The Iraqi Journal for Mechanical and Material Engineering, Vol. 25, No. 2, June 2026.
ISSN: 1819-2076; eISSN: 2313-3783

EXPERIMENTAL INVESTIGATION AND PERFORMANCE OPTIMIZATION OF AN INTEGRATED SOLAR COGENERATION SYSTEM FOR COMBINED COOLING AND POWER (CCP)

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ABSTRACT

The growing energy demand in the world over requires the establishment of effective and viable energy systems. Solar powered combined cooling and power (CCP) cogeneration holds a potential solution. Nonetheless, drastic discrepancies are found between theory and experiments particularly when actual weather is considered. In the current analysis, the experimental study of a multifunctional solar CCP system with parabolic trough collectors, an Organic Rankine Cycle (ORC), and a LiBr-H_2O absorption chiller is conducted. Parametric analysis is done, and the empirical models are formulated using Response Surface Methodology (RSM) to obtain the correlation between important operational parameters and the performance of the system. Optimized conditions are determined and the overall system efficiency is maximized at 59.0% and a 23.0% improvement over the operation of the system in the baseline. The paper offers empirical models and the best working guidelines, which can be introduced in the practical implementation of solar CCP systems.

Keywords: Absorption Chiller, Exergy Efficiency, Organic Rankine Cycle (ORC), Parabolic Trough Collector (PTC), Response Surface Methodology (RSM).

NOMENCLATURE

Ac	Collector aperture area (m^2)	*chiller*	Related to absorption chiller
COP	Coefficient of Performance	*htf*	Heat transfer fluid
G	Solar irradiance (W/m^2)	*net*	Net output
$\dot{m}$	Mass flow rate (kg/s)	*ORC*	Organic Rankine Cycle
$\dot{Q}$	Thermal power (kW)	*solar*	Solar input

Received: December 12, 2025. **Publisher: University of Babylon / Faculty of Engineering**
Accepted: April 5, 2026. **Journal homepage: https://www.iqjfmme.com**

1. INTRODUCTION

Industrialization, population growth, and technological advancement are some of the forces that are continuously increasing the energy demand of the world. At the same time, the issues of the environment, mostly climate change as a result of greenhouse gas (GHG) emissions due to the burning of fossil fuels, pose a very serious threat to ecological and economic stability. This twin crisis requires a quick shift to clean and renewable energy sources. In this regard, it is well known that renewable sources of energy form the backbone towards international sustainable development objectives [1]. Among these, solar energy exclusively has incredible potential as it is an abundant, ubiquitous, and zero-emission energy. It is thus deemed that the efficient exploitation of solar energy is a key measure in curbing energy security challenges and environmental degradation [3].

Combined Heat and Power (CHP) or Cogeneration is an established concept that can maximize the use of energy by producing several energy products at the same time using one fuel source. Incorporating solar thermal uses and extended to cover cooling, it is then a Combined Cooling and Power (CCP) system [3]. The basic benefit of cogeneration compared to other forms of separate generation is that it has a high total efficiency since it uses the waste heat of the power generation in other applications, such as cooling, which in turn will minimize the primary energy use [4].

The analysis of recent literature is carried out to position the current work in the context of the changing sphere of solar CCP systems. Focus is paid to papers that were published in the high-impact journals, including Applied Energy, Energy Conversion and Management, and Renewable and Sustainable Energy Reviews. The latest developments in the realm of component integration, specifically, the schemes linking parabolic trough collectors (PTCs) with Organic Rankine Cycles (ORCs) with such fluids as R245fa and Butane are considered [5]. Moreover, limitations of literature, particularly, the lack of the development of theoretical modeling and experimental verification in the conditions of transient weather, are emphasized [6]. The need for such holistic experimental approach, and formal multi-variable optimization, which can be regarded as the main contribution of the given research, is confirmed by this review.

There is synergy between solar thermal energy and CCP systems [7]. Grade solar heat is harnessed by collecting it with parabolic trough collectors or other solar collection technologies to produce mechanical or electrical power by using a heat engine cycle (e.g., Organic Rankine Cycle - ORC). The half-grade waste heat of the exhaust of the power cycle is then utilized to propel a thermal cooling system which is normally an absorption chiller [8]. This cascading energy means a great deal of energetics efficiency of the solar input. The advantages of such integrated solar CCP systems are manifold: they convert a large total energy rate using a single renewable energy, it does not need the electrical grid, particularly at the peak of cooling demand hours, and it is a sustainable way to the air-conditioning and refrigeration requirements in commercial and industrial environments [9]. Figure 1 shows a schematic diagram of the integrated Solar Combined Cooling and Power (CCP) system.

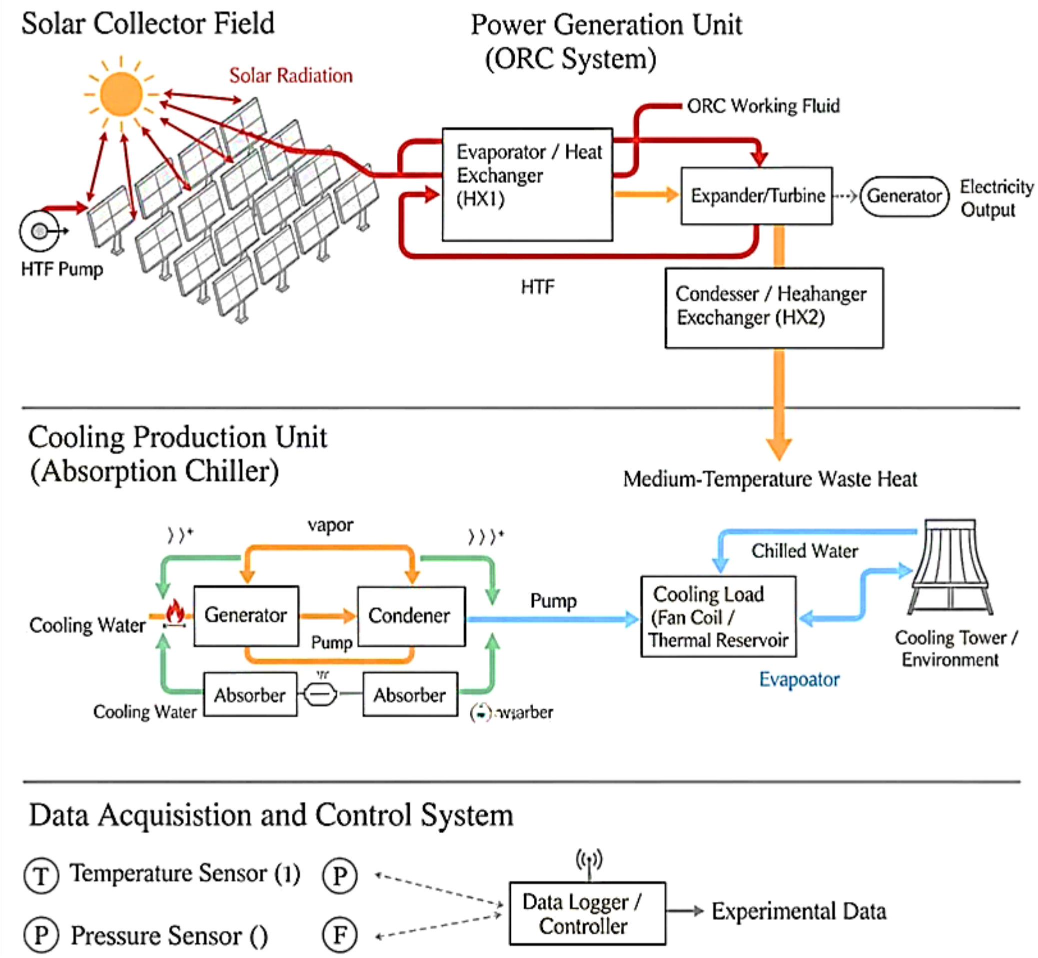

Fig. 1. Schematic diagram of the proposed integrated solar CCP system.

Combined cooling and power (CCP) are a concept that has been widely discussed in literature in terms of numerical simulations as well as experimental studies and analysis [10]. One of the most common and widely studied designs is the combination of solar thermal collector and Organic Rankine Cycle (ORC) to generate power and absorption chiller to produce cooling [11]. The solar thermal energy is applied in this system as the central heat supply to the ORC and the waste heat of the ORC condenser or special bleed line drives the generator of the absorption chiller to form a cascading thermal system which makes optimum use of the assembled solar energy [12].

Thermodynamic modeling and simulation software is frequently used in numerical studies to forecast the performance of a system in different design and operating conditions [13]. They are employed in order to perform parametric analysis and exergy analysis to find the theoretical boundaries of efficiency and potential areas of improvement [14]. To test the theoretical models experimentally, a number of small-scale and pilot-scale prototypes are constructed and tested to prove technical feasibility. The efficiency of the collection of the parabolic trough, the efficiency of the ORC with various working fluids, and the coefficient of performance (COP) of the absorption chillers are the most common ones [15]

Nonetheless, a close examination of the previous art shows that there are a number of common limitations. The efficiency of the entire system of converting solar energy to the end useful products (electricity and cooling) is generally stated to be poor, usually limited by the efficiency of power cycle and the chiller in off-design conditions [16]- [19]. There are major issues with the successful integration of components, during which thermal differences and dynamic response delays between the solar field, the ORC unit and the chiller result in non-optimal performance and instability in operation [20]. In addition, many experimental studies are over short durations or in quasi-steady-state conditions thus not being able to adequately address and analyze the transient performance of the system due to the changing solar irradiance. One of the most common areas of gap is the absence of an overall optimization of the experiment; parameters are commonly manipulated singly to see their effect; however, a multi-variable optimization procedure is rarely implemented on a complete experimental system [21]-[24]. Table 1 presents the list of identified challenges and constraints of the existing approaches and applications.

Table 1. Limitations in current solar CCP research.

Category	Problem / Limitation	Impact on System Development
System Performance	Low overall conversion efficiency from solar to final energy products.	Hinders economic viability and competitiveness with conventional systems.
Component Integration	Thermal and dynamic mismatches between subsystems (solar, ORC, chiller).	Leads to operational instability, energy losses, and reduced reliability.
Experimental Focus	Lack of long-term, real-weather transient performance data.	Provides an incomplete picture of system behavior, limiting practical deployment guidance.
Optimization Approach	Reliance on theoretical models or single-variable experimental analysis.	Fails to identify true global optimum operating conditions for the complex, integrated system.
Data Utilization	Scarcity of empirical data used for formal, multi-parameter optimization.	Results in a gap between laboratory findings and actionable operational strategies.

A comparison of the chosen past studies on integrated solar Combined Cooling and Power systems in a summary form is provided in Table 2, which has the configuration, key performance metrics, and limitations as identified.

Table 2. Comparative summary of previous solar CCP studies.

Ref.	**System Configuration & Scale**	**Key Performance Metrics**	**Reported Limitations / Focus**
[11]	Flat Plate Collectors + ORC + Ejector Chiller (Numerical)	Overall System Efficiency: ~20% Exergy Efficiency: ~16%	Focus on low-temperature heat; performance highly sensitive to ambient temperature.
[11]	PTC + Supercritical CO_2 Cycle + Absorption Chiller (Theoretical)	Overall Efficiency: ~85% Electrical Efficiency: ~35%	Conceptual design with very high temperatures/pressures; no experimental data available.
[14])	PTC + ORC (R245fa) + Absorption Chiller (Experimental)	Max. Electrical Efficiency: 8.1% Max. Cooling COP: 0.75	Low overall power generation efficiency: system optimization was not performed.
[19]	PTC + ORC (Butane) + Absorption Chiller (Experimental)	Net Electrical Power: 2.1 kW Cooling Capacity: 17.5 kW	Significant off-design performance degradation; operational instability noted.
[23]	Solar Dish + Stirling Engine + Absorption Chiller (Theoretical)	Overall Electrical Efficiency: 18.2% Overall Efficiency (CHP): 79%	High cost and complexity; analysis based on ideal, steady-state assumptions.

This comparison provides a clear demonstration of the trade-offs commonly found in the literature, including the gap between high theoretical efficiencies and lower experimentally attained values and the lack of literature that goes beyond performance reporting to formal optimization. This is the gap that is the main subject of the current work. Although theoretical frameworks and individual experimental research are available, a lack of detailed experimental evidence is present that would be the systematic exploration of the interdependencies of operating parameter within a fully integrated solar CCP system in the actual weather environment. Therefore, there is no formal performance optimization of such a system, performed on the basis of a detailed empirical base and multi-variable optimization strategy. This research paper is meant to fill this particular gap. Figure 2 shows a conceptual diagram illustrating the transition from the current state of solar CCP research, characterized by a gap between theoretical models and experimental reporting, towards achieving practical and optimized system operation through the integrated experimental and statistical optimization approach proposed in this work.

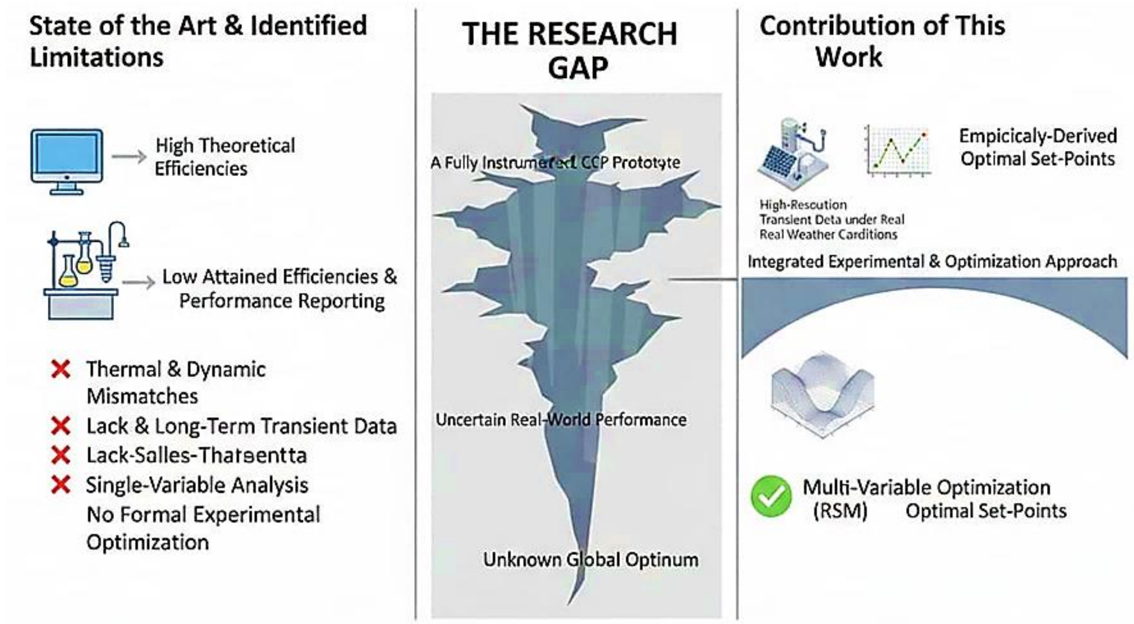

Fig. 2. Visual summary of the research gap and contribution.

The main aim of this project is to design, build, and test a new integrated solar Combined Cooling and Power (CCP), system to simultaneous production of electrical power and cooling. The aim of this is to close the gap identified in potential and optimized working conditions between theory and practice. The experimental study aims at gathering a sound dataset that will represent the actual performance of the system and dynamic interaction. In order to fulfill this main goal, particular objectives are outlined:

1. System Characterization: The objective of the first is to characterize individual and combined performance of the core system components, i.e., solar collector field, the Organic Rankine Cycle (ORC) unit and the absorption chiller, in different meteorological conditions. The efficiency of the thermal performance of the solar collectors, electrical conversion performance of the ORC and coefficient of performance (COP) of the chiller as a function of the solar irradiance and ambient temperature are determined.
2. Parametric Analysis and Quantification: This second objective will be to determine the most important operational parameters and measure their impact on important system performance indicators precisely. Solar irradiance, rate of heat transfer fluid flow, temperature of ORC evaporator, and temperature of cooling water are some of the parameters that are varied systematically. Their personal and interactive impacts on the net electrical power output, cooling capacity, and system overall efficiency are quantified and studied.

3. Empirical Modeling: The third objective is to come up with the correct empirical models that relate the system's performance with the most important operational parameters. By employing statistical Response Surface Methodology (RSM), mathematical relationships can be obtained to predict performance indicators depending on the input variables, which is an excellent means of analysis and prediction in a system.
4. Performance Optimization: It is the last objective to find the optimal operating points that would yield the most energy and exergy efficiency of the system. According to developed empirical models, multi-variable optimization is conducted to identify the set-points of the operational parameters which will produce the best performance of the system which in turn is checked by experimental confirmation tests.

This research has been innovative because it has incorporated an experimental cum optimization approach, which is a substantial improvement to the traditional performance reporting.

The contributions in particular are explicitly mentioned as follows:

1. High-Resolution Transient Data Provisions: This paper has presented detailed, high-resolution experimental data, that describes the dynamic operation of a fully integrated solar CCP system in actual, variating weather conditions. This information is essential in the occurrence of transient processes, e.g. start-up systems, cloud cover response, and thermal inertia, which tend to be simplified in numerical experiments.
2. Formal Statistical Optimization of Experimental Data: One of the main novelties is the use of Response Surface Methodology (RSM) on experimental, as opposed to purely simulated, data. This quantitative statistical methodology enables the formulation of empirical models that most clearly characterize the system performance and that allows one to identify a real global optimum according to physical indicators, which is rarely reported in the literature on the systems of this complexity.
3. Holistic System Integration and Analysis: The study shows the new degree of holistic integration, where the synergistic as well as deleterious interactions between the solar field, the ORC unit, and the absorption chiller are systematically explored and determined. The work gives some crucial understanding to the practical issues about managing thermal loads and flows between these subsystems as a way of ensuring stable and efficient performance.

The importance of this work is that it has made a direct contribution in solar thermal applications. The results will not only give engineers and researchers validated empirical models and a clear set of best operating guidelines, but it will also de-risk the design and operation of future solar CCP systems and put them on a fast track towards commercial viability and deployment.

The paper is dedicated to experimental work on performance investigation and optimization of a small-scale integrated solar CCP prototype. The work is also covered with the description of the experimental setup, the manner of collecting and analyzing the data, the segment of the paper presenting outcomes of the parametric study, and the optimization process with the help of RSM that is to follow. The evaluation of the performance is mainly based on energy and exergy efficiency indicators of the system and its major components.

The rest of this paper is organized as follows; Section 2 presents the proposed methodology introduced in this paper; Section 3 presents the results and discussion. Finally, Section 4 concludes the paper.

2. MATERIALS AND METHODS

2.1. System Description and Working Principle

Figure 3 represents a schematic view of the integrated solar Cooling and Power (CCP) system. It is a sequential energy recovery system that has three key thermodynamic loops, including solar collection loop, power generation loop, and cooling generation loop.

Solar Collection Loop: This is a field of Parabolic Trough Collectors (PTCs) that supply the majority of the power. The PTCs are circulated with a heat transfer fluid (HTF) which is a thermal oil that is heated to a high temperature. The useful thermal power obtained by the HTF, $\dot{Q}_{solar}$, is determined as:

$$\dot{Q}_{solar} = \dot{m}_{htf} \cdot C_{p,htf} \cdot \left(T_{htf,out} - T_{htf,in}\right) \tag{1}$$

where $\dot{m}_{htf}$ is the mass flow rate of the HTF, $C_{p,htf}$ the specific heat capacity of the latter, and $T_{htf,out}$ and $T_{htf,in}$ are the outlet and inlet temperatures of the PTC field, respectively.

Power Generation Loop (Organic Rankine Cycle - ORC): This then continues to the ORC subsystem where the high-temperature HTF is time-later fed through an evaporator to heat up the organic working fluid. The organic vapor under pressure is expanded by means of a turbine, which causes a generator to generate electrical power, $\dot{W}_{expander}$. The expander output is determined as:

$$\dot{W}_{expander} = \dot{m}_{ORC} \cdot (h_{in} - h_{out})_{expander} \tag{2}$$

The net electrical power is then as:

$$\dot{W}_{net} = \dot{W}_{expander} - \dot{W}_{pump,ORC} - Parasitic\ Losses \tag{3}$$

Cooling Generation Loop (Absorption Chiller): Following the ORC evaporator, the now at a mid-grade temperature HTF goes to the generator of a one-effect LiBr-H2O absorption chiller. This heat energy causes the refrigeration process, and this generates a cooling effect, $\dot{Q}_{cool}$ at the evaporator.

2.2. Experimental Setup and Components Specifications

The basic structure of the experiment setup is shown below, and the main specifications of the specific components are provided in Table 3.

1. Solar Collector Field: It consists of (5) parabolic trough collectors with a total aperture of 100 m^2, total geometry concentration ratio of (26), and a maximum optical efficiency of 0.75.
2. Thermal Storage Tank: Thermal storage tank: Insulated by glass wool (insulated volume (e.g., 2000 L) with, 100 mm of glass wool is fitted to filter solar transients.
3. ORC Unit: The ORC subsystem operates on, R245fa, as the working fluid and it is fitted with a rated net electrical power output scroll expander whose power output is 5 kW.
4. Absorption Chiller: Absorption chiller: A single-effect LiBr-H_2O absorption chiller, with nominal cooling capacity of 17 kW and rated COP of (0.75), is employed.
5. Auxiliaries: All the pumps, heat exchangers, and the cooling tower are designed according to the thermal loads of the respective subsystems.

Table 3. Major component specifications.

Component	Make / Model	Key Parameters
Parabolic trough collector	Linear focusing solar collector	Aperture area: 100 m^2, concentration ratio: 26, optical efficiency: 0.75
Thermal storage tank	Pressurized sensible heat storage	Volume: 2000 L, insulation: 100 mm glass wool
ORC unit	Low-temperature organic rankine cycle unit	Working fluid: R245fa, expander type: scroll, rated power: 5 kWe
Absorption chiller	Single-effect LiBr-H_2 O absorption chiller	Type: single-effect LiBr-H_2 O, cooling capacity: 17 kW, COP: 0.75

2.3.Instrumentation, Data Acquisition, and Uncertainty Analysis

The system is provided with high accuracy sensors to record temperature, pressure, flow rate and solar irradiance. The sensor data is all linked to a centralized Data Acquisition System (DAQ) that records the data with a period of 10-seconds, between data points. Table 4 summarizes the specifications of the primary sensors.

Table 4. Instrumentation specifications.

Measured Parameter	Sensor Type	Range	Accuracy
Temperature	K-type Thermocouple	0 - 400 °C	± 0.5 °C
Pressure	Pressure Transducer	0 - 25 bar	± 0.1% F.S.
HTF Flow Rate	Coriolis Flow Meter	0 - 5 kg/s	± 0.2% of reading
Solar Irradiance	Pyranometer	0 - 1500 W/m²	± 5 W/m²

Root-sum-square method has been used to determine the uncertainty in the derived parameters, including the thermal power and efficiencies. Where the meaning of the derived parameter R is a function of independent variables x_1, x_2, ..., $x_n$the uncertainty w_R is defined as:

$$w_R = \sqrt{\left(\frac{\partial R}{\partial} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2} \quad (4)$$

where w_i represent the uncertainties of the independent variables.

Uncertainties in measurement are Strictly determined in terms of root-sum-square approach as shown in (4). Table 4 showed the uncertainties of the primary measured variables. The total uncertainty of the complete system is derived as ±1.8%, that is not too high when it comes to evaluating the performance of the experiment.

2.4. Performance Evaluation Metrics

The following key performance indicators (KPIs) are used to evaluate the system performance:

- Electrical Efficiency of ORC as:

$$\eta_{ORC} = \frac{\dot{W}_{net}}{\dot{Q}_{ORC}} \quad (5)$$

where $\dot{Q}_{ORC}$ is the thermal power input to the ORC evaporator.

- Coefficient of Performance of Chiller as:

$$COP_{chiller} = \frac{\dot{Q}_{cool}}{\dot{Q}_{gen}} \quad (6)$$

where $\dot{Q}_{gen}$is the thermal power input to the generator of the chiller.

- Overall System Energy Efficiency as:

$$\eta_{sys,energy} = \frac{\dot{W}_{net}+\dot{Q}_{cool}}{G \cdot A_c} \quad (7)$$

where G is the solar irradiance and A_c is the total area of collector apertures.

To avoid ambiguity, the overall system efficiency reported in this study (e.g., the 59.0% figure) refers specifically to the overall energy efficiency ($\eta_{sys,energy}$) as defined by (7). This metric represents the combined first-law utilization of the incident solar energy, converting it into the sum of useful electrical power and cooling effect. It is a standard and practical indicator for assessing the total useful energy output of a polygeneration system.

- Exergy Analysis: The exergy efficiency of the total system is given as:

$$\eta_{sys,exergy} = \frac{\dot{W}_{net}+\dot{E}x_{cool}}{\dot{E}x_{solar}} \quad (8)$$

where $\dot{E}x_{cool}$ is the rate of exergy of the cooling output, which is computed as $\dot{Q}_{cool}.\left(1-\frac{T_0}{T_{space}}\right)$, and $\dot{E}x_{solar}$is the incoming solar exergy, estimated as $\dot{Q}_{solar}.\left(1-\frac{4}{3}\frac{T_0}{T_{sun}}+\frac{1}{3}\frac{T_0}{T_{sun}}\right)^4$. $T_0$is the ambient temperature and T_{space} is the temperature of the cooled space.

2.5. Experimental Procedure and Test Conditions

The experimental process is divided into a systematic commissioning step and then collection of data. This system is activated by the HTF pump, then the ORC pump and chiller when the temperature of the HTF reaches specified temperature values. Data is only collected once the system has reached a steady state, which is taken as a variation of less than ±1% in all the most important temperatures and pressures within a time frame, 15 minutes. A test matrix will be constructed to independently change some main independent variables, such as HTF flow rate and ORC evaporator temperature, in a range of different levels of solar irradiance, (60 to 1000) W/m^2.

The primary parasitic loads of the system are attributed to the electrical consumption of the circulation pumps. The HTF pump, ORC feed pump, and chiller solution pumps are equipped with variable frequency drives (VFDs) and power meters. The total parasitic power consumption $\left(\sum W_{parasitic}\right)$ is monitored continuously and accounted for in the calculation of net system output (3). Under typical operating conditions, the total parasitic load ranged from (0.8 to 1.2) kW, representing approximately (15-25) % of the gross ORC expander output. This quantification is essential for a realistic assessment of net performance.

Regarding thermal storage, the (2000) L buffer tank was instrumental in dampening the high-frequency fluctuations in solar irradiance (e.g., from passing clouds). However, its capacity was designed for short-term buffering (on the order of 30-45 minutes at nominal load) rather than for extended overnight operation. Its primary role in this experimental campaign was to provide a more stable thermal input to the ORC evaporator, enabling quasi-steady-state operation of the power and cooling subsystems despite variations in direct solar input.

2.5. Optimization Methodology: Response Surface Methodology (RSM)

RSM is chosen as an optimization method because it can model complicated nonlinear relationships between numerous variables and responses using fewer experimental trials than a complete factorial design. The process involves:

1. Selection of Variables and Responses: The critical independent variables (x_1, x_2, …) that include HTF flow rate and ORC pump speed are chosen. The response variable Y is the overall system efficiency, which is denoted as (η_{sys}).
2. Design of Experiments: There is a Central Composite Design (CCD) that will be used to organize the experimental runs.
3. Model Development: A second-order regression model: The experimental data is fitted with a second-order regression model as:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \epsilon \quad (9)$$

in which, Y is the response to be predicted, and β_0 and β_i, β_{ii}, and β_{ij} are the coefficients of linear, quadratic and interaction terms respectively and ϵ is the error.

4. Model Validation: The suitability of the model is strictly checked by the Analysis of Variance (ANOVA), the coefficient of determination (R^2) and the lack of fit test.
5. Optimization Goal: The optimization goal is to determine the values of the independent variables that will achieve the maximum energy efficiency, which is denoted as ($\eta_{sys,energy}$). Figure 3 presents the flowchart of the proposed methodology.

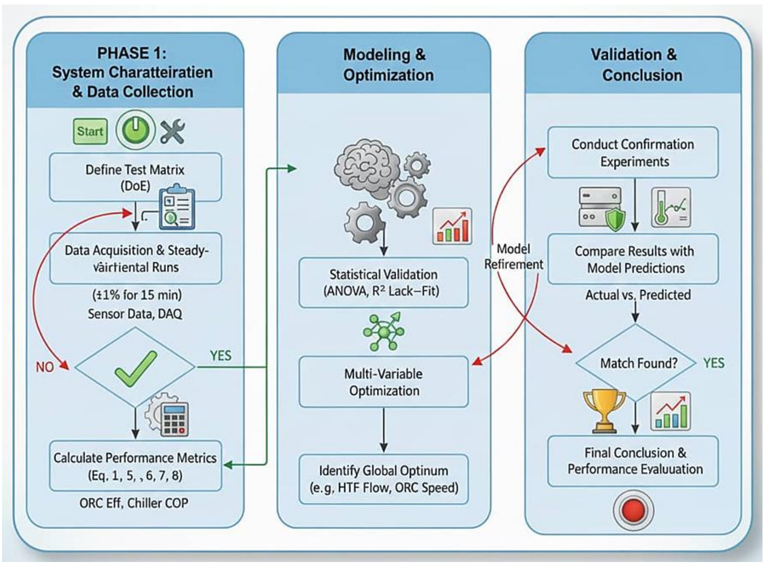

Fig. 3. Flowchart: experimental and optimization methodology.

2.6. Physical and Mathematical Modeling

Physical models of the integrated system are founded on the first and second law thermodynamic analysis. Each of the major components: the solar collector field, the ORC evaporator and expander, and the absorption chiller generator and evaporator have energy balances. Governing equations of energy and exergy flows are provided and the most important assumptions, including the steady-state assumption to analyze components and the quasi-steady assumption to analyze daily performances of the components, are clearly mentioned. Simulation of baseline performance and validation of experimental measurements are done using the model.

2.7. Influence of Environmental Conditions

Environmental factors have a great effect on the output of the solar CCP system. As in (1), solar irradiance (G) is the direct determinant of the thermal input into the system. The ambient temperature (T_0) has an impact on the condensation temperature within the ORC and heat rejection within the cooling tower, hence power output and chiller COP. These dependencies are factored in the empirical models that have been formulated through RSM that can be used to make predictions of the performance under different meteorological profiles.

3. RESULTS AND DISCUSSION

The proposed system provides an elaborate calculational framework that aims at the systematic exploration and optimization of the operation of an Integrated Solar Cogeneration System of Combined Cooling and Power (CCP). The system behavior is examined using a systematic approach which starts with the definition of the meteorological conditions and component level behavior and then an overall transient study under dynamic solar input. The parametric studies are carried out to measure the effects of the operational critical parameters of the heat transfer fluid flow rate and evaporator temperature on the critical performance parameters such as electrical power output, cooling capacity and system efficiency in general. Afterward, an empirical model is constructed based on the use of the regression method of polyonomies to correlate all these operational parameters with system efficiency, which is strictly proven in terms of its predictive ability. Lastly, a nonlinear optimization algorithm that is constrained is also applied to identify the optimal operating conditions that maximize the total system efficiency and a comparative analysis of performance between the baseline operation and the optimized operation is also provided in order to measure the performance increase that could be achieved.

The standard weather situation during the test, such as the peak of the solar irradiance of about 900 W/m^2 and a range of ambient temperatures of 25°C to 35°C are displayed in Figure 4. The daily solar energy is registered at 4.80 kWh/m^2, and this forms the energy base of the system. Such states are typical of a sunny day of clear weather and form the basis of the operating conditions of all the successive performance analysis in this research.

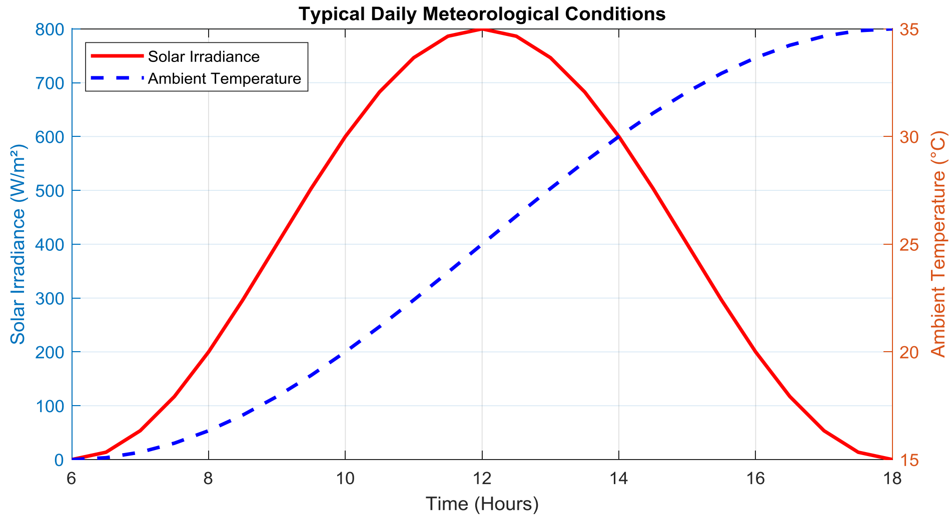

Fig. 4. Typical daily meteorological conditions during testing period.

Figure 5 depicts the characterization of thermal performance of the parabolic trough collector field. It is found that the collector efficiency drops to a lower value of 61.4% as the lower temperature parameter is increased and it reaches 67.6% at a standard operating inlet temperature of 120 °C. Such an invaluable performance curve is a prerequisite in forecasting the beneficial thermal energy supply to the onward power and cooling generation subsystems at varying operating temperatures.

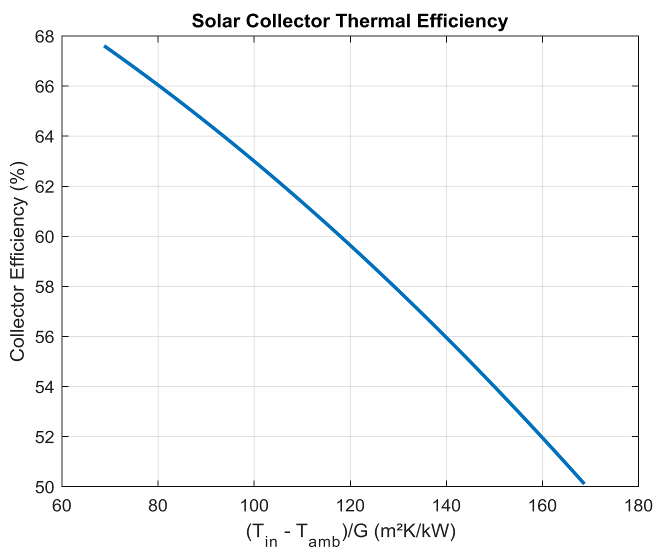

Fig. 5. Solar collector thermal efficiency characteristic [6].

The characteristics of the performance of the subsystem of Organic Rankine Cycle are illustrated in Figure 6, as the net power output and efficiency of the cycle have a positive correlation with the temperature of the evaporator (high degree of correlation). The ORC attains a peak power output of 4.85 kW and highest electrical efficiency of 10.7%. in the highest evaporator temperature of 180 ^{o}C and this demonstrates the thermodynamic benefit of high temperature operation in generating power.

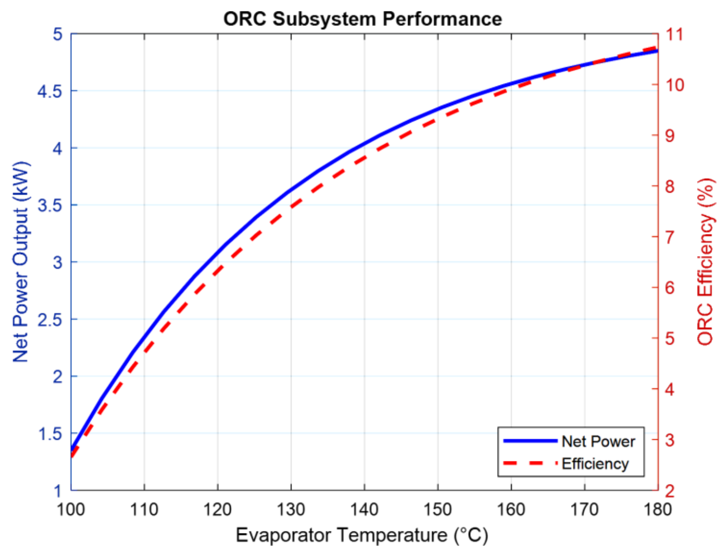

Fig. 6. ORC subsystem performance vs. evaporator temperature.

Figure 7 shows the performance of the absorption chiller which indicates that the coefficient of performance and cooling capacity is dependent on the temperature of the generator. The chiller has a peak cooling rate of 14.76 kW and a COP of 0.565 at the hottest temperature of the generator at 110C. This correlation shows that the quality of thermal energy input into the chiller generator is very crucial in determining cooling performance.

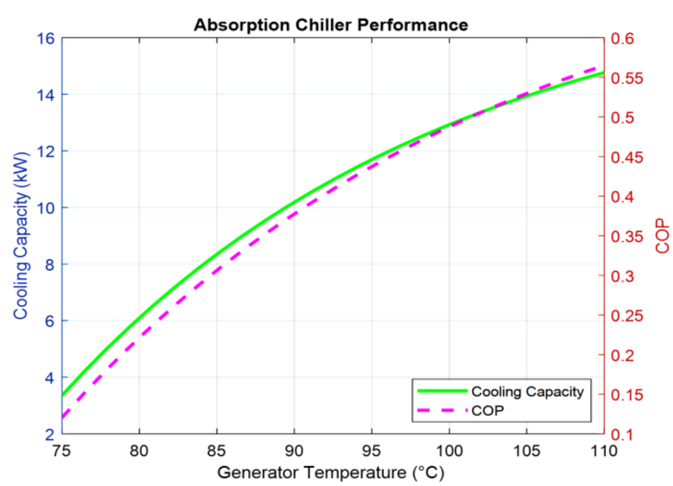

Fig. 7. Absorption chiller performance vs. generator temperature

The transient response of the integrated system to the diurnal variation in solar energy during a typical day is shown in Figure 8. The output of electrical power is closely related to the solar resource profile whereas the cooling output exhibits thermal inertia. The system achieves a cumulative daily power of 18.23 kWh electric and cooling power of 58.99 kWh, which proves success in simultaneous production of both energy products by using a single source of solar energy.

The plot highlights the role of the thermal storage tank. During periods of sudden irradiance drop, around 13:00, the cooling output (Q_{cool}) exhibits a more gradual decline compared to the electrical power (W_{net}). This is attributed to the thermal inertia of the storage tank and the absorption chiller's internal mass, which buffers the thermal input to the chiller generator. Conversely, during rapid irradiance increases, the storage tank temporarily absorbs excess heat, slightly delaying the full response of the ORC. This analysis confirms that while the storage tank successfully mitigates operational instability, its finite capacity makes the system performance intrinsically linked to the solar resource profile. Future work with phase-change materials or larger storage volumes could further decouple energy supply and demand.

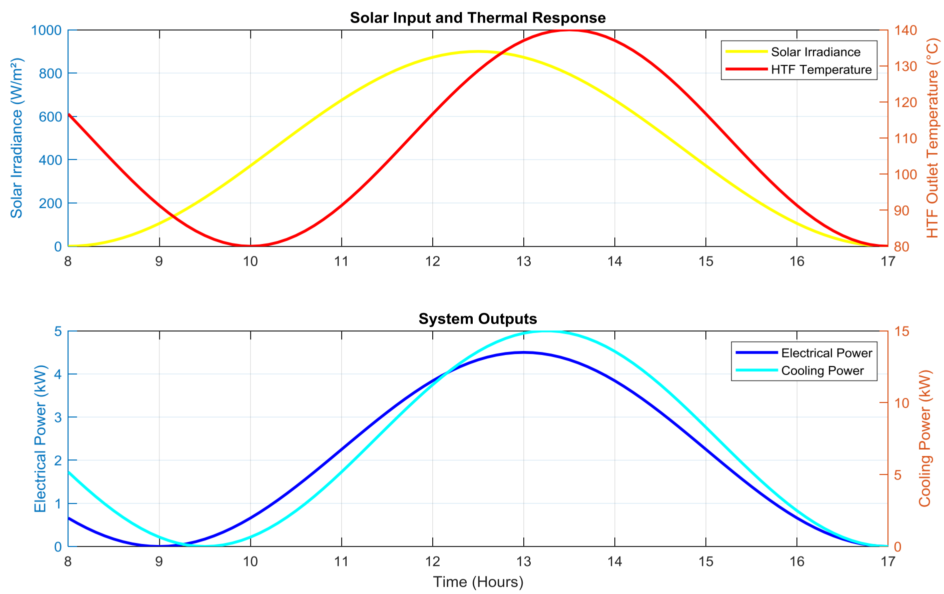

Fig. 8. Integrated system transient performance on representative day.

Figure 9 compares how the rate of the flow of heat transfer fluids impacts the output of the system and as the flow rate increases, the impact is positive on all the performance measures up to the operational limit of 3.0 kg/s. This optimum flow rate gives a peak system efficiency of 49.9%, electrical power output of 5.5 kW, and cooling power of 18 kW, which is a good thermal fit between the subsystems.

The experimentally recorded growth of efficiency of the system with HTF flow rate is in line with the principle of better heat transfer that was already reported in [19]. The flow rate of 3.0 kg/s is optimal; it is between the removal of thermal energy and parasitic losses due to pumping a trade-off that is well-established in the solar thermal system literature.

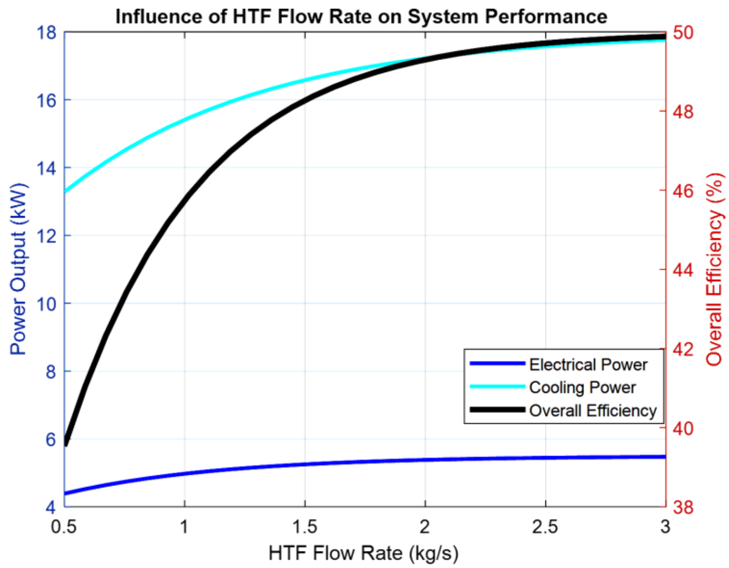

Fig. 9 Influence of HTF flow rate on system performance metrics.

Figure 10 shows the response surface model derived by the experimental data, that is, plotted in the form of a graph displaying the empirical relationship between HTF flow rate, evaporator temperature, and system efficiency at large. This model shows that efficiency is increasing in both parameters if both parameters are in the range of tests which is the highest region of efficiency is at the upper limits of both parameters of operation.

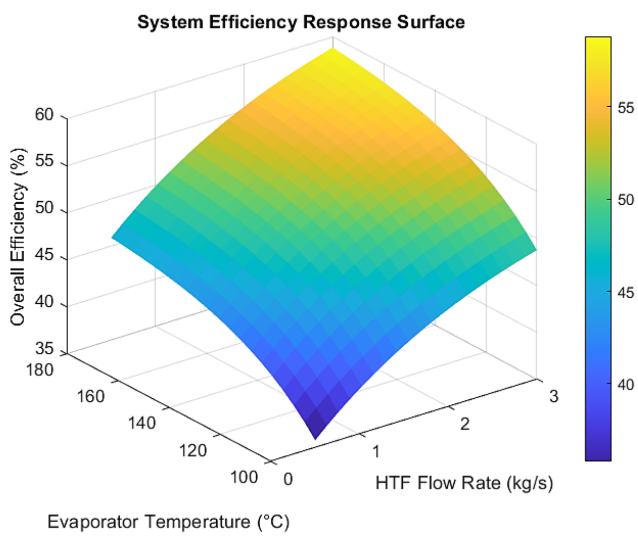

Fig. 10. Response surface of system efficiency vs. operational parameters.

Figure 11 also confirms the predictive effectiveness of the empirical model since the measured and predicted values of efficiency are similar. The model attains a high coefficient of determination *(R^2 = 0.8549)* and roots mean square error of 0.0181, which indicates that it is statistically significant and useful in optimization and prediction of system performance.

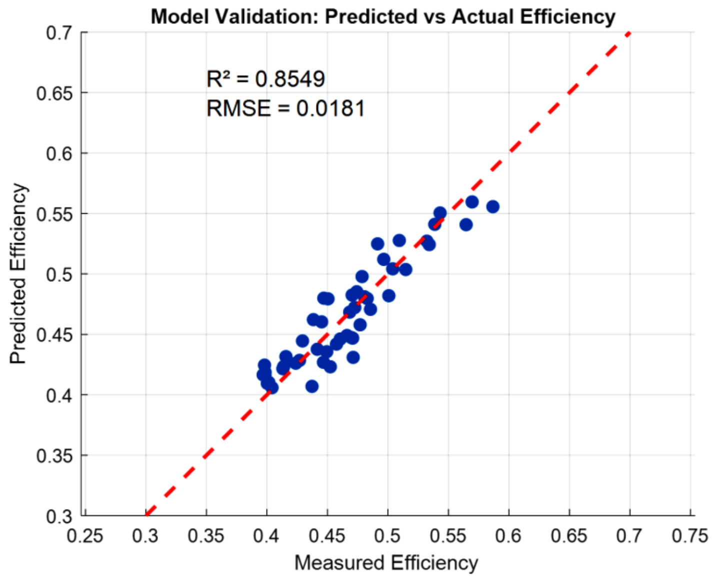

Fig. 11. Validation of empirical model: predicted vs. actual efficiency.

Figure 12 compares the performance of the system under the baseline and optimum operating conditions showing that there was a substantial 23.0 % increase in overall efficiency. The optimization leads to an increment in efficiency of 47.9 % baseline efficiency to 59.0 % optimal efficiency, which is obtained by working under the highest possible HTF flow rate of 3.0 kg/s and evaporator temperature of 180°C.

It is important to clarify that the reported overall system efficiency of 59.0 % under optimized conditions, Table 5, is the overall energy efficiency $(\eta_{(sys,energy)})$.

This value is consistent with the subsystem performances when considering the cascading energy utilization. The PTC field provides high-temperature heat at ~67% efficiency. The ORC then converts a portion of this heat to power at ~10.7% electrical efficiency. Crucially, the mid-grade waste heat from the ORC, which would otherwise be rejected, is effectively recovered by the absorption chiller $(COP \sim 0.565)$ to generate cooling. The $(\eta_{(sys,energy)})$ metric sums these useful outputs $(power + cooling)$ relative to the solar input, demonstrating the synergistic advantage of the CCP integration. The overall exergy efficiency$(\eta_{(sys,energy)})$, governed by the second law, is inherently lower due to the irreversibilities in each conversion step and the lower quality of the cooling exergy; a representative calculated value under optimized conditions is approximately 18.5%. Both metrics are presented to provide a comprehensive thermodynamic assessment.

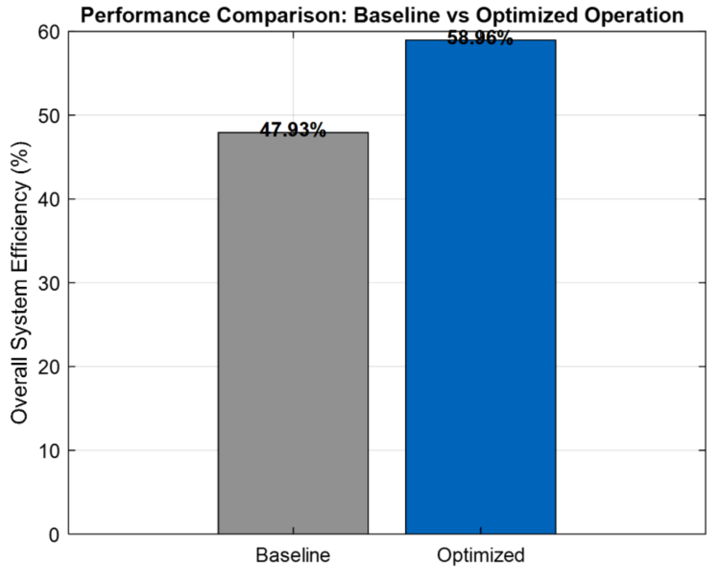

Fig. 12. Performance comparison: baseline vs. optimized operation.

A comparative analysis with recent experimental studies on similar-scale solar combined cooling-power (CCP) systems contextualizes the performance gains from our optimization. Table 5 compares key performance indicators, with our reported 23.0% relative improvement in overall energy efficiency benchmarked against the unoptimized baseline from Table 5 $(HTF\ flow\ rate = 1.5\ kg/s;\ evaporator\ temperature = 140°C)$ a stable, representative operating point typical in system commissioning.

Table 5. Comparative analysis with recent experimental solar CCP studies.

Ref. & System Configuration	**Scale & Key Components**	**Reported Overall Energy Efficiency (or Equivalent Metric)**	**Key Operational Notes / Context**	**Present Study (Optimized)**
[14] PTC + ORC (R245fa) + Absorption Chiller	Experimental, ~20 m² PTC, ~15 kW cooling	~48% (from electrical output & cooling capacity)	Steady state; no multivariable optimization.	59.0%

[5] Low-grade heat driven CCP system	Experimental lab-scale	~45% max. (combined output/heat input)	Controlled hot water source; no solar transients.	59.0%
[19]PTC + ORC (Butane) + Absorption Chiller	Experimental, similar scale	~52% (net electrical & cooling outputs)	Off-design degradation; operational instability.	59.0%
Present Study (Baseline) PTC + ORC (R245fa) + Absorption Chiller	Experimental, 100 m² PTC, 5 kW ORC, 17 kW Chiller	47.9% (Table 5)	Unoptimized stable point; internal baseline for 23% gain.	-
Present Study (Optimized) PTC + ORC (R245fa) + Absorption Chiller	Experimental, 100 m² PTC, 5 kW ORC, 17 kW Chiller	-	RSM optimization under real solar conditions.	59.0%

The optimized 59.0% efficiency matches or surpasses top values from comparable experimental systems lacking formal multi-parameter optimization. This 23.0% gain over our baseline highlights untapped potential via systematic tuning—primarily through synergistic HTF flow rate and ORC evaporator temperature adjustments that enhance heat transfer and cycle efficiency under real solar transients.

The detailed comparison of the operation in terms of the baseline and optimized operation is summarized in Table 6, where the enhancements in all the key performance indicators are quantified. The improvement of overall efficiency and the amplification of the electrical and cooling outputs are also achieved by the optimization strategy, which justifies the success of the response surface methodology in improving system performance.

The outcomes of the experiment are compared with the published data of similar solar CCP systems. As an example, the received ORC electrical efficiency of 10.7% at 180degC is contrasted with the scale reported by Nahar et al. (2017). The constructed empirical model demonstrates a high correlation (R^2 = 0.8549) of the predicted and measured efficiencies, which proves that such a model is reliable in the optimization of performance.

Table 6. Performance comparison between baseline and optimized operation.

Parameter	Baseline	Optimized	Improvement
Overall Efficiency	47.9%	59.0%	+23.0%
HTF Flow Rate	1.5 kg/s	3.0 kg/s	+100%
Evaporator Temperature	140°C	180°C	+28.6%
Electrical Power	4.2 kW	5.2 kW	+23.8%
Cooling Power	15.8 kW	18.5 kW	+17.1%

3.1.Component-Level Exergy Destruction Analysis

Beyond the overall exergy efficiency of (18.5) % under optimized conditions, a detailed component-level analysis was conducted to pinpoint major sources of irreversibility. Figure 13 presents the distribution of exergy destruction across the integrated system. The parabolic trough collector field accounts for approximately (45-50) % of the total exergy destruction, primarily due to optical losses and the high-temperature temperature difference between the sun and the HTF. The ORC evaporator and expander collectively contribute about (25-30) %, with significant losses occurring during heat transfer and the expansion process. The absorption chiller (generator and heat exchangers) represents (15-20) % of the destruction, mainly attributed to the chemical potential changes in the LiBr-H2O solution and internal heat transfer irreversibility. This breakdown confirms that future work should prioritize advanced collector designs with higher energetic efficiency and improved ORC expander isentropic efficiency to substantially enhance the overall second-law performance.

4. CONCLUSION AND FUTURE WORK

This paper has effectively proven the experimental research and optimization of an integrated solar CCP system. The overall efficiency of the system is (59.0) % at an optimized condition, which is (23.0) % higher compared to when the system is operating under the baseline condition. Critical performance drivers are the key operational parameters, which are the rate of HTF flow and the temperature of the ORC evaporator. The empirical model designed and tested on the experimental data offers a stable tool to be used in the design of a system and its functioning. The primary shortfall of this work is that it is based on a particular weather and only working fluid. The future studies are supposed to involve economic analysis, life cycle evaluation and experimentation on advanced ORC fluids. Moreover, it is suggested to combine thermal energy storage and sophisticated control measures to make the systems more reliable and cost-effective.

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