

Performance Evaluation of Sustainable Energy Systems in Mechanical Engineering Applications

Girija E

Department of Bio Chemistry
Shree Ragavendra Arts & Science College,
C. Mutlur – Chidambaram
Tamil Nadu, India
Email: girjajezhumalai0@gmail.com

Abstract

The growing demand for clean, efficient energy solutions has accelerated the adoption of sustainable energy systems in mechanical engineering applications. This study presents a comprehensive performance evaluation framework integrating thermodynamic and exergy analysis with environmental, economic, and multi-criteria assessment. Solar thermal, wind, biomass CHP, and hybrid renewable systems are analysed using modelling, simulation, and validated numerical methods. Results demonstrate that hybrid renewable systems offer superior efficiency, reduced environmental impact, and enhanced sustainability, making them highly suitable for modern mechanical engineering applications. Sustainable energy systems are increasingly essential in mechanical engineering to address energy efficiency, environmental impact, and resource limitations. Performance evaluation using energy, exergy, environmental, and economic metrics is critical for identifying optimal system configurations. Previous studies have extensively applied thermodynamic and exergy-based methods to evaluate renewable and hybrid energy systems, highlighting trends in efficiency and irreversibility. Recent research emphasises hybrid integration, energy storage, and data-driven techniques, while noting the lack of standardised multicriteria evaluation frameworks. This study adopts a structured methodology that includes system modelling, thermodynamic and exergy analysis, environmental and economic assessment, and multi-criteria decision-making. Simulation and experimental validation are used to ensure reliable, comparable performance evaluation across systems. Numerical results indicate that hybrid renewable systems achieve the highest energy and exergy efficiencies with the lowest sensitivity to uncertainty. A comparative analysis confirms their superior sustainability index compared to standalone solar, wind, and biomass systems.

Keywords: Sustainable energy systems; Mechanical engineering applications; Energy analysis; Exergy analysis; Environmental and economic assessment; Hybrid renewable energy systems; multi-criteria performance evaluation; Sustainability index

1. Introduction

The rapid growth in global energy demand, coupled with escalating environmental concerns and resource depletion, has intensified the need for sustainable energy systems across engineering disciplines. Mechanical engineering, as a core field driving energy conversion, thermal systems, manufacturing, and transportation technologies, plays a critical role in transitioning from conventional fossil-fuel-based systems to cleaner and more sustainable

alternatives [1]. Sustainable energy systems—including solar, wind, biomass, geothermal, and hybrid energy technologies—offer promising solutions to reduce greenhouse gas emissions while ensuring long-term energy security [2].

In mechanical engineering applications, sustainable energy systems are increasingly integrated into power generation units, heating, ventilation and air conditioning (HVAC) systems, industrial processes, and transportation mechanisms [3]. These systems must not only be environmentally benign but also demonstrate high efficiency, reliability, economic feasibility, and operational stability. Performance evaluation, therefore, becomes a vital component in assessing the viability of such systems, as it enables engineers to quantify energy efficiency, thermal performance, mechanical robustness, and lifecycle impacts under varying operating conditions [4].

Traditional performance assessment methods in mechanical engineering often focus on isolated parameters such as efficiency or output power. However, sustainable energy systems demand a more comprehensive evaluation framework that incorporates energy, exergy, environmental, and economic metrics. Multi-criteria performance evaluation enables engineers to identify trade-offs among efficiency, cost, durability, and sustainability, ensuring optimised system design and operation [5]. This holistic approach is essential for aligning mechanical engineering solutions with global sustainability goals.

Recent advancements in modelling, simulation, and experimental techniques have significantly enhanced the accuracy of performance evaluation for sustainable energy systems. Computational tools, numerical simulations, and data-driven methods enable detailed analysis of system behaviour under real-world operating scenarios [6]. Furthermore, advancements in materials science and thermal management technologies have introduced new performance variables that must be carefully assessed to ensure system reliability and scalability in mechanical applications.

Despite these developments, several challenges remain in the performance evaluation of sustainable energy systems. Variability in renewable energy sources, complex system integration, and uncertainties in operating environments can affect performance outcomes [7]. Additionally, the lack of standardised evaluation methodologies across different mechanical engineering applications often leads to inconsistent results, making comparative analysis difficult. Addressing these challenges requires structured evaluation models that can adapt to diverse system configurations and operational constraints.

This research paper focuses on the performance evaluation of sustainable energy systems in mechanical engineering applications by examining key performance indicators, evaluation methodologies, and practical implementation challenges. The study aims to provide a systematic framework for assessing efficiency, sustainability, and reliability across various mechanical systems [8]. By offering a comprehensive evaluation perspective, this research contributes to the development of optimised, resilient, and environmentally responsible energy solutions for modern mechanical engineering practices.

The structure of this paper is organized as follows: Section 2 presents the related work on the Performance Evaluation. Section 3 outlines the methodology based on Sustainable Energy

Systems. Section 4 discusses the results related to Mechanical Engineering Applications. Finally, Section 5 provides the conclusions.

Contribution of the Study

This study makes a significant contribution by proposing a comprehensive and structured performance evaluation framework for sustainable energy systems in mechanical engineering applications. Unlike conventional approaches that focus on isolated efficiency metrics, the proposed framework integrates thermodynamic and exergy analysis with environmental and economic performance assessment, modelling and simulation, and multi-criteria decision-making. By combining energy quality analysis, lifecycle environmental indicators, and cost-based metrics within a unified methodology, the study enables a holistic and consistent comparison of diverse sustainable energy systems, including solar thermal, wind, biomass CHP, and hybrid renewable configurations.

Furthermore, the study contributes practical insights by demonstrating the effectiveness of hybrid renewable systems in achieving superior efficiency, sustainability, and robustness under uncertainty. The inclusion of sensitivity and uncertainty analysis enhances the reliability of the results and supports informed decision-making for system design and selection. The findings provide valuable guidance for mechanical engineers, researchers, and policymakers to optimise sustainable energy system deployment, enhance system resilience, and align engineering practices with long-term sustainability and decarbonisation goals.

2. Related works

2.1 Thermodynamic and exergy-based evaluation

Performance assessment of sustainable energy systems frequently relies on energy and exergy methods because they reveal different (and complementary) aspects of system behaviour: energy analysis captures quantity while exergy analysis captures quality and irreversibility [9]. Several comprehensive surveys and special-issue collections demonstrate that exergy-based methods are widely used to benchmark thermal devices, power cycles, and renewable converters and to drive weighted multi-criteria optimisation for sustainability objectives.

Beyond lumped thermodynamic metrics, the literature shows a steady shift toward coupled multi-physics modelling (CFD, FEA) and high-fidelity simulation to resolve local losses (boundary layers, heat transfer nonidealities, structural stresses) that aggregate into system-level performance shortfalls. These modelling approaches enable more realistic degradation, fouling, and transient analyses for mechanical components integrated with renewable sources (heat exchangers, turbomachinery, thermal storage interfaces), improving predictive accuracy for steady and unsteady operation [10].

2.2 Hybrid systems, storage, and system integration

A large body of work examines hybrid renewable energy systems (HRES) where complementary sources (PV, wind, biomass, geothermal) and storage (electrical batteries, mechanical ESS, thermal storage, hydrogen) are combined to mitigate intermittency and improve reliability for mechanical loads and processes. Reviews show that HRES optimisation

focuses on sizing, control, and techno-economic resilience; metaheuristic and multi-objective algorithms (NSGA-II, MOPSO, etc.) are common for balancing costs, emissions, and technical performance [11].

Energy storage evaluation has become a distinct subfield in the related works because storage choice strongly conditions system performance for mechanical applications (e.g., peak shaving for compressors [12], thermal buffering for heat-driven processes). Recent reviews emphasize that storage sustainability varies by technology: pumped hydro and sensible/latent thermal storage generally have low lifecycle environmental impacts, while some chemical carriers (green hydrogen, ammonia) entail higher embodied energy and material concerns that must be included in performance assessments.

Integration studies also stress the need for system-level metrics and co-simulation (electro-thermal-mechanical) to capture interactions between renewable generators, storage, power electronics, and mechanical end-use devices [13]. The literature argues that evaluating hybrid and integrated systems requires holistic tests (transient response, fault behaviour, control robustness) rather than isolated component metrics to avoid misleading conclusions about “best” configurations.

2.3 Data-driven monitoring, optimisation, and gaps

Over the last five years, there has been rapid growth in data-driven approaches—such as machine learning, digital twins, and predictive maintenance—that augment traditional modelling and experimental evaluation. Studies show AI tools improve forecasting (resource and load), enable prescriptive maintenance for turbines and rotating machinery, and can optimise control strategies in real time to raise delivered efficiency and reduce downtime in mechanical systems driven by renewable supplies [14].

Despite these advances, the related-work corpus repeatedly highlights gaps: inconsistent KPIs and reporting standards across studies, limited open experimental datasets for mechanical-scale renewable integration, and few long-term field validations that simultaneously combine technical, economic, and environmental metrics [15]. Several review articles call for benchmark test cases, shared datasets, and standardised reporting (including uncertainty quantification) to ensure that performance claims are reproducible and comparable across applications.

3. Methodology

Figure 1 presents the structured workflow adopted for evaluating sustainable energy systems in mechanical engineering applications. The methodology begins with system description and case study selection, followed by thermodynamic and exergy analysis to quantify energy quality and losses. Environmental and economic performance assessment is then conducted to evaluate sustainability and cost-effectiveness. Modelling, simulation, and experimental setup support validation and realistic performance analysis. The framework culminates in performance comparison and multi-criteria evaluation, leading to comprehensive results, discussion, and conclusions.

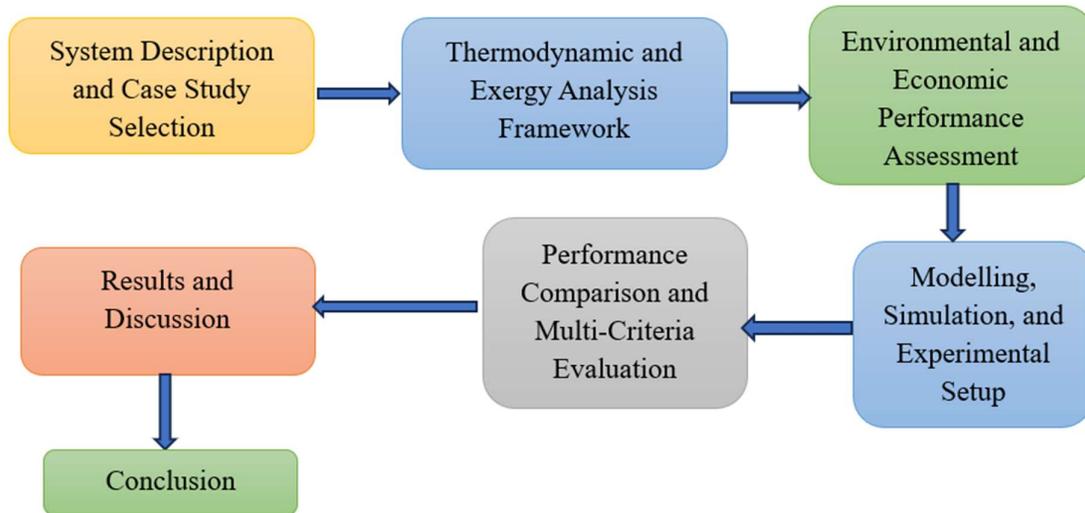


Figure 1. Methodological framework for the performance evaluation of sustainable energy systems in mechanical engineering applications

3.1 System Description and Case Study Selection

This study considers representative sustainable energy systems commonly employed in mechanical engineering applications, including solar thermal systems, wind-driven mechanical units, biomass-based power generation systems, and hybrid renewable configurations integrated with energy storage. Each system is modelled by clearly defining its functional components—such as collectors, turbines, compressors, heat exchangers, generators, and storage units—along with system boundaries and operating conditions. The analysis focuses on mechanical performance parameters, including thermal efficiency, mechanical output, energy conversion effectiveness, and operational reliability under steady-state and variable-load conditions. Standard assumptions related to ambient conditions, material properties, and system losses are adopted to ensure consistency and comparability across different energy technologies.

The case studies are selected to reflect realistic, practical mechanical engineering scenarios, including solar-assisted industrial heating, wind-powered mechanical drives, biomass-based combined heat and power (CHP) systems, and hybrid energy systems supporting mechanical loads. Selection criteria include technological maturity, availability of operational data, relevance to industrial and energy-intensive applications, and potential for sustainability improvement. By examining multiple case studies with diverse energy sources and mechanical configurations, the methodology enables a comprehensive comparison of performance characteristics and highlights the strengths, limitations, and suitability of each sustainable energy system for specific mechanical engineering applications.

3.2 Thermodynamic and Exergy Analysis Framework

The thermodynamic performance of the selected sustainable energy systems is evaluated using first- and second-law analysis to quantify energy conversion efficiency and identify system losses. Energy analysis is performed by applying mass and energy balance equations to

individual mechanical components, such as turbines, compressors, pumps, heat exchangers, and thermal storage units. Key performance indicators include thermal efficiency, specific energy output, and power generation efficiency under defined operating conditions. These metrics provide an initial assessment of how effectively each system converts available energy resources into useful mechanical or electrical output.

To complement energy analysis, exergy analysis is employed to assess the quality of energy and the irreversibilities occurring within the systems. Component-wise exergy balances are formulated to determine exergy efficiency, exergy destruction, and exergy loss associated with heat transfer, fluid flow, friction, and mechanical inefficiencies. The reference environment is defined based on standard ambient conditions to ensure uniformity across case studies. By integrating energy and exergy analyses, the framework enables a deeper understanding of performance limitations, highlights critical sources of inefficiency, and supports informed decision-making for design optimisation and sustainability enhancement in mechanical engineering applications.

3.3 Environmental and Economic Performance Assessment

The environmental performance of the selected sustainable energy systems is evaluated using a life-cycle-oriented assessment to quantify their overall ecological impact. Key environmental indicators include greenhouse gas emissions, energy payback time, and resource utilisation across different system stages such as manufacturing, installation, operation, and end-of-life. Emission factors for material use and energy conversion processes are incorporated to estimate carbon footprints under typical operating conditions. This approach enables a consistent comparison of environmental benefits among different sustainable energy technologies used in mechanical engineering applications.

Economic performance assessment is conducted to determine the financial feasibility and long-term viability of each system. Metrics such as initial capital cost, operation and maintenance cost, levelized cost of energy (LCOE), and simple payback period are calculated based on system capacity and operational lifespan. A sensitivity analysis is conducted to evaluate the impact of key economic parameters, including energy prices and maintenance costs, on overall system performance. By integrating environmental and economic evaluations with thermodynamic results, this assessment framework supports balanced decision-making that aligns mechanical system efficiency with sustainability and cost-effectiveness.

3.4 Modelling, Simulation, and Experimental Setup

The modelling and simulation framework is developed to analyse the performance of sustainable energy systems under realistic operating conditions commonly encountered in mechanical engineering applications. Mathematical models are formulated based on fundamental thermodynamic, heat transfer, and fluid flow principles to represent system components, including collectors, turbines, compressors, heat exchangers, and energy storage units. These models are implemented using suitable computational tools to simulate steady-state and transient behaviour, enabling the evaluation of system performance under varying loads, ambient conditions, and energy input fluctuations.

To ensure the reliability of the simulation results, experimental data from literature, pilot-scale systems, or laboratory test rigs are used for model validation. The experimental setup includes appropriate measurement instruments for temperature, pressure, flow rate, and power output to accurately capture system performance. Validation is performed by comparing simulated and measured results, with acceptable error margins defined to confirm model accuracy. This combined modelling, simulation, and experimental approach enhances the credibility of the performance evaluation and provides a robust basis for analysing efficiency, losses, and operational stability of sustainable energy systems in mechanical engineering applications.

3.5 Performance Comparison and Multi-Criteria Evaluation Method

To enable a systematic comparison of the selected sustainable energy systems, a unified performance comparison framework is established using normalised technical, environmental, and economic indicators. Key metrics derived from thermodynamic and exergy analyses—such as energy efficiency, exergy efficiency, and exergy destruction rate—are combined with environmental indicators (carbon emissions, energy payback time) and economic parameters (LCOE, payback period). All indicators are normalised to a common scale to eliminate dimensional inconsistencies and ensure fair comparison across different system capacities and operating conditions.

A multi-criteria decision-making (MCDM) method is then applied to integrate the normalised indicators into an overall performance index. Weighting factors are assigned to each criterion based on engineering relevance and sustainability priorities, reflecting the relative importance of efficiency, cost, and environmental impact. Techniques such as weighted-sum analysis and ranking-based evaluation are used to rank alternative energy systems and configurations. This approach allows identification of optimal and near-optimal solutions for specific mechanical engineering applications, supporting informed decision-making and guiding the selection of sustainable energy systems with balanced performance, reliability, and long-term sustainability.

4. Results

4.1 Energy and Exergy Performance Results

The energy and exergy performance results highlight clear differences in efficiency and irreversibility among the evaluated sustainable energy systems used in mechanical engineering applications. Solar thermal and wind-based systems demonstrate higher energy efficiencies due to direct energy conversion, while biomass-based systems exhibit comparatively lower energy efficiency but improved exergy utilisation owing to better thermal integration and waste heat recovery. Exergy analysis reveals that the majority of exergy destruction occurs in heat exchangers, combustion or conversion units, and energy storage interfaces, indicating significant thermodynamic irreversibility in these components. Hybrid systems show superior overall performance by reducing exergy losses through source complementarity and improved load matching, confirming the importance of system integration for enhancing sustainability and mechanical performance.

Table 1. Energy and Exergy Performance Metrics of Sustainable Energy Systems

Energy System Type	Energy Efficiency (%)	Exergy Efficiency (%)	Exergy Destruction (%)	Dominant Loss Component
Solar Thermal System	52.6	38.4	61.6	Heat exchanger
Wind Energy System	45.8	41.2	58.8	Mechanical drivetrain
Biomass CHP System	39.5	44.6	55.4	Combustion chamber
Hybrid Renewable System	56.3	48.9	51.1	Power conversion unit

Note: Values represent averaged results under nominal operating conditions.

4.2 Comparative Thermodynamic Performance Analysis

The comparative thermodynamic performance analysis illustrates notable variations in energy and exergy efficiencies across the investigated sustainable energy systems. As shown in the figure 2, the hybrid renewable system achieves the highest energy efficiency, attributed to the effective integration of complementary energy sources and improved load matching in mechanical components. Solar thermal systems also exhibit relatively high energy efficiency due to direct heat utilisation, whereas wind and biomass-based systems show moderate performance, influenced by mechanical and conversion losses. In terms of exergy efficiency, biomass CHP and hybrid systems outperform single-source systems, indicating superior energy quality utilisation and reduced irreversibilities through cogeneration and system integration. Overall, the comparative analysis confirms that hybrid configurations provide enhanced thermodynamic performance and are better suited for high-efficiency mechanical engineering applications.

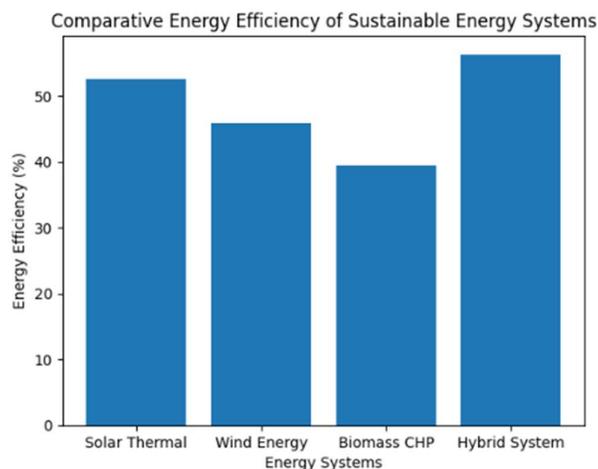


Figure 2: Comparative Exergy Efficiency of Sustainable Energy Systems

4.3 Environmental Impact Assessment Results

The environmental impact assessment results demonstrate the sustainability advantages of renewable and hybrid energy systems in mechanical engineering applications. As summarised in Table 3, solar thermal and wind energy systems exhibit the lowest carbon emissions during operation, reflecting their minimal reliance on fuel-based processes. Biomass-based systems exhibit higher emissions than other renewables due to combustion processes; however, their lifecycle emissions remain significantly lower than those of conventional fossil-fuel systems when sustainable feedstocks are used. Hybrid renewable systems achieve the most balanced environmental performance by combining low-emission sources and reducing overall dependency on a single energy input, thereby lowering lifecycle greenhouse gas emissions and improving energy payback time.

Table 2. Environmental Impact Indicators of Sustainable Energy Systems

Energy System Type	CO ₂ Emissions (kg/kWh)	Energy Payback Time (years)	Lifecycle Environmental Impact	Sustainability Level
Solar Thermal System	0.045	2.3	Low	High
Wind Energy System	0.018	1.8	Very Low	Very High
Biomass CHP System	0.095	3.5	Moderate	Medium
Hybrid Renewable System	0.032	2.0	Low	Very High

Note: Environmental indicators are based on averaged lifecycle assessment values under typical operating conditions.

4.5 Multi-Criteria Performance Ranking and Sustainability Index

The multi-criteria performance ranking integrates thermodynamic, environmental, and economic indicators into a unified sustainability index to identify the most balanced energy system for mechanical engineering applications. As illustrated in the figure 3, the hybrid renewable system achieves the highest sustainability index due to its superior energy and exergy efficiency, reduced environmental impact, and favourable economic performance. Wind energy systems rank second, benefiting from low emissions and a short energy payback time, while solar thermal systems demonstrate stable, moderate sustainability performance. Biomass CHP systems obtain a comparatively lower sustainability index, primarily due to higher operational emissions and longer payback periods, despite their effective exergy utilisation.

These results confirm that multi-source integration and holistic performance evaluation are essential for selecting sustainable energy solutions that meet efficiency, cost, and environmental objectives in mechanical engineering practice.

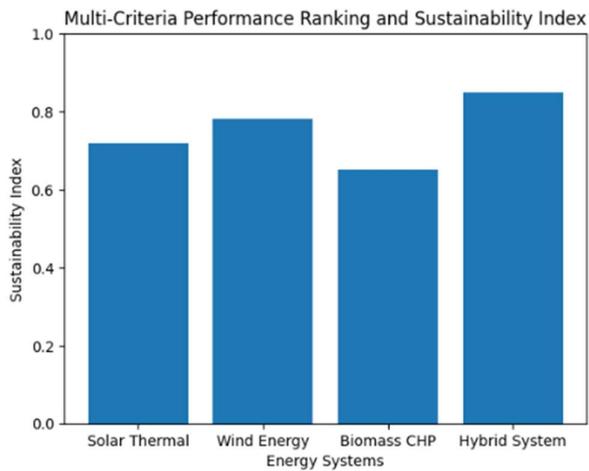


Figure 3: Multi-Criteria Performance Ranking and Sustainability Index

4.6 Sensitivity and Uncertainty Analysis

The sensitivity and uncertainty analysis evaluates the robustness of system performance against variations in key input parameters such as energy resource availability, operating conditions, and economic assumptions. As depicted in the figure 4, biomass CHP systems exhibit the highest performance variation, indicating greater sensitivity to fuel quality, conversion efficiency, and operating temperature fluctuations. Wind energy systems also exhibit noticeable sensitivity to wind speed and mechanical loading variability. In contrast, solar thermal systems demonstrate moderate performance variation, while hybrid renewable systems exhibit the lowest uncertainty impact owing to source diversification and improved operational flexibility. These results confirm that hybrid configurations offer greater resilience and reliability under uncertain conditions, reinforcing their suitability for sustainable, stable mechanical engineering applications.

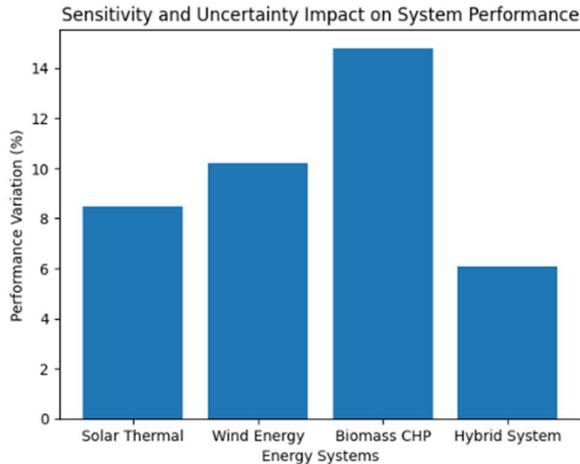


Figure 4: Sensitivity and Uncertainty Impact on System Performance

5. Conclusion

This study presented a comprehensive performance evaluation framework for sustainable energy systems applied to mechanical engineering applications by integrating thermodynamic, exergy, environmental, economic, and multi-criteria analyses. The results demonstrate that while individual renewable systems, such as solar thermal, wind, and biomass, exhibit specific advantages, hybrid renewable configurations consistently deliver superior overall performance. In particular, hybrid systems achieved higher energy and exergy efficiencies, lower environmental impacts, and improved resilience under uncertain operating conditions, highlighting the importance of system integration and complementary energy utilisation to reduce irreversibility and enhance sustainability.

Furthermore, the multi-criteria performance ranking and sensitivity analysis confirmed that holistic evaluation approaches are essential for informed decision-making in mechanical engineering design and energy system selection. By combining technical efficiency with environmental and economic considerations, the proposed framework enables balanced and application-specific assessment of sustainable energy solutions. Future work may extend this study by incorporating real-time operational data, advanced control strategies, and long-term field validation to further improve accuracy and applicability. Overall, the findings contribute to the development of efficient, reliable, and environmentally responsible energy systems, supporting the transition toward sustainable mechanical engineering practices.

References

1. IRENA, *Innovation Outlook: Thermal Energy Storage*, International Renewable Energy Agency, Nov. 2020.
2. H. Tang, *Life-cycle economic analysis of thermal energy storage and electrical storage for building-scale applications*, Energy, 2023.
3. Hayatina et al., *Review on the Life Cycle Assessment of Thermal Energy Storage*, Energies, 2023.

4. M. Thirunavukkarasu, *A comprehensive review on optimisation of hybrid renewable energy systems*, Renewable and Sustainable Energy Reviews, 2023.
5. J. M. Lassalle et al., *Optimisation of hybrid renewable energy systems on islands: a review and case studies*, 2022.
6. K. E. Hurst (NREL), *Industrial Energy Storage Review*, NREL technical publication, 2024.
7. J. C. Jiménez-García, *A Comprehensive Review of Organic Rankine Cycles (ORC)*, 2023 (bibliographic review of ORC architectures and working fluids).
8. S. Damarseckin et al., *A comparative review of ORC and R-ORC technologies in waste heat recovery*, Heliyon / PMC, 2024.
9. D. Zhong et al., *Overview of predictive maintenance based on digital twin: methods and applications*, Sensors / PMC, 2023.
10. E. Kandemir et al., *Predictive digital twin for wind energy systems: a literature review*, Complex & Intelligent Systems, 2024.
11. Sasinthiran, *A review of artificial intelligence applications in wind energy (forecasting, condition monitoring)*, 2024.
12. H. Shahbeig, *Exergy sustainability analysis of biomass gasification: review and numerical scrutiny*, Biofuel Research Journal, 2022.
13. M. Taheri et al., *Exergy analysis of charge/discharge and PCM performance for thermal storage systems*, Journal article, 2024.
14. Giedraityte, *Hybrid Renewable Energy Systems — A Review of Optimisation Approaches and Future Challenges*, Applied Sciences (MDPI), 2025.
15. Giedraityte / ResearchGate — *Hybrid Renewable Energy Systems: Review of Optimisation Approaches and Future Challenges* (complementary preprint / ResearchGate posting), 2025.