting the advantages of HESS. In [18], fuel cell and battery technologies were integrated into a solar PV system, using dynamic programming to maximize efficiency and minimize losses. The results demonstrated optimal performance with the combined approach. Additionally, HESS that integrate batteries and supercapacitors have been extensively studied to address challenges such as durability, charging and discharging limitations, and maintenance costs. Supercapacitors are primarily used alongside BS to reduce battery stress and extend their lifespan. They also help to minimize instantaneous mismatches between electric power generation and load demand, ensuring system stability within the frequency regulation framework [19], [20], [21]. Similarly, Solid Oxide Fuel Cells (SOFCs) combined with BS systems have been employed to effectively manage power flow in renewable energy systems, as highlighted in [22]. Moreover, virtual energy storage systems have been explored to enhance the economic feasibility of wind-solar complementary storage systems and improve the performance of hybrid power systems, as discussed in [23], [24].

Further studies focus on optimizing the sizing HESS by comparing advanced optimization algorithms with traditional methods. In [25], the size and cost of HESS are optimized by considering the State of Charge (SOC) of batteries and supercapacitors in a solar PV-based micro-grid. The optimization model incorporates economic factors and time-of-use pricing to ensure cost-effectiveness and efficiency. Evolutionary and machine learning optimization methods are employed to solve complex, multi-objective problems. For instance, Deep Reinforcement Learning (DRL) is used to achieve real-time optimal energy storage system planning under the renewable energy curtailment, making decisions based on a large dataset from past operations [26], [27]. The same method is applied to minimize operating and energy exchange costs in the networked microgrids, resulting cost reductions of 12.9% and 17% compared to the dueling deep and deep Q-network methods, respectively [28]. The Particle Swarm Optimization (PSO) algorithm is employed to develop an optimized fuzzy logic controller (FLC) for operating an autonomous hybrid green power system (HGPS) with improved performance [29], [30]. In addition, an advanced fuzzy-PSO is used to design a control approach that enhances the reliability, control level, and operation of microgrids with distributed generation sources. This study implements an HESS using BS and supercapacitors [31]. The multi-Objective Grasshopper Optimization Algorithm (MOGOA) is applied to maximum power and improve the Fault Ride-Through capability in Doubly Fed Induction Generator [32]. Moreover, the Non-dominated Sorting Multi-Objective Grey Wolf Optimizer and the Non-dominated Sorting Genetic Algorithm II (NSGA-II) are compared, demonstrating that their validated performance in [33].

When working with renewable energy, optimizing the energy management system to handle uncertainty and power fluctuations is crucial. In [34], an intelligent probabilistic wavelet fuzzy neural network, combined with a deep reinforcement learning algorithm, is used to enhance the energy management system. This approach demonstrates computational accuracy exceeding 98%. Additionally, an intelligent probabilistic wavelet Petri neuro-fuzzy inference algorithm is employed to control the voltage/frequency (V/F) index, effectively reducing fluctuations in V/F [35]. In [36], the Multi-Objective Bees Algorithm (MOBA) is applied for load frequency control in an interconnected multi-area power system. The dynamic performance achieved through this approach significantly suppresses frequency and tie-line power deviations.

Most research has focused on identifying suitable technologies for HESS by comparing different energy storage technologies, while some studies have exploring solutions that involve various renewable energy resources, such as wind and solar. Using energy storage techniques and optimization algorithms, researchers have addressed challenges related to sizing, costing, and energy management of renewable energy systems, identifying appropriate optimization algorithms for these tasks. After selecting energy storage technologies, renewable energy sources, and optimization algorithms, much of the research has concentrated on determining system capacities for the planning horizon. However, this study goes a step further by focusing on identifying the optimal capacities for solar PV and HESS, as well as determining the best time periods to integrate these capacities into the system to maximize overall benefits. To solve the multi-objective optimization problem, NSGA-II effectively identifies a diverse set of solutions using non-dominated sorting and crowding distance, offering fast sorting without the need to assign additional weights for objectives. In addition, this study introduces a novel multi-objective optimization algorithm and an energy management control strategy to effectively balance energy generation and storage within the system constraints.

The primary objective of this research is to develop a roadmap for integrating solar PV capacity, Li-ion BS storage capacity, and PHS capacity using results from a newly developed optimization algorithm for sizing and costing grid-scale HESS. A multi-objective optimization model that incorporates PHS and BS systems has been introduced, with the goal of maximizing solar PV generation while minimizing thermal energy generation. The model aims to minimize capital, operational, and replacement expenditures throughout the lifetime of the project, as well as to reduce costs associated with solar power curtailment and additional oil-fired thermal energy generation. The sub-objectives of this research include developing a novel multi-objective sizing and costing algorithm, along with a multi-objective energy management and control strategy that accounts for the limitations of each solar PV and HES systems. These models are designed to calculate the optimal capacities for solar PV, BS, and PHS systems and identify the optimal timing for integrating each system to maximize overall benefits. Additionally, this research aims to establish a roadmap for incorporating solar PV, BS, and PHS, considering both economic and environmental factors. The proposed algorithm is validated through a case study using real-world data. Finally, a sensitivity analysis is performed to identify the best scenario with minimal cost fluctuations under varying interest rates.

Section 1 provides an overview of the research and its background, outlining the objectives of the proposed work. The other sections of the paper are structured as follows: Section 2 describes the systems and methods used to achieve the research objectives. Section 3 presents the theoretical development of optimization algorithm and energy management strategy. Section 4 summarizes the research findings, discusses the results, and explores their implications. Finally, Section 5 concludes the paper by summarizing the key insights and outcomes, and outlines future requirements and direction for further research.

Section snippets

Sizing strategies

Sizing strategies for the solar PV system, BS system, and PHS system are identified to develop an algorithm to optimizes HESS for maximizing solar energy generation. …

Theoretical development of optimization algorithm and energy management strategy

To identify the optimal capacities for solar PV and BS over the lifetime of the project, sufficiently short time intervals are considered for each optimization cycle to maximize the benefits of the proposed system. Furthermore, the optimal timing for integrating PHS must be determined through economic, environmental, and sensitivity analyses. In this study, the project lifetime is assumed to be 25 years, considering the lifespans of solar PV panels and PHS systems. The construction timelines …

Roadmap of solar and battery capacities for most economical and environmental cases

As outlined in Section 3.2, forty Pareto-optimal solutions are identified and represented on the Pareto optimal front for single-term optimization. This optimization is performed over a two-year period, considering the installation timelines of solar PV and Li-ion BS systems. To illustrate the procedure for selecting the most suitable capacity values from the Pareto-optimal solutions, the first two-year period (2024–2025) of *Case* 6, as shown in Table 1, is utilized. The identified …

Conclusion

This study aims to enhance energy generation by increasing solar power production and reducing oil-fired thermal energy generation to improve system sustainability. To address challenges such as intermittency and unpredictability, a HESS integrating Li-ion BS and PHS is proposed. A multi-objective optimization algorithm is employed to minimize the total costs of the proposed system, including solar power curtailment costs and additional oil-fired thermal energy generation. An energy management …

CRediT authorship contribution statement

H.C. Ganege: Writing – original draft, Validation, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **D.P. Chandima:** Writing – review & editing, Supervision, Project administration, Conceptualization. **J.P. Karunadasa:** Methodology, Conceptualization. **Patrick Wheeler:** Conceptualization. …

Declaration of competing interest

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

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