

Thermodynamic Performance of a Solar Tower-Based Trigeneration System Employing a Cascaded Supercritical CO₂ Cycle

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Abstract

This study presents a solar-powered trigeneration configuration capable of simultaneously generating electricity, heating, and cooling from a single renewable energy source. The proposed arrangement utilizes a solar power tower as the primary energy supplier and incorporates a cascaded supercritical carbon dioxide Brayton cycle for power generation. To maximize the utilization of available thermal energy, an Organic Rankine Cycle (ORC) and an Ejector Refrigeration System (ERS) are integrated for waste heat recovery and cooling production. Comprehensive energy and exergy analyses are conducted to evaluate the thermodynamic performance of the integrated system and to determine the locations of major irreversibilities. The simulation outcomes indicate that the system can produce a net electrical output of 12,678 kW while delivering 59.65 kW of heating and 9.99 kW of cooling. The overall energy and exergy efficiencies are found to be 24.56% and 27.76%, respectively, demonstrating effective conversion and utilization of solar energy. Exergy destruction analysis shows that the solar power tower contributes the largest share of total irreversibility, representing nearly 79.31% of the total exergy losses within the system. This finding suggests that improvements in solar energy collection and heat transfer mechanisms can further enhance overall performance. The results confirm that combining advanced power, heating, and cooling technologies within a single solar-driven framework can significantly improve energy utilization and sustainability. The outcomes of this work provide valuable guidance for the development and optimization of next-generation renewable trigeneration systems.

Keywords: Trigeneration; Exergy analysis; Energy analysis, solar power tower; cascaded sCO₂ cycle; Ejector refrigeration system

1. Introduction

The continuous growth in global energy consumption, along with increasing environmental concerns associated with greenhouse gas emissions, has intensified the search for clean and efficient energy conversion systems. In this context, trigeneration systems—commonly referred to as Combined Cooling, Heating, and Power (CCHP) systems—have emerged as a highly effective solution for meeting multiple energy demands simultaneously. These systems generate electricity while utilizing the waste heat from power production to supply heating and cooling, thereby significantly improving overall energy efficiency and reducing reliance on conventional fossil fuels. Consequently, trigeneration technologies play a vital role in advancing sustainable energy systems and achieving long-term emission reduction goals [1–5]. Among various renewable energy options, solar energy stands out due to its wide availability and environmentally benign nature. Solar-based trigeneration systems, particularly those employing Concentrated Solar Power (CSP) technologies, offer considerable potential for high-efficiency energy generation. Solar Power Tower (SPT) systems, which use a field of heliostats to concentrate solar radiation onto a central receiver, are capable of delivering high-temperature thermal energy suitable for advanced thermodynamic cycles such as the Brayton cycle [2–8]. However, despite their high-temperature capability, a substantial portion of the energy in such systems is rejected as waste heat, highlighting the need for effective recovery and utilization strategies to enhance overall system performance [9–12].

To address this challenge, Organic Rankine Cycles (ORC) are commonly integrated as bottoming cycles to recover low- and medium-grade waste heat for additional power generation. Furthermore, ejector refrigeration systems (ERS) present

a promising approach for converting thermal energy into cooling without the need for significant electrical input. Due to their simple configuration, low maintenance requirements, and ability to operate using thermal energy, ERS technologies are particularly well suited for integration with solar-based energy systems [13–18]. Although several studies have investigated solar-assisted Brayton–ORC systems, notable gaps remain in the existing literature [19–25]. Many previous works primarily focus on electricity generation or heating applications, with limited attention given to simultaneous cooling production. In addition, commonly used working fluids such as air and carbon dioxide dominate Brayton cycle applications, while helium—despite its advantageous thermophysical properties, including high thermal conductivity and specific heat capacity—has received comparatively less consideration. Moreover, studies that incorporate cooling systems often treat them as separate units or combine them with absorption-based technologies, rather than integrating them within a unified bottoming cycle framework.

To overcome these limitations, the present work proposes a novel solar-driven trigeneration system that integrates a helium-based Brayton cycle (HBC) with an Organic Rankine Cycle (ORC) and an ejector refrigeration system. In this configuration, the high-temperature helium Brayton cycle serves as the primary power generation unit, while the waste heat recovered through the ORC is utilized to drive the ejector refrigeration system. This integrated approach enables the simultaneous production of electricity, heating, and cooling, with cooling delivered at 10 °C and heating at 50 °C, making the system suitable for applications such as hospitals, residential complexes, and commercial facilities.

The main objectives of this study are: (i) to develop a comprehensive thermodynamic model of the proposed HBC–ORC–ERS trigeneration system; (ii) to conduct detailed energy, exergy, and exergo-environmental analyses under steady-state conditions; (iii) to perform parametric investigations to evaluate the influence of key operating parameters, including turbine inlet temperature, solar radiation intensity, and ejector performance characteristics; and (iv) to compare the performance of the proposed system with conventional configurations to assess improvements in efficiency and operational effectiveness.

The novelty of this study lies in the integration of an ORC-driven ejector refrigeration system with a high-temperature solar power tower-based trigeneration framework incorporating advanced cycle configurations. This unified system enhances waste heat recovery, reduces exergy losses, and enables efficient multi-output energy generation from a single renewable source. The outcomes of this work contribute to the development of next-generation solar-assisted trigeneration technologies with improved thermodynamic and environmental performance.

2. Proposed Model Description

The schematic layout of the proposed solar-assisted trigeneration system is illustrated in Figure 1. The system is driven by thermal energy supplied from a solar power tower (SPT) subsystem. Air is selected as the heat transfer fluid (HTF) due to its availability and cost-effectiveness. The thermal energy captured by the SPT is transferred through an internal heat exchanger (IHE) to a cascaded supercritical CO₂ (sCO₂) cycle, which operates as the primary power generation (topping) cycle. In this configuration, compressed sCO₂ exiting the main compressor (MC) is divided into different flow paths. A portion of the fluid passes through the low-temperature recuperator (LTR) and high-temperature recuperator (HTR) before entering the low-temperature turbine (LT). Another portion is directed to the IHE, where it absorbs high-temperature solar energy and subsequently expands in the high-temperature turbine (HT). The exhaust streams from the turbines pass through the recuperators, where residual heat is recovered to preheat the incoming compressed fluid, thereby improving the overall cycle efficiency. The remaining thermal energy is then routed to a waste heat recovery unit (WHRU), where it is utilized by the bottoming cycle. The bottoming cycle consists of an integrated Organic Rankine Cycle–Ejector Refrigeration System (ORC–ERS), with isopentane employed as the working fluid. The ORC utilizes the recovered heat from the WHRU to generate power, which in turn drives the ejector refrigeration system for cooling production. This combined arrangement enables the delivery of useful cooling at approximately 10 °C and heating at around 50 °C, making it suitable for residential, commercial, and industrial applications. Heating is obtained from the condenser of the ORC, while cooling is produced through the ejector refrigeration process. Overall, the proposed system effectively combines solar-driven power generation with advanced waste heat recovery techniques. By integrating the cascaded sCO₂ cycle with the ORC–ERS unit, the system achieves simultaneous production of electricity, heating, and cooling from a single renewable energy source, leading to improved energy utilization and system performance.

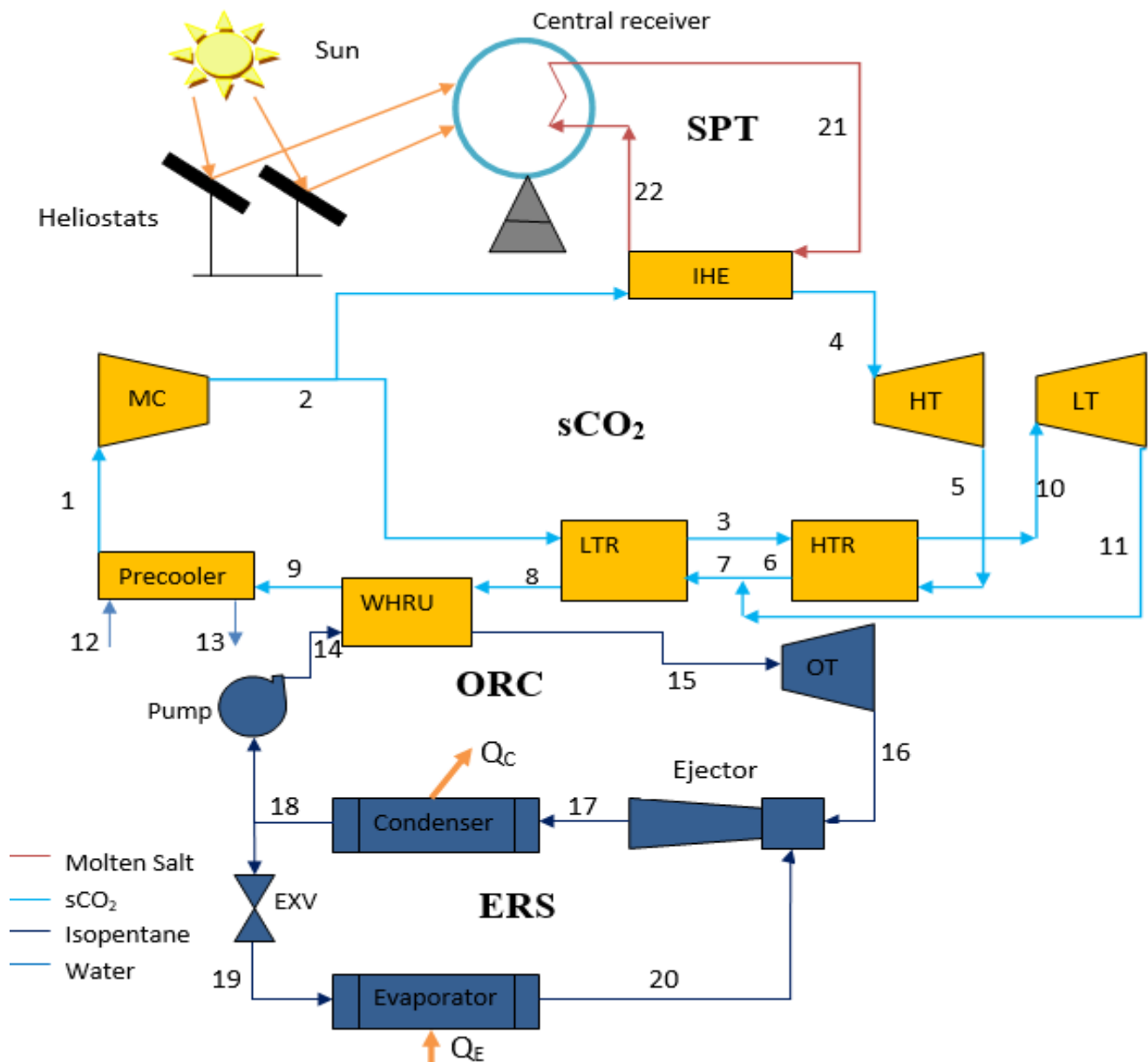


Figure 1. The diagram of proposed plant

3. Mathematical Modelling

3.1. Thermodynamic Assessment

The analysis of the proposed system is carried out based on the following assumptions:

- All components are considered to operate under steady-state conditions with one-dimensional fluid flow.
- Pressure losses within individual components are taken into account as specified in Table 1.
- Changes in kinetic and potential energy are neglected throughout the system.
- The isentropic efficiencies of turbines, pumps, and compressors are assumed and listed in Table 1.
- The working fluid at the pump inlet is assumed to be in a saturated liquid state.
- The blower or compressor associated with the solar power tower (SPT) loop is not included in the model, as its effect on the overall thermodynamic performance is considered negligible [9, 20].

Table 1 Base data for Simulation [16-20]

Parameter	Value
Ambient temperature	25 °C
Area of heliostats (A_{hel})	12.84×9.45 m ²
Atmospheric pressure	101.3 kPa

Inlet pressure of compressor	7.14 MPa
Isentropic efficiency of compressor	0.9
Condenser pinch	5 °C
Diffuser efficiency	0.95
Heat exchanger effectiveness	0.945
Efficiency of heliostat field (η_{field})	0.6428
Efficiency of mixing	0.86
Efficiency of nozzle	0.901
Heliostat number (N_{hel})	624
Area of receiver (A_{rec})	68.20 m ²
Receiver efficiency (η_{rec})	0.749
Solar irradiation in (DNI)	855 W/m ²
Sun temperature (apparent) (T_{Sun})	4500 K
Temperature at HT	650 °C
Temperature of OT inlet	197.2 °C
WHRU pinch	10 °C

For thermodynamic evaluation, the overall system is divided into three main subsystems: the cascaded supercritical CO₂ cycle, the ORC–ERS unit, and the solar subsystem. Each component is modelled as an individual control volume and simulated using the Engineering Equation Solver (EES) software. Based on steady-state operation, the governing energy and exergy balance relations for each control volume are formulated as follows:

$$\dot{Q}_{CV} - \dot{W}_{CV} + \sum(\dot{m}_i h_i) - \sum(\dot{m}_e h_e) = 0 \quad (1)$$

$$\dot{E}D = \dot{E}X_{in} - \dot{E}X_{out} \quad (2)$$

In this formulation, $\dot{E}X_{in}$ and $\dot{E}X_{out}$ represent the exergy entering and leaving the control volume, respectively. The terms $\dot{W}_{CV}$ and $\dot{Q}_{CV}$ denote the work interaction and heat transfer associated with the control volume. By neglecting chemical exergy as well as variations in kinetic and potential energies, the physical exergy of the fluid stream can be expressed as follows:

$$\dot{E}X_i = \dot{m}[(h_i - h_0) - T_0(s_i - s_0)] \quad (3)$$

A portion of the collected solar energy is lost to the surroundings due to the temperature difference between the heliostat field and the ambient environment. The remaining thermal energy is absorbed by the receiver [16, 25].

$$\dot{Q}_{rec,in} = \eta_{field} \dot{Q}_{Sun} = \eta_{field} \cdot A_{hel} \cdot N_{hel} \cdot DNI \quad (4)$$

In this context, the heliostat field efficiency (η_{field}) is adopted from reported data of an operating solar power plant [16]. Determination of this parameter is beyond the scope of the present work; therefore, established values from the literature are used. The receiver efficiency and the rate of heat absorbed by the receiver are expressed as follows [30]:

$$\eta_{rec} = \frac{\dot{Q}_{rec,net}}{\dot{Q}_{rec,in}} \quad (5)$$

$$\dot{Q}_{rec,in} = \dot{Q}_{rec,net} + \dot{Q}_{rec,loss} = \dot{m}_{air}(h_{21} - h_{22}) + \dot{Q}_{rec,loss} \quad (6)$$

Here, $\dot{Q}_{rec,loss}$ represents the thermal energy dissipated to the surroundings due to conduction, convection, and radiation losses. The proposed plant's energy and exergy efficiency can be stated as follows [30, 31]:

$$\eta_{en} = \frac{\dot{W}_{net} + \dot{Q}_E + \dot{Q}_C}{\dot{Q}_{Sun}} \quad (7)$$

$$\eta_{ex} = \frac{\dot{W}_{net} + \dot{Q}_E \left(1 - \frac{T_0}{T_E}\right) + \dot{Q}_C \left(1 - \frac{T_0}{T_C}\right)}{\dot{Q}_{Sun} \left(1 - \frac{T_0}{T_{Sun}}\right)} \quad (8)$$

Here, T_{sun} denotes the effective solar temperature considered for exergy evaluation [30]. The net power output of the system is defined as follows:

$$\dot{W}_{net} = \dot{W}_{HT} + \dot{W}_{LT} - \dot{W}_{MC} + \dot{W}_{OT} - \dot{W}_{pump} \quad (10)$$

3.3. Modelling validation

The earlier research served as validation for the suggested system. The current model's accuracy with literature is demonstrated by the results. The bottoming ORC–ERS model is validated by comparing its results with the baseline data reported by Dai et al. [35]. Key parameters, including enthalpy values as well as heat and work interactions, are evaluated against the reference results. The comparison presented in Table 2 shows a maximum deviation of 1.5%, indicating a high level of agreement and confirming the reliability of the developed model.

Table 2 Validation of ORC-ERS

Parameters	Present study	Dai et al. [35]
Q_E	60.66	60.4
$\dot{m}_c$	5.11	5.310
$\dot{m}_e$	0.398	0.389
$\dot{W}_{net}$	110.119	110.690

4. Results and Discussion

4.1. Performance Evaluation at Reference Conditions

The thermophysical properties at different state points were determined using the built-in property functions available in the EES software. The results obtained under the baseline operating conditions are summarized in Table 3. The overall system generated a power output of 15,888 kW with an energy efficiency of 24.56%. The standalone cascaded supercritical carbon dioxide cycle received thermal energy from the internal heat exchanger at a rate of approximately 31,027 kW, resulting in a net power output of about 12,675 kW and an energy efficiency of 42.56% under the specified conditions. Furthermore, the combined Organic Rankine Cycle and ejector refrigeration subsystem exhibited an energy conversion efficiency of 13.89%. The waste heat from the topping cycle, amounting to nearly 12,789 kW, is recovered through the waste heat recovery unit, where it is partially utilized to produce useful outputs such as cooling, heating, and additional power via the condenser and the organic turbine.

Table 3 Outcomes of Energy and Exergy Evaluation

Subsystem	Energy analysis				Exergy analysis			
	Energy input (kW)	Energy output (kW)	Loss (kW)	Energy efficiency	Exergy Input (kW)	Exergy Output (kW)	Destruction (kW)	Exergy efficiency
Cascaded sCO ₂ cycle	29098	12676.50	18223.98	42.34%	22514.99	13364.78	9149.98	60.89%
Heliostat field	59456	41368.78	22988.45	59.87%	60093.8	38627.45	21464.9	64.25%
Solar receiver	41368.7	31026.8	10340	74.9%	38627.6	22514.8	16112.7	58.30%
Overall plant	59456	15888	45678	24.56%	59897	17888	43896	27.76%

The energy assessment indicates that the solar power tower (SPT) subsystem is the primary contributor to system irreversibility. This is primarily due to the significant temperature mismatch between the high-temperature solar radiation source (approximately 4500 K) and the receiver's operating temperature of around 1000 °C. Among all components, the heliostat field accounts for the highest exergy destruction [16, 20], with an energy efficiency of 59.89%.

In contrast to conventional thermal power systems, the absence of combustion significantly reduces irreversibility within the cycle. Consequently, the temperature difference between helium and the heat transfer fluid (HTF) in the internal heat exchanger (IHE) remains minimal, enhancing system performance. This leads to a relatively high energy efficiency of 56.40% for the sCO₂–ORC–ERS combined cycle.

Despite these advantages, substantial energy losses in the heliostat field and receiver lower the overall plant efficiency. Component-wise analysis reveals that the heliostat field incurs the largest energy loss (22,654 kW), whereas the expansion valve incurs the least (99.98 kW). The helium turbine demonstrates the highest energy efficiency among all components. Individually, the standalone sCO₂ cycle achieves an efficiency of approximately 59.36%, while the ORC–ERS cogeneration subsystem operates at about 47.22%. The comparatively lower efficiency of the ORC–ERS is attributed to additional system components that introduce further losses [32]. Overall, the trigeneration SPT system records a total energy destruction of 47,888 kW, resulting in a net plant efficiency of around 27.66%.

4.2. Parametric Analysis

By changing the compressor pressure ratio (CPR), the performance of the trigeneration facility was assessed. As seen in Figure 2, energy and exergy efficiency first increased as CPR increased, peaking at 2.4 CPR before gradually decreasing. Once a CPR of 2.4 is reached, this drop starts.

The observed trend is primarily associated with the increasing expansion and compression work as the cycle pressure ratio (CPR) rises up to 2.4. In this range, the gain in expansion work outpaces the corresponding increase in compression work, leading to improved overall performance. As a result, the integrated ORC–ERS subsystem reaches maximum energy and exergy efficiencies of 50.22% and 63.56%, respectively. Meanwhile, the overall plant operates at energy and exergy efficiencies of approximately 24.43% and 26.21%. "The cycle may have lost a significant amount of energy, but this loss was negligible because the energy was of poor quality, which explains why the cycle's energy and energy efficiency differed.

Heliostats and receivers were responsible for 79.31% of the total energy loss in the solar field alone, meaning that only 40485 kW of solar field energy was lost out of 46642 kW of plant energy. The peak net power outputs of the overall plant and the HBC subsystem were determined to be 12,254 kW and 15,005 kW, respectively, at an optimal cycle pressure ratio (CPR) of 2.4. The integration of the ORC–ERS contributed an additional 1,700 kW to the net power generation. Under the same operating condition, the maximum cooling and heating capacities were recorded as 9.99 kW and 59.65 kW, respectively. It is also observed that energy efficiency, power output, and overall energy performance exhibit similar trends with varying CPR [33].

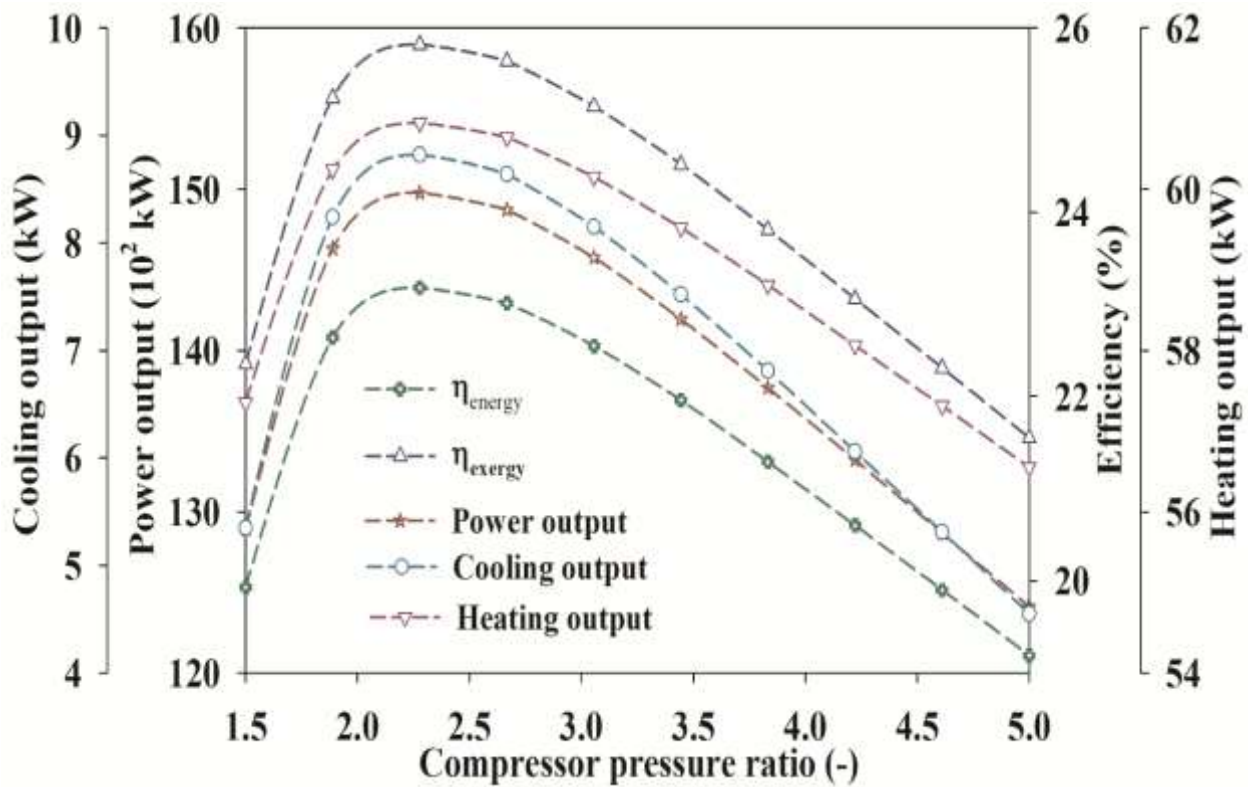


Figure 2. Effect of CPR on performance

The inlet temperature of the high-temperature (HT) stream plays a crucial role in determining overall system performance. As shown in Fig. 3, increasing the HT inlet temperature leads to noticeable improvements in power output, energy efficiency, and exergy efficiency, which rise from 14,009 kW to 16,012 kW, 22.76% to 25.56%, and 22.99% to 26.87%, respectively. This trend can be attributed to the higher turbine inlet temperature, which increases the enthalpy drop during expansion and consequently enhances the turbine work output. As a result, the overall thermodynamic efficiency and net power generation of the system improve. These results were obtained under operating conditions of a compressor pressure ratio of 2.4, an organic turbine inlet temperature of 197.5°C, and a direct normal irradiance of 850 W/m². Furthermore, an increase in HT inlet temperature also positively influences the thermal outputs, with the cooling capacity rising from 7.99 kW to 9.89 kW and the heating capacity increasing from 60.01 kW to 61.39 kW as the temperature varies from 700°C to 900°C [12].

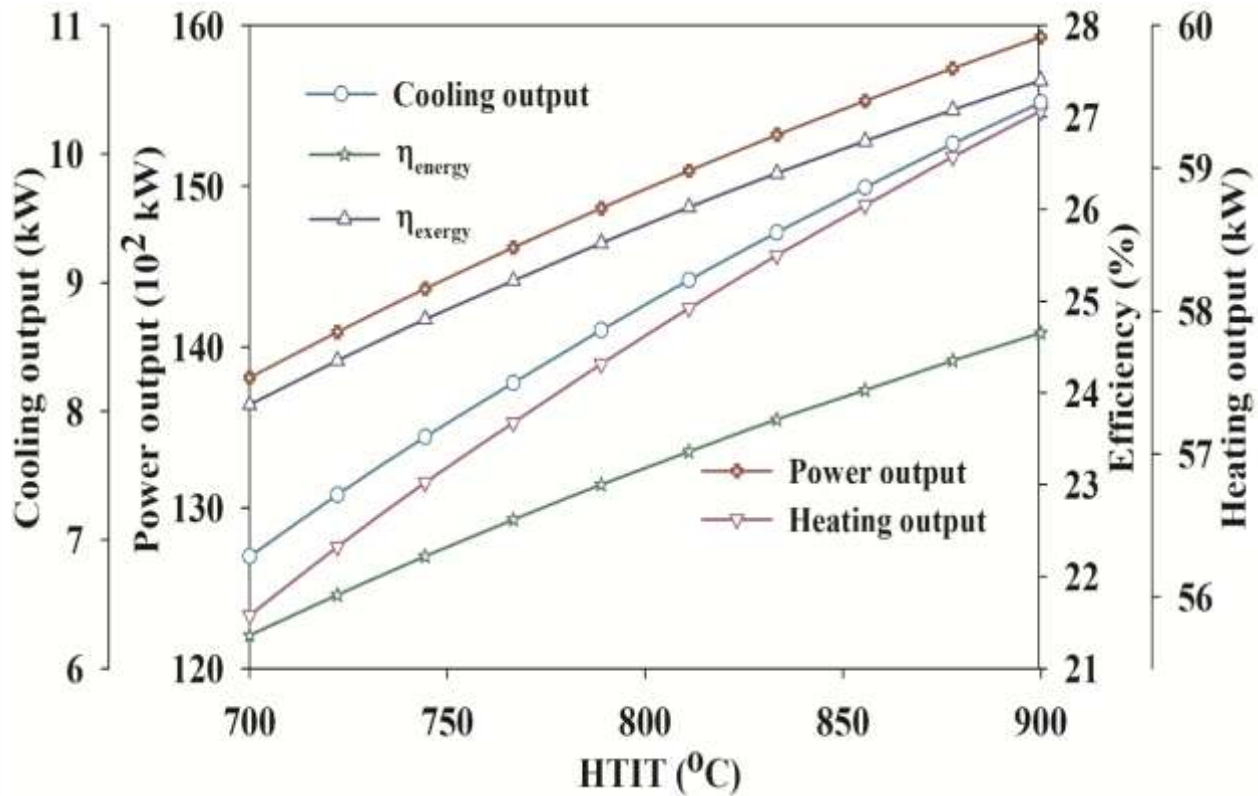


Figure 3. Performance variation with the HTIT

The Figure 4 illustrates the influence of inlet temperature (T_1) on system performance parameters, including power output, cooling capacity, heating output, and energy and exergy efficiencies. As (T_1) increases from approximately 25 °C to 35 °C, a gradual decline is observed in most performance indicators.

The net power output shows a slight but consistent decrease with increasing inlet temperature. This behavior can be attributed to the reduction in the thermodynamic driving force, which limits the effectiveness of expansion processes within the cycle. Similarly, both energy and exergy efficiencies exhibit a marginal downward trend, indicating that higher inlet temperatures adversely affect the overall system performance.

The cooling output remains relatively stable across the temperature range, with only a minor reduction at higher temperatures. This suggests that the cooling subsystem is less sensitive to variations in inlet temperature compared to power generation. In contrast, the heating output maintains an almost constant value, indicating strong thermal stability of the heating subsystem despite changes in operating conditions.

Overall, the results suggest that lower inlet temperatures are more favorable for achieving enhanced power generation and higher system efficiencies, while the heating and cooling outputs remain largely unaffected. This highlights the robustness of the trigeneration system, particularly in maintaining thermal outputs under varying ambient conditions.

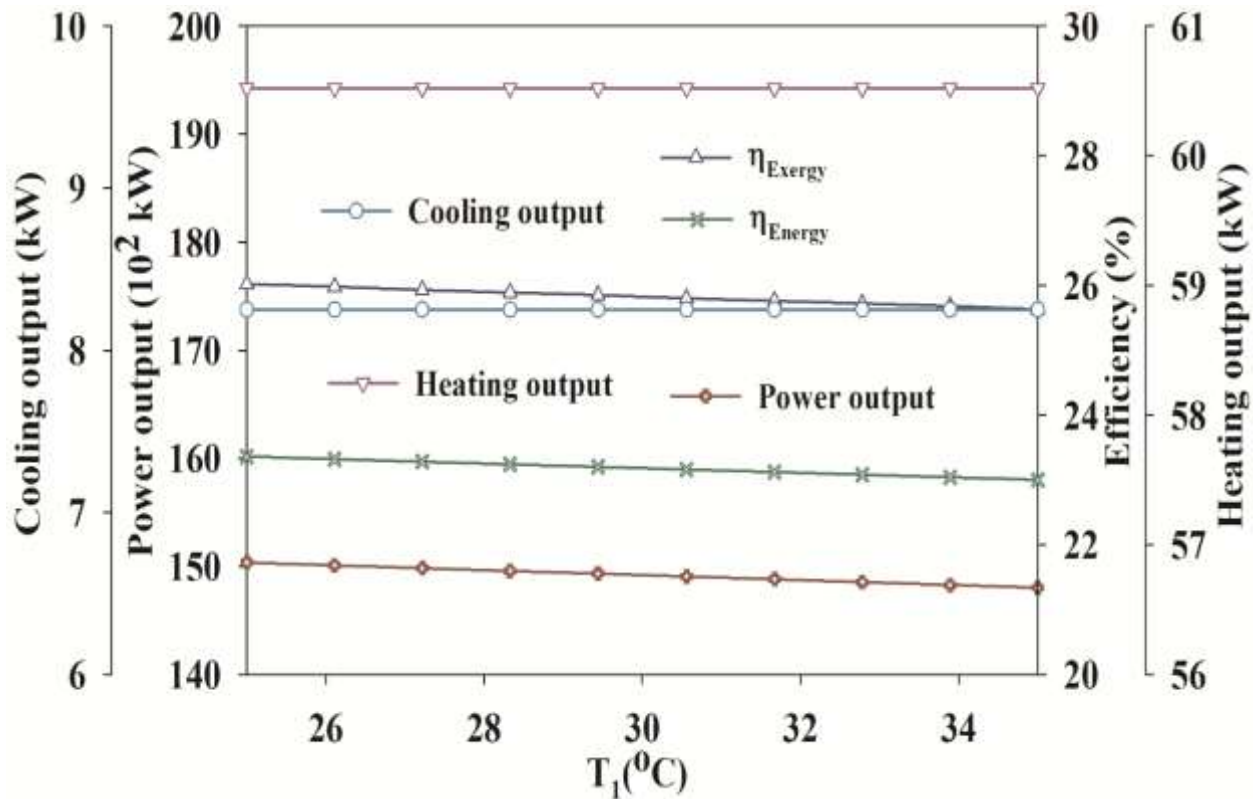


Figure 4. Performance variation with the CIT

The pump pressure ratio (PPR) has a pronounced impact on system behavior. Keeping the cycle pressure ratio (CPR) fixed at 2.4, the system's thermal response was evaluated over a range of PPR values. The overall plant performance shows a rise in efficiency at lower PPR, followed by a gradual decline after reaching an optimum point, indicating the presence of a peak operating condition.

As illustrated in Figure 5, the maximum plant energy and exergy efficiencies occur at a PPR of 2.89, with corresponding values of 24.76% and 22.54%. The cooling performance remains nearly unchanged across the examined range, suggesting minimal sensitivity to PPR variations. In contrast, the heating output increases steadily as PPR rises. This trend can be explained by the higher pumping work required at elevated PPR, which does not contribute to improved refrigeration performance. Instead, it leads to increased heat rejection in the condenser to satisfy the system's energy balance, thereby enhancing the heating output. Quantitatively, a 3.01% rise in PPR results in an approximate 5.29% increase in heating capacity.

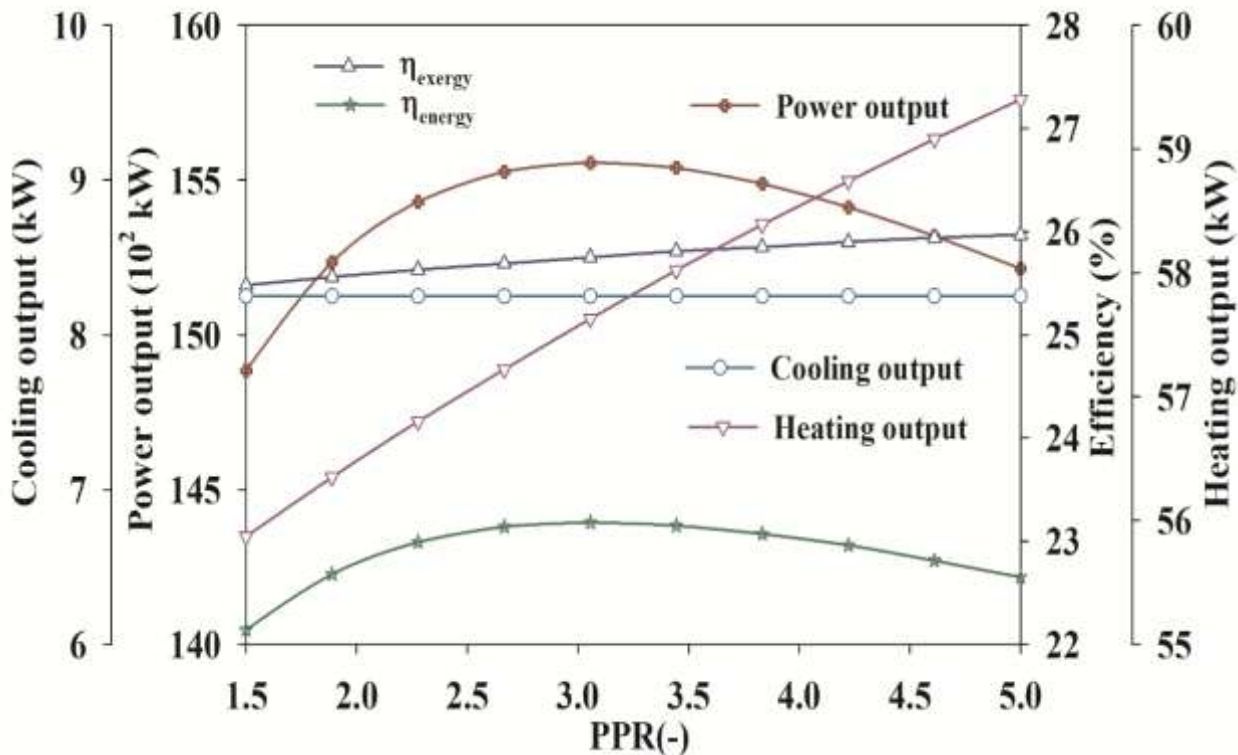


Figure 5. PPR effect on performance

Figure 6 presents the response of the trigeneration system to changes in evaporator temperature, highlighting its importance in governing system performance. As the evaporator temperature rises, the system exhibits improved thermodynamic behavior, reflected in higher efficiencies and increased power generation.

The net power output shows a noticeable rise from 16,001 kW to 17,123 kW over the examined range. Similarly, both energy and exergy efficiencies improve, increasing from 23.21% to 24.54% and from 25.75% to 25.89%, respectively. In contrast, the heating demand remains largely unaffected by these variations, indicating that the heating subsystem is insensitive to evaporator temperature changes. However, the cooling capacity is significantly influenced and improves with increasing evaporator temperature. This trend occurs because the evaporator operates independently of the condenser's thermodynamic conditions. Raising the evaporator temperature increases the corresponding pressure, which enhances the refrigeration effect without altering the condenser performance [6, 20].

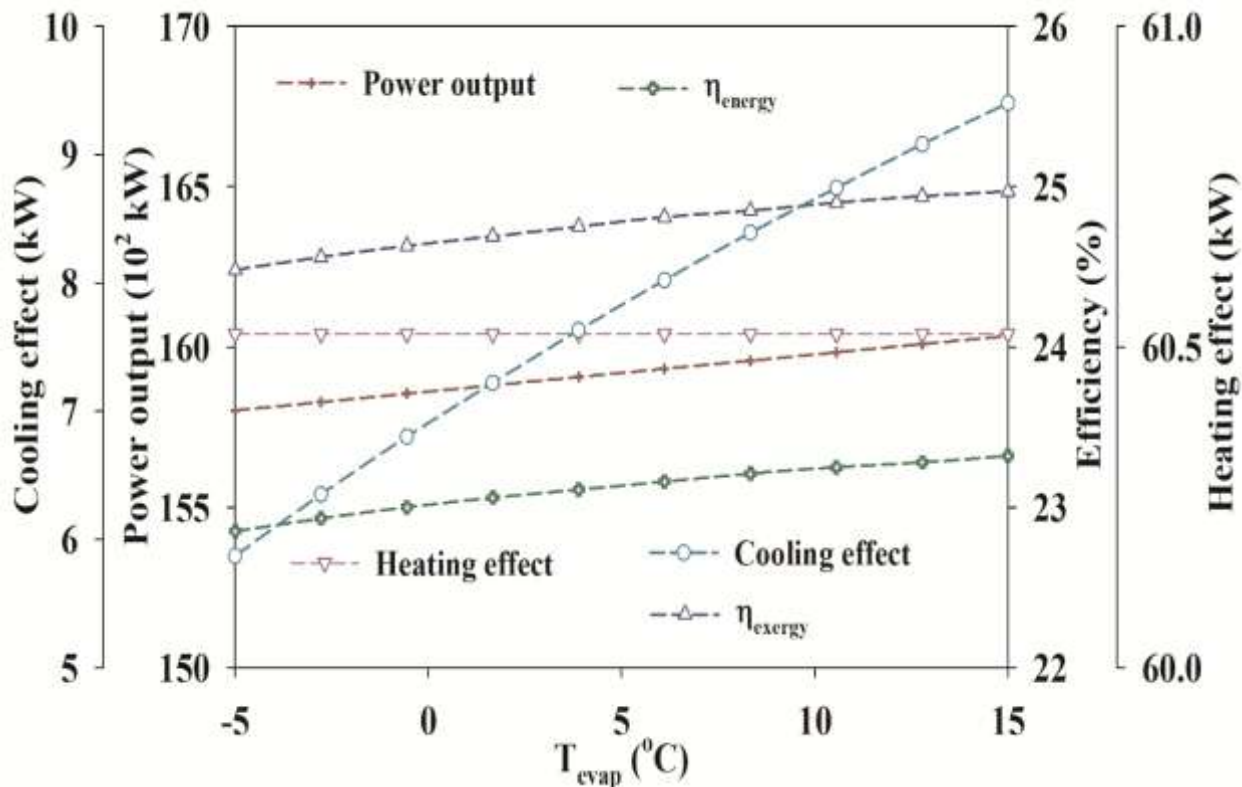


Figure 6. Performance variation with evaporator temperature

Additionally, Figure 7 shows how DNI increases power production. The average DNI in Indian climate conditions was found to be 850 W/m². Higher DNI values are anticipated to increase receiver efficiency, which will improve the plant's energy performance. Figure 7 shows the changes in energy efficiency, power output, and energy efficiency as DNI levels increased from 600 to 1000 W/m². These changes range from 23.01% to 25.56%, 20.78% to 23.56%, and 14001 kW to 16023 kW, respectively. Additionally, when DNI increases, so do the cooling and heating demands. The rise in DNI gives the cycle more energy, which increases the amount of energy that is transformed into useful output and raises the loads associated with heating and cooling [35]. For example, Figure 9 shows that the heating and cooling loads dropped from 56.01 kW to 60.59 kW and 7.05 kW to 10.12 kW, respectively, while the DNI increased from 600 to 1000 W/m².

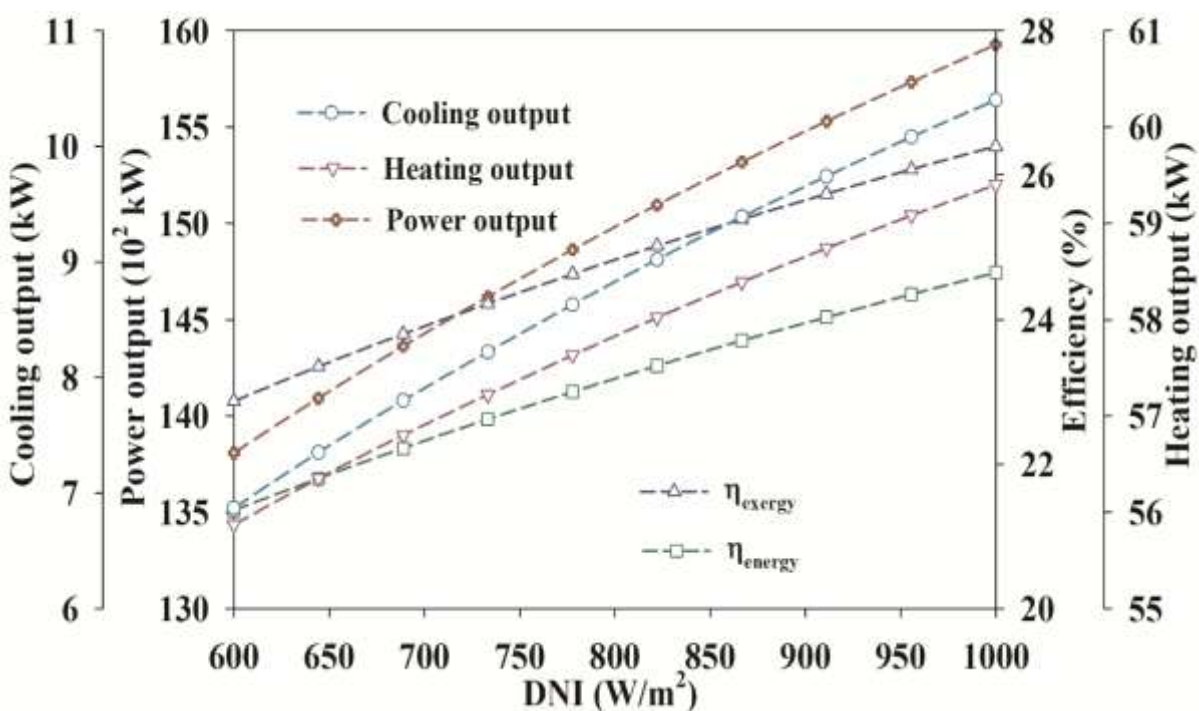


Figure 7. Performance variation with the DNI

4.3. Comparative Study

Based on available literature, various components of solar power tower (SPT) systems inherently experience irreversibility, which cannot be entirely eliminated. To enhance overall system performance, it is therefore essential to develop more efficient and optimized power generation configurations. In this context, the performance of the proposed integrated SPT-based system is compared with previously reported systems from the literature. For consistency, all systems are evaluated under identical solar irradiation conditions, and the comparative results are presented in Table 4. The findings indicate that the proposed configuration outperforms conventional systems reported by earlier studies. This improvement is primarily attributed to the advanced configuration of the topping cycle and the more effective utilization of waste heat, in contrast to standalone Rankine and supercritical carbon dioxide cycles [3]. Furthermore, as shown in Table 4, the proposed SPT-based cascaded supercritical carbon dioxide cycle integrated with Organic Rankine Cycle and ejector refrigeration system demonstrates higher efficiency than both the basic supercritical carbon dioxide cycle and the conventional SPT-driven Rankine cycle.

Table 4 Comparison with others studies

Systems	η_{rec}	$\eta_{field} \times \eta_{rec}$	DNI (kW/m ²)	η_{field}	$\eta_{en,comb}$ (%)	$\eta_{en,Plant}$ (%)	$\eta_{ex,Plant}$ (%)
Regenerated [36]	0.9	-	0.8	0.75	37.9	22.9	24.5
Present system	0.9	-	0.8	0.75	55.65	39.11	42.32
CO ₂ cycle [37]	-	0.62	1	-	42.48	26.23	28.14
Present system	-	0.62	1	-	58.87	40.65	42.73

5. Conclusions

The following conclusion have been made:

- A solar-driven trigeneration system integrating a Solar Power Tower, supercritical carbon dioxide Brayton cycle, Organic Rankine Cycle, and Ejector Refrigeration System was successfully developed and evaluated for simultaneous power, heating, and cooling generation.
- The proposed configuration effectively utilized high-temperature solar energy in the sCO₂ Brayton cycle, while recovering waste heat through the ORC and ERS, thereby enhancing overall energy utilization.
- The integrated sCO₂–ORC–ERS subsystem achieved a maximum energy efficiency of 47.88% and exergy efficiency of 62.78% at a direct normal irradiance of 850 W/m² and a compression ratio of 2.4, indicating efficient heat recovery and low thermodynamic losses.
- The overall plant attained energy and exergy efficiencies of 24.56% and 27.76%, respectively, with performance limitations mainly arising from optical and thermal losses within the solar power tower subsystem.
- The system generated a net power output of 12.678 MW, together with 59.65 kW of heating and 9.99 kW of cooling, demonstrating its capability for multipurpose energy production.
- Exergy analysis revealed that the Solar Power Tower was the primary source of irreversibility, contributing approximately 79.31% of the total exergy destruction within the plant.
- Performance enhancement can be achieved through improvements in receiver design, heliostat-field optical efficiency, and heat exchanger effectiveness, which would reduce exergy losses and increase overall system efficiency.
- The integration of advanced thermodynamic cycles with concentrated solar power technology offers a sustainable and efficient pathway for combined power, heating, and cooling generation.
- The results confirm the technical viability of the proposed trigeneration system and highlight its potential to support renewable energy deployment, reduce fossil-fuel consumption, and mitigate environmental impacts.

Statements & Declarations

Funding The research work has not been funded from anywhere.

Competing Interests: - The authors have no relevant financial or non-financial interests to disclose.

Ethics Approval: - This research work is original and has not been submitted elsewhere in any journal for publication.

Consent to Participate: - Not Applicable.

Consent for Publication: All authors agree to publish this article.

Availability of data and materials: All data are available in the manuscript.

Authors' Contributions **Pragya Mishra:** Investigation, Writing – original draft, Writing – review & editing.

Pushpraj Singh: Writing–review, conceptualisation, & editing, Supervision.

Abhay Agrawal: Writing–original draft, Review & editing, Supervision.

Prashant Singh Chauhan: Writing–original draft, Review & editing, Supervision.

References

- [1] Khan Y, Tevatia A, Apparao D, et al. experimental investigation to evaluate thermal performance of a solar cooker with evacuated tube solar collector using different heat transfer fluids. *Journal of Thermal Engineering* 2024; 10(5):1346–1357.
- [2] Khan Y, Raman R, Rashidi MM, et al. Thermodynamic analysis and experimental investigation of the water spray cooling of photovoltaic solar panels. *Journal of Thermal Analysis and Calorimetry* 2023. doi:10.1007/s10973-023-12119-y
- [3] Khan Y and Mishra RS. Thermo-economic analysis of the combined solar-based pre-compression supercritical CO₂ cycle and organic Rankine cycle using ultra-low GWP fluids. *Thermal Science and Engineering Progress* 2021; 23:100925. doi: 10.1016/j.tsep.2021.100925
- [4] Chauhan MK, Chauhan AK, Khan Y, et al. Experimental and theoretical investigation of thermal efficiency and productivity of single slope basin type solar distillation system using honey-comb. *Journal of Thermal Engineering* 2023; 9 (6): 1559–1571.
- [5] Khan Y, Mishra RS, and Singh AP. Performance comparison of organic Rankine cycles integrated with solar based combined cycle: A thermodynamic and exergoenvironmental analysis. *Proc IMechE Part C: J Mechanical Engineering Science* 2024; 238(1):233–248.
- [6] Pal JS, Sapali SN, Deshmukh PW. Estimation and analysis of exergy loss and performance evaluation of marine freshwater generating system. *Journal of Thermal Engineering* 2024; 10(5): 1266–1274.
- [7] Bader NM and Mushatet KS. An experimental study for a single-pass solar air heater integrated with artificial roughness. *Journal of Thermal Engineering* 2024; 10(5): 1292–1305.
- [8] Kushwah A, Kumar A, Gaur MK. Techno-economic analysis of solar still with nano-phase change material and heating coil: A novel approach for sustainable development. *J Ther Eng* 2025;11(2):476–492.
- [9] Khan Y and Mishra R.S. Performance analysis of a solar based novel trigeneration system using cascaded vapor absorption-compression refrigeration system, *International Journal of Refrigeration* 2023; 155: 207–218.
- [10] Guo J, Li M, He Y, et. al. A systematic review of supercritical carbon dioxide (S-CO₂) power cycle for energy industries: Technologies, key issues, and potential prospects. *Energy Conversion and Management* 2022; 258:115437.
- [11] Gkountas AA, Benos LT, Nikas KS, et al. Heat transfer improvement by an Al₂O₃-water nanofluid coolant in printed-circuit heat exchangers of supercritical CO₂ Brayton cycle, *Thermal Sci. Eng. Progr.* 2020; 20:100694.

- [12] Chai L and Tassou SA. A review of printed circuit heat exchangers for helium and supercritical CO₂ Brayton cycles. *Therm. Sci. Eng. Prog.* 2020; 18: 100543.
- [13] Qin L, Xie G, Ma Y. et al. Thermodynamic analysis and multi-objective optimization of a waste heat recovery system with a combined supercritical/transcritical CO₂ cycle. *Energy*, 2023; 265:126332.
- [14] Khatoon S and Kim M. Preliminary design and assessment of concentrated solar power plant using supercritical carbon dioxide Brayton cycles. *Energy Conversion and Management* 2022; 252: 115066.
- [15] Khan Y and Mishra RS. Performance analysis of solar driven combined recompression main compressor intercooling supercritical CO₂ cycle and organic Rankine cycle using low GWP fluids. *Energy and Built Environment* 2022; 3(4): 496-507
- [16] Zare V and Hasanzadeh M. Energy and exergy analysis of a closed Brayton cycle-based combined cycle for solar power tower plants. *Energy Conversion and Management* 2016; 128:227–237.
- [17] Khan Y, Singh D, Caliskan H, et.al. Exergoeconomic and Thermodynamic Analyses of Solar Power Tower Based Novel Combined Helium Brayton Cycle-Transcritical CO₂ Cycle for Carbon Free Power Generation. *Global Challenges* 2023: 2300191.
- [18] Bi Y and Ju Y. Design and analysis of an efficient hydrogen liquefaction process based on helium reverse Brayton cycle integrating with steam methane reforming and liquefied natural gas cold energy utilization. *Energy* 252; 2022:124047.
- [19] Li Q, Erqi E, Qiu Y. Triple-objective optimization of He Brayton cycles for ultra-high-temperature solar power tower. *Energy Conversion and Management* 2022; 270: 116210.
- [20] Zhou J, Ali MA, Zeki FM, et al. Thermoeconomic investigation and multi-objective optimization of a novel efficient solar tower power plant based on supercritical Brayton cycle with inlet cooling. *Thermal Science and Engineering Progress* 2023; 39:101679.
- [21] Wang M, Wang J, Zhao P, Dai Y. Multi-objective optimization of a combined cooling, heating and power system driven by solar energy. *Energy Conversion and Management* 2015; 89:289-297.
- [22] Mishra SK, Rehalia AS, Verma AK, Yadav L. Thermo-Economic Analysis of Solar-Powered Trigenation System with Integrated Ejector-Absorption Recompression and Modified Organic Rankine Cycle. *J. Eng. Gas Turbines Power* 2024, 146(5): 051024.
- [23] Ogaili HH, Khalilarya S, Chitsaz A, Mojaver P. Energy, exergy, and economic performance analysis of integrated parabolic trough collector with organic Rankine cycle and ejector refrigeration cycle. *Energy Conversion and Management: X* 2025, 25: 100843.
- [24] Saladi JK, Suresh R, Datta SP. Diurnal performance investigation of solar integrated ejector-based Combined Cooling, Heating, and Power (CCHP) system for Indian climate. *Applied Thermal Engineering* 2025: 263: 125250.
- [25] Khan Y and Mishra RS. Performance evaluation of solar based combined pre-compression supercritical CO₂ cycle and organic Rankine cycle. *International Journal of Green Energy* 2021; 18 (2):172–186.
- [26] Khan Y and Mishra RS. Parametric (exergy-energy) analysis of parabolic trough solar collector-driven combined partial heating supercritical CO₂ cycle and organic Rankine cycle. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 2020. doi:10.1080/15567036.2020.1788676
- [27] Li M, Wang J, He W, Gao L, Wang B, Ma S, et al. Construction and preliminary test of a low-temperature regenerative Organic Rankine Cycle (ORC) using R123. *Renew Energy* 2013; 57:216–22.

- [28] Olumayegun O, Wang M and Kelsall G. Closed-cycle gas turbine for power generation: a state-of-the-art review. *Fuel* 2016; 180:694–717.
- [29] Dunham MT and Iverson BD. High-efficiency thermodynamic power cycles for concentrated solar power systems. *Renew Sustain Energy Rev* 2014; 30:758–770.
- [30] Xu C, Wang Z, Li X, Sun F. Energy and exergy analysis of solar power tower plants. *Appl Therm Eng* 2011; 31:3904–3913.
- [31] Bellos E, and Tzivanidis C. Multi-objective optimization of a solar driven trigeneration system. *Energy* 2018; 149:47-62.
- [32] Li H, Cao F, Bu X, Wang L, Wang X. Performance characteristics of R1234yf ejector-expansion refrigeration cycle. *Applied Energy* 2014; 121:96-103
- [33] Wang J, Dai Y, Sun Z. A theoretical study on a novel combined power and ejector refrigeration cycle, *International Journal of Refrigeration* 2009; 32(6):1186-1194
- [34] Zare V, Mahmoudi SMS and Yari M. On the exergoeconomic assessment of employing Kalina cycle for GT-MHR waste heat utilization. *Energy Convers. Manag.* 2015; 90: 364–374. doi: 10.1016/j.enconman.2014.11.039.
- [35] Dai Y, Wang J, Gao L. Exergy analysis, parametric analysis and optimization for a novel combined power and ejector refrigeration cycle. *Applied Thermal Engineering* 2009; 29(10):1983-1990
- [36] Xu C, Wang Z, Li X, et al. Energy and exergy analysis of solar power tower plants. *Applied Thermal Engineering* 2011; 31:3904–3913.
- [37] Chacartegui R, Muñoz de Escalona JM, and Sánchez D. Alternative cycles based on carbon dioxide for central receiver solar power plants. *Applied Thermal Engineering* 2011; 31:872–879.