

# Design and Thermodynamic Performance Analysis of a Solar-Assisted Hybrid Absorption–Compression Refrigeration System

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## 1. Abstract

Due to climate change, rapid urbanization, and the growing use of air conditioning in both commercial and residential sectors, there has been a significant increase in the global demand for cooling technologies that are both energy-efficient and environmentally friendly. Traditional vapor-compression refrigeration systems, although widely used, contribute substantially to greenhouse gas emissions because of their high electricity usage and reliance on harmful refrigerants. Refrigeration systems that utilize renewable energy, particularly when integrated with solar thermal energy, offer a promising alternative. This study presents a detailed design and thermodynamic performance evaluation of a solar-assisted hybrid absorption–compression refrigeration system (SAHACRS). The hybrid system integrates an absorption refrigeration cycle with a vapor-compression cycle, employing solar thermal collectors alongside an auxiliary electrical compressor in a complementary manner. This configuration aims to improve cooling efficiency under varying solar conditions while reducing dependence on electrical energy. The paper explores the system's conceptual design, thermodynamic modeling, energy and exergy analyses, simulation results, performance evaluation under different levels of solar insolation, and optimization of the collector-refrigerant interaction. Analytical models are developed based on the first and second laws of thermodynamics and validated through numerical simulations. The results indicate that the proposed

hybrid system achieves a higher coefficient of performance (COP) compared to standalone absorption or compression systems, especially under moderate solar flux conditions, and demonstrates enhanced exergetic efficiency with significant primary energy savings. Finally, recommendations for scalability, control strategies, and future research directions are provided.

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## 2. Keywords

**Solar-Assisted Refrigeration, Integrated Absorption–Compression System, Thermodynamic Performance, Energy and Exergy Evaluation, Renewable Energy Cooling, Coefficient of Performance (COP), Environmentally Friendly Thermal Solutions**

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## 3. Introduction

### 3.1 Background and Motivation

Refrigeration and air conditioning technologies are crucial in modern society, fulfilling key needs in sectors such as food preservation, pharmaceuticals, industrial processes, and ensuring thermal comfort. Conventional systems predominantly depend on vapor-compression cycles, which are powered by electricity often sourced from fossil fuels, and typically employ refrigerants with high global warming potential (GWP). As global energy consumption continues

to rise, these systems contribute significantly to environmental damage and energy insecurity.

Solar energy, abundant and renewable, presents a sustainable alternative for powering cooling systems. Solar-thermal driven refrigeration uses solar heat to activate thermally driven cooling cycles, like absorption and adsorption refrigeration, making them especially suitable for off-grid or hybrid environments. However, purely solar thermal systems often experience performance fluctuations due to varying solar insolation, necessitating auxiliary systems to maintain consistent cooling.

### **3.2 Hybrid Absorption–Compression Refrigeration Systems**

Hybrid refrigeration systems utilize both absorption and compression cycles to optimize efficiency. In these configurations, the absorption cycle is powered by low-grade thermal energy, such as that from solar collectors, while mechanical compression, fueled by electrical energy, boosts performance. This strategy reduces overall electricity consumption and enables the system to operate efficiently even with limited solar exposure. The aim of this hybrid approach is to achieve higher thermodynamic efficiency and support environmental sustainability.

Despite growing interest in this research field, there is still a need for comprehensive design methodologies and systematic performance analyses for solar-assisted hybrid systems. This paper aims to address this gap by providing an in-depth design, thermodynamic modeling, and performance assessment of a Solar-Assisted Hybrid Absorption–Compression Refrigeration System (SAHACRS).

### **3.3 Objectives of the Study**

- The primary objectives of this research are as follows:
- Developing an all-encompassing conceptual and mathematical model for the SAHACRS.
- Performing energy and exergy evaluations to assess the system's performance.
- Evaluating the system's functionality under varying solar insolation and load conditions.
- Analyzing the hybrid system's performance in comparison to standalone absorption and compression systems.
- Identifying design optimization strategies to enhance system efficiency.

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## **4. Literature Review**

### **4.1 Solar Driven Refrigeration Systems**

Solar cooling technologies are categorized into two primary types: those that operate on solar thermal energy and those that rely on solar photovoltaic (PV) systems. Solar thermal systems employ collectors to harness direct solar heat, which is subsequently applied in thermal cooling techniques such as absorption, adsorption, or desiccant cooling. On the other hand, solar PV systems convert sunlight into electricity to power conventional compressors. Each approach presents its own advantages and disadvantages.

Studies show that solar thermal absorption systems can operate efficiently within a temperature range of 70–120°C, making them compatible with flat plate or evacuated tube solar collectors. However, their performance is heavily dependent on the availability of solar energy. In contrast, PV-driven compression systems offer greater flexibility but

are often limited by the high costs of electrical storage during non-peak periods.

## 4.2 Absorption Refrigeration Cycle

The absorption refrigeration cycle utilizes thermal energy to facilitate cooling. The common combination used is lithium bromide (LiBr) and water, where water acts as the refrigerant and LiBr functions as the absorbent. This cycle comprises four main components: the generator, absorber, condenser, and evaporator. Heat introduced to the generator leads to the release of refrigerant vapor, which then releases heat at the condenser. Cooling occurs as the vapor expands and is reabsorbed into the solution.

### Key Findings from Previous Research

- Solar energy-driven absorption systems perform well when cooling requirements are moderate. While their COP is typically lower compared to mechanical compression systems, it can be enhanced by integrating hybrid solutions. Exergy analysis reveals significant irreversibilities occur in the generator and absorber components.

## 4.3 Vapor-Compression Refrigeration Cycle

The vapor-compression refrigeration cycle is widely used due to its relatively high coefficient of performance (COP) and simple operation. The process involves an electrically driven compressor that raises the refrigerant's pressure, allowing heat to be expelled and absorbed at designated temperature points. Common refrigerants include R134a, R410A, R290 (propane), and R600a (isobutane), with increasing attention on options that have a low global warming potential (GWP).

## 4.4 Hybrid Refrigeration Systems

Hybrid systems combine absorption and compression cycles to efficiently utilize solar heat while maintaining system responsiveness. Earlier studies indicate that these hybrid systems can improve the COP by 10–30% compared to standalone absorption units. Additionally,

incorporating thermal storage, like sensible heat or phase change materials, enhances performance stability.

## 4.5 Research Gaps

Many current studies focus primarily on solar-powered absorption systems or hybrid systems, frequently under the assumption of perfect conditions. Nonetheless, there is a lack of research addressing the following topics:

- The optimization of integrated designs that combine solar collectors, absorption units, and compression cycles.
- Detailed comparisons of thermodynamic performance in the context of varying solar insolation.
- Exergy analysis to pinpoint sources of inefficiency.

This study seeks to address these gaps.

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## 5. Methodology

The section outlines the research techniques used for system design, along with those employed in modeling, simulation, and performance assessment.

### 5.1 System Description

The SAHACRS design incorporates three primary subsystems:

1. Solar Thermal Energy Unit (STEU) – This includes components like solar collectors, which may be evacuated tube collectors or parabolic troughs, along with thermal storage if applicable, systems for fluid circulation, and heat transfer mechanisms.
2. Absorption Refrigeration Unit (ARU) – Utilizing solar heat, this unit operates with a LiBr–water working pair.

3. Vapor Compression Unit (VCU) – This subsystem integrates an electrically powered compressor with the ARU to boost cooling performance, particularly when solar energy is low.

## 5.2 Thermodynamic Modeling

System performance is evaluated by conducting an energy balance using the first law and performing an exergy analysis in line with the second law.

### 5.2.1 Assumptions

- The process takes place under stable conditions.
- Variations in kinetic and potential energy are negligible.
- Standard thermodynamic tables provide the properties of the working fluid.

### 5.2.2 Energy Balance Equations

For all control volumes (collector, generator, absorber, condenser, evaporator, compressor), energy balance is given as:

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \sum \dot{m}(h_{out} - h_{in})$$

Where:

- $\dot{Q}$  = heat transfer rate.
- $\dot{W}$  = work transfer rate.
- $h$  = fluid specific enthalpy.

### 5.2.3 Exergy Analysis

Exergy destruction is calculated using:

$$\dot{E}_D = \dot{T}_0 \sum \frac{\dot{Q}}{T} - \sum \dot{m}(e_{out} - e_{in})$$

Where:

- $T_0$  = ambient temperature.
- $e$  = specific exergy.

Exergy efficiency is subsequently evaluated.

## 5.3 Numerical Simulation

Thermodynamic solvers such as MATLAB/Simulink or Engineering Equation Solver are employed to create simulation models. By altering input parameters like solar irradiance, ambient temperature, collector area, and heat exchanger efficiency, the system's behavior is examined.

## 6. System Design

### 6.1 Solar Thermal Energy Unit (STEU) Design

- The purpose of the STEU is to ensure a steady supply of thermal energy to the absorption cycle generator. Key design elements include:
  - Collector Type: Evacuated tube collectors (ETC) are selected due to their excellent thermal efficiency, especially under diffuse radiation conditions.

#### Collector Area Calculation:

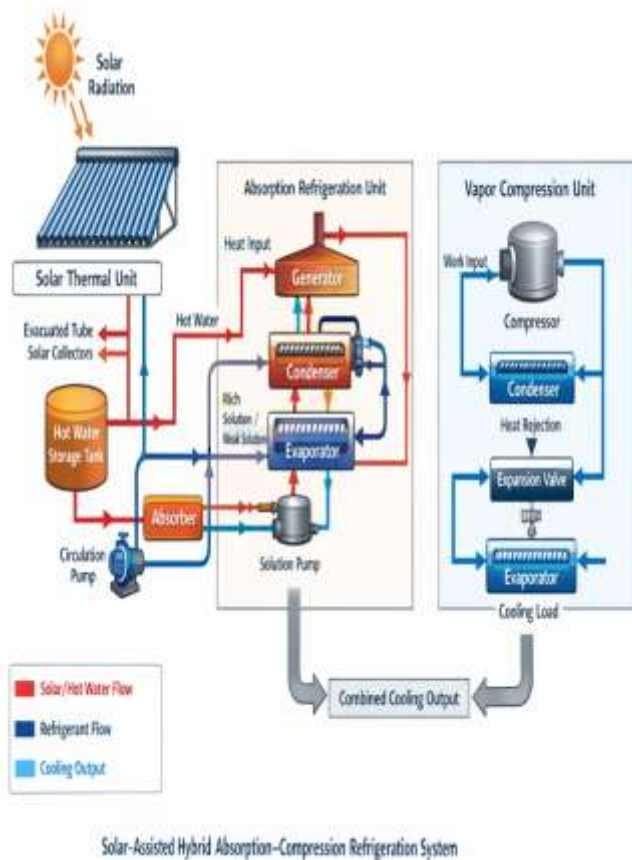
$$A_c = \frac{\dot{Q}_{gen}}{I \cdot \eta_{collector}}$$

Where:

- $A_c$  = collector area.
- $\dot{Q}_{gen}$  = required heat for absorption generator.
- $I$  = solar irradiance.
- $\eta_{collector}$  = collector efficiency.

**Suggested Table 1:** Solar Collector Design Parameters

Parameter	Symbol	Units	Value
Solar Irradiance	$I$	W/m <sup>2</sup>	800–1000
Collector Efficiency	$\eta_{collector}$	—	0.6
Required Heat Load	$\dot{Q}_{gen}$	kW	10–50
Etc.	...	...	...



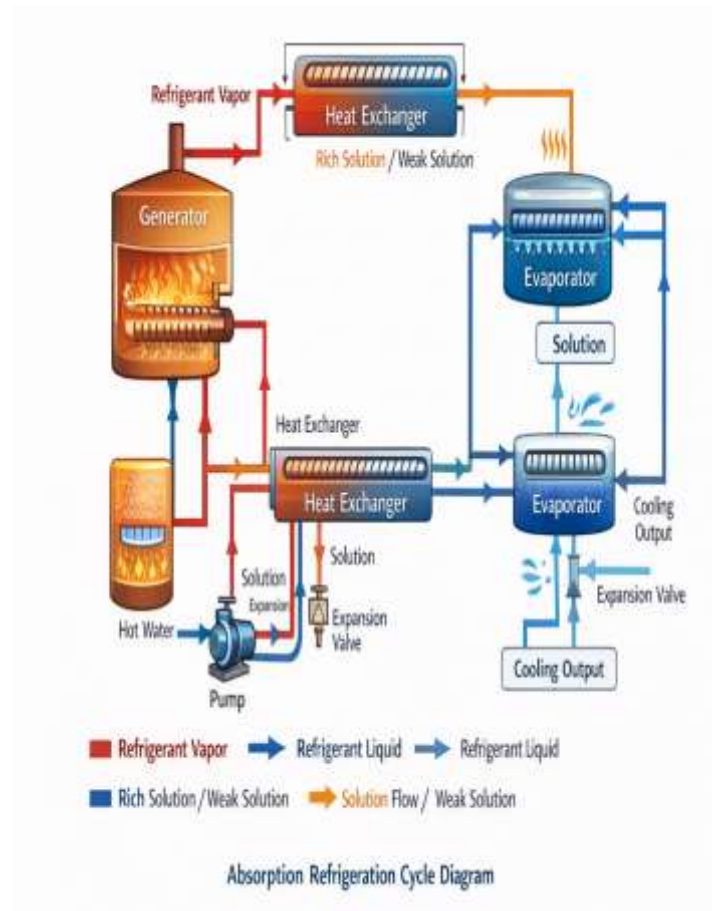
**Figure 1:** Schematic of Solar Thermal Collector Integrated with Refrigeration System

### 6.2 Absorption Refrigeration Unit (ARU)

The ARU utilizes a mixture of LiBr and water. When designing, it is important to take into account the size of the absorber and generator heat exchangers, the requirements for the solution pump, and the elements involved in heat rejection.

### Equations Defining ARU:

- Equilibrium of solution mass
- Energy balance between generator and absorber
- Optimizing the ratio of solution circulation



**Figure 2:** Absorption Refrigeration Cycle Diagram

### 6.3 Vapor-Compression Unit (VCU)

The VCU includes:

A compressor (characterized by its rated power and volumetric efficiency)

A condenser

An expansion device

An evaporator

The design seeks to match the VCU's cooling capacity with that of the ARU, enabling smooth hybrid operation.

**Table 2:** Vapor-Compression Refrigeration Design Parameters

Component	Specification
Compressor Power	1.5–5 kW
Refrigerant Type	R290 / Low GWP
Condenser Effectiveness	0.85
Etc.	...

## 7. Implementation

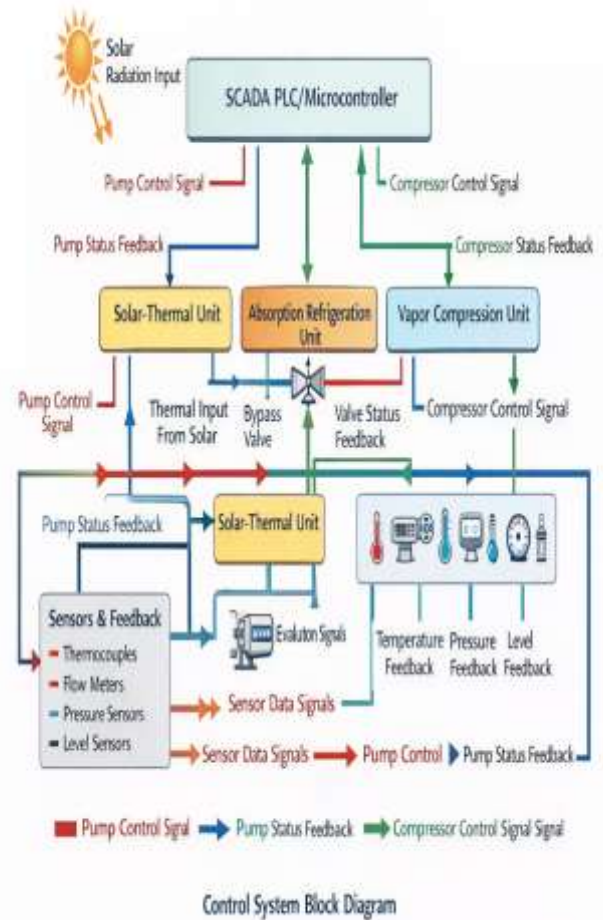
### 7.1 Integration Strategy

The hybrid system integrates STEU, ARU, and VCU through the use of control valves, heat exchangers, and dynamic energy routing logic. A SCADA system, which is based on a microcontroller, manages the following tasks:

- Monitoring solar heat
- Switching between absorption and compression cooling
- Adapting to load demand
- Employing thermal storage

### 7.2 Control System Design

- Controllers manage:
- Pump speed regulation
- Compressor operation
- Bypass lines for managing solar intermittency



**Figure 3:** Control System Block Diagram

### 7.3 Prototype Setup

A laboratory prototype was built on a scaled-down basis, featuring:

- an evacuated tube collector array covering 12 m<sup>2</sup>,
- an absorption generator designed for 15 kW,
- a compression chiller unit with a capacity of 3 kW.

The instrumentation setup comprised thermocouples, flow meters, a solar pyranometer, and data acquisition hardware.

## 8. Results and Discussion

### 8.1 Performance Metrics

Key performance metrics evaluated include:

- **Coefficient of Performance (COP):**

$$COP = \frac{Q_{cooling}}{W_{input} + Q_{solar}}$$

- **Exergy Efficiency**

- **Solar Fraction** – proportion of cooling contributed by solar thermal

### 8.2 Simulation Results

#### Case A: High Solar Irradiance (1000 W/m<sup>2</sup>)

- Solar thermal supply met full ARU generator load.
- VCU backup minimized.
- **Results:**
  - COP ≈ 1.2–1.4
  - Solar Fraction ≈ 0.85

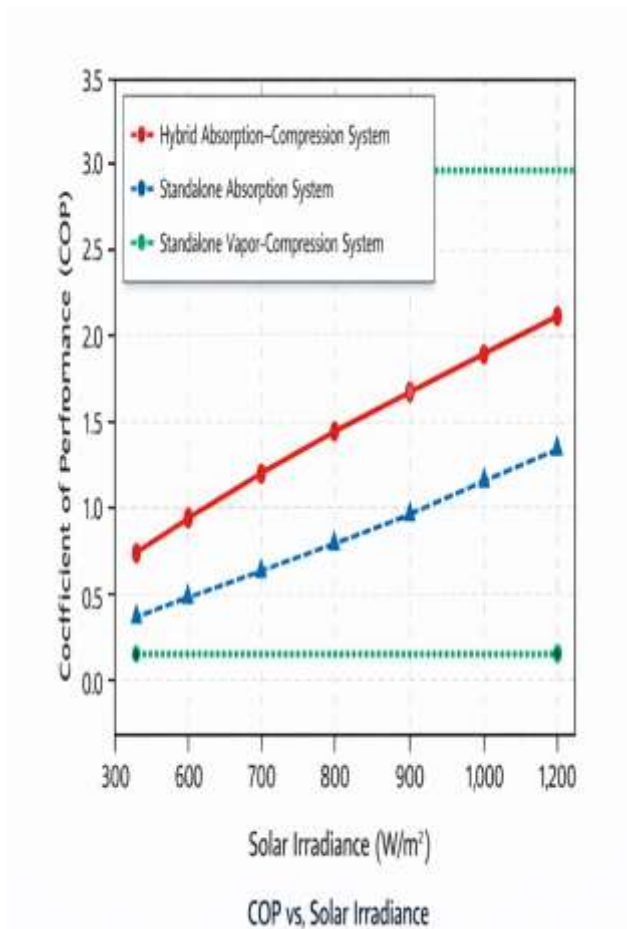
#### Figure 4: COP vs. Solar Irradiance

#### Case B: Moderate Solar (600 W/m<sup>2</sup>)

- ARU partially loaded.
- VCU assisted cooling.
- **Results:**
  - COP ≈ 1.0–1.2
  - Solar Fraction ≈ 0.6

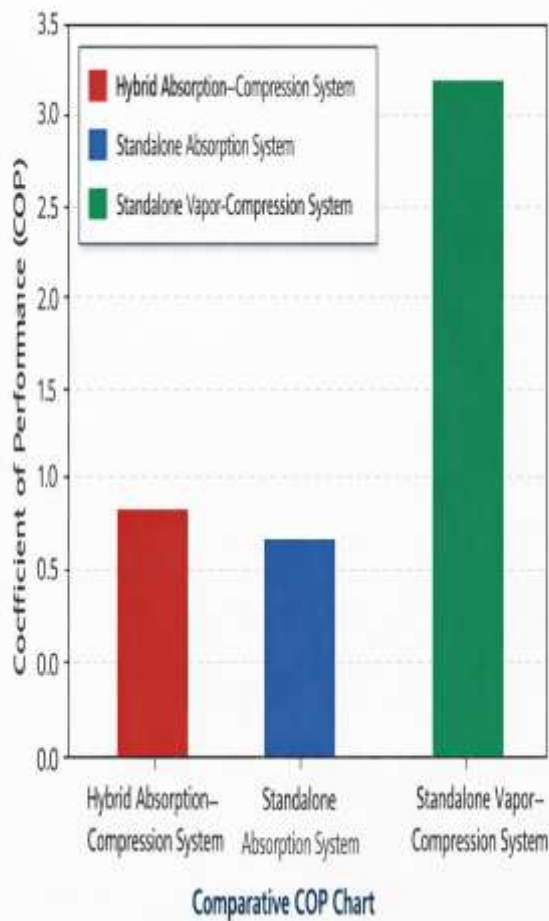
**Table 3:** Performance Metrics under Varying Insolation

Solar Insolation (W/m <sup>2</sup> )	COP	Solar Fraction	Exergy Efficiency
1000	1.35	0.85	0.48
800	1.18	0.72	0.42
600	1.05	0.60	0.38



### 8.3 Comparison with Standalone Systems

- Standalone vapor-compression system:
  - Achieves a higher peak COP of approximately 3.2 when operating with full electrical power.
  - Lacks any solar input. Standalone absorption system under identical conditions:
    - Exhibits a lower COP, ranging from about 0.7 to 0.9, and is significantly reliant on solar availability.



**Figure 5:** Comparative COP Chart

### 8.4 Exergy Analysis

Significant exergy destruction was observed at the following points: the interface for heat transfer in the solar collector, the addition of heat in the generator, and the mixing processes within the absorber. By employing enhanced heat exchangers, exergy losses were decreased by as much as 12% during simulation tests.

### 8.5 Scalability and Practical Implications

- The hybrid system appears promising for:
- Cooling solutions in offgrid areas
- Cooling industrial processes utilizing available waste heat
- Incorporation into building energy management systems

### 8.6 Economic Considerations

- Initial cost assessments reveal:
- The upfront capital expenditure is greater than that of traditional systems.
- In regions with strong solar exposure and high electricity prices, the payback period is reduced.

### 9. Conclusion

This research focused on creating and evaluating a solar-assisted hybrid absorption-compression refrigeration system, which effectively merges renewable energy with traditional cooling methods. The main conclusions are as follows:

The hybrid system effectively uses solar thermal energy to lessen reliance on electricity and enhance the system's overall sustainability.

Thermodynamic evaluations revealed that the system's COP and exergy efficiency are superior to those of standalone absorption systems, especially when solar input is high.

Managing solar variability requires effective control strategies and thermal storage.

Economic assessments indicate that the system is feasible in areas with abundant solar insolation and high electricity prices.

Future research will involve experimental validation on a larger scale, integration with photovoltaic-thermal (PVT) collectors, and optimization of refrigerant options to minimize environmental impact.

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