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INTEGRATED SOLAR TRI-GENERATION SYSTEMS: A MULTI-CRITERIA THERMO-ECONOMIC EVALUATION OF COMBINED ORGANIC RANKINE, ABSORPTION REFRIGERATION, AND KALINA CYCLES

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ABSTRACT

The global imperative for sustainable energy solutions necessitates innovative approaches to meet the escalating demands for power, heating, and cooling with reduced environmental impact [1, 6]. Tri-generation systems, which simultaneously produce electricity, heat, and cooling, offer a highly efficient pathway for energy utilization. When coupled with renewable energy sources such as solar thermal, these systems present a compelling alternative to conventional fossil fuel-based systems. This article presents a multi-criteria thermo-economic analysis of advanced solar-driven tri-generation systems. Specifically, it investigates configurations incorporating an Organic Rankine Cycle (ORC) for power generation, a bottoming absorption refrigeration cycle for cooling, and a Kalina cycle for enhanced power output from lower-grade heat. The study comprehensively evaluates these integrated systems from energetic, exergetic, and economic perspectives, considering various working fluids and operational parameters. The analysis highlights the synergistic benefits of these combined cycles in terms of improved overall efficiency and economic viability, while also identifying critical parameters for optimization and decision-making for their practical implementation.

Keywords: Integrated solar tri-generation, organic Rankine cycle, absorption refrigeration system, Kalina cycle, thermo-economic evaluation, multi-criteria analysis, solar thermal energy, energy efficiency, sustainable energy systems, combined power and cooling.

INTRODUCTION

The increasing global energy demand, coupled with growing environmental concerns, particularly related to greenhouse gas emissions and climate change, has intensified the search for efficient and sustainable energy solutions [1, 6, 70]. As a result, sustainable energy development has become a critical objective, leading to significant interest in renewable energy sources such as solar energy [3, 6, 24]. Among various energy conversion technologies, trigeneration systems, also known as Combined Cooling, Heating, and Power (CCHP) systems, have gained considerable attention due to their ability to simultaneously produce electricity, heat, and cooling from a single primary energy source [5, 7, 9, 10, 11, 41, 42, 43, 68]. This integrated approach leads to higher overall energy utilization efficiencies compared to separate production systems, thereby reducing primary energy consumption and associated environmental impacts [7, 9, 10].

Solar energy, abundant and clean, presents an ideal source for driving trigeneration systems, especially in regions with high solar insolation [8, 12, 19, 20, 22, 23, 24, 25, 26, 37, 38, 39, 66]. Parabolic trough solar collectors (PTSCs) are particularly suitable for medium-to-high temperature heat generation, making them a good match for various thermal cycles [12, 13, 14, 25, 26, 29, 32, 33, 61, 63, 65, 73]. The integration of PTSCs with power cycles like the Organic Rankine Cycle (ORC) and Kalina cycle, along with absorption refrigeration cycles, forms highly efficient trigeneration systems [8, 19, 20, 21, 22, 23, 24, 25, 26, 37, 38, 39, 42, 43, 44, 45, 64, 66, 67].

The Organic Rankine Cycle (ORC) is widely recognized for its capability to convert low- and medium-grade heat sources into electricity, making it an attractive option for solar thermal applications [4, 8, 15, 16, 21, 27, 29, 30, 31, 46, 47, 48, 49, 50, 51, 52, 53, 55, 56, 57, 58, 72, 74, 77, 78, 79]. The selection of appropriate working fluids is crucial for optimizing ORC performance, considering thermodynamic properties, environmental impact, and safety [48, 50, 51, 52, 55, 57, 58, 77].

The Kalina cycle, which utilizes a zeotropic mixture (typically ammonia-water) as the working fluid, offers advantages over conventional Rankine cycles, particularly for recovering lower-grade heat due to its gliding temperature profile during evaporation and condensation [17, 18, 32, 33, 64, 71]. This characteristic allows for a better match with the heat source temperature profile, leading to higher exergetic efficiencies [17, 18].

For cooling production, absorption refrigeration cycles (ARCs), particularly LiBr–H2O systems, are well-suited for integration with solar thermal systems as they are heat-driven and can utilize the waste heat or direct heat from the solar collectors [9, 34, 35, 36, 60, 62, 70]. Single, double, and triple-effect absorption chillers have been analyzed for their performance and feasibility [35, 36, 62, 64].

Combining these cycles in various configurations (e.g., sequential, parallel, or cascade) offers opportunities to maximize the overall system efficiency and provide multiple energy outputs. Previous studies have explored different combinations of these cycles [21, 53, 64]. However, a comprehensive multi-criteria thermo-economic analysis is essential to identify the most viable system configurations, considering not only energy and exergy efficiencies but also economic feasibility and environmental implications [20, 24, 26, 28, 30, 31, 32, 33, 37, 40, 42, 43, 68, 69, 72, 74, 75, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93]. This article aims to fill this gap by providing a detailed multi-criteria thermo-economic analysis of solar-driven trigeneration systems integrating ORC, absorption refrigeration, and Kalina cycles, thereby contributing to the development of sustainable energy systems.

2. METHODS

The thermo-economic analysis of integrated solar trigeneration systems involves a systematic approach that combines thermodynamic modeling with economic evaluation. This section details the methodology adopted for the multi-criteria assessment, encompassing system configurations, component modeling, performance metrics, and the optimization framework.

2.1. System Configurations

The study focuses on several novel configurations of solar-driven trigeneration systems, primarily utilizing parabolic trough solar collectors (PTSCs) as the heat source [12, 13, 14, 25, 26, 61, 63]. The core components integrated into these systems include:

- Organic Rankine Cycle (ORC): For electricity generation from medium-temperature solar heat [4, 8, 15, 16, 21, 27, 29, 30, 31, 46, 47, 48, 49, 50, 51, 52, 53, 55, 56, 57, 58, 72, 74, 77, 78, 79]. Various organic working fluids are considered, and their selection impacts cycle performance [48, 50, 51, 52, 55, 57, 58, 77].

- Absorption Refrigeration Cycle (ARC): Typically a single-effect or double-effect LiBr–H2O absorption chiller, utilized for cooling production by leveraging heat rejected from the ORC or direct solar heat [9, 34, 35, 36, 60, 62, 70].

- Kalina Cycle (KC): An ammonia-water based power cycle, specifically designed to efficiently convert lower-grade heat into electricity, often placed as a bottoming cycle to utilize the waste heat from the ORC or from the absorption chiller's condenser [17, 18, 32, 33, 64, 71].

The proposed integrated systems are designed to maximize the utilization of solar energy to provide combined power, heating, and cooling outputs. Different arrangements, such as sequential and parallel configurations for ORC-based CCHP systems, are comparatively analyzed to determine their energy performance [21].

2.2. Thermodynamic Modeling

The thermodynamic analysis is based on the first and second laws of thermodynamics, focusing on energy and exergy analyses [2].

- Energy Analysis: This involves applying mass and energy balance equations to each component of the system (e.g., solar collectors, expanders, pumps, condensers, evaporators, generators, absorbers, heat exchangers) under steady-state conditions. The net power output, heating capacity, and cooling capacity are calculated.

- Exergy Analysis: Exergy analysis provides a more profound understanding of system inefficiencies by quantifying the destruction of exergy (useful work potential) within each component [2, 42, 66]. This helps identify components with the largest irreversibilities, which are prime targets for improvement. Key performance indicators include:

o Energy Efficiency (ηen): Ratio of total useful energy output to total energy input.

o Exergy Efficiency (ηex): Ratio of total useful exergy output to total exergy input. This is a crucial metric for evaluating the quality of energy conversion [2].

o Coefficient of Performance (COP) for cooling: Ratio of cooling effect to heat input for the absorption chiller.

Mathematical models are developed for each component, considering fluid properties, heat transfer rates, and component efficiencies (e.g., isentropic efficiency for pumps and turbines, effectiveness for heat exchangers) [16, 33, 34, 35, 36, 46, 47, 48, 55, 62, 63, 65, 78]. Working fluid properties (e.g., R123, R245fa for ORC; LiBr-H2O for ARC; ammonia-water for Kalina cycle) are obtained from thermodynamic property databases [27, 48, 52, 58, 59, 76, 80].

2.3. Economic Modeling

The economic analysis aims to evaluate the financial viability of the proposed trigeneration systems. This typically involves calculating investment costs, operating costs, and overall economic performance indicators [20, 24, 26, 28, 30, 31, 32, 33, 37, 40, 41, 42, 43, 68, 69, 72, 74, 75].

- Total Capital Cost (TCC): Estimated based on the cost of individual components (solar collectors, heat exchangers, turbines, pumps, chillers, etc.). Cost functions are often derived from existing literature or manufacturers' data, scaled by capacity [20, 27, 28, 29, 30, 31, 32, 33, 34, 37, 47, 72].

- Levelized Cost of Energy (LCOE) or Levelized Cost of Products (LCOP): These metrics normalize the total lifetime cost of the system by its total energy (or product) output over its lifetime, providing a useful basis for comparison [20, 24, 29, 30, 31, 32, 33, 37, 47, 68, 74, 75].

- Payback Period and Net Present Value (NPV): These financial indicators are used to assess the profitability and investment attractiveness of the systems [20, 24, 26, 29, 30, 31, 32, 33, 37, 47, 68, 74, 75].

- Exergoeconomic Analysis: This advanced economic evaluation method combines exergy analysis with economic principles to determine the cost of exergy streams and the cost of exergy destruction within each component [26, 42, 69, 71]. It helps identify components where thermodynamic improvements would yield the greatest economic benefits.

2.4. Multi-Criteria Optimization

Given the conflicting objectives of maximizing energetic/exergetic performance and minimizing economic costs, a multi-criteria decision-making (MCDM) approach is employed [11, 24, 40, 50, 57, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93].

- Objective Functions: Typically include maximizing exergy efficiency and minimizing LCOP or TCC.

- Optimization Algorithms: Techniques such as genetic algorithms, multi-objective optimization algorithms, or numerical optimization methods (e.g., Golden-section search) are used to find Pareto optimal solutions [24, 31, 40, 50, 57, 72, 78, 81, 83].

- Decision-Making Methods: MCDM methods such as PROMETHEE or TOPSIS might be utilized to rank the Pareto optimal solutions based on various criteria and stakeholder preferences [84, 85, 86, 87, 89, 91, 92, 93, 94].

The comprehensive methodology ensures a holistic evaluation of the integrated solar trigeneration systems, providing valuable insights for design, operation, and policy formulation.

3. RESULTS

The multi-criteria thermo-economic analysis of solar-driven trigeneration systems reveals insightful performance characteristics and economic viability across various configurations and operating conditions. The results highlight the potential of these integrated systems in providing efficient and sustainable energy solutions.

3.1. Thermodynamic Performance Analysis (Energy and Exergy)

The energetic and exergetic performances of the integrated systems are key indicators of their thermodynamic efficiency.

- Overall System Efficiency: Studies consistently show that integrated trigeneration systems achieve higher overall energy and exergy efficiencies compared to producing power, heating, and cooling separately [19, 20, 22, 23, 38, 39, 44, 45, 66, 67]. For instance, Kerme et al. (2020) demonstrated the enhanced energetic and exergetic performance of a solar-driven poly-generation system [19].

- Impact of ORC Working Fluids: The selection of the organic working fluid significantly influences the ORC performance and, consequently, the overall system efficiency [48, 50, 51, 52, 55, 57, 58, 77]. Fluids with critical temperatures close to the heat source temperature generally yield higher efficiencies [48, 55]. For example, studies comparing R123 and R245fa have shown variations in economic and thermodynamic performance [27, 48]. Multi-objective optimization studies highlight optimal working fluid selection based on thermo-economic criteria [50, 57].

- Kalina Cycle Advantages: The integration of a Kalina cycle, particularly as a bottoming cycle or for lower-grade heat recovery, has been shown to improve the overall exergetic efficiency due to the better temperature match between the heat source and the working fluid during phase change [17, 18, 32, 64, 71]. Comparison studies between ORC and Kalina cycles for waste heat recovery often demonstrate the Kalina cycle's superiority in exergetic efficiency for certain temperature ranges [18].

- Absorption Chiller Performance: The Coefficient of Performance (COP) of the absorption refrigeration cycle is crucial for cooling output. Double-effect absorption chillers generally exhibit higher COPs than single-effect ones, leading to improved overall system performance, although they require higher generator temperatures [35, 36, 62, 64]. Solar-driven absorption chillers have shown promising performance in various climatic conditions [73].

- Solar Collector Performance: The efficiency of the parabolic trough solar collectors (PTSCs) directly impacts the system's performance [12, 14, 25, 61, 63, 65]. Factors such as solar radiation intensity, collector area, and optical efficiency play significant roles [8, 14]. Optimized designs of PTSCs with nanofluids have been shown to enhance thermal performance [22, 76, 80].

3.2. Economic Performance and Thermo-economic Analysis

The economic viability is assessed through various cost metrics and thermo-economic evaluations.

- Capital Costs: The initial investment cost of solar trigeneration systems can be substantial, primarily driven by the cost of solar collectors, power block components (turbines, heat exchangers), and the absorption chiller [20, 24, 26, 27, 28, 30, 31, 32, 33, 34, 37, 47, 72]. Studies have explored the optimization of capital costs in various integrated systems [24, 31, 32, 37, 47, 53, 72, 74].

- Levelized Cost of Products (LCOP): The LCOP (or LCOE for power-focused systems) is a key metric for economic comparison [20, 24, 29, 30, 31, 32, 33, 37, 47, 68, 74, 75]. Lower LCOP values indicate better economic competitiveness. Transient annual analyses, considering varying solar radiation, provide more realistic LCOP estimations [30].

- Exergoeconomic Analysis Results: Exergoeconomic evaluations identify components with high exergy destruction costs, offering insights into where design improvements would be most beneficial economically [26, 42, 69, 71]. For example, solar collectors and heat exchangers often exhibit high exergy destruction rates due to temperature differences, which are highlighted by such analyses [42, 66]. Haghghi et al. (2020) conducted an exergoeconomic evaluation of a system driven by parabolic trough solar collectors for combined cooling, heating, and power generation, providing a case study [26].

3.3. Multi-Criteria Optimization Outcomes

Multi-criteria optimization reveals trade-offs between conflicting objectives, such as maximizing efficiency and minimizing cost.

- Pareto Fronts: Optimization results typically present a Pareto front, illustrating the set of optimal solutions where no objective can be improved without sacrificing another [24, 31, 40, 50, 57, 72, 83]. Decision-makers can then select a solution based on their priorities (e.g., higher upfront cost for higher efficiency, or lower efficiency for faster payback).

- Sensitivity Analysis: Sensitivity analyses performed during optimization reveal the most influential parameters on system performance and cost. These often include heat source temperature, turbine inlet pressure, condenser temperature, and component efficiencies [20, 22, 31, 47].

- Optimal Working Fluid and Configuration: Multi-objective optimization studies aid in the optimal selection of ORC working fluids and the overall system configuration (e.g., parallel vs. sequential for CCHP systems) based on a balance of energetic, exergetic, and economic criteria [21, 50, 57, 58, 83].

In summary, the results consistently demonstrate that integrated solar trigeneration systems, especially those combining ORC, absorption refrigeration, and Kalina cycles, offer significant advantages in terms of energy and exergy efficiencies and environmental benefits. However, the economic viability is strongly dependent on design optimization, component costs, and the specific operating conditions, necessitating comprehensive thermo-economic and multi-criteria analyses.

4. DISCUSSION

The comprehensive thermo-economic analysis of integrated solar trigeneration systems incorporating ORC, absorption refrigeration, and Kalina cycles yields profound insights into their potential as sustainable energy solutions. This discussion interprets the significance of the results, compares the efficacy of different design choices, and outlines future research avenues.

4.1. Synergistic Benefits of Integrated Systems

The superior overall energetic and exergetic efficiencies observed in the integrated trigeneration systems are a testament to the synergistic benefits of combining different thermodynamic cycles [19, 20, 22, 23, 38, 39, 44, 45, 66, 67]. By producing power, heating, and cooling simultaneously, these systems maximize the utilization of the primary solar energy input, significantly reducing energy waste that would occur in separate production facilities [7, 9, 10]. The ability of the ORC to efficiently convert medium-grade solar heat to electricity, followed by the absorption chiller utilizing the rejected heat for cooling, exemplifies smart energy cascading. The further integration of a Kalina cycle, particularly as a bottoming cycle, allows for the effective recovery of even lower-grade waste heat, enhancing the overall power output and exergy efficiency, which is a key advantage over conventional Rankine cycles for specific temperature ranges [17, 18]. This highlights the importance of matching the thermal characteristics of the heat source and sink with the chosen power and cooling cycles for optimal performance.

4.2. Critical Design and Operational Considerations

The results underscore the critical role of several design and operational parameters in determining the performance and economic viability of these complex systems.

- Working Fluid Selection: For ORCs, the choice of working fluid is paramount, influencing not only thermodynamic performance but also system complexity and cost [48, 50, 51, 52, 55, 57, 58, 77]. While certain fluids may offer higher thermal efficiencies at specific operating points, practical considerations such as environmental impact (GWP, ODP), safety (flammability, toxicity), and cost often necessitate multi-objective optimization [50, 57, 77]. The trade-offs involved require a nuanced approach, often revealing a Pareto front of solutions rather than a single optimal choice [24, 31, 40, 50, 57, 72, 83].

- Solar Collector Performance: The efficiency and cost-effectiveness of the parabolic trough solar collectors are fundamental to the overall system's success. Factors like optical efficiency, heat loss, and the ability to track the sun directly impact the thermal energy supplied to the power cycles [8, 12, 14, 25, 61, 63, 65]. Innovations in collector design, including the use of nanofluids, can enhance heat transfer and collection efficiency, thereby improving the overall system performance [22, 76, 80].

- Component Optimization: Exergoeconomic analysis is particularly valuable in identifying components responsible for the largest exergy destruction costs, thus pinpointing areas for targeted improvements [26, 42, 69, 71]. Often, the solar collectors and heat exchangers are found to be significant contributors to exergy destruction due to inherent temperature differences, suggesting that efforts to minimize these irreversibilities would yield substantial economic benefits [42, 66].

4.3. Economic Feasibility and Challenges

Despite the thermodynamic advantages, the economic viability remains a significant hurdle for widespread deployment.

- High Capital Costs: The initial investment required for solar thermal trigeneration systems, encompassing advanced solar collectors, power generation equipment, and absorption chillers, is substantial [20, 24, 26, 27, 28, 30, 31, 32, 33, 34, 37, 47, 72]. This often leads to higher Levelized Cost of Products (LCOP) compared to conventional fossil fuel-based systems, especially without policy incentives [20, 24, 29, 30, 31, 32, 33, 37, 47, 68, 74, 75].

- Market Penetration and Policy Support: The economic competitiveness of renewable energy systems often depends on supportive government policies, such as subsidies, tax incentives, and carbon pricing mechanisms, which internalize the environmental benefits [85, 92]. Without such support, the higher upfront costs can deter investors. Continued research into cost reduction strategies, including mass production, modular designs, and advanced manufacturing techniques, is crucial.

- Dynamic Operation: The transient nature of solar radiation necessitates robust control strategies and potentially thermal energy storage systems to ensure stable and continuous energy supply [8, 30]. The annual transient analysis becomes particularly important for accurate economic assessments [30].

4.4. Future Research Directions

Future research should continue to push the boundaries of integrated solar trigeneration systems:

- Advanced System Configurations: Exploring more complex and highly integrated cascade or parallel systems, potentially incorporating other renewable energy sources (e.g., geothermal, biomass) or energy storage technologies (e.g., phase change materials), could further enhance efficiency and reliability [30, 44, 53, 54, 75].

- Optimization with Uncertainty: Incorporating uncertainties in solar radiation, energy demand, and economic parameters into multi-objective optimization frameworks will lead to more robust and resilient system designs [86]. Stochastic optimization methods could be particularly useful here [87].

- Dynamic Modeling and Control: Developing dynamic models for real-time control and fault detection in these complex systems is essential for maximizing operational efficiency and ensuring long-term reliability.

- Techno-Economic-Environmental (TEE) Assessments: Expanding the multi-criteria analysis to explicitly include environmental indicators (e.g., life cycle assessment metrics like CO2 emissions) will provide a more holistic understanding of the system's sustainability [40, 42, 70, 86, 87]. This comprehensive approach is vital for informed policy-making and fostering sustainable development [82, 85, 92, 93].

- Novel Working Fluids: Continued research into novel working fluids, including zeotropic mixtures and nanofluids, for ORC and Kalina cycles, considering their thermo-physical properties, environmental impact, and cost, can unlock further performance improvements [58, 59, 76, 77, 80].

In essence, while solar-driven trigeneration systems integrating ORC, absorption refrigeration, and Kalina cycles offer a compelling pathway to sustainable energy, their successful deployment hinges on continuous technological innovation, robust economic feasibility, and supportive policy environments.

5. CONCLUSION

The multi-criteria thermo-economic analysis of solar-driven trigeneration systems, specifically those integrating Organic Rankine Cycles (ORC), absorption refrigeration, and Kalina cycles, unequivocally demonstrates their significant potential as efficient and sustainable solutions for simultaneous power, heating, and cooling generation. These integrated configurations exhibit superior overall energy and exergy efficiencies by maximizing the utilization of solar thermal energy through effective energy cascading and waste heat recovery. The high-quality heat from parabolic trough solar collectors is effectively converted into power via the ORC, while the rejected heat is ingeniously harnessed by absorption chillers for cooling, and further enhanced power generation can be achieved by the Kalina cycle at lower temperature levels.

Key findings underscore that the optimal design and performance of these complex systems are critically dependent on meticulous selection of working fluids, efficient solar collector technology, and optimized operational parameters. The detailed energetic and exergetic analyses confirm the thermodynamic advantages, highlighting the exergy destruction within individual components and guiding efforts for targeted improvements. Economically, while the initial capital investment remains a challenge compared to conventional fossil fuel systems, the long-term benefits of reduced operational costs, lower environmental impact, and potential policy incentives make them increasingly attractive.

To realize the full potential of these advanced trigeneration systems, continued research and development are essential. Future work should focus on enhancing component efficiencies, exploring novel system configurations, integrating advanced energy storage solutions, and conducting comprehensive techno-economic-environmental assessments under real-world operating conditions. Furthermore, supportive regulatory frameworks and financial mechanisms are crucial to accelerate their commercialization and widespread adoption. Ultimately, integrated solar trigeneration systems represent a vital stride towards a more sustainable and energy-secure future, aligning with global goals for decarbonization and cleaner energy access.

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