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Optimization of Biomass-Powered Organic Rankine Cycle

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ABSTRACT:
Background

Biomass energy, often referred to as conversion-from-biomass-to-energy, has long been recognised as a renewable source particularly suitable for low- and medium-temperature power generation systems. Biomass resources are abundant and versatile, producing both electricity and heat from agricultural residues, forestry waste, and energy crops. The Organic Rankine Cycle (ORC) has emerged as an effective technology for exploiting such resources, with applications ranging from small-scale decentralised rural electrification to large-scale industrial combined heat and power (CHP) systems. Despite these advantages, biomass-powered ORCs face limitations related to thermodynamic efficiency, economic viability, and environmental sustainability. These challenges are closely linked to factors such as working fluid selection, component design, and system configuration.

Methods

This review synthesises recent advances in optimisation strategies for biomass-powered ORC systems. Emphasis is placed on three major areas:

- Working fluid optimisation – evaluation of fluids and mixtures with lower global warming potential and better thermodynamic performance.
- Component and system design – optimisation of heat exchangers, turbines, and layout for improved exergy efficiency.
- Hybridisation and multi-objective approaches – integration with solar energy, part-load operation analysis, and thermoeconomic methods that simultaneously address performance, cost, and environmental impacts.

Results

The literature indicates that optimised working fluid selection and improved heat exchanger design can enhance system efficiency by approximately 10–20%. Hybrid solar–biomass configurations demonstrate superior flexibility, enhanced efficiency, and reduced carbon emissions compared to stand-alone biomass systems. Moreover, multi-objective optimisation frameworks provide balanced solutions that improve energy and exergy efficiency while reducing the levelised cost of electricity (LCOE). Despite these advances, significant research gaps remain, particularly in the areas of large-scale demonstration, advanced control strategies, and integration with polygeneration systems.

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Conclusion

Biomass-powered ORCs have the potential to become cost-effective and sustainable solutions within the global low-carbon energy transition. Achieving this requires systematic optimisation across thermodynamic, economic, and environmental dimensions. With further progress in hybridisation strategies, digitalised control systems, and large-scale validation, optimised biomass-ORC technologies could play a central role in delivering reliable, clean, and efficient energy on both small and large scales.

Keywords- Biomass energy; Organic Rankine Cycle; Exergy analysis; Thermoeconomic optimization; Renewable energy systems; Sustainability

Introduction

The sweeping change toward sustainable energy solutions empowered increased focus on renewable technologies capable of meeting the fellow concerns of environment and energy security. In a generic way, biomass energy has been considered carbon-neutral and has indeed been widely available and energy source of heat and electricity commercially (Alvi, Guan, & Imran, 2024). From an energy conversion perspective, the Organic Rankine Cycle (ORC) uses heat sources capable of producing energy at low to medium temperatures from heat, and because of its huge flexibility and adaptability, it has also been favored in comparison with a conventional Rankine cycle (Heidarnejad, Genceli, Hashemian, Asker, & Al-Rawi, 2024).

Biomass plants fed by ORC can provide wide-scale application from small-scale rural electrification to big industrial combined heat and power (CHP) applications. They remain open to the use of several biomass sources comprising live or dead biomass of agricultural residues, forestry wastes, and even energy crops, thus enabling it to be fairly flexible and scalable (Heidarnejad et al., 2024). Yet, many factors influence the performance of these systems, such as the choice of working fluid, heat exchanger design, turbine efficiency, and systems integration (Douvartzides, Tsiolikas, & Charisiou, 2022). Without such optimization efforts, biomass-ORC might suffer from inadequate thermodynamic performance, increase in operation costs, and suboptimal environmental performance.

Optimization possibilities for biomass-ORC systems have been explored in recent literature. For instance, Alvi et al. (2024) investigated the hybrid solar-biomass ORC systems and pointed out that hybridization could improve the system's flexibility, energy efficiency, and carbon emission reduction. Calli & Colpan (2021) also studied thermoeconomic biomass-solar ORCs under part load conditions and demonstrated that a much better energy and exergy efficiency could be achieved through competent control and good component choice. Other works focus on component-level optimization with screening of working fluids, design of heat exchangers,

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and turbine performances to maximize system performance while minimizing economic and environmental cost (Douvartzides et al., 2022; Ehyaei, Heberle, & Brüggemann, 2024).

The optimization of biomass-ORCs is not only restricted in thermodynamic optimization. Economic factors such as levelized cost of electricity (LCOE), capital expenditure, and maintenance cost largely influence the feasibility of large-scale deployment (Karthikeyan & Kumar, 2023; Ren, Xu, Qian, Huang, & Wang, 2024). Exergoeconomic analyses have been widely used for evaluating trade-offs between energy out and economic cost to provide direction to design decisions for industrial and residential applications (Calli & Colpan, 2019). In addition, sustainability assessments, such as life cycle analysis and environmental impact assessment, are increasingly integrated into optimization studies to guarantee that better performance is not at the cost of ecological responsibility (Gonidaki & Bellos, 2025).

Despite improvements, there still remain numerous research gaps. Few studies focus on the challenges related to large-scale implementation, hybridization with several renewable sources, and integration of advanced control strategies for real-time optimization. There is also a need to study working fluid selection more thoroughly, especially binary mixtures and environmentally friendly alternatives, for best thermodynamic and environmental performance (Douvartzides et al., 2022; Heidarnejad et al., 2024). Filling these gaps is essential to increase the viability of biomass-ORC systems as a sustainable energy solution.

The current study aims to give an extensive review of biomass-powered ORC optimization strategies in terms of thermodynamic, techno-economic, and sustainability aspects. By synthesizing recent research covering hybrid solar biomass systems, studies of part-load behavior, and multi-objective optimization, this article intends to point to best practices, trends in performance, and areas that require further research. The findings should be seen as a guide for researchers, engineers, and policymakers in harnessing optimized biomass-ORC systems to contribute toward a low-carbon energy future (Alvi et al., 2024; Calli & Colpan, 2021; Karthikeyan & Kumar, 2023).

1. Thermodynamics of Biomass-ORC

One of the key issues for the rating of ORC systems is thermodynamic efficiency. According to Heidarnejad et al. (2024), a broad review was presented on biomass-fueled ORCs, asserting that system efficiency varies generally from 15% to 25%, mainly depending on working fluids, temperature of heat source, and configuration of the system. Douvartzides, Tsiolikas, and Charisiou (2022) dealt with the exergy-based screening of refrigerants, hydrocarbons, and siloxanes for biomass ORCs, evidencing that working fluid selection really matters about energy and exergy efficiency. In this context, hydrocarbon and siloxane mixtures could be considered promising working fluids as they may reduce exergy destruction whilst increasing heat-transfer in the evaporator.

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Calli and Colpan (2019, 2021) studied biomass solar hybrid ORCs under part-load conditions. Their work showed that hybridization enhances system flexibility and overall exergy efficiency, especially under variable load conditions. The introduction of solar thermal input helps keep the heat supply consistent, minimizing thermodynamic losses during periods of low biomass availability. Ren et al. (2024) applied this to biomass gasification with an ORC, reporting increases in thermal efficiency due to the integration of waste heat recovery through externally fired gas turbines and steam Rankine cycles.

2. Economic Analysis and Techno-Economic Optimization

Economic considerations are crucial in the large-scale adoption of biomass-ORCs. The techno-economic analysis by Karthikeyan and Kumar (2023) of a hybrid solar-biomass cascade system for dairy plants highlighted that through an intricate optimization of system components, one can drive down the levelized cost of electricity (LCOE) and make the system profitable overall. Ehyaei, Heberle, and Brüggemann (2024) tackled a more residential realm, questioning cost and performance impact in the case of battery integration and coming out with the conclusion that energy storage hybridization is beneficial for increasing back-up capability and reducing operational costs but might raise the initial capital cost.

Alvi, Guan, and Imran (2024) emphasized the importance of multi-objective optimization approaches that take into consideration energy output, economic cost, and sustainability metrics simultaneously. Their review highlights how factored thermodynamic, economic, and environmental objectives allow for balanced design strategies that can maximize the performance of a system without placing too great a financial burden upon the user. These integrated approaches arise as most pertinent when dealing with hybrid systems within the solar and biomass context where input fluctuates on a seasonal basis.

3. Environmental and Sustainability Considerations

Sustainability considerations concerning biomass-powered ORCs have lately become highly relevant due to world carbon reduction targets. Alvi et al. (2024) indicated the possibility that hybrid solar–biomass ORCs could reduce CO_2 emissions by 30% as compared to biomass-only systems, thanks to factors such as greater system efficiency and less fuel consumption. Gonidaki and Bellos (2025) reviewed the multi-source ORC systems and stated that environmental performance is influenced not only by energy efficiency but also by the criteria of the working fluid and type of biomass. Environmentally friendly fluids of low global warming potential (GWP) and zero ozone depletion potential (ODP) are recommended to synergize with sustainability considerations.

Calli and Colpan (2021) used life cycle assessment (LCA) indicators in their study, demonstrating that hybrid ORC systems combined with solar energy offer better environmental impacts, especially concerning greenhouse gas emissions and resource utilization.

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Consequently, integration for sustainability evaluation of biomass-ORC systems should consider thermodynamic efficiency allied to environmental impact metrics.

4. Component-Level Optimization

Enhancement of the performance of biomass-ORCs through component-level optimization has been well explored. Their work (Douvartzides et al., 2022) stresses that losses of exergy are mainly affected by heat exchanger design. Optimized designs of evaporators, like multi-tube and triple-tube evaporators, will result in increased heat transfer and greater reduction of temperature mismatches between the heat source and working fluid. On the other hand, the turbine and expander efficiencies mostly influence the system performance, while the appropriate matching between turbine characteristics and working fluid will increase output power significantly (Heidarnejad et al., 2024; Ren et al., 2024).

The integration of energy storage as a buffer to fluctuations in biomass availability is an attractive option, as well as optimized control strategies for enhancing part load efficiency (Ehyaei et al., 2024; Karthikeyan and Kumar, 2023). Together they imply that overall system performance gains can be achieved through combined working fluid selection with heat exchanger design, turbine optimization, and the control strategy.

5. Research Gaps and Perspectives for Future Research

Despite significant prior work, developments yet to take place: Holistic large-scale deployment studies for optimized biomass-ORCs remain sparse, the real-world performance of biomass-ORCs under fluctuating biomass supply and hybrids application yet to be well recorded (Alvi et al., 2024; Gonidaki and Bellos, 2025). Another aspect is the AI-driven control integration, predictive maintenance, and digital twin modeling-assisted operation enhancement, with the potential largely untapped and narrow empirical emphasis. Multi-objective optimization that simultaneously considers thermodynamic efficiency, economic feasibility, and environmental sustainability is still underdeveloped, particularly for hybrid systems combining biomass, solar and other renewable inputs (Heidarnejad et al., 2024; Calli and Colpan, 2021).

Conclusion of Literature Review

According to the literature, biomass- powered ORCs can be optimized for considerable improvements concerning efficiency, cost-effectiveness, and sustainability of the working fluids, components, system integration, and control strategies. Performance and environmental effects can be further enhanced by solar hybridizations and multi-objective thermoeconomic optimization. However, to completely exploit the potential of optimized biomass-ORC systems, one requires large-scale demonstration, real-world validation, and advanced control approaches. This literature review will bring out foundations for the subsequent sections, which will highlight methodological approaches, synthesized results, and suggestions for future development.

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Table 1 Summary of Key Biomass-ORC Studies

Reference	System Type	Efficiency (%)	Optimization Focus
Alvi et al., 2024	Hybrid Solar–Biomass ORC	20–25	Thermoeconomic, sustainability
Heidarnejad et al., 2024	Biomass ORC	15–22	Working fluid & system design
Calli & Colpan, 2021	Biomass-Solar ORC	18–24	Part-load performance
Karthikeyan & Kumar, 2023	Solar–Biomass ORC	17–23	Multi-objective optimization
Ren et al., 2024	Biomass Integrated ORC	18–24	Combined cycle & waste heat
Ehyaei et al., 2024	Residential Biomass ORC	15–21	Battery & thermoeconomic
Douvartzides et al., 2022	Biomass Boiler ORC	16–22	Exergy-based fluid & heat exchanger

Methodology

This paper uses a comprehensive review and an analytical approach for studying the optimization of biomass-fueled Organic Rankine Cycle (ORC) systems with thermodynamic, economic, and environmental performance aspects in mind. The methodology employs an optimization roadway in three steps: literature selection, classification, and synthesis.

1. Literature Selection

Research papers were selected from reviewing journals, including Biomass, Energies, Sustainable Energy Technologies and Assessments, Entropy, and Energy Conversion and Management. Keywords used in the search include "biomass ORC," "Organic Rankine Cycle," "thermoeconomic analysis," "hybrid solar-biomass ORC," and "optimization." The publications from 2019 to 2025 were prioritized to allow for capturing very recent developments on working fluid selection, component optimization, hybrid system design, techno-economic evaluation, etc. The ten main references, forming the backbone of this review, were chosen according to relevance, citation impact, and whether optimization studies were experimental or simulation-based (Alvi, Guan, & Imran, 2024; Heidarnejad et al., 2024; Calli & Colpan, 2021; Karthikeyan & Kumar, 2023).

2. Classification and Data Extraction

- The selected studies were systematically classified subject to the following key criteria:
- System Type: biomass-only ORC, hybrid solar-biomass ORC, residential versus industrial uses.

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- Working Fluids: types, properties, and environmental impacts (GWP, ODP).
- Performance Metrics: thermal efficiency, exergy efficiency, part-load performance, CO_2 reductions.
- Optimization Objective: thermodynamic, economic, component level, or multi-objective.
- Integration and Control: whether energy storage, hybridization, or advanced control strategies are used.
- Data from every study were extracted and tabulated to allow comparisons of performance trends, optimization approaches, and sustainability outcomes.

3. Analytical Framework for Optimization

An analytical framework used for synthesizing the insights from the literature is as follows:

- ✓ Thermodynamic Analysis: Assessment of energy and exergy efficiencies, considering the heat source temperature, working fluid properties, and configuration of the system.
- ✓ Techno-Economic Analysis: Evaluation of capital cost, levelized cost of electricity (LCOE), payback period, and operational cost.
- ✓ Sustainability Assessment: Further consideration to environmental indicators, such as CO_2 emissions, life-cycle impacts, and the employment of environmentally friendly working fluids.
- ✓ Optimization Strategy Identification: Best practices and strategies as reported in the literature are extracted and presented, covering working fluid selection, heat exchanger design, turbine/expander efficiency, and hybrid system integration.

4. Synthesis and Comparative Study

The comparative findings were presented on the basis of both qualitative and quantitative descriptions:

- **Qualitative**: narrative synthesis expounding on trends, major gaps, and recommendations toward system improvements;
- **Quantitative**: tabular comparison on system efficiencies, working fluid performances, and techno-economic indicators for visualization on how optimization has made an impact across different studies.
- Through the complete method, a rigorous and systematic review of biomass-fueled ORC systems could be ensured while also shining a light on potential areas for performance cost and sustainability optimization.

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Table 2 Summary of Methodology for Review of Biomass-ORC Systems

Step	Description	Key Elements
Literature Selection	Identification of relevant studies	Peer-reviewed journals (2019–2025), keywords: "biomass ORC," "hybrid solar-biomass," "optimization"
Classification & Data Extraction	Organizing studies for analysis	System type, working fluid, performance metrics, optimization focus, integration/control
Analytical Framework	Structured evaluation of systems	Thermodynamic efficiency, techno-economic analysis, sustainability assessment, optimization strategies
Synthesis & Comparative Analysis	Integration of findings	Qualitative trends, quantitative comparisons (efficiency, cost, environmental impact)

Results

The synthesis of the ten studies selected on biomass-powered Organic Rankine Cycle (ORC) systems provides the ultimate overview of system performance, optimization strategies, and sustainability outcomes. The results are broadly classified into three categories: thermodynamic performance, economic feasibility, and environmental sustainability.

1. Thermodynamic Performance

Of primary importance in evaluating biomass-ORC feasibility is thermodynamic efficiency. The thermal efficiencies reported in the selected studies varied between 15% and 25%, depending on the system arrangement, working fluid, and heat input (Alvi, Guan, & Imran, 2024; Heidarnejad et al., 2024; Calli & Colpan, 2021). Purely biomass-type ORCs were generally said to have efficiencies of 15–22%, while the hybrid solar-biomass configurations were able to go as far as 20–25%, showing that the integration of another renewable heat source is indeed advantageous.

Across all papers reviewed, working fluid selection was predominant among factors conditioning performance." Douvartzides, Tsiolikas, and Charisiou (2022) showed that hydrocarbon and siloxane mixtures reduce exergy destruction and improve heat transfer in the evaporator. Similarly, Ren et al. (2024) demonstrated how, with the integration of externally fired gas turbines and steam Rankine cycles, there is better waste heat recovery, hence increasing overall system efficiency. Calli and Colpan (2021) also observed that part-load operation or common operational scenarios in real life can detrimentally affect the system performance, but that hybridization with solar energy helps alleviate such impediments by stabilizing the heat supply and reducing thermal losses.

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2. Economic Feasibility

Some studies show the economic feasibility with different measures, such as the levelized cost of electricity (LCOE), capital cost, and operational cost. Karthikeyan and Kumar (2023) have concluded that hybrid solar–biomass ORC systems can reduce LCOE from 10–15% compared to the biomass-only systems, largely because of the higher energy output and more efficient component usage. Ehyaei, Heberle, and Brüggemann (2024) dealt with residential ORCs and determined that while the integration of batteries for energy storage increases the capital cost at the outset, it enhances dispatchability and operational cost.

Alvi et al. (2024) argued for multi-objective optimization methods, in which energy efficiency, economic costs, and sustainability indicators are simultaneously considered. Such strategies allow systems to be designed to strike a balance between performance and financial practicability, especially when hybrid or industrial kinds are a concern. In summary, the studies imply that pertinent optimization of components, working fluids, and hybridization strategies can further considerably accelerate economic performance.

3. Environmental Sustainability

Sustainability assessments, with a special focus on CO_2 abatement and life-cycle environmental impact, were common among the hybrid ORC studies. Hybrid solar–biomass ORCs are reported by Alvi et al. (2024) to reduce CO_2 emissions by an order of 25–30% compared with biomass-only systems on account of higher efficiencies and lower biomass consumption. Gonidaki and Bellos (2025) stress that environmental performance is impacted not only by system efficiency but also by working fluid selection. Fluids that have a low GWP and zero ODP increase overall sustainability.

Hybrid ORC systems with solar supplementation are found by Calli and Colpan (2021), in their LCA, to reduce GHG emissions as well as resource use. This stresses further the significance of adhering to thermodynamic optimization and green design choices to ensure a sustainable system operation.

4. Component-Level Optimization

Some studies emphasize the necessity for component-level design to achieve adequate performance. Douvartzides et al. (2022) have demonstrated that placing more emphasis on optimizing the evaporator configuration, for example through the multi-tube or triple-tube design, improves heat transfer yet reduces exergy losses. On the other side, turbine and expander efficiencies have been found to greatly influence the output power, and when correctly matched with working fluid properties, will better convert energy into useful work (Heidarnejad et al., 2024; Ren et al., 2024). Ehyaei et al. (2024) even discuss that the integration of energy storage can smooth fluctuations in biomass supply, thus benefiting part-load

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efficiency, and Karthikeyan and Kumar (2023) stress that advanced control strategies are critical to realize such benefits within hybrid configurations.

5. Comparative Insights

A comparative summary of the main outcomes of the ten studies can be found in Table 3. This table highlights differences based on system type, efficiency, optimization focus, and sustainability results, providing a quick background for judging the effects of various design and operational strategies.

Table 3 Comparative Summary of Key Findings from Reviewed Biomass-ORC Studies

Reference	System Type	Efficiency (%)	Optimization Focus	Sustainability Outcome
Alvi et al., 2024	Hybrid Solar–Biomass ORC	20–25	Thermoeconomic & hybrid integration	CO_2 reduction ~25–30%
Heidarnejad et al., 2024	Biomass ORC	15–22	Working fluid & system design	Moderate environmental improvement
Calli & Colpan, 2021	Biomass-Solar ORC	18–24	Part-load optimization	Reduced emissions via hybrid integration
Karthikeyan & Kumar, 2023	Solar–Biomass ORC	17–23	Multi-objective optimization	Improved cost-effectiveness & environmental performance
Ren et al., 2024	Biomass Integrated ORC	18–24	Waste heat recovery & component optimization	Moderate sustainability improvement
Ehyaei et al., 2024	Residential Biomass ORC	15–21	Battery & thermoeconomic optimization	Better part-load performance; lower emissions
Douvartzides et al., 2022	Biomass Boiler ORC	16–22	Working fluid & heat exchanger design	Environmentally safer fluids recommended

Summary of the Results

The review clearly reveals that the hybrid solar-biomass ORCs will always be more efficient, more economically viable, and more environmentally sound than biomass-alone systems. For optimization, consideration must be given to working fluid selection, component design (particularly of the heat exchangers and turbines), hybridization, and advanced control strategies. Part-load and real-conditions operations are critical to residential and decentralized

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applications, while industrial-scale systems benefit from combined-cycle integration and multi-objective optimization tools.

Discussion

The synthesis of the most recent scientific studies on biomass-based Organic Rankine Cycle (ORC) systems reveals some important trends, challenges, and opportunities for the enhancement of its performance, cost-effectiveness, and sustainability. The results indicate that hybrid solar–biomass ORC systems usually outrank their biomass-only configurations in higher thermal and exergy efficiencies, better economic grounds, and lesser environmental impacts (Alvi et al., 2024; Calli & Colpan, 2021).

1. Thermodynamic Implications

Thermodynamic performance is a primary reason behind ORC optimizations. Such greater efficiency exhibited by hybrid systems (20-25%) in comparison to biomass-only systems (15-22%) implies that supplying biomass heat with solar energy constitutes a more stable thermal input; thereby, less part-load operation losses occur and furthermore, turbine operation is more optimum (Heidarnejad et al., 2024; Ren et al., 2024). Also, the working fluid choice influences the performance; fluids like siloxanes, hydrocarbons, and R245fa mixtures further reduce exergy destruction and assist in the heat transfer process in the evaporator (Douvartzides et al., 2022). These studies indicate how some working fluid properties as well as source temperature ranges deserve careful consideration to improve energy conversion from designers' perspective.

2. Economic Considerations

Economic analysis from across the literature in this review shows that component design, hybridization, and operation strategies optimization will affect the levelized cost of electricity (LCOE) and, in consequence, the overall system feasibility (Karthikeyan & Kumar, 2023; Ehyaei et al., 2024). With a view toward thermodynamic, economic, and sustainability criteria, multi-objective optimization identifies potential system configurations that pragmatically contend with efficiency and cost (Alvi et al., 2024). Storage solutions increase dispatchability for residential or decentralized projects, yet they increase capital expenditure. Hence, a trade-off between upfront investment and long-term operational savings must be appraised.

3. Sustainability Insights

Environmental sustainability is closely related to system efficiencies and working fluid choices. Hybrid solar–biomass systems reduce CO_2 emissions by up to 30% and improve resource utilization efficiencies (Alvi et al., 2024; Gonidaki & Bellos, 2025). Working fluids that are low GWP and zero ODP impact the sustainability agenda quite heavily. LCA studies (Calli & Colpan, 2021) conclude that having solar input put in place improves efficiency and

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lessens biomass-related environmental impacts at every stage of accepting, processing, and combustion.

4. Component-Level and System Integration Insights

Heat exchangers and turbine designs are intended to maximize performance. Multi-tube evaporators and turbine-expander configurations present fewer exergy losses and promise more energy conversion (Douvartzides et al., 2022; Heidarnejad et al., 2024). Hybridization, particularly involving solar energy, further enhances system flexibility and stability, allowing ORCs to maintain their level of efficiency while biomass availability fluctuates. Moreover, the combined-cycle integration, such as in the form of coupling with steam Rankine or externally fired gas turbines, can realize efficiency improvements at the industrial scale (Ren et al., 2024).

5. Limitations and Research Gaps

Several gaps exist, in spite of progress. Most of the works represent simulations or at best small laboratory experiments, so little in the way of real demonstration data are available. Large-scale hybrid deployments and advanced control strategies, as well as the integration with polygeneration systems (electricity, cooling, hydrogen production), are yet to be adequately examined (Karthikeyan & Kumar, 2023; Gonidaki & Bellos, 2025). Although many worked on multi-objective optimization, few have addressed very dynamic operational scenarios, part-load fluctuations, or seasonal variations in biomass and solar availability. It is therefore important to address these gaps in order to scale biomass-ORC systems while enhancing efficiency, cost-effectiveness, and environmental performance.

6. Conclusions for Design and Policy

This finding encourages policymakers and engineers to consider hybridization strategies, eco-working fluids, and multi-objective optimization in their development of biomass-ORC systems. Subsidies toward hybrid solar-biomass deployment might further speed the uptake of this class of low carbon technologies, whereas standards for designing components and selecting fluids might imperil system reliability and sustainability. Endorsed demonstration schemes would be necessary for verifying simulation work and optimizing it in real life under variants of operating conditions.

Summary of Discussion

In synthesis, the literature indicates that optimized biomass-powered ORC are able to achieve:

- ✓ Higher thermodynamic efficiencies through hybridization and fluid selection.
- ✓ Better economic performance with multi-objective optimization.
- ✓ Reduced environmental impacts through LCA-based design and low-GWP working fluids.

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However, to transition from experimental and simulation studies to real-world applications, large-scale deployment, control strategies, and seasonal operational challenges require bridging. There must be integration among thermodynamic, economic, and environmental criteria in the design of robust, scalable, and sustainable biomass-ORC systems.

Conclusion

This study works toward a complete review and synthesis of recent developments pertaining to biomass-powered ORC systems for thermodynamic performance, economic feasibility, and environmental sustainability. The analysis of key research yielded ten important insights:

Thermodynamic Performance: Hybrid solar–biomass ORC systems maintain better thermodynamic efficiency than that of solely biomass-based configurations, generating from 20 to 25% thermal efficiency, while biomass alone yields from 15 to 22%. The selection of working fluid, the design of heat exchangers, and turbine optimization remain prime factors that result in maximized energy conversion and exergy efficiencies (Alvi, Guan, & Imran, 2024; Douvartzides, Tsiolikas, & Charisiou, 2022).

Economic Feasibility: Multi-objective optimization-based methodologies that incorporate thermodynamics, economics, and sustainability parameters best reduce the LCOE and lead to a more cost-efficient operation. At the residential level, incorporating an energy-storage system will increase dispatchability, while at the industrial level, it has become more cost-efficient through combined-cycle integration and components optimization (Karthikeyan & Kumar, 2023; Ehyaei, Heberle, & Brüggemann, 2024).

Environmental Issues: Solar hybridization reduces CO_2 emissions by around 30% and increases resource efficiency. The use of environmentally friendly working fluids having low to zero GWP and ODP further improves the environmental performance, as shown by life-cycle assessments (Calli & Colpan, 2021; Gonidaki & Bellos, 2025).

Optimization Insights: Component-level improvements such as multi-tube evaporators, optimized turbines, and advanced control strategies will be paramount in ensuring maximum performance under full-load and part-load operating conditions. Hybrid integration and combined-cycle options add to sufficient increases in efficiency.

Research Gaps: While most simulation and small-scale experimental works successfully demonstrate the promising potential of optimized biomass-ORCs, issues regarding large-scale deployment and implementation, validation under dynamic operational conditions, and seasonal variability are not well addressed. Hence, future research should look into real-life demonstration and implementation of biomass-ORC power plants, design of advanced control strategies, and integration with multi-generation systems of electricity, cooling, and hydrogen production.

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In general, biomass-based ORC systems, especially when solar hybridization and multi-objective optimizations are involved, present a promising pathway toward low-carbon energy conversion that is technically efficient, sustainable, and commercially viable. This review has opened the way to further research and practical design consideration involving biomass-ORC systems, with the hope that thermodynamics, economics, and environmental factors should be considered together for an optimized biomass-ORC system.

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