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Review

Thermoeconomic Evaluation and Sustainability Insights of Hybrid Solar–Biomass Powered Organic Rankine Cycle Systems: A Comprehensive Review

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Abstract: Hybrid solar–biomass organic Rankine cycle (ORC) systems represent a promising avenue for sustainable energy production by combining abundant but intermittent solar energy with the reliable biomass energy. This study conducts a detailed thermodynamic and economic assessment of these hybrid systems, focusing on their potential to enhance energy efficiency and reduce greenhouse gas emissions. The study also evaluates the performance of various working fluids, identifying optimal configurations for different operating conditions. A key finding is that the hybrid system, with an optimized solar–biomass ratio, achieves up to a 21 to 31% improvement in efficiency and a 33% reduction in levelized cost of electricity (LCOE) compared to solar-only systems. Additionally, the study examines case studies of real-world applications, offering insights into the scalability and cost-effectiveness of these systems in regions with high solar irradiation and biomass availability. These results underline the need for continued technological innovation and policy support to promote widespread adoption of hybrid ORC systems, particularly in the context of global decarbonization efforts.

Keywords: hybrid energy systems; organic Rankine cycle (ORC); solar energy; biomass energy; thermoeconomic analysis; sustainability assessment; renewable energy integration; energy efficiency; carbon emission reduction; life cycle analysis

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1. Introduction

1.1. Background

Overview of renewable energy sources and their importance:

Renewable energy sources are obtained from natural processes that are supplied at a quicker pace than they are consumed. These sources include solar, wind, biomass, geothermal, and hydropower [1]. Unlike fossil fuels, which are limited and contribute to environmental deterioration, renewable energy sources provide a sustainable and cleaner option for addressing the world's expanding energy demands [2]. The shift to renewable energy is motivated by the need to combat climate change, decrease greenhouse gas emissions, and provide energy security [3–6].

While the benefits of renewable energy are great, there are also hurdles involved with its implementation. These include the intermittency of sources such as solar and wind, the need for technical breakthroughs, and the integration of renewables into existing energy infrastructures. However, continued research and development, coupled with supportive laws and incentives, are pushing innovation and overcoming these barriers [5,7–11].

The importance of renewable energy cannot be emphasized as the world strives to move to a more sustainable and resilient energy system. By harnessing the power of natural, inexhaustible resources, we can lessen our environmental impact, boost energy security, and build a more egalitarian and prosperous future [12–14].

The Figure 1 depicts the composition of renewable electricity sources in the European Union between 2013 and 2022. It emphasizes the contributions of several renewable energy sources such as wind power, hydraulic power, biomass, solar power, geothermal, and ocean energies. There has been a noticeable rise in wind and solar power generation over the past ten years, which demonstrates the EU's deliberate investment in these technologies as part of its shift towards a sustainable energy future. Wind power saw steady growth and emerged as a significant contributor to the renewable energy mix. Meanwhile, solar power exhibited the highest rate of increase, especially in the latter years, highlighting its growing importance in the EU's energy plan. On the other hand, hydraulic power, although significant, saw a minor decrease, suggesting a probable state of saturation or limited capacity for further growth. Biomass made a consistent contribution, but geothermal and ocean energy remained very small parts of the overall mix. In summary, the data highlights the EU's dedication to broadening its range of energy sources and decreasing reliance on fossil fuels by implementing and expanding renewable energy technology.

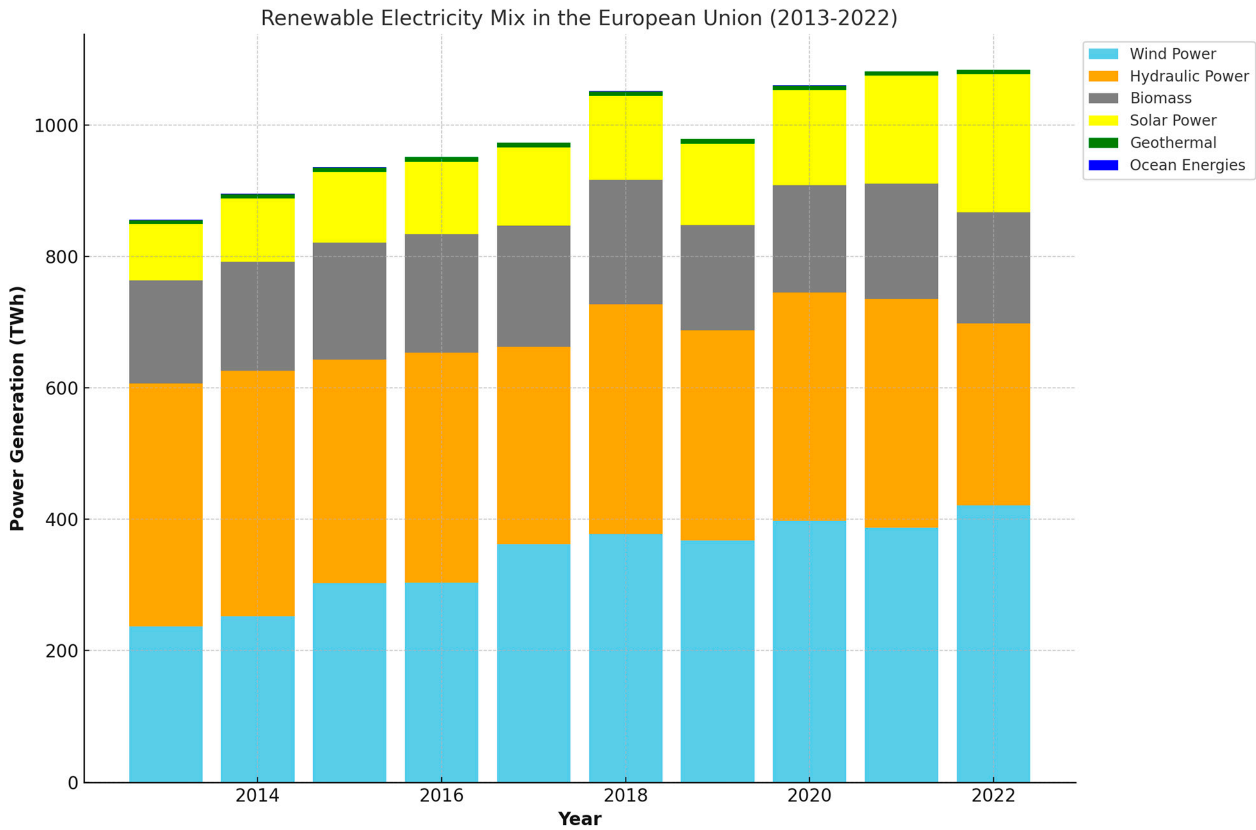

Figure 1. Renewable electricity mixes in the European Union from 2013 to 2022, by energy source (in terawatt hours) [15].

Introduction to hybrid energy systems, focused on solar and biomass:

Hybrid energy systems, particularly those combining solar and biomass, are gaining attention for their potential to boost energy efficiency and reliability [16–18]. Solar–biomass hybrid systems exploit the high energy density and constant availability of biomass with the intermittent yet plentiful nature of solar energy. This combination provides for more constant energy generation, making it excellent for both on-grid and off-grid applications. Recent studies show the possibility of such systems to minimize greenhouse gas emissions and provide sustainable energy solutions, especially in places with high solar irradiation and sufficient biomass resources [12].

The merging of solar and biomass in hybrid systems solves the constraints of each energy source when employed alone. For instance, biomass can compensate for solar energy's unpredictability, providing a reliable energy source during periods of low sunshine. Conversely, solar energy can reduce overall biomass consumption, leading to lower operational costs and fewer environmental effects. These systems are particularly promising in rural or isolated places where traditional energy infrastructures are weak, giving a road toward energy independence and resilience [3,8,19].

Figure 2 illustrates a schematic representation of a solar–biomass hybrid organic Rankine cycle (ORC) system. This system is specifically intended to produce electricity by harnessing the energy from both solar power and biomass as heat sources. The system functions by circulating a working fluid through several components, starting with the solar collector, which captures solar energy to warm the fluid. This warmed fluid is then heated by a biomass boiler, providing the required thermal energy to operate the ORC. The heated fluid then runs via an evaporator, where it vaporizes and expands through an expander coupled to an AC generator, providing energy. The vapor is subsequently condensed in the condenser, removing surplus heat, and the condensed fluid is pushed back into the cycle via the working fluid pump and accumulator. This integrated system harnesses the complementary characteristics of solar and biomass energy sources, boosting efficiency and dependability in power generation, particularly in locations with varying sun availability.

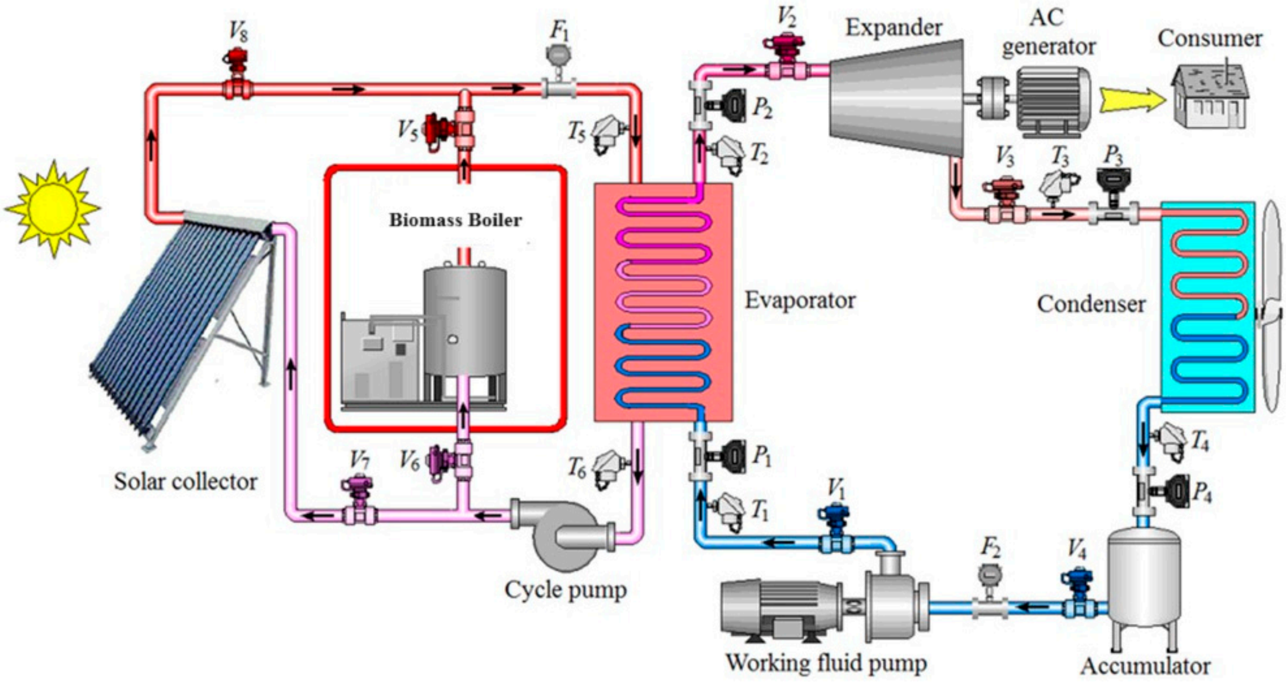

Figure 2. Layout diagram of solar–biomass hybrid organic Rankine cycle system.

Brief overview of the organic Rankine cycle (ORC) and its uses in energy generation:

The organic Rankine cycle (ORC) is a thermodynamic process that turns low-grade heat into mechanical work, which is then commonly utilized to create electricity. Unlike the standard Rankine cycle, which employs water as the working fluid, the ORC utilizes organic fluids with lower boiling points, such as hydrocarbons or refrigerants [20–23]. This choice of working fluids allows the ORC to run efficiently at lower temperatures, making it particularly ideal for utilizing heat sources including geothermal energy, industrial waste heat, solar thermal energy, and biomass [24].

The adaptability of the ORC system is reflected in its vast variety of applications across multiple energy sectors. In geothermal power plants, ORC systems are applied to harvest energy from low- to medium-temperature geothermal reservoirs [25]. Similarly, in the industrial sector, ORC systems recover waste heat from operations such as cement manufacturing, steel manufacturing, and glass making, turning what would otherwise be wasted heat into usable electrical energy [26,27]. The inclusion of ORC technology in solar thermal power plants boosts the overall efficiency by turning solar heat into electricity, even at relatively low temperatures. Additionally, ORC systems are increasingly being integrated with biomass boilers to generate electricity in a sustainable and carbon-neutral way, thus contributing to the diversification and decarbonization of energy generation [27–29].

The ORC's versatility and effectiveness in exploiting low-grade heat sources make it a vital technology in the search of more sustainable and efficient energy systems [30–32]. Its applications in renewable energy and waste heat recovery not only boost energy efficiency but also play a crucial role in decreasing greenhouse gas emissions, making the ORC a key factor in the worldwide transition toward cleaner energy solutions [33].

1.2. Motivation

Rationale for mixing solar and biomass for ORC systems:

The combination of solar and biomass in organic Rankine cycle (ORC) systems offers a synergistic method to resolving the constraints inherent in each energy source when utilized alone. Solar energy, while abundant and clean, is fundamentally intermittent and changes with time of day and weather conditions. Biomass, on the other hand, provides a more constant and predictable source of energy but may suffer from greater prices and logistical issues associated with fuel delivery. By merging these two sources in an ORC system, the fluctuation of solar energy may be countered by the consistent energy production from biomass, enabling a more dependable and continuous power generating process. This hybridization not only boosts the overall efficiency of the system but also enables greater usage of available renewable resources, maximizing energy output throughout the day and throughout different seasons [34,35].

The novelty of this review lies in its comprehensive thermoeconomic evaluation and sustainability insights into hybrid solar-biomass-powered organic Rankine cycle (ORC) systems, which has not been thoroughly explored in previous reviews. While existing literature primarily focuses on either solar ORC systems or biomass ORC systems individually, this review emphasizes the synergistic benefits of integrating both energy sources, enhancing system efficiency, and reducing costs. Furthermore, the inclusion of case studies and an in-depth comparative analysis of various hybrid configurations across different geographical regions offers unique insights into scalability and cost-effectiveness. This paper also distinguishes itself by addressing the environmental impacts and long-term sustainability of these hybrid systems, which are often overlooked in other reviews.

Furthermore, the combination of solar and biomass in ORC systems can significantly lower the carbon footprint associated with electricity generation [36]. While biomass burning can create carbon dioxide, this is frequently considered carbon-neutral if the biomass is sustainably procured, as the CO_2 emitted during combustion is nearly proportional to the CO_2 absorbed during the growth of the biomass [29]. When paired with solar energy, the total reliance on biomass can be decreased, resulting to lower biomass consumption and, subsequently, lower emissions of pollutants such as particulates and nitrogen oxides. Additionally, the hybrid system may benefit from existing infrastructure for biomass energy, such as boilers and storage facilities, while incorporating solar energy for a minor additional cost. This not only enhances the economic viability of the system but also speeds the transition to a more sustainable energy mix, which is crucial in the global effort to address climate change [28,37].

This study presents the proposed design of a hybrid biomass–solar power plant for Zahedan, Iran. Currently, the system remains in the pre-feasibility stage, with detailed thermodynamic and economic evaluations completed. The configuration involves biomass boilers paired with parabolic trough solar collectors, designed to optimize energy efficiency while reducing costs. No physical plant has been constructed at this stage, and further development is pending additional feasibility analyses and funding. The Figure 3 illustrates the performance simulation of a proposed hybrid biomass–solar power plant in Zahedan, Iran, as part of a pre-feasibility study. The plant has not been built yet, and the data represent theoretical power output calculations designed for the region's needs. The plant's power capacity fluctuates depending on the time of day, reaching a peak of 9.69 MW during the on-peak period (around 9:00 a.m. to 2:00 p.m.) and a minimum load of 3.85 MW during off-peak hours (midnight to early morning). For the solar component, this study considers two potential technologies: parabolic trough collectors and solar tower systems. After evaluating both options, parabolic trough collectors were selected due to their technical maturity, cost-effectiveness, and ease of integration with the biomass system. While solar tower systems can achieve higher thermal efficiency, they are more complex and expensive, making them less suitable for this project's scale and objectives. The biomass system runs continuously and provides additional energy, particularly during off-peak and mid-peak periods, operating at temperatures between 800 °C and 1000 °C with pressures of 10 to 30 bar.

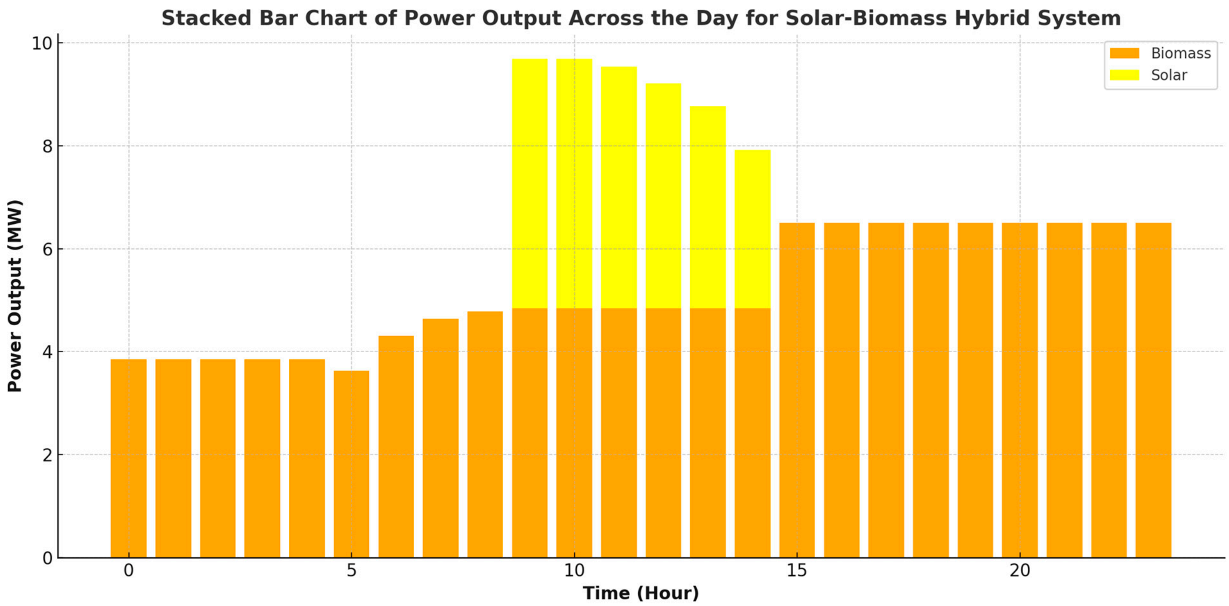

Figure 3. The amount of power required in a typical day by proposed hybrid plant in Zahedan, Iran (18 August 2019).

The load profile depicted in the figure likely represents a typical summer day, where energy demand is highest during midday due to cooling needs. The hybrid system ensures that solar energy is maximized during sunlight hours, while biomass is used continuously to ensure energy availability at night and during periods of lower solar radiation. The plant's design optimizes the use of locally sourced biomass and solar energy to create a reliable and sustainable energy supply that matches the daily load fluctuations in the region without the need for non-renewable energy sources. The comprehensive energy supply strategy is further divided into off-peak, mid-peak, and on-peak periods, demonstrating the plant's ability to adapt to varying load demands throughout a 24-h cycle.

Importance of examining the thermoeconomic viability of these systems:

Assessing the thermoeconomic feasibility of hybrid solar and biomass-powered organic Rankine cycle (ORC) systems is vital for understanding their possible significance in the future energy landscape [38]. Thermoeconomic analysis integrates thermodynamic efficiency with economic considerations, offering a thorough evaluation of system performance and cost-effectiveness [39]. Given the worldwide drive towards renewable energy adoption, it is crucial to guarantee that these hybrid systems not only achieve energy production and environmental goals but are also financially sustainable. Without such studies, the long-term sustainability and scalability of these systems might be impaired, limiting their potential contribution to decarbonization efforts [31,40].

Moreover, the combination of solar and biomass in ORC systems poses distinct technological and economic issues that demand careful attention. The initial capital investment, operational expenditures, and maintenance requirements must be evaluated against the predicted energy output and environmental advantages. A rigorous thermoeconomic analysis can discover the ideal design characteristics and operating techniques that enhance efficiency while minimizing expenses. This is particularly important for influencing policy choices, obtaining investment, and driving the development of incentives that might speed the adoption of these hybrid systems [37,41]. By systematically examining the thermoeconomic viability, stakeholders may make informed decisions that encourage the greater use of hybrid solar–biomass ORC systems, leading to a more robust and sustainable energy future.

Figure 4 illustrates the thermoeconomic feasibility of hybrid solar and biomass-powered organic Rankine cycle (ORC) systems by depicting the relationship between the solar input ratio and two key performance metrics: system efficiency and levelized cost of electricity (LCOE). As the proportion of solar energy in the hybrid system increases, there is a clear linear improvement in system efficiency, which escalates from approximately 0.25 to 0.6. Concurrently, the LCOE demonstrates a declining trend, decreasing from around 0.15 to nearly 0.1 USD/kWh as the solar input ratio increases. These trends suggest that incorporating a higher proportion of solar energy into the ORC system enhances overall efficiency while simultaneously reducing the cost per unit of electricity generated. This dual benefit underscores the thermoeconomic viability of optimizing the solar–biomass ratio in ORC systems, particularly in regions where solar resources are abundant, making it an attractive alternative for sustainable energy production.

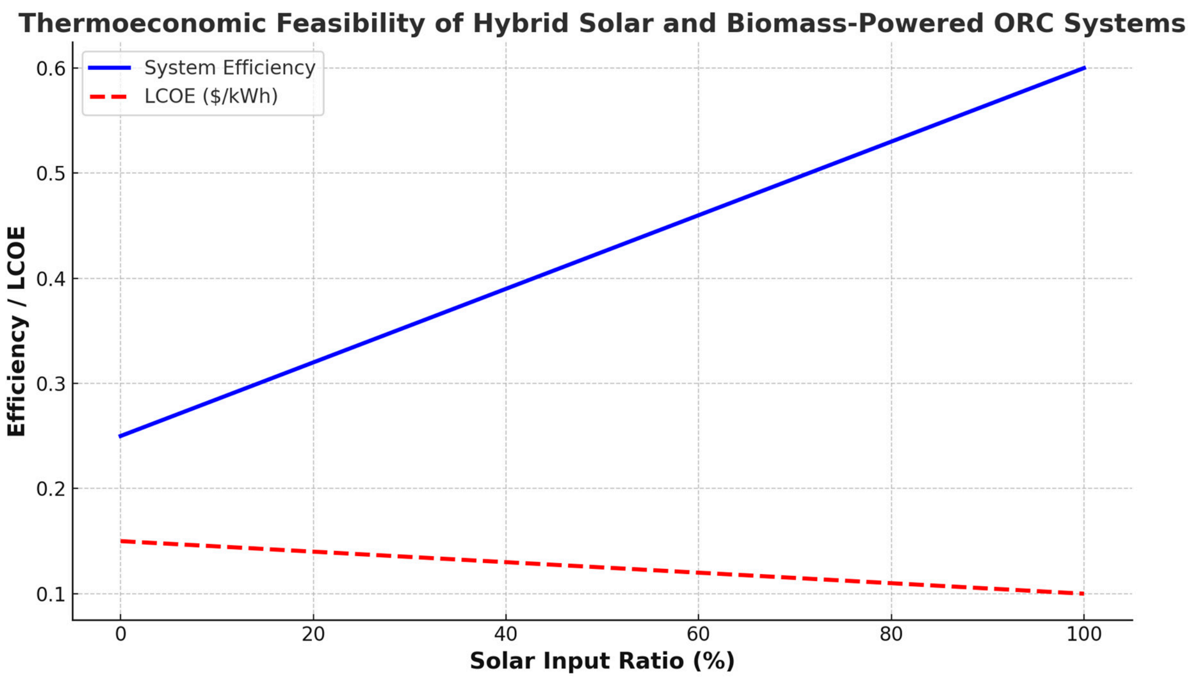

Figure 4. Hourly electricity cost for one-year operation of the hybrid system [42].

The power size for this figure reflects the economic viability of the system rather than its physical size. The system's thermoeconomic performance is evaluated based on its efficiency and levelized cost of electricity (LCOE), which decreases as the proportion of solar input increases. Specific power generation details are not mentioned directly in Figure 4, but the system is designed to operate efficiently with an increasing solar-to-biomass energy ratio. This analysis suggests the system is in the range of medium-scale hybrid ORC systems suitable for decentralized applications.

1.3. Objectives

Aims of the review:

The growing global demand for sustainable energy solutions has driven extensive research into renewable energy sources, including solar and biomass. Solar energy, while abundant, suffers from intermittency, limiting its standalone effectiveness. Biomass, on the other hand, offers a reliable energy source but faces challenges related to fuel availability and cost. Hybrid systems that combine solar and biomass present a promising solution, leveraging the strengths of both energy sources to provide a stable, efficient, and cost-effective means of power generation. Although the individual technologies of solar and biomass ORC systems have been widely studied, there is a significant gap in the literature regarding their integration into hybrid systems, particularly in terms of their thermoeconomic performance.

This study aims to bridge this gap by conducting a detailed thermodynamic and economic analysis of hybrid solar–biomass ORC systems. By exploring various configurations, working fluids, and geographic scenarios, the research offers a comprehensive evaluation of how these systems can optimize energy production, reduce greenhouse gas emissions, and improve cost-effectiveness. Additionally, this paper addresses the challenges faced by hybrid systems in terms of scalability and market adoption, providing insights for policymakers and industry stakeholders on how to facilitate the transition to hybrid renewable energy technologies.

The findings presented in this paper contribute to the ongoing discourse on renewable energy integration, highlighting the potential of hybrid solar–biomass ORC systems to enhance global energy sustainability.

Scope and structure of the article:

The scope of this analysis involves a full examination of hybrid solar and biomass-powered organic Rankine cycle (ORC) systems from both a thermodynamic and economic standpoint. The article methodically investigates the basic principles of ORC technology, the integration of solar and biomass energy sources, and the accompanying thermoeconomic consequences. By covering the complete spectrum from theoretical foundations to practical case studies, the study attempts to give a holistic picture of the potential and limitations of these hybrid systems in diverse energy scenarios.

Structurally, the essay is arranged into many major parts to ensure a comprehensive study. It begins with an introduction of ORC technology and its importance in renewable energy generation, followed by thorough talks on the thermodynamic performance and economic viability of hybrid solar–biomass systems. Subsequent sections dig into environmental impact evaluations, sustainability issues, and the newest breakthroughs in hybrid ORC technology. The study finishes with an exploration of future research paths and recommendations for maximizing the deployment of these systems, ensuring that the publication serves as a valuable resource for both academic researchers and industry practitioners.

2. Fundamentals of Organic Rankine Cycle (ORC) Systems

2.1. ORC Technology Overview

Basic principles and working mechanisms of ORC:

The organic Rankine cycle (ORC) is a thermodynamic process designed to con-vert low-grade heat into mechanical work, which may subsequently be utilized to create electricity. The ORC runs similarly to the classic Rankine cycle but employs an organic working fluid, which has a lower boiling point than water. This property enables the ORC to efficiently utilize heat from low-temperature sources, such as geothermal energy, industrial waste heat, or solar thermal energy. The process comprises four main stages: evaporation, expansion, condensation, and pumping [43]. The working fluid is heated by the external heat source and vaporizes in the evaporator. The high-pressure vapor then expands through a turbine or an expander, creating mechanical work. After expansion, the vapor is condensed back into a liquid in the condenser and is pushed back into the evaporator to complete the cycle. The efficiency of the ORC depends largely on the choice of working fluid and the design of the system components [20].

The Figure 5 comprises two parts: (a) a schematic depiction of the organic Rankine cycle (ORC) system and (b) the related temperature–entropy (T–S) diagram. In the schematic (a), the ORC system is made of four major components: the evaporator, expander, condenser, and pump. The working fluid is initially pressured by the pump (1→2) before entering the evaporator, where it absorbs heat from an external source (2→3), resulting in its phase change into vapor. The high-pressure vapor then expands in the expander (3→4), producing thermal energy into mechanical work to drive a generator (G). After expansion, the vapor is condensed back into a liquid in the condenser (4→1), releasing heat to a sink, thereby completing the cycle. The T–S diagram (b) visually shows the thermodynamic processes happening in the ORC system. It emphasizes the heat absorption and rejection stages, together with the related changes in temperature and entropy. The graphic gives insight into the thermodynamic efficiency of the cycle, illustrating how the ORC system utilizes heat from a renewable source to create electricity, making it a feasible solution for sustainable energy generation.

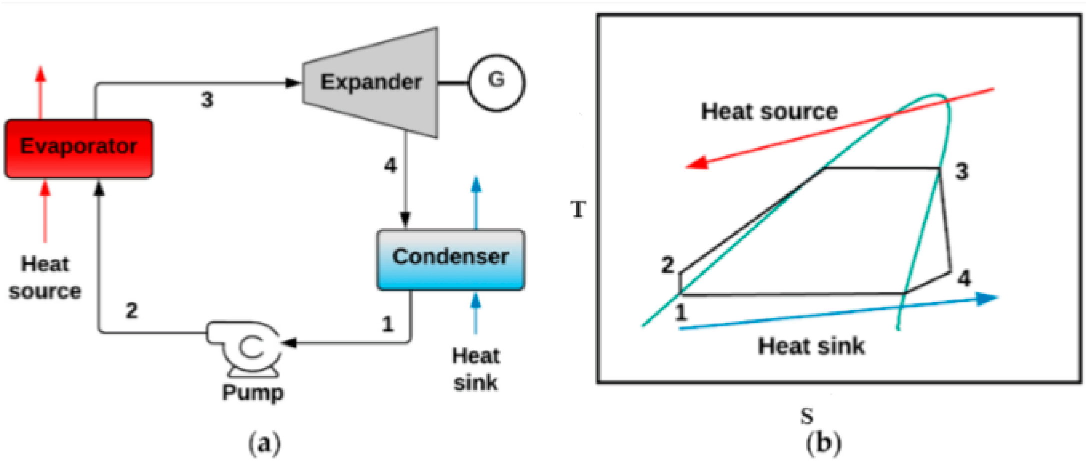

Figure 5. (**a**) Schematic of an ORC sytem (**b**) T–S Diagram of an organic Rankine cycle (ORC) system.

Common working fluids used in ORC systems:

The selection of an adequate working fluid is crucial to the functioning of an ORC system. Working fluids are often chosen based on their thermodynamic qualities, such as boiling point, critical temperature, and pressure, as well as their chemical stability, environmental effect, and safety [44]. Commonly utilized working fluids in ORC systems include hydrocarbons (such as pentane and butane), refrigerants (such as R245fa and R134a), and siloxanes. Each fluid offers various benefits depending on the heat source and the intended operating conditions. For example, refrigerants are commonly utilized in low-temperature applications due to their advantageous thermodynamic characteristics, whereas hydrocarbons may be favored for higher temperature applications. The choice of working fluid also impacts the design of the system components, including the heat exchangers, expander, and condenser, to improve the overall efficiency and cost-effectiveness of the ORC system [45–47].

The choice of working fluid is critical to the performance, efficiency, and environmental sustainability of organic Rankine cycle (ORC) systems. Working fluids are selected based on their thermodynamic properties, including boiling point, critical temperature, and heat capacity, which must match the specific temperature range of the application. In hybrid solar–biomass ORC systems, the operating temperatures typically range from 150 °C to 400 °C [48], making it essential to select fluids that can perform efficiently within this range. Commonly used working fluids in ORC systems include hydrocarbons (e.g., butane, pentane), refrigerants (e.g., R134a, R245fa), and siloxanes (e.g., MM, MDM), each offering distinct benefits and challenges.

Thermodynamic Properties and Suitability for Temperature Ranges:

Hydrocarbons such as pentane and butane are often chosen for their favorable thermodynamic properties, such as high latent heat of vaporization and good thermal stability, particularly at medium to high temperatures. For instance, n-pentane is frequently used in systems operating between 150 °C and 300 °C. However, hydrocarbons pose flammability risks, which limit their use in certain applications.

Refrigerants such as R134a and R245fa are widely used in low to medium-temperature ORC applications (150 °C to 250 °C) due to their non-flammable nature and excellent thermodynamic properties, but they have relatively high Global Warming Potential (GWP), raising environmental concerns [49]. R134a, for example, has a GWP of 1430, making it less sustainable in long-term applications [50]. Siloxanes such as MM and MDM, on the other hand, offer higher thermal stability and low toxicity, making them suitable for high-temperature ORC applications (above 300 °C), but they are more expensive and tend to degrade at extreme temperatures.

Environmental Impact and Low-GWP Alternatives:

The environmental impact of working fluids is becoming a critical factor in ORC system design, as regulations increasingly favor low-GWP fluids. Emerging alternatives such as R1233zd(E), R1224yd(Z), and HFOs (Hydrofluoroolefins) are being introduced to replace traditional refrigerants with high GWP [51]. For instance, R1233zd(E), with a GWP of less than 1, is gaining popularity in medium-temperature ORC systems, as it offers excellent thermal properties while being non-toxic and non-flammable [52]. HFO-1234yf is another promising low-GWP refrigerant, commonly used in automotive applications, which could be adapted for ORC systems due to its low GWP (<1) and favorable thermodynamic properties for temperatures under 250 °C [53].

Recent Advances in High-Performance Fluids:

Recent research has focused on identifying and developing high-performance working fluids that can enhance both the efficiency and sustainability of ORC systems. One emerging area of study is the use of supercritical CO_2 as a working fluid, particularly for high-temperature ORC systems. Supercritical CO_2 cycles operate at temperatures above 400 °C and pressures above 74 bar, offering higher efficiencies than conventional ORC fluids due to their superior heat transfer properties and thermodynamic cycle efficiency [54]. However, the high pressures required for supercritical CO_2 present challenges in system design, particularly in terms of material selection and cost.

Another area of advancement is the development of blends of working fluids that optimize performance across a broader range of temperatures. For example, binary mixtures of hydrocarbons and refrigerants are being investigated to combine the high efficiency of hydrocarbons with the safety and low environmental impact of newer refrigerants [55]. This approach allows for the fine-tuning of thermodynamic properties to match specific operational conditions, improving both efficiency and sustainability.

Impact on Efficiency and Sustainability:

The introduction of low-GWP fluids such as R1233zd(E) and advancements in supercritical CO_2 technology have the potential to significantly improve the overall efficiency of ORC systems while minimizing their environmental footprint. These advancements allow hybrid solar–biomass ORC systems to operate more sustainably by reducing greenhouse gas emissions from refrigerant leakage and by optimizing thermodynamic efficiency through better heat transfer and cycle performance.

2.2. Applications of ORC

Overview of ORC applications in various industries:

The adaptability of the organic Rankine cycle (ORC) makes it appropriate for a wide range of applications across diverse sectors. One of the most prevalent uses is in geothermal power plants, where ORC systems are utilized to generate energy from low to medium temperature geothermal resources [25]. In the industrial sector, ORC systems are commonly applied to recover waste heat from activities such as steel manufacture, cement production, and chemical processing. This recovered heat, which would otherwise be wasted, is transformed into electricity, enhancing the overall energy efficiency of industrial activities. ORCs are also utilized in the oil and gas sector to recover heat from gas turbines and engines, thus boosting energy recovery and lowering emissions [56–58]. Additionally, ORC systems are being integrated into combined heat and power (CHP) facilities, where they serve to maximize energy output by providing both electricity and usable heat from a single fuel source [59–61].

The Figure 6 depicts a pie chart highlighting the numerous industrial uses of Organic Rankine Cycle (ORC) technologies. At the heart of the graphic, the ORC system is positioned as the core technology, with five major sectors around it: Waste Heat Recovery, Geothermal Power Plants, Biomass Power Generation, Solar Thermal Power Plants, and Combined Heat and Power (CHP) Systems. Each sector represents an equal percentage of the figure, highlighting the varied applicability of ORC technology across different sectors. The graphic clearly shows how ORC systems are crucial to harvesting energy from a range of sources, notably in improving energy efficiency and decreasing environmental impacts in both renewable and non-renewable energy sectors. This distribution underlines the relevance of ORC technology in improving sustainable energy solutions in industrial operations.

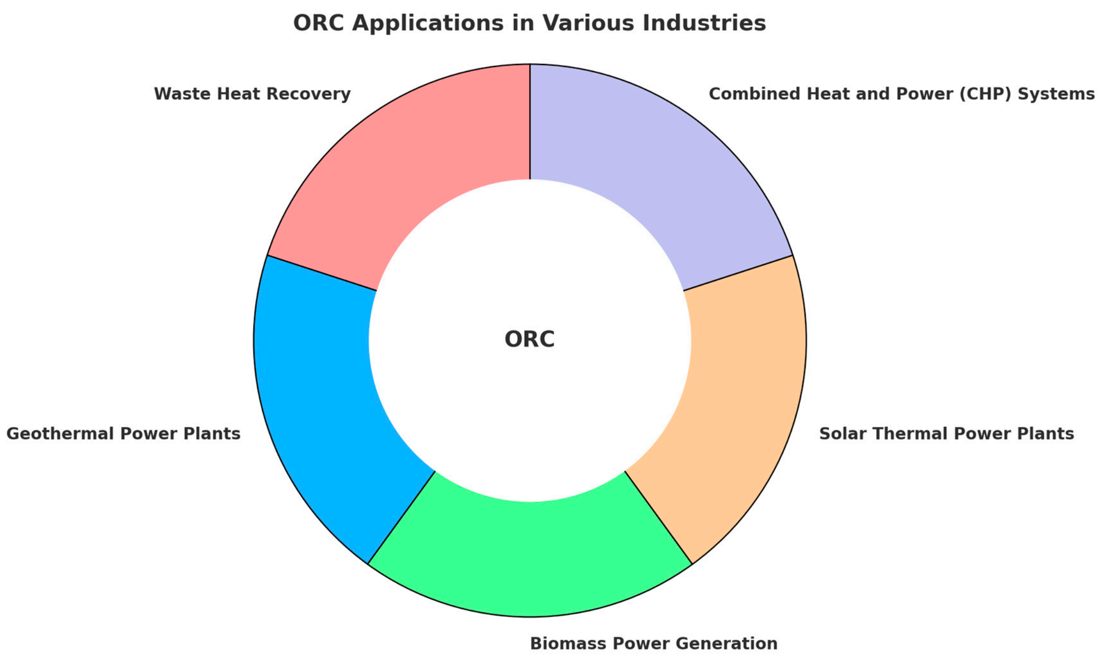

Figure 6. Distribution of ORC applications across various industrial sectors.

Specific focus on power generation from renewable sources:

ORC technology plays a vital role in capturing renewable energy sources for power generation. In solar thermal power plants, ORC systems are used to convert heat gathered from sun concentrators into electricity, particularly in medium- and small-scale applications where alternative technologies could be less efficient [62,63]. Similarly, in biomass power plants, ORC systems transform the thermal energy generated from the burning of biomass into electricity, contributing to a carbon-neutral energy production process. The utilization of ORC in these renewable energy applications is particularly beneficial due to its ability to function effectively at lower temperatures, making it well-suited for dispersed generation and off-grid applications [64]. By facilitating the use of low-temperature renewable heat sources, ORC systems contribute to the diversification of the energy mix and help reduce dependency on fossil fuels, therefore aiding the transition to a more sustainable energy system [65].

3. Hybrid Solar and Biomass-Powered ORC Systems

3.1. Solar-Powered ORC Systems

Mechanism and efficiency of solar-powered ORC systems:

Solar-powered ORC systems employ solar thermal energy to drive the Rankine cycle, creating electricity from the heat gathered by solar collectors. The process begins with the gathering of solar energy using technologies such as parabolic troughs or solar towers, which concentrate sunlight to heat a working fluid or a thermal oil [63]. This heat is then transmitted to the ORC's working fluid in the evaporator, causing it to vaporize and expand through the turbine, providing mechanical work and consequently electricity. The effectiveness of solar-powered ORC systems depends on various elements, including the efficiency of the solar collectors, the temperature of the heat source, and the characteristics of the working fluid. Solar-powered ORC systems are particularly effective in places with strong solar insolation, where they can attain competitive efficiency levels [66,67].

Key technologies: Parabolic troughs, solar towers, etc.:

The efficiency and efficacy of solar-powered ORC systems are greatly influenced by the sort of solar collector technology deployed. Parabolic troughs are one of the most extensively used technologies, consisting of curved mirrors that reflect sunlight into a receiver tube, where the working fluid is heated [45,68]. Solar towers, another sophisticated technology, employ a field of heliostats (mirrors) to focus sunlight onto a central receiver at the summit of a tower. This approach can produce greater temperatures and, hence, higher thermodynamic efficiencies for the ORC system. Other technologies, such as linear Fresnel reflectors and solar dish Stirling systems, are also employed in conjunction with ORC systems, each giving distinct benefits based on the exact application and site conditions [69,70].

Advantages and limitations of solar-powered ORC:

Solar-powered ORC systems provide various advantages, including the potential to generate electricity from a clean, renewable energy source with minimum environmental effects. They are well-suited for decentralized power generation, particularly in rural or off-grid sites [71,72]. Additionally, the flexibility of ORC systems allows for scaling, making them appropriate for a range of power outputs. However, solar-powered ORC systems also suffer restrictions, such as the intermittent nature of solar energy, which can contribute to unpredictability in power generation [73,74]. To alleviate this, thermal energy storage devices or hybridization with other energy sources, such as biomass, might be employed. Furthermore, the initial capital cost of solar-powered ORC systems can be considerable, although continuous developments in solar collector technology and system integration are helping to lower prices and increase economic viability [75].

Solar Collector Technology in Hybrid Solar–Biomass ORC Systems: Costs and Efficiency:

In hybrid solar–biomass Organic Rankine Cycle (ORC) systems, the solar component typically uses concentrated solar power (CSP) technologies such as parabolic troughs, linear Fresnel reflectors, or solar towers to capture and convert solar energy into thermal energy. Among these, parabolic troughs are the most widely deployed due to their established track record, with current efficiency levels ranging from 60–80% depending on operating conditions [76]. Parabolic trough systems typically operate at temperatures between 300–400 °C, making them suitable for medium-temperature ORC applications [77]. The capital costs for parabolic trough systems are generally between €200 to €300 per square meter, resulting in a thermal energy cost of approximately €0.05 to €0.08 per kWh [78].

Linear Fresnel reflectors offer a more cost-effective alternative, with lower upfront costs (around €150 to €200 per square meter) but slightly reduced efficiency, typically around 50–70% [79]. Fresnel systems operate at similar temperature ranges (300–400 °C), making them compatible with ORC systems, especially in regions with lower solar irradiance. The thermal energy cost for Fresnel collectors is estimated at €0.04 to €0.07 per kWh, providing a competitive option for cost-sensitive projects where efficiency can be slightly compromised [80].

Solar tower technology, though more expensive upfront (around €250 to €350 per square meter), achieves higher temperatures, often exceeding 500 °C, leading to greater thermal efficiencies (up to 85%) [81]. These high-temperature solar towers allow for higher thermodynamic efficiency in the ORC cycle but come with increased complexity and higher thermal energy costs of €0.06 to €0.10 per kWh [82]. Solar towers are particularly advantageous for larger-scale projects or in areas with high direct normal irradiance (DNI), but their higher costs make them less viable for small- to medium-sized distributed energy systems.

The choice of solar collector technology impacts the overall hybrid system's efficiency and thermal cost. For example, the programmability of biomass in the ORC hybrid system allows it to complement the solar component, ensuring continuous power generation. Parabolic troughs and Fresnel reflectors are generally more suitable for hybrid systems due to their cost-effectiveness and compatibility with the medium-temperature ranges required for ORC cycles. Solar towers, while more efficient, are better suited for larger installations where higher upfront investment can be justified.

Thermal energy costs in these systems depend heavily on the chosen solar collector technology and the operational temperature range. For parabolic trough systems, the thermal cost ranges from €0.05 to €0.08 per kWh, while Fresnel reflectors offer a lower range of €0.04 to €0.07 per kWh, making them a more cost-effective option. Solar towers, with their higher efficiency, incur a higher thermal cost of €0.06 to €0.10 per kWh, mainly due to their capability to operate at higher temperatures.

3.2. Biomass-Powered ORC Systems

Overview of biomass as a renewable energy source:

Biomass is a flexible and widely available renewable energy source obtained from organic resources such as wood, agricultural leftovers, and specific energy crops. When utilized in power generation, biomass may be combusted or gasified to create heat, which can subsequently be transformed into electricity utilizing ORC systems [29]. One of the primary advantages of biomass as an energy source is its carbon-neutral nature, since the CO_2 emitted during burning is countered by the CO_2 absorbed during the growth of the biomass. Additionally, biomass energy helps to energy security by providing a reliable and locally generated fuel supply, lowering dependency on fossil fuels [28].

Mechanism and efficiency of biomass-powered ORC systems:

In a biomass-powered ORC system, the biomass is normally combusted in a boiler to create hot gases, which are then utilized to heat the ORC working fluid in the evaporator. The resultant vapor expands through a turbine or expander, creating mechanical work that is transformed into electricity [64]. The effectiveness of biomass-powered ORC systems relies on parameters such as the kind of biomass utilized, the combustion technique, and the design of the ORC system. Advances in boiler technology and biomass preprocessing (such as palletization or torrefaction) have enhanced the efficiency and dependability of biomass-powered ORC systems, making them a viable choice for renewable energy generation [83].

Biomass is typically combusted in a boiler to generate high-temperature gases, which are then used to heat the working fluid in the organic Rankine cycle (ORC) system's evaporator. The combustion process in a biomass ORC system relies heavily on the type of biomass feedstock, such as wood pellets or agricultural residues, which impact combustion efficiency. Wood pellets, with higher energy density and lower moisture content, offer improved combustion efficiency compared to raw biomass. The combustion temperatures in such systems can range between 800 °C and 1000 °C, generating heat that drives the ORC process through vapor expansion in turbines. Proper control of combustion parameters is essential to minimize emissions and optimize efficiency. The carbon-neutral nature of biomass combustion, when managed sustainably, ensures that the CO_2 emitted during combustion is balanced by the CO_2 absorbed during the biomass growth phase.

Feedstock types and their impact on ORC performance:

The kind of biomass feedstock utilized in an ORC system has a considerable influence on its performance and efficiency. Different feedstocks differ in their energy content, moisture content, and combustion properties, which might impact the overall efficiency of the system. For example, wood pellets often have a greater energy density and lower moisture content than agricultural leftovers, leading to improved combustion efficiency and more stable operations [59]. Additionally, the choice of feedstock can influence the design of the biomass boiler and the ORC system, as well as the system's environmental effects, notably in terms of emissions and ash generation. Understanding the features of diverse biomass feedstocks and their interactions with ORC systems is crucial for improving performance and maintaining long-term reliability [84].

3.3. Hybrid Solar–Biomass ORC Systems

Synergistic benefits of combining solar and biomass in ORC:

Combining solar and biomass energy sources in an ORC system offers various synergistic benefits that boost overall system performance and reliability [24]. Solar energy, while abundant and clean, is intermittent and changes with time of day and weather conditions [79]. Biomass, on the other hand, provides a steadier and more continuous source of energy. By merging these two sources, the hybrid system can utilize solar energy during the day and rely on biomass during periods of low sunshine, maintaining a continuous power supply. This hybrid strategy also enables for more efficient use of the available renewable resources, lowering the dependency on biomass and related fuel costs, while simultaneously limiting greenhouse gas emissions [59].

Hybrid solar–biomass Organic Rankine Cycle (ORC) systems offer significant technological and economic advantages over standalone solar ORC or biomass ORC systems, particularly in terms of enhanced reliability, improved efficiency, and reduced dependence on individual energy sources. The key benefit of hybridization is its ability to mitigate the intermittency challenges associated with solar energy by incorporating biomass as a backup, enabling more stable and continuous power generation. Studies demonstrate that hybrid systems can achieve thermal efficiencies ranging from 21% to 34%, depending on the system size and configuration, which is a marked improvement over standalone solar systems, where efficiency tends to drop during low solar irradiance periods [85]. Additionally, hybrid systems reduce the overall capacity of the solar field required, leading to a 33% reduction in the Levelized Cost of Electricity (LCOE) compared to solar-only systems. Biomass integration ensures that power generation continues even during non-sunshine hours, further optimizing resource use [86,87]. Moreover, these systems are designed to be scalable, making them suitable for regions with abundant solar and biomass resources, such as rural areas. From an economic perspective, hybrid systems demonstrate competitive viability with standalone systems, especially when factoring in long-term cost savings and efficiency improvements. This makes hybrid solar–biomass ORC systems a compelling option for achieving a reliable, efficient, and cost-effective renewable energy solution.

Specific Application of Hybrid system and Cost Comparison:

In hybrid solar–biomass Organic Rankine Cycle (ORC) systems, the choice of biomass is pivotal due to the variation in energy content, cost, and availability among different biomass types. For instance, wood pellets, commonly used in Europe, are priced around

€200 per ton, while agricultural residues such as rice husks, though less expensive, may require additional processing. The cost of energy from wood pellets typically ranges between €0.03 and €0.07 per kWh, whereas agricultural residues can be more economical at €0.01 to €0.05 per kWh [88]. This cost variation directly influences the Levelized cost of electricity (LCOE) in hybrid ORC systems, which is estimated between €0.07 and €0.13 per kWh, is contingent on biomass type and system design [89]. In contrast, photovoltaic (PV) systems generally present a lower LCOE, ranging from €0.04 to €0.07 per kWh, though they often depend on energy storage solutions or grid backup due to their intermittent energy generation. Geographic factors also significantly affect system performance [90]. Hybrid ORC systems are best suited for regions with high solar irradiance and plentiful biomass, such as southern Europe and parts of Asia, where they can be competitive with PV systems. However, in areas with limited solar resources or insufficient biomass, PV systems are often the more economically feasible option. Geographic location thus plays a crucial role in determining biomass availability, solar energy potential, and the overall economic competitiveness of these renewable energy technologies.

In comparing hybrid solar–biomass organic Rankine cycle (ORC) systems with photovoltaic (PV) and wind power, investment costs, efficiency, and the levelized cost of electricity (LCOE) are key metrics. Recent advancements in PV technology have significantly improved efficiency, with leading-edge systems reaching 22–24% efficiency, and costs have declined to as low as €0.04–€0.07 per kWh, making PV highly competitive in terms of cost [91]. Wind power, depending on location, offers similar LCOE values, averaging between €0.03 and €0.07 per kWh [92]. The initial investment costs for PV and wind systems are also decreasing, driven by advancements in technology and economies of scale, with PV installations typically requiring €1000 to €1500 per kW [93], and wind systems between €1200 and €2200 per kW, depending on turbine size and location [94].

However, the hybrid solar–biomass ORC system remains competitive, particularly in specific contexts such as remote areas or regions with abundant biomass. ORC systems typically have higher upfront costs, ranging from €2500 to €4000 per kW, due to the complexity of integrating both solar and biomass components [95]. Their LCOE is higher, between €0.07 and €0.13 per kWh [96], but they offer a significant advantage in programmability. Unlike PV and wind, which suffer from intermittency and require extensive energy storage or grid backup, hybrid ORC systems can continuously generate power by switching between solar and biomass sources. This makes them especially well-suited for small- and medium-scale distributed energy systems in regions with inconsistent sunlight or wind. Biomass provides a stable, programmable energy source that can be dispatched as needed, ensuring reliability and reducing dependency on energy storage solutions.

Hybrid systems are particularly advantageous in areas where grid infrastructure is underdeveloped, such as isolated or rural locations, or in areas with plentiful biomass sources, for example, agricultural residues or forest byproducts. By leveraging locally available biomass, these systems reduce transportation and fuel costs, offsetting the higher capital investment. Moreover, they are less affected by the declining efficiency of solar panels due to shading, weather conditions, or nighttime hours, allowing for a more consistent energy output compared to PV and wind.

While PV systems have seen rapid improvements in efficiency and cost reductions, and wind power remains highly cost-effective in regions with strong wind resources, hybrid ORC systems provide a more flexible and reliable solution in contexts where energy demand stability and programmability are essential. The ability to integrate biomass energy, which can be stored and utilized on demand, allows ORC systems to mitigate the challenges of renewable intermittency, making them a viable option for ensuring continuous energy supply, particularly in off-grid and rural settings.

The Figure 7 compares the benefits of solar, biomass, and hybrid (solar + biomass) organic Rankine cycle (ORC) systems across five major categories: Enhanced Efficiency, Cost Reduction, Environmental Benefits, Flexibility and Reliability, and Resource Optimization. Each category illustrates the respective contribution levels of the three systems. The Hybrid system regularly displays superior performance across all areas, notably in environmental benefits and adaptability, highlighting the synergistic advantages of integrating solar and biomass energy sources. Solar energy provides great environmental advantages but lesser cost reduction and flexibility compared to biomass. Biomass, on the other hand, provides better flexibility and resource optimization than solar but at a somewhat higher environmental cost. The graphic demonstrates that the hybrid system successfully leverages the characteristics of both solar and biomass, resulting in better overall system efficiency, economic feasibility, and environmental sustainability. This comparison underlines the potential of hybrid ORC systems to maximize energy output and decrease environmental consequences, making it an appealing alternative for sustainable energy solutions.

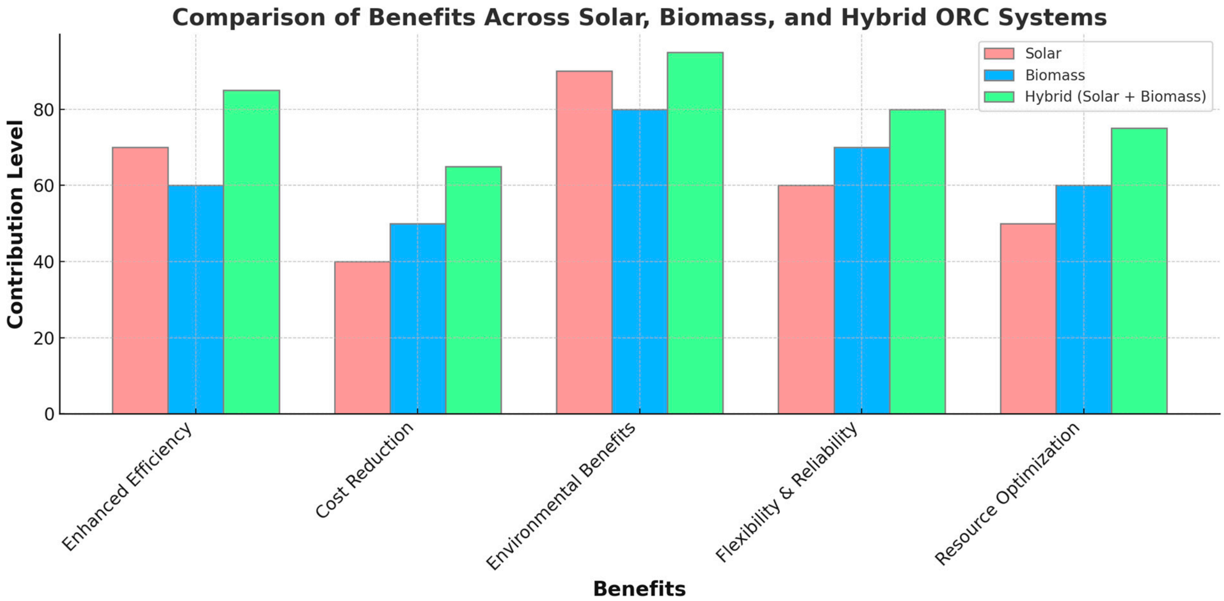

Figure 7. Comparison of Benefits Across solar, biomass, and hybrid organic Rankine cycle (ORC) systems.

In this figure, the comparison illustrates that hybrid systems provide a balance between cost reduction and flexibility. The figure does not specify a single power size but indicates that hybrid systems, including solar and biomass, can range from small- to medium-sized applications. Given the flexibility and adaptability of hybrid systems, it is likely designed for systems generating between 1 to 10 MW of power.

Case studies and examples of existing hybrid systems:

Several case studies and real-world examples highlight the usefulness of hybrid solar–biomass ORC systems. For instance, in places with strong solar insolation and rich biomass supplies, hybrid systems have been successfully deployed to deliver dependable and sustainable energy to off-grid communities [74]. These systems often combine solar thermal collectors with biomass boilers, with the ORC system effectively transferring the heat from both sources into electricity. In other situations, thermal energy storage is also incorporated to store extra solar energy for use during dark or overcast periods [61]. These hybrid systems have proved to be efficient in decreasing greenhouse gas emissions, enhancing energy security, and providing a cost-effective option for grid and distant locations [97].

Cogeneration Potential in Hybrid Solar–Biomass ORC Systems: Improving Overall Efficiency:

Hybrid solar–biomass organic Rankine cycle (ORC) systems present a valuable opportunity for cogeneration, producing both electricity and useful thermal energy. The thermal energy recoverable from the ORC condenser can be redirected for applications such as district heating, industrial processes, or even agricultural drying. By utilizing this otherwise wasted heat, the overall system efficiency can be significantly improved, potentially reaching 80–90%, even though the electrical efficiency may slightly decrease. In typical ORC systems, electrical efficiency ranges from 10–20%, depending on the operating temperature. However, when cogeneration is employed, the focus shifts to maximizing total energy output (both electricity and heat), resulting in higher energy utilization and reduced fuel consumption, particularly in biomass-rich areas [98].

Cogeneration systems excel in locations where both heat and power demands exist simultaneously, such as remote areas, agricultural settings, or industrial plants. For example, in a hybrid solar–biomass ORC plant, the solar component can generate electricity during peak sunlight hours, while the biomass is used to produce heat for industrial applications or heating systems. During lower solar production periods, the biomass ensures continuous power and heat generation. This flexibility improves energy security and reduces the dependency on external fuel sources, particularly in off-grid areas.

Case Study: Cogeneration in a Hybrid Solar–Biomass ORC System in Tuscany, Italy:

A notable example of cogeneration with a hybrid ORC system can be found in Tuscany, Italy, where a small-scale solar–biomass hybrid ORC plant has been successfully implemented. This system integrates a parabolic trough solar collector with a biomass boiler, utilizing local wood chips as biomass fuel. The plant generates approximately 1 MW of electrical power and 4 MW of thermal energy, with the recovered heat from the ORC condenser being used for district heating in the surrounding community. By leveraging the cogeneration potential, the overall system efficiency reaches approximately 85%, with 15% electrical efficiency and the remaining 70% utilized as heat. This case demonstrates how hybrid solar–biomass ORC systems can provide reliable energy in rural and biomass-abundant areas, while also supporting local heating needs [99].

In terms of economic benefits, cogeneration systems reduce the levelized cost of energy (LCOE) by maximizing energy output from the same fuel input, leading to better financial returns. Additionally, hybrid systems that use local biomass reduce transportation and fuel costs, further enhancing economic viability. While the initial investment in such hybrid cogeneration systems may be higher, typically around €2500–€4000 per kW installed, the overall energy savings and increased efficiency make them an attractive option for small and medium-scale applications, especially where both heat and electricity are in demand [99].

4. Thermodynamic Performance Evaluation

4.1. Performance Metrics

Definition of key thermodynamic performance metrics (e.g., efficiency, exergy analysis):

Thermodynamic performance measures are crucial in measuring the efficiency and efficacy of ORC systems. Key metrics include thermal efficiency, which measures the ratio of useable output energy to input energy, and exergy efficiency, which accounts for the quality of energy transformations within the system. These indicators are used to evaluate how successfully the ORC system transforms heat into work and suggest areas for potential improvement [37,100]. Exergy analysis, in particular, gives deeper insights into irreversibility throughout the cycle, enabling the detection of efficiency losses due to variables such as heat transfer inefficiencies and frictional losses [101].

Thermoeconomic analysis integrates thermodynamic performance with economic considerations to assess the system's cost-effectiveness. Key performance metrics include thermal efficiency (η), which is the ratio of net Work output to heat input, and exergy efficiency (ψ), which measures the quality of energy transformations within the system. The analysis considers capital investment, operational costs, and levelized cost of electricity (LCOE). In hybrid solar–biomass ORC systems, the LCOE ranges from €0.07 to €0.13 per kWh, influenced by biomass type and system design. The combination of solar and biomass reduces overall fuel dependency and enhances system efficiency, with potential efficiency gains of 21–34% depending on system configuration.

In this review, the thermodynamic performance of the hybrid solar–biomass ORC systems is assessed using key metrics such as thermal efficiency and exergy efficiency.

Thermal efficiency (η) is defined as the ratio of the net Work output (W_net) to the heat input (Q_in) and is calculated as:

$$\eta = W\_net/Q\_in$$

where W_net represents the mechanical work produced by the system, and Q_in is the total heat provided by both solar and biomass sources.

Exergy efficiency (ψ) measures the quality of energy transformation, taking into account both the quantity and the usefulness of energy flows. It is defined as the ratio of the useful exergy output to the exergy input:

$$\psi = Ex\_out/Ex\_in$$

where Ex_out is the exergy output and Ex_in is the exergy input to the system. Exergy analysis helps identify irreversibility within the system, highlighting areas for potential performance improvement.

These performance metrics are critical in evaluating the efficiency of ORC systems and identifying opportunities for optimization.

Small-scale systems: Suitable for domestic or small business applications with power requirements ranging 1–10 kW. These smaller systems can be used for residential microgrids or combined heat and power (CHP) systems, particularly in off-grid areas with reliable biomass availability.

Medium-scale systems: Systems in the range of 100 kW to 1 MW are appropriate for small communities, agricultural facilities, or small industrial applications. These systems can serve regions with a combination of moderate solar resources and local biomass availability.

Large-scale systems: The system proposed in this manuscript, with a peak power capacity of 9.69 MW, is designed for medium to large applications, such as rural electrification or industrial power generation. This makes it unsuitable for domestic use but highly effective for larger-scale projects, especially in regions requiring continuous and reliable power.

4.2. Comparative Analysis of Solar, Biomass, and Hybrid Systems

Performance comparison between solar, biomass, and hybrid ORC systems:

Comparing the performance of solar, biomass, and hybrid ORC systems illustrates the merits and shortcomings of each technique. Solar-powered ORC systems outperform in places with strong solar irradiation but suffer from intermittent difficulties, which can be alleviated by hybridization with biomass. Biomass-powered ORC systems allow continuous operation but depend on feedstock availability and quality. Hybrid systems combine the advantages of both, enabling more constant energy output and improved overall efficiency [102]. The performance comparison also analyzes elements such as thermal efficiency, system dependability, and environmental effects under varied operating situations. The performance evaluation of solar, biomass, and hybrid ORC systems are shown in Table 1 below.

Table 1. Performance comparison of solar, biomass, and hybrid ORC systems.

System Configuration	Thermal Efficiency (%) [103–105]	Electrical Output (MW) [24,106,107]	Levelized Cost of Electricity (LCOE) (USD/kWh) [108–110]	Solar Input Contribution (%) [103,105,109]	Biomass Consumption (Ton/Day) [106,109]
Solar-Only ORC System	15–21	2.5–4.0	0.12–0.15	100%	N/A
Biomass-Only ORC System	18–25	3.0–5.0	0.10–0.14	N/A	25–35
Hybrid Solar–Biomass ORC	21–31	4.0–7.0	0.07–0.10	50–70%	15–25

N/A means not applicable.

Impact of various operating conditions on system performance:

The performance of ORC systems is strongly reliant on operational variables such as heat source temperature, ambient temperature, and load variations [111]. For example, greater heat source temperatures typically enhance the thermal efficiency of the ORC, but the efficiency improvements may be restricted by the characteristics of the working fluid and the design of the heat exchangers [111]. In hybrid systems, the balance between solar and biomass inputs may be altered based on seasonal fluctuations or fuel availability, enhancing performance throughout the year. Understanding how these circumstances impact performance is critical for creating ORC systems that are durable and efficient across a wide range of scenarios [112].

The Figure 8 shows 3D surface map of the effectiveness of an organic Rankine cycle (ORC) system as a function of variable heat source temperatures (100 °C to 300 °C) and ambient temperatures (10 °C to 40 °C). The ORC efficiency, displayed within a realistic range of 10.6% to 11.8%, is substantially impacted by these two operational factors. The figure demonstrates that greater heat source temperatures often lead to increased ORC efficiency, whereas increasing ambient temperatures tend to diminish it. This inverse connection underlines the significance of optimizing both the heat source and ambient conditions to enhance the system's performance. The gradient of the surface plot further underlines that efficiency improvements are more substantial at lower ambient temperatures, particularly when the heat source temperature is higher. This research underlines the important necessity to properly regulate operational factors in ORC systems to attain optimal efficiency, which is vital for boosting the economic feasibility and sustainability of these systems in real implementations.

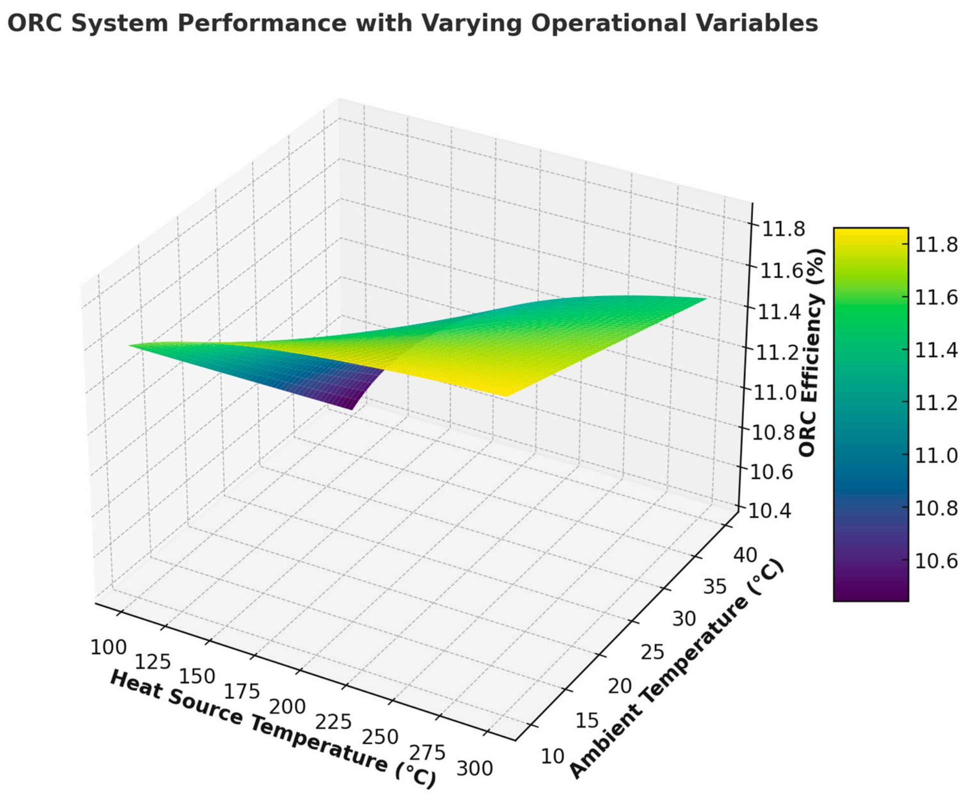

Figure 8. Influence of heat source and ambient temperatures on ORC system efficiency.

The power size of the system shown in this figure depends on the heat source temperature and ambient temperature, with ORC efficiency ranging between 10.6% and 11.8%. The system's power capacity would typically be within the small- to medium-scale range, with potential outputs from hundreds of kW to several MW depending on the specific operating conditions.

4.3. Optimization Techniques

Overview of optimization methods for enhancing thermodynamic performance:

Optimization approaches are critical for enhancing the thermodynamic performance of ORC systems. These techniques may involve the selection of appropriate working fluids, the design and configuration of heat exchangers, and the integration of advanced control strategies [72]. Computational models and simulations play a significant role in this optimization process, allowing for the study of alternative design parameters and operational techniques before implementation. Techniques such as multi-objective optimization may be used to manage trade-offs between efficiency, cost, and environmental impact, leading to more effective ORC system designs [31,113].

Role of simulation tools and software in system design and analysis:

Simulation tools and software are crucial in the design and study of ORC systems. These technologies enable the thorough modeling of thermodynamic processes, allowing engineers to forecast system behavior under varied operating situations. Software such as Aspen Plus (https://www.aspentech.com/en/products/engineering/aspen-plus), EES (Engineering Equation Solver) (https://fchartsoftware.com/ees/), and MATLAB (https://www.mathworks.com/products/matlab.html) are commonly used for this purpose [114]. These technologies assist in the optimization of system components, the assessment of various working fluids, and the investigation of transient behaviors in hybrid systems. By offering insights into possible performance improvements and finding inefficiencies, simulation tools contribute to the development of more efficient and cost-effective ORC systems [41].

5. Economic Assessment

5.1. Capital and Operational Costs

Analysis of capital costs for solar, biomass, and hybrid ORC systems:

The capital costs of ORC systems vary greatly depending on the heat source, system size, and technical components. Solar-powered ORC systems often involve greater upfront costs due to the necessity for solar collectors and thermal storage [115]. Biomass-powered ORC systems, while typically less expensive in terms of equipment, need significant investment in biomass handling and storage infrastructure. Hybrid systems include components from both, potentially leading to even larger initial capital expenditures. A full cost study must incorporate the unique context of deployment, including local energy pricing, resource availability, and finance conditions [102].

Operational and maintenance costs associated with each system type:

Operational and maintenance (O&M) expenses are another key component in the economic assessment of ORC systems. Solar-powered systems generally have reduced O&M expenses owing to the absence of fuel needs but may incur greater costs for cleaning and maintaining solar collectors [41]. Biomass-powered systems, on the other hand, require frequent fuel supply management and maintenance of combustion systems, which can drive up O&M expenditures. Hybrid systems can benefit from shared O&M methods but may also create complexity in system administration. Understanding these expenses is critical for assessing the long-term economic feasibility of ORC systems [45,112].

5.2. Economic Viability

Payback period, levelized cost of energy (LCOE), and other economic indicators:

The economic feasibility of ORC systems is commonly analyzed using measures such as the payback period and the levelized cost of energy (LCOE). The payback period reflects the time necessary to repay the initial expenditure from the savings or revenue created by the system [41]. A shorter payback period suggests a more economically advantageous investment. LCOE, on the other hand, indicates the average cost of generating electricity over the lifespan of the system, incorporating both capital and operational expenses. These variables are impacted by factors such as system efficiency, fuel costs, and power prices, and are critical for assessing the economic performance of different ORC configurations [116].

The Figure 9 depicts the connection between the levelized cost of energy (LCOE) and CO_2 emissions for a hybrid ORC system as a function of the compression ratio rc,AC. The LCOE curve (black line) first lowers dramatically with increasing rc,AC, reaching a minimal point before gradually rising again. This suggests that there is an ideal compression ratio where the cost of energy generation is reduced. On the other hand, the CO_2 emission curve (red line) constantly increases with larger rc,AC, demonstrating a trade-off between economic efficiency and environmental effects. The image emphasizes the essential balance that must be reached in developing ORC systems, particularly hybrid ones combining solar and biomass, to optimize both economic and environmental performance. This research underlines the significance of carefully selecting operating parameters to optimize costs while simultaneously considering the implications for greenhouse gas emissions.

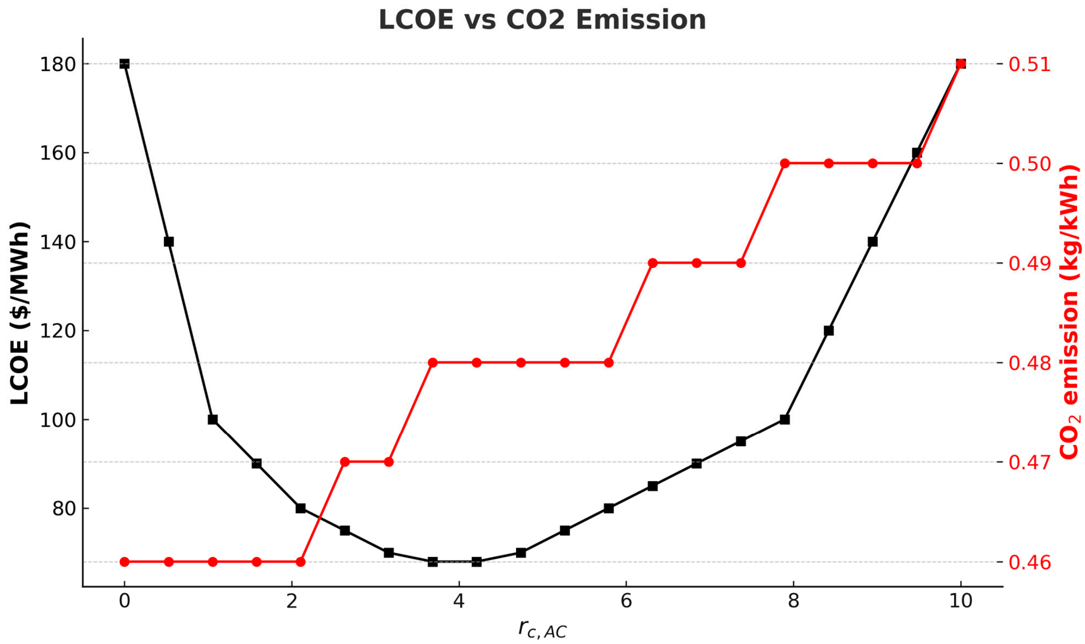

Figure 9. Effects of air compressor pressure ratio on the system performance.

This figure highlights the relationship between the system's levelized cost of energy (LCOE) and CO_2 emissions as a function of the compressor pressure ratio. While the power size is not explicitly mentioned, the system is optimized to balance between economic performance and environmental impact, implying a system size typically suited for medium-scale applications, likely in the 1 to 10 MW range.

LCOE and cost analysis for Solar-only, Biomass-only, and Hybrid ORC Systems are shown in Table 2 below.

Table 2. LCOE and Cost Analysis Table for solar-only, biomass-only, and hybrid ORC Systems.

System Configuration	LCOE (USD/kWh) [25,28,40,117]	Capital Costs (USD/kW) [31,37,39,103]	Operational Costs (USD/Year) [21,32,36]	LCOE Reduction in Hybrid (%) [21,117]
Solar-Only ORC System	0.12–0.15	2500–4000	80,000–120,000	N/A
Biomass-Only ORC System	0.10–0.14	2000–3500	70,000–100,000	N/A
Hybrid Solar–Biomass ORC	0.07–0.10	3000–4500	90,000–110,000	25–33%

N/A means not applicable.

Sensitivity analysis for different cost parameters:

Sensitivity analysis is a great technique for evaluating how changes in key cost factors impact the economic performance of ORC systems. For example, variations in fuel prices, changes in power tariffs, or fluctuations in maintenance costs can greatly alter the overall cost-effectiveness of a system [118]. By doing sensitivity analysis, researchers may identify the most significant aspects impacting economic viability and devise ways to manage possible hazards. This analysis also assists in improving system design and operation to achieve the greatest potential economic outcomes under various market conditions [119].

5.3. Market Potential

Market trends and potential for hybrid solar–biomass ORC systems:

The market potential for hybrid solar–biomass ORC systems is expanding as the demand for renewable and sustainable energy solutions develops internationally. Market trends show a developing interest in decentralized energy systems, particularly in countries with rich solar and biomass resources [84]. Hybrid ORC systems are well-positioned to address this need by providing stable, renewable energy with decreased environmental effects. The potential for these systems is further bolstered by developments in ORC technology, lowering prices of solar components, and increased availability of biomass feedstocks. This research evaluates existing market trends, projects future growth, and identifies important countries and industries where hybrid ORC systems might play a significant role [102].

Policy incentives and subsidies for renewable energy systems:

Policy incentives and subsidies are major drivers of market adoption for hybrid solar–biomass ORC systems. Governments worldwide are establishing policies to encourage renewable energy, including feed-in tariffs, tax credits, and subsidies that minimize the financial hurdles to adopting ORC technology [120]. These incentives not only im-prove the economic attractiveness of ORC systems but also speed the transition to a low-carbon energy mix. This review analyze the influence of present regulations on the deployment of ORC systems, identifies best practices from different countries, and provides policy suggestions to boost the market potential of hybrid solar–biomass ORC systems [121].

6. Environmental Impact and Sustainability

6.1. Environmental Benefits

Reduction in greenhouse gas emissions with hybrid ORC systems:

Hybrid solar–biomass ORC systems have considerable environmental advantages, particularly in terms of decreasing greenhouse gas (GHG) emissions [120]. By integrating solar and biomass energy sources, these systems may generate power with low reliance on fossil fuels, hence reducing CO_2 emissions. Biomass combustion, when sustainably controlled, is termed carbon-neutral, since the CO_2 emitted is compensated by the CO_2 absorbed during the development of the biomass [122]. Solar energy, being totally renewable, adds no direct emissions. Together, these sources contribute to a large decrease in the carbon footprint of power generation, making hybrid ORC systems a powerful instrument in the battle against climate change [102].

Comparison of the environmental footprint of solar, biomass, and hybrid systems:

The environmental footprint of ORC systems varies depending on the energy sources employed. Solar-powered ORC systems have a small environmental effect, with the major problems being land usage and the resources necessary for manufacturing and disposing of solar collectors [119]. Biomass-powered ORC systems, while renewable, have a more substantial environmental impact due to land usage, water consumption, and emissions related with biomass production, harvesting, and combustion [121]. Hybrid systems include both impacts, but the overall footprint may be minimized by lowering biomass usage and incorporating sophisticated emission control technologies. This review evaluates the environmental footprints of different ORC systems and provides solutions for decreasing their impact [48]. Carbon emission reductions comparing carbon emissions across solar-only, biomass-only, and hybrid solar–biomass systems are shown in Table 3 below.

Table 3. Carbon Emission Reduction Table comparing the carbon emissions across solar-only, biomass-only, and hybrid solar–biomass systems.

System Configuration	Carbon Emissions (g CO_2/kWh) [31,37,40,59]	Biomass Consumption Reduction (%) [25,28,39]	CO_2 Emission Reduction Compared to Conventional Systems (%) [21,36,38]
Solar-Only ORC System	0–5 [31,59]	N/A	90–100% [36,38]
Biomass-Only ORC System	150–250 [37,40]	N/A	40–50% [21,36]
Hybrid Solar–Biomass ORC	50–150 [37,40]	33% [25,28]	60–70% [21,38]

N/A means not applicable.

6.2. Sustainability Assessment

Long-term sustainability of hybrid solar–biomass ORC systems:

The long-term sustainability of hybrid solar–biomass ORC systems depend on various aspects of its implementation, including resource availability, environmental effects, and economic feasibility. Solar energy, being unlimited, adds to the sustainability of these systems [123]. However, the sustainability of biomass depends on the careful management of feedstock resources to minimize overexploitation and guarantee that biomass production does not compete with food production or contribute to deforestation. This review analyzes the sustainability of hybrid ORC systems from numerous perspectives, including resource management, life-cycle emissions, and economic sustainability, offering a thorough evaluation of their long-term viability.

Life cycle analysis and resource availability:

Life cycle analysis (LCA) is a vital technique for analyzing the environmental effects and sustainability of ORC systems over their full lifespan, from raw material extraction to disposal or recycling [4]. For hybrid solar–biomass ORC systems, LCA may disclose the cumulative environmental consequences associated with each component, including the production of solar collectors, biomass cultivation, and system operation. Additionally, the availability of resources, particularly biomass feedstocks, is vital for the long-term viability of these systems. This paper covers the results of current LCA studies, highlighting the environmental trade-offs and sustainability problems associated with hybrid ORC systems and providing techniques for optimizing resource use and minimizing environmental consequences. Resource optimization and life cycle impact are shown in Table 4, below.

Table 4. Resource optimization and life cycle impact.

Geographic Region	Solar Irradiation (kWh/m^2/Day) [24,31]	Biomass Availability (Ton/Day) [37,61]	Biomass Consumption Rate (Ton/Day) [25,28]	Solar Usage Efficiency (%) [38,39]	Hybrid System Efficiency (%) [21,36]
Southern Europe	4.5–5.5	50–100	10–20	50–60	20–28
Northern Europe	3.0–4.0	30–50	15–25	35–45	18–22
South Asia	5.0–6.5	100–150	25–35	60–70	27–32
North America (Southwest)	6.0–7.0	200–250	30–40	65–75	28–35

7. Challenges and Future Prospects

7.1. Technical Challenges

Key technical barriers in the development of hybrid ORC systems:

The development and implementation of hybrid solar–biomass ORC systems have encountered several technological hurdles that must be solved to reach their full potential.

These include the integration of diverse heat sources with varied temperatures, along with the design of efficient heat exchangers and storage systems, and the optimization of the ORC cycle for combined heat inputs. Additionally, regulating the thermal and mechanical strains on system components owing to variable operating conditions can involve substantial technical issues. Advanced control techniques and resilient system designs are necessary to enable dependable and efficient operation under various and dynamic conditions [124].

Reliability and durability concerns in hybrid systems:

The dependability and durability of hybrid ORC systems are vital for their long-term economic viability and environmental advantages. Continuous cycling between solar and biomass energy inputs can lead to wear and tear on system components, particularly in the turbine, heat exchangers, and control systems. The combination of solar and biomass also creates complexity in system operations, requiring sophisticated monitoring and control methods to prevent failures and maintain optimal performance. Ensuring the lifespan of these systems through the development of durable materials, dependable components, and effective maintenance procedures is vital for lowering downtime and operational costs [4].

7.2. Economic and Market Barriers

Economic challenges and market acceptance of hybrid systems:

Economic constraints, such as high initial capital costs and unclear returns on investment, might hamper the broad adoption of hybrid solar–biomass ORC systems. The complicated structure of hybrid systems generally leads to greater upfront costs due to the necessity for specialist equipment, such as integrated solar and biomass boilers, advanced control systems, and thermal storage solutions [23]. Market acceptability of these systems is further hindered by the rivalry with more established renewable energy sources, such as standalone solar PV or wind power. Addressing these economic hurdles involves establishing long-term cost reductions, environmental advantages, and possibilities for government incentives associated with hybrid ORC systems.

Barriers related to policy and regulation:

Policy and regulatory frameworks have a crucial impact in the adoption and deployment of hybrid ORC systems. Inconsistent or insufficient policy support, such as the lack of subsidies or advantageous tariffs for hybrid systems, might limit market expansion. Furthermore, regulatory obstacles relating to permits, grid interconnection, and emissions norms might create further impediments. Overcoming these issues needs concerted efforts by policymakers, industry stakeholders, and researchers to design supporting policies that incentivize the deployment of hybrid ORC systems. This review investigates current policy landscapes, identifies best practices, and provides recommendations for building a hospitable environment for hybrid ORC technologies [122].

7.3. Research and Development Opportunities

Emerging technologies and innovations in ORC systems:

Ongoing research and development (R&D) activities are vital for developing hybrid ORC systems. Innovations in working fluids, heat exchanger design, and thermal storage technologies have the potential to greatly increase the efficiency and cost-effectiveness of these systems. Additionally, the integration of modern control techniques, including machine learning and artificial intelligence, can optimize system performance and boost dependability. R&D activities are also researching the use of alternative energy sources, such as waste heat or biofuels, in combination with solar and biomass, to further increase the application of ORC systems [124]. This review emphasizes cutting-edge research and new technologies that are driving the future of ORC systems.

Future research directions for improving thermoeconomic viability:

To increase the thermoeconomic feasibility of hybrid ORC systems, future research should focus on improving system design, decreasing capital and operational costs, and boosting energy efficiency. This involves the development of novel materials for heat exchangers, enhanced working fluids with higher thermodynamic characteristics, and unique hybridization procedures that maximize resource usage. Research should also examine the scalability of hybrid ORC systems, particularly for decentralized and off-grid applications. Additionally, integrating detailed LCA and economic assessments into the design process can assist in uncovering cost-effective solutions and assure the long-term sustainability of these systems [41]. This review identifies significant topics for future study and gives recommendations for furthering the discipline.

8. Conclusions

8.1. Summary of Key Findings

Recap of the thermodynamic and economic performance of hybrid ORC systems:

This research has studied the thermodynamic and economic performance of hybrid solar–biomass ORC systems, showing its promise as a sustainable and efficient energy option. The research reveals that hybrid systems may efficiently combine the capabilities of solar and biomass energy, delivering a stable and continuous power generating alternative. While solar energy provides a clean and abundant resource, its intermittency is well balanced by the consistent production of biomass, leading to increased overall system efficiency and dependability. However, the economic assessment finds that the initial capital expenditures and operating difficulties of hybrid systems face substantial hurdles, which must be solved to gain broad acceptance.

Overview of environmental and sustainable aspects:

The environmental advantages of hybrid ORC systems are substantial, particularly in terms of decreasing greenhouse gas emissions and supporting sustainable energy consumption. By incorporating renewable resources, these systems contribute to a smaller carbon footprint and promote the transition to a more sustainable energy future. However, the sustainability of biomass supplies and the environmental effects of system components, such as solar collectors and thermal storage, demand careful attention. This evaluation underscores the relevance of life cycle analysis and resource management in assuring the long-term sustainability of hybrid ORC systems.

8.2. Recommendations

Policy and research recommendations for the advancement of hybrid solar–biomass ORC systems:

Government incentives, feed-in tariffs (FiTs), and subsidies play a critical role in shaping the economic feasibility of hybrid solar–biomass organic Rankine cycle (ORC) systems, but these policies differ substantially across countries. In regions such as Europe, hybrid systems have historically benefited from generous biomass subsidies and solar energy incentives, making them an attractive investment. For example, in Germany and Italy, FiTs have guaranteed favorable rates for renewable energy producers, enabling the profitability of hybrid systems by ensuring fixed revenue for electricity fed into the grid. In the United States, hybrid systems have capitalized on the Investment Tax Credit (ITC) and Production Tax Credit (PTC) for both biomass and solar power, reducing initial capital expenditures. These policies have been crucial in offsetting the higher upfront costs associated with hybrid ORC systems, which range from €2500 to €4000 per kW [125].

However, recent changes in renewable energy policies, particularly regarding biomass, have impacted the deployment of hybrid ORC systems. Many governments, particularly in Europe, are scaling back subsidies for biomass energy due to concerns over sustainability, deforestation, and competition for land. The European Union's Renewable Energy Directive (RED II), for instance, introduced stricter sustainability criteria for biomass, limiting subsidies for imported biomass fuels such as wood pellets. This reduction in biomass incentives challenges the economic attractiveness of hybrid systems in areas that rely heavily on these subsidies [126]. Conversely, solar incentives remain robust in many countries as governments prioritize decarbonization efforts. Solar energy incentives, such as Spain's competitive renewable energy auctions, continue to support solar components of hybrid systems, but these systems must increasingly rely on market mechanisms such as power purchase agreements (PPAs) instead of traditional feed-in tariffs [127].

In addition to changes in biomass subsidies, the shift toward competitive renewable energy auctions has created a more challenging environment for hybrid systems. For example, countries such as Spain and India have moved away from guaranteed FiTs toward auction-based systems that prioritize cost-competitive renewable solutions. This environment favors technologies such as solar photovoltaics (PV) and wind power, which have seen significant cost reductions in recent years [128]. However, hybrid ORC systems remain competitive in regions with abundant local biomass resources or where continuous energy production is needed, such as off-grid or rural areas. The programmability of biomass allows hybrid systems to provide a stable energy output, mitigating the intermittency of solar power and offering a more reliable energy solution in settings where grid reliability or energy storage solutions are lacking.

8.3. Final Thoughts

The future of renewable energy systems and the role of hybrid ORC technology:

As the world progresses towards a more sustainable energy future, hybrid ORC systems have the potential to play a vital role in diversifying and decarbonizing the energy mix. By properly harvesting solar and biomass resources, these systems may supply dependable and clean electricity, particularly in places with plentiful renewable resources. The continuing progress of ORC technology, together with supporting legislation and market circumstances, are critical for achieving the full potential of hybrid systems. Ultimately, hybrid ORC technology promises a possible avenue towards a more resilient and sustainable energy infrastructure, capable of addressing the rising worldwide demand for clean energy.

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