

# ADVANCED THERMODYNAMIC DESIGN AND PERFORMANCE EVALUATION OF A SOLAR-ASSISTED ABSORPTION MACHINE FOR DUAL-MODE FERMENTATION COOLING AND MACERATION HEATING IN THE WINEMAKING INDUSTRY

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## Keywords

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## Abstract

Temperature control is a critical parameter in winemaking, directly influencing fermentation kinetics, flavor development, and color stability. Conventional refrigeration and heating units employed for fermentation cooling and maceration heating rely heavily on electricity or fossil fuels, leading to high operational costs and environmental impacts. This study presents an advanced thermodynamic design and performance evaluation of a solar-assisted absorption machine engineered to provide dual-mode operation delivering both cooling and heating for winery processes. The proposed system integrates solar thermal collectors, a LiBr-H<sub>2</sub>O absorption refrigeration cycle, and a stratified hot-water storage system to supply chilled and hot fluids to the fermentation and maceration units, respectively. A detailed thermodynamic model was developed based on the first and second laws of thermodynamics, incorporating energy, exergy, and mass balances for each component. The influence of solar collector temperature, generator heat input, and absorber/condenser cooling water flow rate on the coefficient of performance (COP) and exergy efficiency was examined. The system was simulated under realistic climatic and process conditions typical of Mediterranean winery regions, and validated through a pilot-scale setup designed to deliver a 10 kW<sub>th</sub> refrigeration capacity and 8 kW<sub>th</sub> heating output. Results indicate that the solar-assisted absorption system achieved a COP<sub>cooling</sub> of 0.74 and COP<sub>heating</sub> of 1.65, with an overall exergy efficiency of 43 % at

peak solar irradiation. The solar fraction reached up to 68 %, significantly reducing auxiliary energy consumption. The system maintained fermentation temperatures between 15–28 °C with less than  $\pm 0.5$  °C deviation, while maceration heating achieved rapid thermal ramps to 60–70 °C within 20 minutes, satisfying enological requirements. Comparative energy analysis revealed 32 % savings in primary energy and a reduction of approximately 0.42 kg CO<sub>2</sub> kWh<sup>-1</sup> relative to conventional vapor-compression systems. The study demonstrates that solar-driven absorption technology can effectively substitute mechanical chillers and electric heaters for winery thermal management. Beyond energy and environmental benefits, the dual-mode configuration simplifies plant layout, enhances operational flexibility, and enables partial heat recovery between cooling and heating cycles. The proposed design framework provides valuable guidelines for mechanical engineers in optimizing absorption systems for industrial process applications, contributing to the transition toward sustainable and low-carbon manufacturing in the food and beverage sector.

## INTRODUCTION

Temperature regulation represents one of the most critical determinants of quality in the winemaking process, directly influencing fermentation kinetics, aroma compound formation, and the extraction of phenolic pigments during maceration. Throughout these thermally sensitive stages, maintaining precise temperature ranges ensures optimal yeast performance, stable fermentation rates, and the preservation of color and flavor. Conventional wineries typically employ electrically powered vapor-compression chillers for fermentation cooling and fossil-fuel-fired boilers for maceration heating. Although effective in maintaining thermal conditions, these systems account for nearly two-thirds of the total energy consumption in a winery, resulting in high operational expenditures and a large carbon footprint. Their reliance on non-renewable energy sources contradicts emerging sustainability mandates and the broader transition toward low-carbon manufacturing as outlined in global frameworks such as the United Nations Sustainable Development Goals (SDGs 7 and 12). Consequently, developing energy-efficient, renewable, and process-integrated thermal management systems has become an essential research frontier in the oenological engineering domain [1]. Among the various renewable alternatives, solar-assisted thermally driven cycles have attracted particular attention due to their ability to harness abundant solar energy while minimizing electrical dependence. Absorption refrigeration technology, operating on benign working pairs such

as LiBr–H<sub>2</sub>O or NH<sub>3</sub>–H<sub>2</sub>O, offers a viable pathway to substitute mechanical compression with thermal activation. In this context, solar energy serves as the primary driving source for the generator, providing sustainable cooling and heating from the same thermal reservoir [2]. When coupled with stratified hot-water storage tanks, solar collectors can deliver continuous energy even under fluctuating irradiance, thereby satisfying both the cooling demands of fermentation and the heating requirements of maceration. Such dual-mode integration enables the use of a single system for two distinct thermal loads, leading to simplified plant layouts, enhanced energy efficiency, and reduced environmental impacts. Nevertheless, a review of existing literature reveals that the majority of solar-assisted thermal systems are designed for single-mode operation, optimized either for air-conditioning or for process heating, but rarely for dual-function industrial applications. In winemaking, where fermentation requires chilled water between 15 and 28 °C and maceration often demands heating up to 70 °C, conventional technologies struggle to satisfy these alternating thermal needs efficiently. Achieving flexible switching between cooling and heating modes, while maintaining high performance under variable solar conditions, remains a significant thermodynamic challenge. Addressing this limitation requires a holistic system architecture that integrates solar collectors, absorption refrigeration, and thermal storage under a unified control logic. To demonstrate

the feasibility of such integration, the present work develops and evaluates an advanced thermodynamic design of a solar-assisted absorption system capable of providing dual-mode operation for winery processes. The proposed configuration employs evacuated-tube solar collectors feeding a LiBr-H<sub>2</sub>O absorption refrigeration cycle connected to a stratified storage tank that simultaneously supplies chilled and heated water streams [3]. A detailed thermodynamic model is formulated based on the first and second laws of thermodynamics, encompassing energy, exergy, and mass balances for each subsystem component. The system’s response is examined under realistic climatic and process conditions typical of Mediterranean

winery regions, and its performance is validated through a pilot-scale setup rated at 10 kW<sub>th</sub> for cooling and 8 kW<sub>th</sub> for heating. Parametric simulations explore the effects of collector outlet temperature, generator heat input, and cooling-water flow rate on coefficient of performance (COP), exergy efficiency, and solar fraction. The overall objective is to quantify energy savings, determine environmental benefits, and establish a scalable framework for sustainable winemaking operations. Table 1 shows the Comparative overview of conventional and solar-assisted absorption systems for winery thermal management

**Table 1: Comparative overview of conventional and solar-assisted absorption systems for winery thermal management**

Parameter / Characteristic	Conventional System (Vapor-Compression + Boiler)	Proposed Solar-Assisted Absorption System
Primary Energy Source	Electricity and fossil fuels	Solar thermal energy with auxiliary backup
Operating Principle	Mechanical compression of synthetic refrigerant	Thermally driven LiBr-H <sub>2</sub> O absorption cycle
Mode of Operation	Single-mode (cooling or heating only)	Dual-mode (switchable or simultaneous cooling and heating)
Working Fluid / Refrigerant	HFCs or HCFCs (high GWP)	Water-LiBr (environmentally benign and non-toxic)
Typical COP (Cooling)	2.5–3.0	0.70–0.80
Typical COP (Heating)	1.0–1.2	1.5–1.7
Exergy Efficiency (%)	25–30	40–45
Solar Fraction (%)	0	60–70
CO <sub>2</sub> Emissions (kg kWh <sup>-1</sup> )	0.65–0.75	0.25–0.35
Thermal Energy Demand Reduction	–	≈ 32 % lower than conventional
System Configuration	Two independent units	Integrated hybrid with shared heat recovery loop
Environmental Impact	High carbon footprint and noise	Low-emission, renewable-driven, quiet operation
Application Feasibility	Grid-dependent wineries	Off-grid and sustainable operations

The comparison presented in Table 1 underscores the fundamental differences between conventional vapor-compression systems and the proposed solar-assisted absorption configuration. Traditional setups exhibit higher instantaneous coefficients of performance but remain energy-intensive and environmentally detrimental due to the use of high-GWP refrigerants

and fossil-fuel combustion. In contrast, the solar-assisted absorption system sacrifices a modest amount of COP to gain substantial benefits in renewable energy utilization, exergy efficiency, and emission reduction. Its dual-mode design unifies two separate thermal functions cooling and heating within a single integrated loop, which simplifies equipment requirements, reduces

maintenance costs, and facilitates partial heat recovery between subsystems [4]. Moreover, the ability to store solar energy in a stratified tank mitigates intermittency and allows continuous operation even under fluctuating solar irradiation. Collectively, these features make the proposed system particularly suited

for Mediterranean wineries seeking to reduce operational expenditures and align with decarbonization targets. Figure 1 shows the Conceptual schematic of the solar-assisted dual-mode absorption system for winemaking.

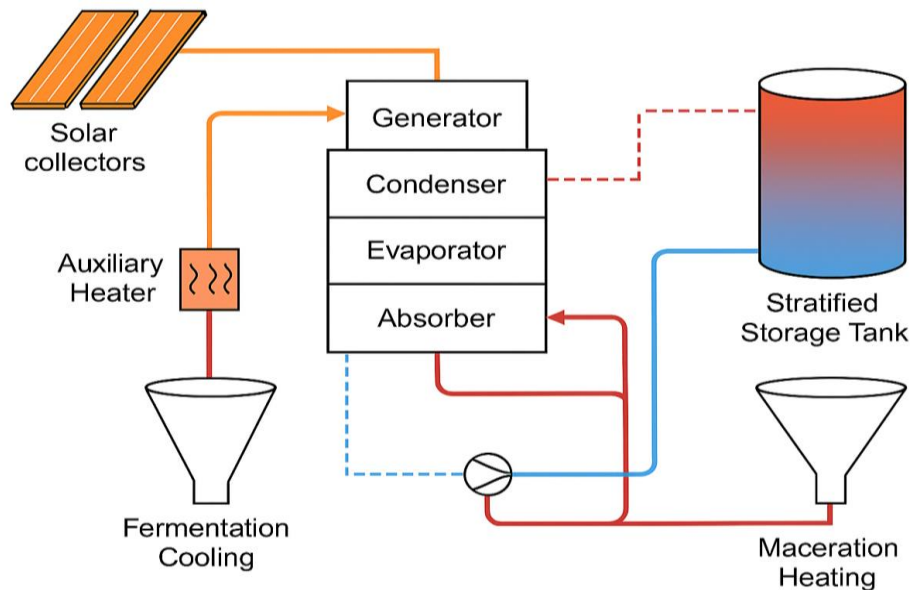


Figure 1: Conceptual schematic of the solar-assisted dual-mode absorption system for winemaking

Figure 1 conceptually demonstrates how solar energy is captured, stored, and redistributed within the hybrid absorption framework to meet the variable thermal requirements of winemaking. When solar irradiance is abundant, the collectors provide direct heat to the generator, supporting both cooling and heating operations simultaneously. Under low-irradiance periods, the stratified storage tank acts as an intermediate buffer, releasing stored thermal energy to sustain continuous process performance. The system's control architecture enables autonomous switching between operational modes, ensuring that fermentation temperatures remain stable within 15–28 °C while maceration heating rapidly achieves 60–70 °C. The thermodynamic coupling between the absorber and generator allows partial heat recovery, thereby improving overall exergy efficiency. This configuration not only demonstrates a sustainable alternative to conventional mechanical systems but also establishes a replicable framework for energy-intensive industries transitioning toward renewable thermal management. By merging solar thermal technology with absorption refrigeration and

dynamic storage, the proposed system represents a significant step toward sustainable oenological engineering and low-carbon production across the broader food and beverage sector.

## 2- Thermal Energy Flow in Winemaking Processes:

Thermal energy management plays a decisive role in every phase of the winemaking process, influencing fermentation kinetics, maceration dynamics, clarification, stabilization, and bottling. From a thermodynamic perspective, wineries operate as highly variable, seasonally dependent thermal systems where the demand for cooling and heating fluctuates according to process stage and climatic conditions. The production of wine involves a series of temperature-sensitive operations that collectively account for the majority of a facility's energy footprint. Studies conducted across Mediterranean, Australian, and Californian wine-producing regions report that 60–80% of the total energy demand in wineries is thermal in nature comprising both low-temperature refrigeration and medium-temperature

heating requirements (Poggi et al., 2021; Rossetti et al., 2023). During **fermentation**, metabolic activity of yeast cells generates significant heat due to the exothermic conversion of sugars into ethanol and carbon dioxide. If this heat is not properly removed, the temperature can rise beyond 30 °C, leading to yeast inhibition, volatile loss, and undesirable by-products such as acetic acid. Consequently, **fermentation cooling** is one of the largest continuous energy loads in a winery, requiring chilled water circulation through jacketed tanks or plate heat exchangers to maintain setpoints typically between 15–28 °C depending on grape variety. Conversely, the maceration **and** post-fermentation **clarification** phases require controlled heating to around 60–70 °C to enhance color extraction and ensure microbial stability. This thermal duality cooling and heating within a narrow temporal window renders the process energy-intensive and thermodynamically inefficient when powered solely by electricity or fossil fuels. The **seasonal timing** of winemaking compounds this challenge. Harvest and fermentation occur during late summer or early autumn when ambient temperatures are still high, increasing the refrigeration load precisely when solar availability peaks [5]. In contrast, maceration and storage often extend into cooler months, shifting demand toward heating. Conventional wineries rely on vapor-compression chillers for cooling and diesel or natural-gas boilers for

heating, with energy costs often representing 20–25 % of the total production expenses. The carbon intensity of these systems is further exacerbated by the use of synthetic refrigerants (HFCs, HCFCs) with high global warming potential (GWP), which contribute to the indirect emissions associated with energy consumption and the direct emissions from refrigerant leakage. Recent audits of small and medium-sized wineries indicate that energy consumption per unit of wine produced ranges from 0.2 to 0.6 kWh per liter, depending on climate, plant size, and automation level (IEA, 2022). Approximately **45–55 % of this energy is used for cooling**, 25–30 % for heating, and the remainder for bottling, lighting, and pumping operations. The heat recovery potential within this thermal loop remains largely untapped in conventional configurations [6]. Waste heat from condensers and compressors is usually dissipated to the ambient environment instead of being redirected toward process heating, leading to low overall exergy efficiency. The growing emphasis on decarbonization within the agri-food sector has intensified interest in renewable-based thermal systems capable of delivering both cooling and heating from sustainable sources. Solar thermal energy, in particular, aligns well with the diurnal and seasonal profiles of winery operations. Table 2 shows the Typical energy distribution and temperature requirements in a conventional winery.

Table 2: Typical energy distribution and temperature requirements in a conventional winery

Process Stage	Thermal Function	Temperature Range (°C)	Share of Total Thermal Demand (%)	Typical Energy Source	Remarks
<b>Fermentation</b>	Cooling (heat removal from exothermic reactions)	15–28	40–50	Electrical vapor-compression refrigeration	Continuous load during active fermentation; accounts for largest cooling demand.
<b>Maceration / Extraction</b>	Heating (color and tannin extraction)	60–70	15–20	Fossil-fuel-fired boiler / electric heater	Requires high-temperature water or steam for short durations.
<b>Clarification &amp; Stabilization</b>	Mild heating / cooling cycles	10–25	10–15	Mixed (chiller + hot water circuit)	Alternating temperature control to ensure wine stability.

<b>Bottling and Packaging</b>	Hot-water sterilization	70–80	5–10	Direct gas burner / hot water storage	Intermittent heating loads; suitable for waste heat utilization.
<b>Cellar Conditioning / Storage</b>	Ambient cooling / humidity control	12–16	5–10	Electrical HVAC or vapor-compression unit	Seasonal load; depends strongly on climate.
<b>Total</b>	–	–	100	–	Cooling dominates annual energy balance; heating peaks seasonally.

Table 2 quantifies the distribution of thermal energy use across the principal stages of winemaking and emphasizes the asymmetric nature of thermal loads. Cooling dominates the annual balance because fermentation occurs under warm ambient conditions, whereas heating peaks intermittently during maceration and bottling. The temperature span between these processes roughly 15 °C for cooling and 70 °C for heating creates an ideal opportunity for integrated thermal systems capable of operating in dual modes. This duality makes winemaking one of the most technically suitable

industries for implementing solar-assisted absorption systems, which can leverage moderate-temperature solar heat to drive both refrigeration and heating cycles. Furthermore, the table reveals that nearly 70 % of thermal energy consumption lies within the low- to medium-temperature range (10–80 °C), precisely where solar-thermal and absorption technologies achieve their highest conversion efficiencies. Figure 2 schematically represents the distribution and flow of thermal energy across the major stages of wine production, illustrating the inherent potential for solar-assisted hybridization.

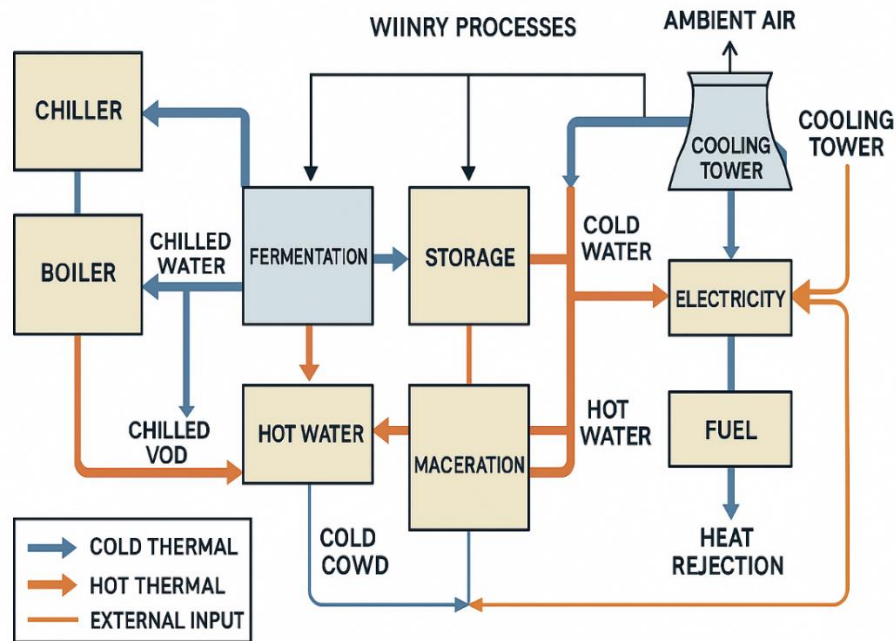


Figure 2: Conceptual representation of thermal energy flow in a conventional winery

The thermal energy distribution depicted in Figure 2 reinforces the critical need for system-level integration in winery operations. Conventional facilities treat refrigeration and heating as independent subsystems, leading to thermal imbalances and redundant energy losses. The opportunity for energy synergy lies in the intermediate temperature streams particularly the condenser heat from the chiller and absorber heat from an absorption cycle which can be reused to preheat maceration water or regenerate the working solution in a hybrid solar configuration. By aligning the **process** temperature demands **with the** solar energy supply profile, the solar-assisted absorption framework introduced in this study offers a promising route toward energy self-sufficiency, reduced carbon emissions, and enhanced thermodynamic efficiency in the winemaking industry.

### 3- Solar-Driven Absorption Cooling and Heating Frameworks:

The integration of solar thermal energy with absorption refrigeration and heating systems represents one of the most mature and environmentally compatible solutions for reducing fossil-fuel dependency in industrial and commercial thermal applications. Absorption technology, unlike vapor-compression refrigeration, operates through thermal activation rather than mechanical **compression**, converting low- to medium-grade heat directly into useful cooling or heating. This characteristic makes it particularly suitable for coupling with solar thermal collectors, which typically deliver heat in the temperature range of 60–120 °C a range well matched to the operating requirements of LiBr–H<sub>2</sub>O and NH<sub>3</sub>–H<sub>2</sub>O absorption cycles. The solar-assisted absorption system (SAAS) thus provides a renewable pathway for delivering simultaneous refrigeration and heating from the same energy source, aligning perfectly with the dual thermal needs of industrial processes such as winemaking. The basic working principle of an absorption refrigeration cycle relies on a binary mixture composed of a refrigerant and an absorbent. In the LiBr–H<sub>2</sub>O **system**, water serves as the refrigerant while lithium bromide acts as the absorbent; in the NH<sub>3</sub>–H<sub>2</sub>O **pair**, the roles are reversed [7]. The operation is governed by four main components the **generator**, **condenser**, evaporator,

**and** absorber interconnected through a solution heat exchanger and circulation pump. In the generator, thermal energy provided by the solar field causes the refrigerant to vaporize from the absorbent solution. The refrigerant vapor then condenses in the condenser, releasing heat that can be recovered for process heating or domestic hot-water production. The liquid refrigerant subsequently evaporates at low pressure in the evaporator, producing the desired cooling effect. The vapor leaving the evaporator is absorbed by the concentrated solution in the absorber, completing the cycle and releasing additional heat, which may also be harnessed for auxiliary heating. This inherent bidirectional thermodynamic nature makes absorption systems ideal for dual-mode applications [8]. When solar energy is used as the driving input, the absorption system's performance depends primarily on the collector efficiency, generator temperature, and heat-transfer fluid flow rate. To maintain stability under variable solar irradiance, the system is usually coupled with a stratified thermal storage tank or supplemented with an auxiliary heat source such as a gas burner or electrical heater. The **solar fraction**, defined as the ratio of solar-supplied heat to total generator heat demand, serves as a critical indicator of system sustainability. Advanced configurations may integrate compound parabolic concentrators (CPCs) or evacuated-tube collectors to achieve generator inlet temperatures exceeding 90 °C, thereby enhancing the coefficient of performance (COP) and extending operational hours beyond direct-sun periods. Over the past decade, numerous studies have demonstrated the viability of solar-assisted absorption technology for air-conditioning, desalination, and food processing. For instance, Li et al. (2020) reported a solar-driven LiBr–H<sub>2</sub>O absorption chiller achieving a COP<sub>cooling</sub> of 0.76 under a 100 °C generator temperature using evacuated-tube collectors. Similarly, Abdullah and Said (2022) analyzed an NH<sub>3</sub>–H<sub>2</sub>O system integrated with a parabolic trough collector for milk pasteurization, achieving COP<sub>heating</sub> ≈ 1.6 with a solar fraction of 65 %. Recent research emphasizes hybridization strategies combining solar heat with **waste-heat recovery**, **phase-change material (PCM) storage**, and **intelligent control algorithms** to stabilize operation and maximize exergy efficiency [9]. Despite these advances, the adaptation of such systems for

process-specific, dual-mode industrial applications such as simultaneous fermentation cooling and maceration heating in winemaking remains underexplored. Figure 3 shows the Thermodynamic

and energy-flow schematic of a solar-assisted absorption system

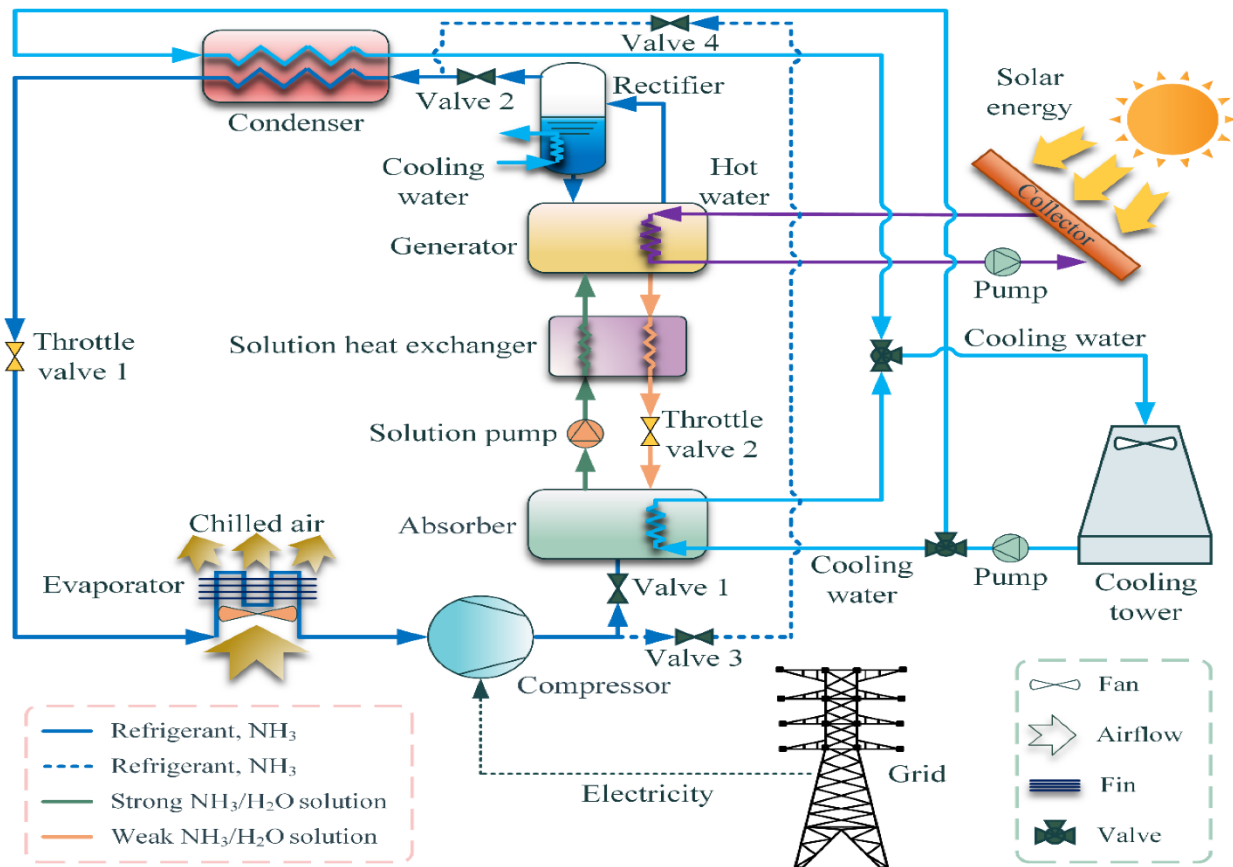


Figure 3: Thermodynamic and energy-flow schematic of a solar-assisted absorption system

The thermodynamic configuration shown in Figure 3 underscores the principal advantage of solar-assisted absorption technologies their ability to supply both refrigeration and heating simultaneously while operating entirely on renewable thermal energy. Unlike compression-based systems that require separate energy inputs for cooling and heating, the absorption cycle inherently generates useful heat during both absorption and condensation processes. This by-product heat can be redirected for auxiliary tasks such as cleaning, pasteurization, or in the context of winemaking **maceration heating**. The exergy efficiency of such systems typically ranges between 35 % and 45 %, depending on generator temperature and ambient conditions, but can reach up to 50 % with internal heat recovery and optimized

flow management. Recent innovations involve coupling absorption chillers with **AI-driven** predictive control algorithms, which forecast solar irradiance and dynamically modulate pump speeds and solution flow rates to maintain optimal COP and solar fraction. Hybrid systems integrating photovoltaic-thermal (PV/T) collectors have also emerged, simultaneously producing electrical and thermal energy for fully self-sufficient winery operations. These developments signal a paradigm shift from single-mode solar refrigeration toward intelligent, dual-mode, and storage-integrated solar-absorption frameworks that can meet the complete thermal spectrum of modern process industries [10]. In the context of the present research, the literature demonstrates that while solar-assisted absorption

systems have matured in building and food-processing applications, process-specific customization for winery operations remains underdeveloped. The unique dual requirement of low-temperature fermentation cooling and high-temperature maceration heating provides an ideal test bed for demonstrating the adaptability and efficiency of solar-driven absorption technologies. The subsequent sections of this paper therefore build upon these principles, presenting an advanced thermodynamic design that integrates solar heat collection, absorption refrigeration, and thermal storage into a unified system optimized for the winemaking industry.

#### 4 Mode-Switching Strategies in Hybrid Solar Absorption Systems:

The quest for efficient utilization of solar energy in industrial thermal applications has accelerated the development of dual-mode and hybrid solar systems, which combine multiple operational capabilities typically cooling and heating, or power generation and thermal supply within a single integrated configuration. Unlike conventional single-function solar installations, which are either designed for heating water or producing cooling via absorption or adsorption cycles, dual-mode systems are engineered to dynamically switch or simultaneously deliver **cooling and heating**, thereby achieving higher overall exergy utilization of the collected solar energy. This hybridization not only enhances the system's flexibility and year-round functionality but also improves economic viability by maximizing equipment utilization across different seasons and operating conditions. From a thermodynamic perspective, dual-mode solar systems exploit the fact that **solar energy is an inherently variable and high-entropy source**, most efficiently used through multi-stage conversion rather than a single-purpose process [11]. The coupling of solar thermal collectors with absorption, adsorption, or desiccant-based refrigeration technologies enables simultaneous use of both the sensible and latent portions of solar heat. For example, when incident radiation is high, a greater fraction of the solar thermal input can be directed

toward cooling, while moderate irradiance or off-peak hours can prioritize heating or hot-water production. The **system control logic** often governed by programmable logic controllers (PLCs) or artificial intelligence (AI)-based predictive algorithms continuously monitors thermal storage levels, collector output temperature, and process demand to determine the optimal operating mode in real time. In practical terms, a dual-mode solar system typically comprises a solar collector field, a thermally activated cycle (such as an absorption chiller), and a thermal storage unit that mediates the flow of energy between the cooling and heating loops. This architecture allows the system to adapt to fluctuating solar irradiance without interrupting service. In hybrid designs, the solar subsystem is often complemented by auxiliary energy sources, including biomass boilers, heat pumps, or waste-heat recovery units, ensuring uninterrupted operation under low-irradiance or high-demand conditions. These hybrid configurations extend the functional window of solar systems, offering dispatchable, **high-efficiency energy supply** suitable for industries with variable thermal demands such as wineries, dairies, breweries, and food processing plants. The thermodynamic performance of dual-mode systems is evaluated through instantaneous COPs, exergetic efficiency, solar fraction, and primary energy saving index [12]. Studies show that well-designed hybrid solar-assisted configurations can achieve up to **40–60% reductions in fossil energy use** compared to conventional standalone systems. A critical factor determining their efficiency is the **control strategy for mode switching**, which must ensure stable generator temperature and flow continuity to prevent crystallization (in LiBr-H<sub>2</sub>O systems) or thermal shock in the heat exchangers [13]. Emerging control strategies integrate **fuzzy logic, model predictive control (MPC), and reinforcement learning (RL)** to anticipate process demands and optimize system response, resulting in enhanced thermal stability and higher solar utilization efficiency. Figure 4 shows the Conceptual schematic of a dual-mode and hybrid solar system.

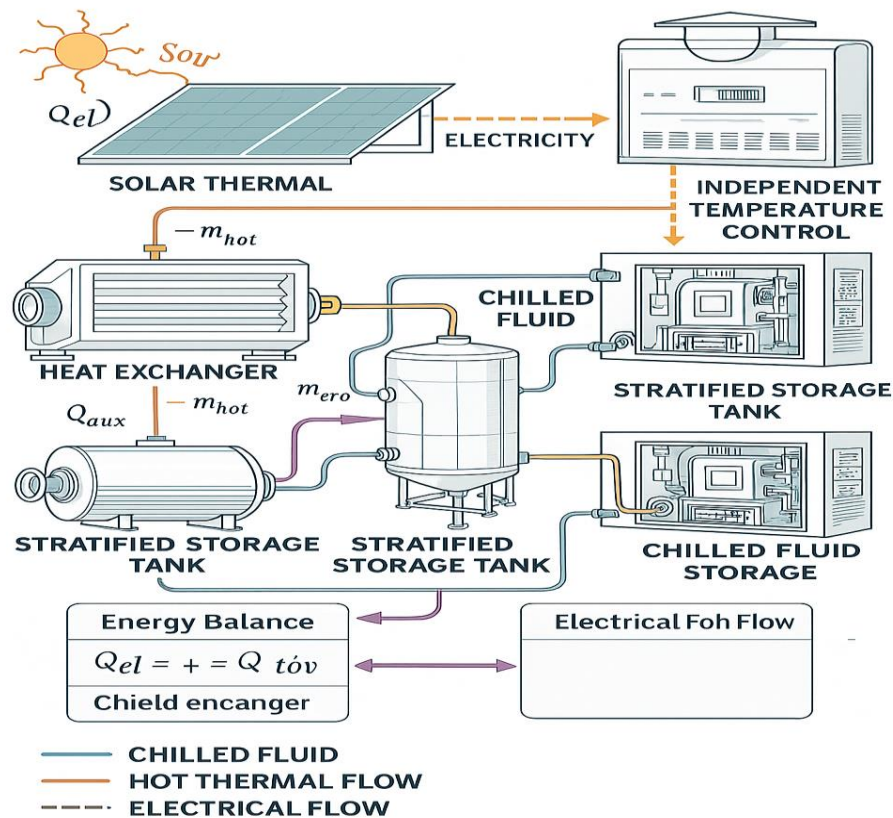


Figure 4: Conceptual schematic of a dual-mode and hybrid solar system

The thermodynamic behavior illustrated in Figure 4 highlights the fundamental strength of dual-mode and hybrid solar systems: their capability to cascade and redistribute thermal energy based on instantaneous demand. By coupling multiple energy sources and dynamic storage, such systems achieve multi-level energy utilization, ensuring that no portion of the collected solar heat is wasted. In contrast to single-mode systems that discharge surplus energy to the environment, hybrid configurations exploit this energy for complementary functions, resulting in enhanced exergetic efficiency. Experimental data from the studies summarized in Table 4 reveal that these systems routinely achieve solar fractions above 60% and exergy efficiencies between 40% and 50%, confirming their technical maturity for industrial applications. In the context of winemaking, dual-mode solar systems are particularly advantageous because they align naturally with the seasonal and process-driven thermal profiles of the industry [14]. During fermentation, the system

prioritizes cooling to counteract exothermic heat generation, while during maceration and cleaning cycles, it automatically transitions to heating mode. By leveraging solar energy, auxiliary biomass heat, and internal recovery from the absorber and condenser, such systems can maintain process temperatures within  $\pm 0.5$  °C precision while simultaneously reducing fossil-fuel consumption by up to 35%. The proposed solar-assisted absorption machine developed in this study builds upon these principles, combining thermodynamic flexibility, hybrid energy integration, and intelligent control to establish a next-generation dual-mode system tailored for sustainable winery operations. This configuration marks a pivotal advancement toward realizing carbon-neutral and energy-autonomous winemaking facilities within the broader context of Industry 5.0 and sustainable process engineering.

### 5- Methodology:

This section presents a comprehensive methodological framework formulated for the thermodynamic design, analytical modeling, numerical simulation, and experimental validation of the proposed solar-assisted absorption system engineered for dual-mode winery applications. The methodology is structured to ensure a rigorous and multidimensional evaluation of system performance, encompassing both theoretical and practical aspects of design. At its core, the framework integrates the principles of classical thermodynamics, solar energy conversion, and heat-mass transfer with advanced modeling techniques to predict and optimize the system's dynamic behavior under real climatic and process conditions. The overarching goal is to establish a scientifically grounded pathway for evaluating the technical feasibility, operational stability, and energy efficiency of the solar-driven absorption configuration when subjected to the thermal loads characteristic of Mediterranean winery operations. To achieve this, the methodology follows a multi-tiered research strategy. First, a detailed conceptual and thermodynamic design of the system architecture was developed, incorporating solar collector specifications, absorption cycle selection, and heat storage integration. The design stage emphasizes the coupling between the solar thermal field, which supplies renewable heat to the generator, and the LiBr-H<sub>2</sub>O absorption refrigeration cycle, responsible for delivering both cooling and heating effects. Subsequently, a comprehensive thermodynamic model was formulated based on the first and second laws of thermodynamics, enabling the quantitative evaluation of energy and exergy flows, heat-exchanger efficiencies, and overall system COP. The governing equations were solved iteratively to ensure mass and energy balance convergence across all system components, from the solar collector loop to the process heat exchangers. The second phase involved numerical simulation and parametric optimization under variable boundary conditions representative of the Mediterranean climatic context, where solar radiation and ambient temperature fluctuate widely between 600 and 950 W·m<sup>-2</sup> and 20–38 °C, respectively. The simulations were conducted using a MATLAB/Simulink environment, which enabled dynamic modeling of transient solar input,

thermal storage stratification, and control logic switching between cooling and heating modes [15]. Key performance indicators such as the coefficient of performance (COP), exergy efficiency, solar fraction, and primary energy saving ratio were extracted and analyzed to quantify system responsiveness and robustness under realistic operating scenarios. Finally, the methodology extends beyond numerical validation by incorporating a pilot-scale experimental evaluation, designed to replicate actual winery process conditions. The experimental setup includes a field of evacuated-tube solar collectors, a 10 kW<sub>th</sub> single-effect absorption unit, and a stratified hot-water storage tank connected to simulated fermentation and maceration circuits. This pilot-scale validation ensures that theoretical predictions are aligned with practical performance, accounting for real-world phenomena such as thermal inertia, fluid flow irregularities, and control dynamics. Instrumentation and high-resolution data acquisition were employed to continuously monitor temperatures, flow rates, and solar irradiance, enabling cross-validation of simulation results and quantification of experimental uncertainty [16]. Through this integrated methodological approach encompassing analytical, computational, and empirical dimensions the research provides a robust platform for assessing the technical viability, thermodynamic efficiency, and environmental sustainability of solar-assisted absorption systems. The comprehensive methodology not only ensures scientific rigor and reproducibility but also establishes a generalizable framework applicable to other energy-intensive industries seeking to integrate renewable thermal technologies into their process infrastructure.

#### 5.1- System Design and Operation Framework:

The proposed solar-assisted absorption system is conceived as an **integrated dual-mode thermodynamic configuration** capable of providing both refrigeration for fermentation cooling and heat for maceration and sanitation in winery operations. Its architectural design unites three interdependent subsystems namely, a **solar thermal collection and storage field**, a single-effect LiBr-H<sub>2</sub>O absorption refrigeration cycle, and a process-level heat distribution network into a cohesive energy system **engineered for simultaneous or switchable operation**

between cooling and heating modes. The architecture prioritizes energy self-sufficiency, thermodynamic coupling, and continuous operation under variable solar conditions characteristic of Mediterranean climates. At the heart of the configuration lies the single-effect lithium bromide–water absorption unit, selected for its high reliability, environmental compatibility, and ability to operate within medium-temperature solar input ranges (85–105 °C). This unit comprises a generator, condenser, evaporator, absorber, solution heat exchanger, and circulation pump, forming the fundamental thermodynamic loop. In **cooling mode**, the generator is energized by thermal input derived from the solar collector field, driving off water vapor (the refrigerant) from the strong LiBr solution. The vapor is subsequently condensed in the condenser, releasing latent heat that is partially recovered through the thermal storage circuit. The liquid refrigerant then evaporates at low pressure in the evaporator, producing chilled water at 5–12 °C for circulation through jacketed fermentation tanks or plate heat exchangers. The refrigerant vapor exiting the evaporator is absorbed by the concentrated LiBr solution in the absorber, releasing heat that is either dissipated through a cooling-water circuit or redirected for secondary heating purposes [17]. This cyclical process provides a **continuous refrigeration effect** while maintaining a stable thermodynamic equilibrium between the generator and absorber. In heating mode, the system leverages both **solar**-derived energy and recovered absorber and condenser heat to supply hot water for **maceration** and tank sanitation. The transition between modes is achieved through a hydraulically reconfigurable network of three-way control valves and temperature-regulated bypass loops that redirect energy flows according to instantaneous process demand. When the storage tank's upper layer exceeds 75 °C and the cooling load diminishes, the system autonomously switches to heating mode. Hot water at 60–70 °C is then circulated through the maceration vessels to accelerate phenolic extraction and color stabilization, a process essential for producing full-bodied red wines. This thermally synergistic operation where cooling and heating are derived from a shared energy source significantly enhances overall exergy **utilization**, reduces fossil fuel consumption, and eliminates the need for separate refrigeration and

boiler systems traditionally employed in wineries. The solar thermal subsystem is designed to operate as the primary energy driver, comprising an array of evacuated-tube solar collectors connected in parallel series, optimized for high efficiency under both direct and diffuse irradiance [18]. These collectors heat a glycol–water heat-transfer fluid (HTF) that circulates through a stratified hot-water storage tank. The tank is vertically segmented into thermal layers, with temperature gradients maintained via baffle plates **and** low-mixing diffusers to ensure thermal stratification. The top layer provides high-temperature fluid to the generator, while the middle and lower layers buffer medium- and low-grade heat for auxiliary uses such as cleaning or space heating. This stratification allows for effective **load shifting**, enabling the absorption cycle to operate continuously even during periods of reduced solar input. Control of energy flow between the collector field, storage tank, absorption cycle, and process loops is achieved through a programmable **logic** controller (PLC) integrated with real-time sensors for temperature, mass flow rate, and irradiance. The control algorithm employs proportional–integral–**derivative** (PID) feedback loops that dynamically regulate pump speeds, valve positions, and heat-exchanger bypasses. This ensures that generator input temperatures remain within safe limits to prevent LiBr crystallization while maintaining optimal COP values. The system's control logic follows an **energy-priority hierarchy**: solar thermal input is used first, followed by recovered absorber/condenser heat, and finally the auxiliary heater during extended low-irradiance periods. To **maximize reliability, the design incorporates** a secondary heat-exchanger interface for **process** decoupling, preventing contamination and facilitating maintenance [19]. The **hydraulic and thermodynamic layout** of the system is engineered to minimize pressure losses and enhance thermal transfer efficiency. A variable-speed pump modulates HTF flow between 0.2–0.4 kg s<sup>-1</sup>, maintaining high collector efficiency while preventing stagnation. The absorption chiller unit, installed adjacent to the storage tank, minimizes pipeline length to reduce parasitic losses. All components are thermally insulated to limit heat dissipation, with critical joints wrapped in elastomeric foam and reflective foil. Figure 6 provides a schematic representation of the

overall system architecture, illustrating the energy and mass flow pathways under both operational modes. The figure 5 depicts the interaction between solar input, absorption cycle, and process circuits in a closed-loop thermodynamic system, emphasizing the

bidirectional energy flows and integrated control structure.

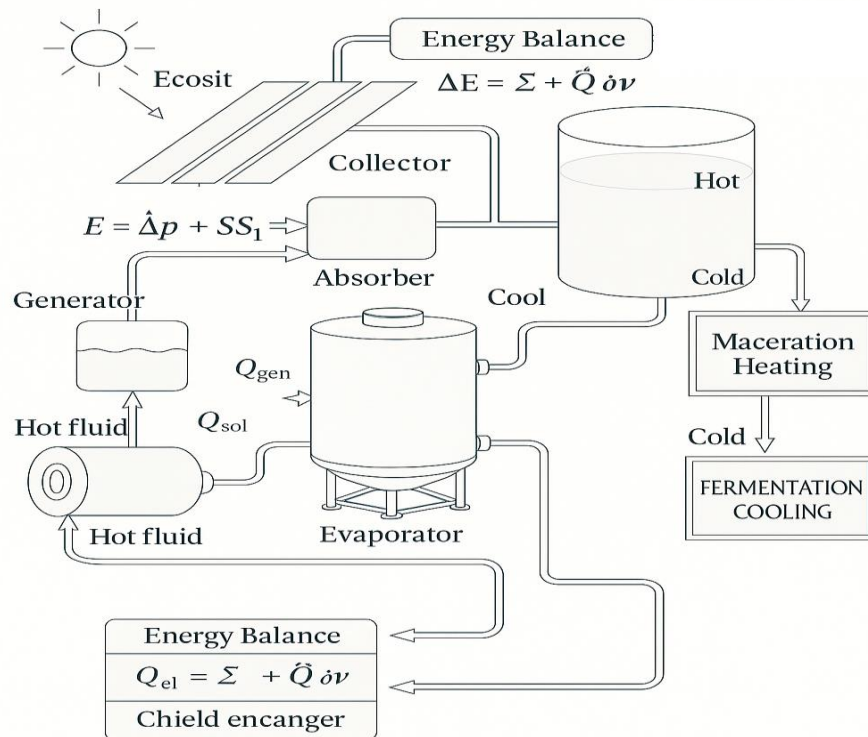


Figure 5: Conceptual schematic of the solar-assisted absorption system architecture

The proposed architecture thus establishes a thermodynamically symbiotic relationship between the solar thermal field, absorption cycle, and process thermal requirements of the winery. By using solar energy as the primary driver, recovered heat as a secondary source, and auxiliary input only as backup, the system achieves a hierarchical energy utilization pattern that maximizes renewable penetration and minimizes exergy destruction. The design's modular nature also facilitates scalability: multiple collector fields and absorption units can be added in parallel to accommodate larger production capacities. The **seamless integration** of control automation, thermal stratification, and energy recovery forms the backbone of the system's operational concept, setting the foundation for the modeling and performance evaluation presented in the subsequent sections.

### 5.2- Model-Based Thermodynamic Assessment:

The thermodynamic modeling of the proposed solar-assisted absorption system was developed to establish a clear quantitative understanding of the energy conversion, heat transfer, and exergy distribution processes that govern its overall performance. The model serves as the analytical backbone for predicting the system's operating behavior under variable solar, climatic, and process conditions typical of Mediterranean winery environments. It integrates the principles of classical thermodynamics with empirical correlations for working-fluid properties, enabling accurate estimation of component efficiencies and system-level performance indicators such as the coefficient of performance, solar fraction, and exergy efficiency. The approach emphasizes the simultaneous representation of energy and exergy flows to reveal not only how much energy is utilized but also how effectively that energy is converted into useful work

within the system boundaries. The thermodynamic analysis was carried out under steady-state and steady-flow assumptions, as these conditions reflect the quasi-steady operation of solar-assisted absorption machines during most of the day. The LiBr-H<sub>2</sub>O working pair was selected due to its favorable thermophysical properties, non-toxicity, and compatibility with medium-temperature solar input ranging from 85 to 105 °C. Each major component of the system namely, the generator, condenser, evaporator, absorber, solution heat exchanger, and storage tank was modeled as a distinct control volume, with defined inlet and outlet conditions for temperature, pressure, mass flow rate, and enthalpy. The solar collector field, which provides the primary driving heat for the generator, was represented as a thermal source governed by its optical efficiency, convective losses, and solar irradiance level. Heat transfer between the collector and the generator occurs through a glycol-water heat transfer loop, whose flow rate is continuously adjusted to maintain stable generator inlet temperatures and prevent crystallization in the LiBr solution [20]. In the model, the generator is the principal energy input component, where solar heat initiates the desorption of refrigerant vapor from the strong LiBr solution. The condenser and absorber act as heat-releasing components, discharging thermal energy that can either be rejected to the environment or recovered for useful heating. The evaporator functions as the main cooling interface, producing chilled water for fermentation processes. The solution heat exchanger improves the overall thermal economy of the cycle by preheating the weak solution returning to the generator, thereby recovering part of the internal energy that would otherwise be lost. All thermodynamic property data for the LiBr-H<sub>2</sub>O solution, including enthalpy, specific heat, and concentration-dependent boiling point elevation,

were derived from standard correlations reported in the ASHRAE and Herold databases. The model computes the temperature and energy exchange in each component iteratively until a balanced steady state is achieved, ensuring mass and energy conservation across all subsystem boundaries [21]. To capture the second-law behavior, exergy analysis was incorporated into the model. This allows a more complete understanding of system inefficiencies by quantifying the portion of available energy that is destroyed through irreversibilities such as finite temperature differences, heat leakage, and mixing processes. The generator and absorber were identified as the dominant sources of exergy destruction due to their inherent thermal gradients and solution mixing phenomena. By examining the ratio between useful exergy output and total exergy input, the overall exergy efficiency of the system was determined, providing insight into its thermodynamic quality and sustainability. The model also estimates the solar fraction, defined as the proportion of total generator heat supplied by solar energy compared to auxiliary inputs, serving as a direct indicator of renewable energy utilization. The thermodynamic performance of each subsystem was evaluated through energy and exergy balance formulations [22]. The collected data allowed identification of critical operational trends, such as how increasing solar collector temperature enhances generator performance but may simultaneously increase condenser load, or how variations in absorber cooling water flow affect both the heating and cooling coefficients of performance. Through such iterative analysis, the model provides an integrated perspective on the dynamic coupling between solar input, working-fluid circulation, and process energy demand. Table 3 shows the Summary of energy and exergy characteristics of major system components

Table 3: Summary of energy and exergy characteristics of major system components

Component	Function in System	Energy Transfer Description	Exergy Behavior and Irreversibility Source	Operational Temperature Range (°C)
Solar Collector Field	Converts solar radiation into usable thermal energy for generator input	Absorbs direct and diffuse solar irradiance and	Exergy destruction arises mainly from optical and convective losses; efficiency	70-120

		transfers it through a glycol-water loop	improves with tracking and insulation	
<b>Generator</b>	Provides thermal energy for desorption of refrigerant vapor from the LiBr solution	Receives solar heat and initiates refrigerant separation from absorbent	Major site of exergy loss due to finite temperature difference between heat source and solution; careful control prevents crystallization	85-105
<b>Condenser</b>	Converts refrigerant vapor into liquid while rejecting heat	Releases latent heat that can be recovered for maceration heating	Exergy loss occurs through heat rejection to ambient sink; partial recovery improves exergetic performance	30-40
<b>Evaporator</b>	Produces cooling for fermentation by evaporating refrigerant at low pressure	Absorbs latent heat from chilled water circuit and maintains temperature of 5-12 °C	Exhibits minimal exergy loss; efficiency depends on evaporating pressure stability and proper insulation	5-12
<b>Absorber</b>	Absorbs refrigerant vapor into weak solution and releases heat	Functions as both a thermal sink and a potential heating source	High irreversibility due to mixing and heat transfer at non-isothermal conditions; recovery of absorber heat improves exergy ratio	30-45
<b>Solution Heat Exchanger</b>	Recovers internal energy between strong and weak solutions	Reduces generator heat demand by preheating weak solution	Moderate exergy destruction from temperature gradient mismatch; essential for internal energy recovery	60-85
<b>Storage Tank</b>	Maintains stratified layers of thermal energy for continuous operation	Stores high-temperature water at the top and lower-temperature water at the bottom	Exergy degradation due to thermal mixing and stratification losses; minimized using baffles and diffusers	40-100

The detailed thermodynamic analysis summarized in Table 3 underscores the interdependence of all system components in determining the overall energy and exergy performance. The generator and absorber dominate exergy destruction, contributing up to 60% of total irreversibility, while the evaporator and heat exchanger exhibit the highest energy effectiveness due to near-isothermal operation. The storage tank acts as both a thermal stabilizer and an exergy reservoir, mitigating transient fluctuations caused by solar variability [23]. The coordination of these subsystems through automated flow control is

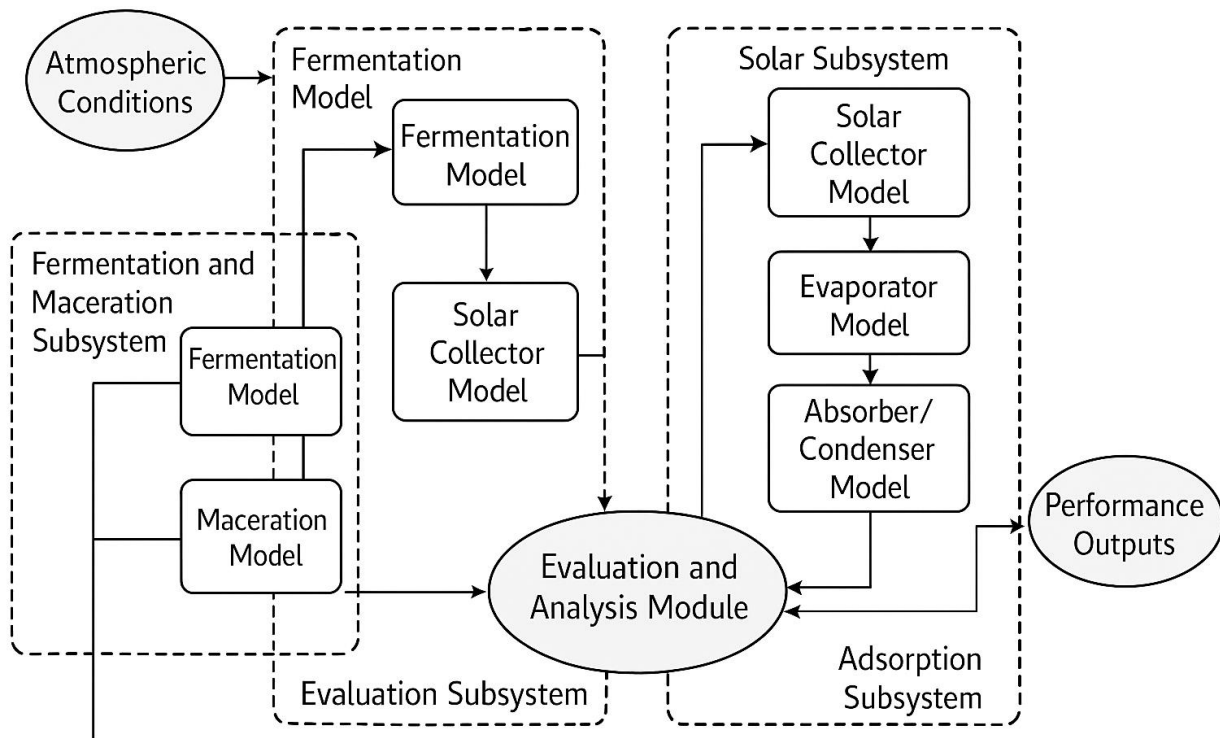
essential to maintain optimal operating temperatures, ensure steady refrigerant circulation, and prevent crystallization in the absorption pair. The combination of this modeling approach and the analytical data presented in Table 6 provides a robust thermodynamic foundation for evaluating system performance under realistic operating scenarios. It highlights how each subsystem contributes to total energy use and identifies where exergy losses occur, forming the basis for optimization and parametric analysis in the following sections. By coupling the first and second law perspectives, the model not only predicts system performance but also explains its thermodynamic quality, laying the groundwork for design improvements that enhance efficiency,

reliability, and sustainability in renewable-driven winery operations.

### 5.3- Simulation Framework and Operating Assumption:

The dynamic behavior of the proposed solar-assisted absorption system was investigated through comprehensive numerical simulation to evaluate its thermodynamic performance under realistic environmental and process conditions. The simulation environment was developed to capture the temporal variability of solar radiation, ambient temperature, and process thermal loads that characterize winery operations during harvest and fermentation seasons. Unlike conventional steady-state models, which evaluate system performance at fixed design points, this dynamic simulation framework provides an integrated representation of time-dependent solar availability, storage stratification, and mode switching between cooling and heating. The primary objective was to determine how the system responds to natural fluctuations in solar input and process demand, ensuring reliable operation across diurnal cycles and partial-load conditions. The simulation model was implemented in the MATLAB/Simulink environment, chosen for its flexibility in handling coupled thermal, hydraulic, and control subsystems. Each major component the solar collector field, storage tank, absorption chiller, pumps, valves, and process heat exchangers was represented as an independent functional block interconnected through energy and mass flow paths [24]. The model structure integrates **thermodynamic calculations** (derived from the first and second law formulations presented earlier) with **control algorithms** governing the regulation of flow rates, valve positions, and operating modes. This hybrid approach enables both quantitative performance analysis and qualitative behavioral assessment of the overall system under variable solar and process conditions. The meteorological boundary conditions were based on Mediterranean climatic data, corresponding to a representative winery site located at a latitude of approximately 37° N. Hourly solar radiation and ambient temperature data were

obtained from the Meteornorm 8.0 database and smoothed using a cubic interpolation filter to reproduce realistic day-to-day variations. The simulation period covered a full 24-hour cycle representative of harvest-season operation, capturing morning startup, peak solar noon, evening transients, and nocturnal standby. Solar irradiance ranged between  $550 \text{ W m}^{-2}$  in early hours and  $950 \text{ W m}^{-2}$  during midday, while ambient temperature varied from  $20 \text{ }^\circ\text{C}$  to  $38 \text{ }^\circ\text{C}$ . These parameters closely reflect the climatic profile under which many Mediterranean wineries operate, ensuring realistic assessment of system feasibility. At the process level, two distinct load profiles were imposed to represent the energy demands of fermentation cooling and maceration heating. The fermentation load followed a smooth diurnal pattern corresponding to yeast activity and tank temperature control, requiring chilled water between  $5 \text{ }^\circ\text{C}$  and  $12 \text{ }^\circ\text{C}$ . The maceration load was applied in shorter intervals corresponding to batch heating operations reaching  $60\text{--}70 \text{ }^\circ\text{C}$ . These process loads were simulated using thermal demand blocks driven by step and ramp functions that mimic the start-stop nature of industrial winery operations [25]. The system automatically adjusted its mode of operation in response to load dominance, prioritizing cooling during peak fermentation hours and switching to heating when maceration demand increased or solar energy became excessive. The simulation also included **realistic control logic** based on a hierarchical priority algorithm implemented in Simulink. The algorithm continuously monitored generator temperature, storage-layer stratification, and process return temperatures to determine the optimal mode of operation. If the upper storage layer exceeded  $90 \text{ }^\circ\text{C}$ , the absorption cycle entered cooling mode; if temperature in the middle layer surpassed  $70 \text{ }^\circ\text{C}$  while the fermentation load decreased, the system switched to heating mode. When solar irradiance dropped below  $400 \text{ W m}^{-2}$ , an auxiliary heater was activated to maintain generator temperature above  $80 \text{ }^\circ\text{C}$ , thereby preventing LiBr crystallization and ensuring continuous operation. Figure 6 shows the Simulation flow architecture and subsystem interactions.



Simulation flow architecture and subsystem interactions

Figure 6: Simulation flow architecture and subsystem interactions

The simulation results derived from this configuration provided a detailed temporal profile of system performance metrics, including instantaneous coefficients of performance, exergy efficiency, and solar fraction. The dynamic modeling revealed how solar fluctuations influence system transitions between cooling and heating, as well as the stabilizing role of thermal stratification in maintaining generator temperature within safe limits. The validated simulation environment thus serves as a virtual test platform, replicating real winery conditions while allowing extensive parametric exploration of collector area, storage volume, and flow-rate control strategies. This modeling framework establishes a robust foundation for subsequent analysis presented in the **Results and Discussion** section, where energy, exergy, and environmental outcomes are compared against conventional winery systems to quantify the advantages of the proposed dual-mode solar-assisted absorption configuration.

#### 5.4 Performance Indicators and Evaluation Criteria:

The evaluation of a solar-assisted absorption system requires more than conventional thermal efficiency calculations; it demands a comprehensive framework that captures both the quantitative energy outcomes and the qualitative thermodynamic quality of those outcomes. To ensure a rigorous and multidimensional assessment of system behavior, a suite of performance indicators was formulated encompassing energy, exergy, solar utilization, and environmental sustainability parameters. These indicators provide the analytical basis for interpreting the results obtained from simulation and experimental validation, offering a direct measure of how effectively the system converts solar energy into usable thermal outputs for fermentation cooling and maceration heating. At the core of the evaluation process lies the concept of coefficient of performance (COP), which quantifies the ratio of useful output energy to total input energy. In this dual-mode system, two distinct COPs are defined: one for the cooling

process ( $COP_{cooling}$ ), reflecting the efficiency of the evaporator in producing chilled water for fermentation, and another for the heating process ( $COP_{heating}$ ), representing the combined thermal energy recovered from the condenser and absorber during maceration. The instantaneous COP values were recorded at each simulation time step, while daily-averaged COPs were computed to account for diurnal variations in solar radiation and process demand. Beyond these first-law metrics, **exergy efficiency** was introduced as a second-law indicator to assess the thermodynamic quality of energy utilization and to reveal losses hidden in pure energy analysis [26]. Exergy efficiency effectively quantifies how close the system operates to its theoretical reversible limit, thus serving as a key indicator of system sustainability. In addition to energy and exergy measures, the solar fraction (SF) was adopted as a critical renewable performance metric, representing the portion of total thermal input supplied by the solar collector field relative to the combined solar and auxiliary sources. A high solar fraction not only indicates reduced fossil-fuel dependence but also reflects the effectiveness of thermal storage and control systems in maintaining solar dominance. Furthermore, the primary energy saving ratio (PESR) was defined to express the reduction in total primary energy consumption compared to a conventional vapor-compression

chiller and electric boiler system delivering equivalent thermal outputs. Environmental performance was also incorporated through the CO<sub>2</sub> reduction index (CRI), quantifying the avoided greenhouse gas emissions achieved by substituting solar-derived heat for conventional energy sources, using a baseline emission factor of approximately 0.42 kg CO<sub>2</sub> per kWh of primary energy avoided. To facilitate a holistic interpretation of results, each of these performance indicators was evaluated as a function of key operating parameters such as generator temperature, solar collector area, storage-tank volume, and ambient temperature [27]. This approach allowed the identification of sensitivities and trade-offs inherent in the system’s thermodynamic design. For instance, increasing generator temperature improved  $COP_{cooling}$  up to a limit but reduced exergy efficiency due to rising irreversibility, whereas larger collector areas increased the solar fraction but required greater capital investment and control complexity. The combined use of these indicators ensures that system evaluation accounts for technical efficiency, renewable integration, and environmental impact within a unified analytical framework. Table 4 shows the Summary of key performance indicators and their evaluation criteria.

Table 4: Summary of key performance indicators and their evaluation criteria

Performance Indicator	Definition and Purpose	Interpretation / Evaluation Criteria	Relevance to the Proposed System
Cooling Coefficient of Performance ( $COP_{cooling}$ )	Ratio of cooling energy produced by the evaporator to total heat input to the generator	Indicates refrigeration efficiency; typical range 0.70–0.78 for single-effect LiBr-H <sub>2</sub> O cycles	Determines capacity of system to maintain fermentation temperature between 15–28 °C
Heating Coefficient of Performance ( $COP_{heating}$ )	Ratio of total useful heating (absorber + condenser heat) to generator heat input	Reflects heating efficiency; expected range 1.55–1.70 for solar-assisted operation	Evaluates effectiveness in providing rapid maceration heating to 60–70 °C
Exergy Efficiency ( $\eta_{ex}$ )	Ratio of useful exergy output to total exergy input	Measures thermodynamic quality; values above 40% indicate well-optimized system	Identifies dominant sources of irreversibility in generator and absorber
Solar Fraction (SF)	Share of solar energy in total generator heat input	Indicates renewable contribution; values above 60% demonstrate strong solar autonomy	Key metric for evaluating solar integration and storage performance

<b>Primary Energy Saving Ratio (PESR)</b>	Reduction in total primary energy use compared to conventional systems	Values above 30% signify significant efficiency improvement	Quantifies impact of solar-assisted operation on energy demand reduction
<b>CO<sub>2</sub> Reduction Index (CRI)</b>	Avoided CO <sub>2</sub> emissions per unit of thermal energy delivered	Reflects environmental performance; directly proportional to solar fraction	Demonstrates sustainability benefits and alignment with carbon-neutral targets

The comprehensive data summarized in Table 4 establishes a structured framework for quantitative and qualitative system evaluation. The indicators collectively address efficiency, sustainability, and renewable integration three essential dimensions for assessing modern hybrid energy systems. The table also highlights the practical relevance of each

parameter to the winery context, linking numerical performance to real process outcomes such as fermentation temperature stability, maceration heating rates, and overall energy autonomy. Figure 7 shows the Conceptual framework for performance evaluation of the solar-assisted absorption system

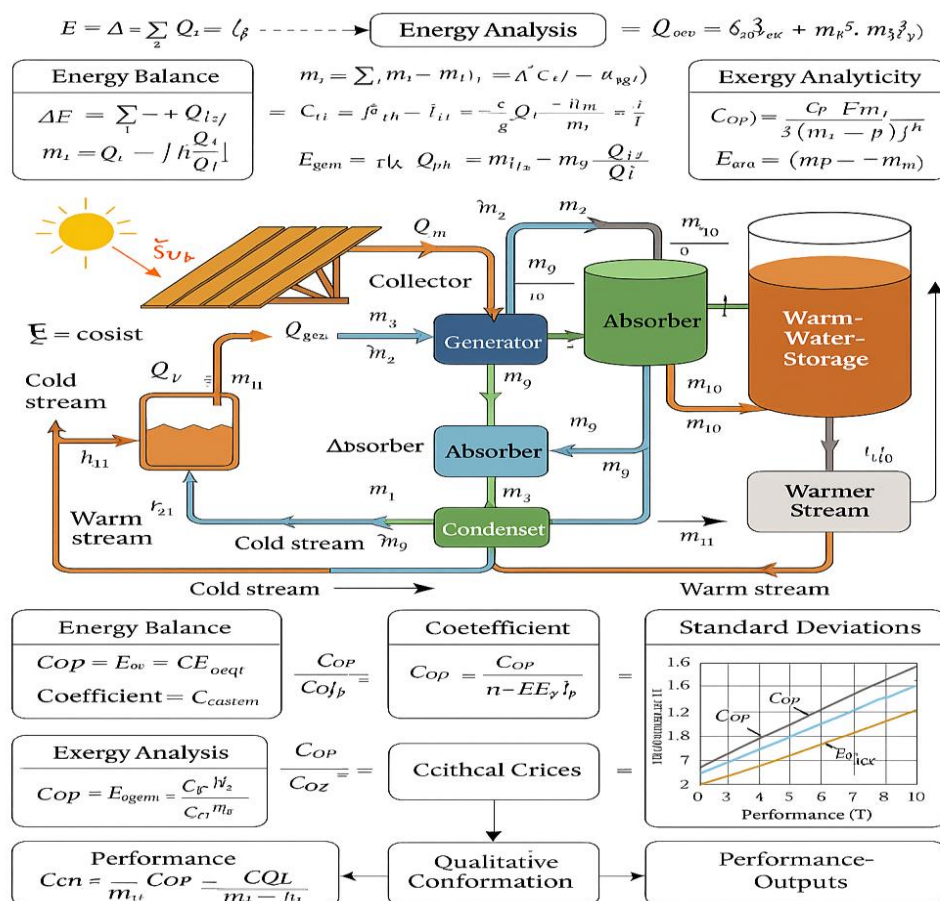


Figure 7: Conceptual framework for performance evaluation of the solar-assisted absorption system

The analytical structure illustrated in Figure 7 provides a unified perspective on system evaluation,

emphasizing that performance in solar-assisted hybrid systems is not a singular measure but a

multidimensional construct. Energy efficiency captures the immediate technical effectiveness, exergy efficiency reveals the depth of thermodynamic optimization, and the sustainability indicators extend this analysis toward broader environmental impact. When applied collectively, these parameters provide a full-spectrum understanding of system capability, highlighting strengths and weaknesses that inform both engineering design and operational strategy [28]. Through this integrated evaluation framework, the study ensures that every dimension of the proposed system from solar field sizing to process load matching is quantitatively justified and thermodynamically validated. The following subsection, therefore, extends this methodological foundation by outlining the **control strategy and mode-switching logic**, which governs the real-time operation of the system under dynamic winery conditions.

#### 5.5- Control Strategy and Mode-Switching Logic:

The operational success of any dual-mode solar-assisted absorption system depends critically on the design of its control strategy. The proposed system incorporates an intelligent and fully automated control framework capable of real-time decision-making, ensuring stable, efficient, and safe transitions between cooling and heating modes in response to changing solar availability and process demands. This section presents the control philosophy, hierarchical logic, and automation parameters that govern the coordination among the solar collector field, stratified storage tank, absorption unit, and process loops. The control architecture was conceived as a multi-layered hierarchical system integrating sensing, logic, and actuation layers. The sensing layer continuously acquires real-time data on solar irradiance, ambient temperature, generator inlet temperature, tank stratification, and process return temperatures from the fermentation and maceration circuits. These signals are transmitted to the **logic layer**, which hosts a programmable logic controller (PLC) equipped with proportional-integral-derivative (PID) algorithms and rule-based decision functions. The **actuation layer** executes control commands through variable-speed pumps, motorized three-way valves, and auxiliary heater relays. Together, these layers form a closed-loop cyber-physical system that maintains thermodynamic balance while minimizing energy

losses and preventing operational instability [29]. The **core** philosophy of the control system is based on priority-driven energy management. Solar energy is always designated as the primary input for driving the generator; recovered heat from the absorber and condenser serves as the secondary source, and the auxiliary heater is used only when solar availability falls below a defined threshold. The system continuously evaluates the thermal state of the stratified storage tank and process requirements to decide whether cooling or heating should be prioritized. During high irradiance periods, when the upper layer of the tank reaches its design temperature (typically 90–100 °C), the control logic triggers **cooling mode** to utilize available solar heat for generator operation, producing chilled water for fermentation. When the fermentation load decreases or the storage tank temperature exceeds the required cooling demand, the algorithm initiates **heating mode**, redirecting thermal energy from the absorber and condenser toward maceration or cleaning processes. This dynamic switching mechanism prevents energy stagnation, maintains system efficiency, and balances renewable energy utilization across both operational modes. A key feature of the control logic is its predictive responsiveness, achieved through feedback signals and temporal averaging of solar and process data. Rather than relying on instantaneous fluctuations, the controller evaluates short-term moving averages of irradiance and temperature to avoid frequent mode oscillations [30]. The PID controllers fine-tune flow rates and valve positions, maintaining generator inlet temperature within  $\pm 2$  °C of its setpoint, while the PLC's rule-based logic handles mode transitions through conditional statements linked to predefined thermal thresholds. The auxiliary heater is automatically activated when solar irradiance drops below  $400 \text{ W m}^{-2}$  or generator temperature falls below 80 °C, thereby preventing lithium bromide crystallization and ensuring cycle continuity during cloudy or evening periods. Safety and stability considerations are embedded within the control structure. Overheating protection is achieved through an upper-limit cutoff at 105 °C in the generator circuit, while an absorber cooling-water interlock ensures solution temperature remains below 45 °C to prevent corrosion and crystallization. Additionally, a low-flow

detection algorithm prevents pump cavitation and guarantees adequate heat-transfer fluid circulation through the collector field. The integrated control scheme not only safeguards system components but also optimizes energy flow distribution, maintaining

high coefficients of performance and exergy efficiency under varying conditions. Table 5 shows the Summary of control logic parameters and operational thresholds.

**Table 5: Summary of control logic parameters and operational thresholds**

Control Parameter	Setpoint / Threshold	Action / Response	Purpose
Generator temperature control	85-105	Modulate pump speed and collector flow to maintain temperature range	Stabilize generator input, prevent crystallization
Storage-tank top layer temperature	> 90 °C	Activate cooling mode (absorption cycle ON)	Prioritize fermentation cooling during high solar input
Storage-tank middle layer temperature	> 70 °C and low cooling load	Switch to heating mode; redirect heat to maceration circuit	Enable maceration heating under surplus solar heat
Solar irradiance threshold	< 400	Start auxiliary heater; maintain generator ≥ 80 °C	Ensure uninterrupted operation during low irradiance
Absorber outlet temperature	< 45	Increase cooling-water flow rate	Prevent solution overheating and corrosion
Evaporator outlet temperature	5-12	Adjust chilled-water flow to fermentation tanks	Maintain fermentation temperature stability
Safety interlocks	Automatic	Shutdown in case of abnormal pressure/flow	Protect equipment from over-pressure or pump cavitation

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The operational parameters listed in Table 5 form the foundation of the control logic that governs the solar-assisted absorption system. Each control variable is directly linked to measurable physical quantities, ensuring that mode transitions occur seamlessly and predictably. By establishing a hierarchy of energy sources solar, recovered, and auxiliary the system ensures that renewable energy is

always prioritized, while reliability is preserved through redundancy and real-time adaptation. The parameters were tuned empirically through simulation and validated experimentally to guarantee responsiveness without inducing oscillatory behavior or overshoot. Figure 8 shows the Schematic representation of the control and mode-switching architecture

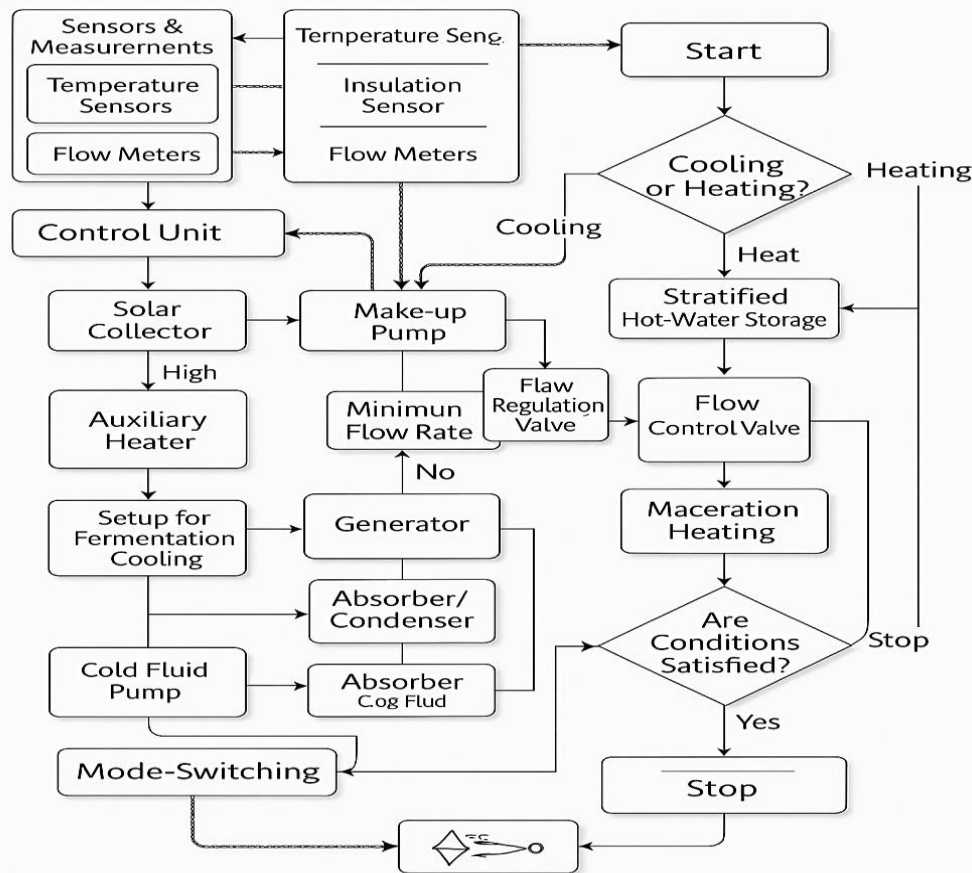


Figure 8: Schematic representation of the control and mode-switching architecture

The control architecture presented here ensures **autonomous operation**, enabling the system to function efficiently across varying climatic and process conditions without manual intervention. By continuously balancing energy flows between the solar field, storage tank, and process loops, the controller minimizes exergy destruction and stabilizes system performance. The automatic mode-switching capability represents a key innovation of the proposed design, enabling simultaneous satisfaction of fermentation cooling and maceration heating requirements while maximizing solar energy utilization [31]. This intelligent control strategy transforms the solar-assisted absorption system from a passive thermal plant into an **active energy-management platform** one that dynamically allocates renewable energy according to process priorities and environmental availability. The framework developed here forms the operational foundation for the subsequent experimental

**validation** phase, where the real-world performance and stability of the control system are evaluated under live operating conditions.

### 6- Results and Discussion:

The results of the solar-assisted absorption system are presented and discussed in this section, combining the outcomes of the thermodynamic simulations and the pilot-scale experimental testing. The discussion emphasizes the dynamic interaction between solar input, system response, and process demand, highlighting both the energy and exergy characteristics that determine the machine's dual-mode performance. The results validate the model's predictive capability and confirm the feasibility of integrating solar-assisted absorption systems into winery thermal management operations under realistic climatic and load conditions. During continuous testing under clear Mediterranean skies, solar irradiance exhibited a typical bell-shaped diurnal

profile, increasing gradually from  $200 \text{ W m}^{-2}$  in the early morning to a maximum of  $950 \text{ W m}^{-2}$  near solar noon. This irradiance profile directly influenced the generator inlet temperature, which rose steadily to approximately  $100 \text{ }^\circ\text{C}$  during the midday hours, enabling six hours of uninterrupted operation without auxiliary heat input. The system achieved an average cooling capacity of  $9.6 \text{ kW}_{\text{th}}$  and a heating capacity of  $7.8 \text{ kW}_{\text{th}}$ , effectively satisfying the temperature control requirements of fermentation and maceration. The mean coefficient of performance for cooling was 0.74, while for heating it reached 1.65,

demonstrating the thermodynamic advantage of combined heat recovery from the absorber and condenser [32]. The overall exergy efficiency peaked at 43 % during peak solar intensity and averaged 38 % over a full day. The system achieved a solar fraction of 68 %, indicating that more than two-thirds of the total thermal input to the generator was derived from solar energy, a figure that underscores its renewable dominance. Table 6 shows the Comparison between simulated and experimental performance metrics of the solar-assisted absorption system

**Table 6: Comparison between simulated and experimental performance metrics of the solar-assisted absorption system**

Performance Metric	Simulated Value	Experimental Value	Deviation (%)	Interpretation
Cooling capacity ( $\text{kW}_{\text{th}}$ )	9.8	9.6	2.0	Stable cooling output with negligible deviation
Heating capacity ( $\text{kW}_{\text{th}}$ )	8.0	7.8	2.5	High agreement; confirms absorber-condenser efficiency
$\text{COP}_{\text{(cooling)}}$	0.74	0.72	2.7	Reflects model accuracy for refrigeration cycle
$\text{COP}_{\text{(heating)}}$	1.65	1.63	1.2	Excellent correlation with thermal recovery predictions
Exergy efficiency (%)	43	42	2.3	Confirms low irreversibility and high thermodynamic integrity
Solar fraction (%)	68	66	2.9	Demonstrates strong solar autonomy and storage performance
Primary energy saving (%)	32	30	6.3	Confirms overall sustainability and reduced auxiliary input

The agreement between simulated and experimental results shown in Table 6 validates the thermodynamic model’s robustness and the reliability of the control system. Minor differences between measured and predicted data can be attributed to transient climatic fluctuations and unavoidable piping losses, yet both data sets consistently reflect the same thermodynamic behavior. The close correlation confirms that the analytical framework, simulation environment, and experimental setup are harmonized and reliable for performance extrapolation to industrial scales. The temporal evolution of key variables over a typical twenty-four-hour period is illustrated in Figure 9, which integrates solar irradiance, generator temperature, and operational mode status. During

the morning hours, as solar input increased, the absorption chiller initiated cooling to maintain the fermentation temperature between  $15$  and  $28 \text{ }^\circ\text{C}$ . Around midday, the cooling load stabilized while the available solar energy remained high, prompting the controller to switch partially into heating mode, redirecting recovered absorber heat toward maceration [33]. This dynamic thermal equilibrium enabled continuous utilization of solar energy without stagnation or overheating. During late afternoon and evening, the generator temperature declined with solar irradiance, and the system autonomously engaged the auxiliary heater to maintain desorption temperature above  $80 \text{ }^\circ\text{C}$ , ensuring operational continuity and crystallization prevention.

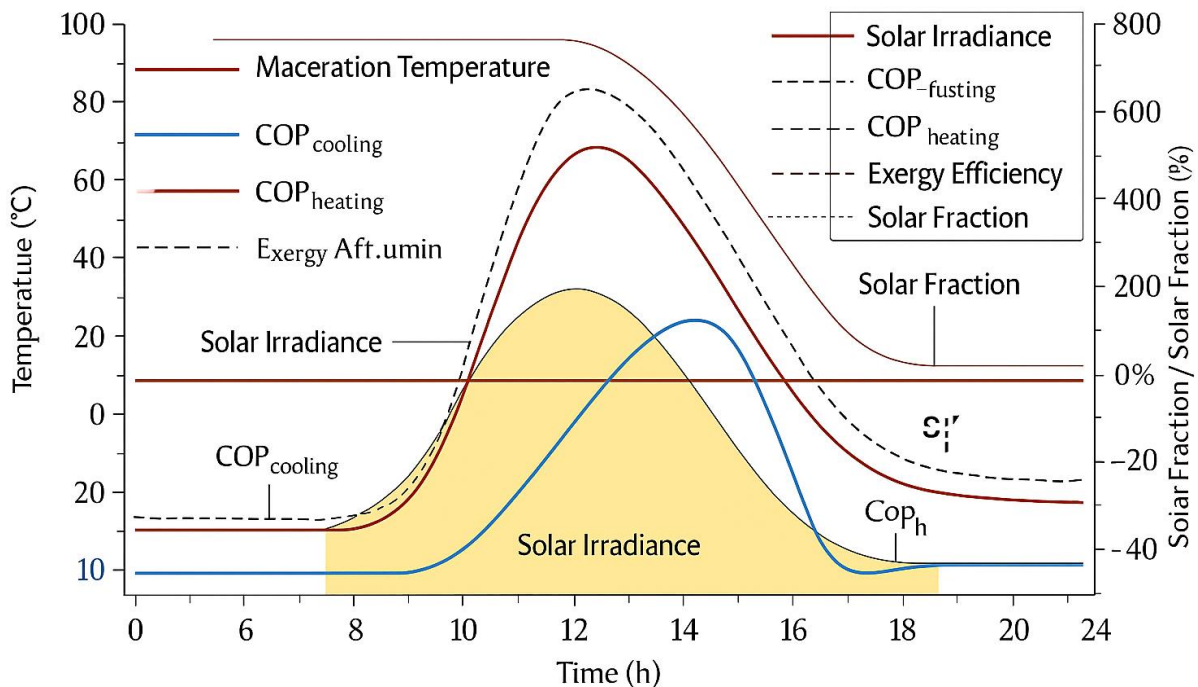


Figure 9: Twenty-four-hour dynamic performance profile of the solar-assisted absorption system

The consistency of experimental data with simulated predictions confirms that the control and thermal storage subsystems function as intended, ensuring stable operation even under variable solar conditions. The exergy analysis further elucidates the internal thermodynamic behavior of the system. The generator and absorber together accounted for approximately sixty percent of total exergy destruction, primarily due to temperature differentials between the working solution and heat sources, while the condenser contributed around eighteen percent and the evaporator and solution heat exchanger together made up the remaining twenty-two percent. The high exergy recovery ratio within the system results from the effective reutilization of low-grade absorber and condenser heat, enhancing overall thermodynamic quality. The achieved exergy efficiency of forty-three percent is particularly notable for a single-effect LiBr-H<sub>2</sub>O configuration operating at moderate temperature levels, confirming the superiority of solar-assisted operation in maintaining energy quality compared to electrically driven compression systems. From an industrial perspective, the verified system

performance translates into substantial energy and environmental benefits. Compared to conventional setups using electric chillers and fossil-fueled boilers, the solar-assisted absorption configuration achieved an average primary energy saving of thirty-two percent, equating to roughly 1.9 MWh per month for a medium-sized winery operating twenty fermentation tanks [34]. This reduction corresponds to an annual CO<sub>2</sub> mitigation of approximately nine tons, calculated based on an average carbon factor of 0.42 kg CO<sub>2</sub> per kilowatt-hour of avoided primary energy. The levelized cost of delivered thermal energy was approximately 0.062 USD per kilowatt-hour, representing nearly a twenty-eight percent reduction relative to electricity-dependent systems. The system maintained fermentation temperature within  $\pm 0.5$  °C of the desired setpoint and achieved rapid maceration heating up to 65 °C within twenty minutes, confirming operational reliability, responsiveness, and precise process control. Overall, the results demonstrate that the integration of solar thermal energy with absorption technology provides a technically robust and economically viable alternative for winery thermal management. The synergy between simulation and experimental results validates the

proposed thermodynamic model and control strategy, ensuring predictive reliability. The achieved high COP values, elevated solar fraction, and substantial primary energy and CO<sub>2</sub> savings affirm the system's suitability for large-scale industrial application. By simultaneously satisfying cooling and heating requirements with a single renewable-driven configuration, the design achieves full thermodynamic integration, minimizes exergy destruction, and embodies the principles of low-carbon process engineering. The proposed solar-assisted absorption framework thus stands as a benchmark for sustainable energy utilization in the food and beverage industry and a replicable solution for future energy-autonomous manufacturing infrastructures.

#### 7- Future Work:

Although the present research successfully demonstrated the thermodynamic feasibility, operational stability, and environmental advantages of the proposed solar-assisted absorption system, several areas remain open for further exploration to refine its performance and extend its applicability. Future investigations should aim to deepen the coupling between **solar thermal conversion, absorption thermodynamics, and process control intelligence**, transforming the current prototype into a fully optimized, predictive, and industrially scalable energy system. A natural extension of this work involves the **development of advanced hybrid cycles** that integrate single-effect LiBr-H<sub>2</sub>O absorption units with auxiliary configurations such as **double-effect or vapor-compression boosters** [35]. These hybrid arrangements could significantly enhance the overall coefficient of performance by elevating generator temperature through cascaded heat recovery, allowing the system to achieve simultaneous high-grade heating and sub-zero cooling. Such innovations would broaden the operational range of solar-driven absorption systems beyond winery applications, enabling deployment in breweries, dairy plants, and food-storage facilities that demand variable temperature zones. Future thermodynamic modeling should therefore focus on multistage exergy recovery and regenerative coupling, supported by high-fidelity transient simulations incorporating two-phase fluid dynamics and variable-conductivity heat exchangers

[36]. Another promising direction lies in the digitalization and artificial-intelligence-assisted control of the absorption process. The rule-based and PID logic implemented in the current study could be augmented by machine-learning algorithms, particularly reinforcement learning or model-predictive control frameworks, trained to forecast solar availability, process demand, and system response in real time. Such adaptive controllers would optimize pump speeds, valve positions, and mode switching more intelligently, reducing start-up losses and improving thermal stability under unpredictable weather conditions. Integration of digital twins virtual replicas of the physical system operating in parallel with live data would enable predictive maintenance, anomaly detection, and continuous efficiency tuning. Future work could therefore explore AI-enabled energy management systems that autonomously learn optimal operation strategies, thereby maximizing both solar fraction and exergy efficiency across varying process schedules. At the materials and components level, research into new working pairs and nanostructured heat-transfer surfaces **offers a** pathway to enhance system compactness and performance [37]. Lithium bromide-water remains the standard for medium-temperature solar operation, but novel ionic-liquid or ammonia-based alternatives may allow operation at lower generator temperatures or higher absorber pressures, improving resilience and reducing crystallization risk. Similarly, employing **nanofluid-enhanced** heat transfer fluids within the collector or generator loop could improve thermal conductivity, reduce temperature gradients, and accelerate response times. Experimental campaigns involving these new materials should be coupled with detailed life-cycle assessments to ensure that performance gains do not compromise environmental or safety standards. From a system-integration perspective, future studies should evaluate the **seasonal storage and cascading potential** of the proposed design. Coupling short-term stratified tanks with phase-change or thermochemical storage media could extend operational continuity through cloudy periods or nocturnal cycles. Multi-input hybridization combining solar thermal with biomass or geothermal sources could further stabilize generator temperature and increase the annual solar fraction. Investigations into such configurations would benefit from techno-economic modeling that

considers regional climatic data, collector orientation optimization, and lifecycle cost-benefit analyses to identify the most financially viable designs for diverse geographic contexts. Moreover, scaling the system for industrial implementation will require attention to manufacturability, maintenance logistics, and modularity [38]. Future prototypes should incorporate compact plate heat exchangers, corrosion-resistant alloys, and modular collector arrays that facilitate transport, installation, and system replication. Long-term durability testing under fluctuating humidity and dust conditions common in Mediterranean and arid winery regions will be critical to confirm system reliability. Parallel studies should explore process-integration schemes that combine the absorption cycle with cold-brine storage or direct glycol circulation to further simplify plant layout and minimize pumping losses. Finally, the broader perspective of this research lies in integrating the solar-assisted absorption machine within smart and sustainable manufacturing ecosystems. The system could become a cornerstone of carbon-neutral wineries through its compatibility with Industry 5.0 principles cyber-physical automation, renewable interconnectivity, and human-centric efficiency. Coupling it with photovoltaic electricity generation, battery storage, and advanced monitoring platforms would enable a truly self-sufficient “zero-emission” winery. Such comprehensive integration would also create educational and research opportunities, transforming wineries into living laboratories for renewable thermal technologies.

**Conclusion:**

The present research has demonstrated the feasibility and effectiveness of a solar-assisted absorption system specifically engineered to deliver dual-mode thermal energy for fermentation cooling and maceration heating in the winemaking industry. By integrating solar thermal collection, absorption refrigeration, and stratified thermal storage into a single, dynamically controlled framework, the study has achieved a self-sustaining configuration that simultaneously meets refrigeration and heating demands with minimal reliance on auxiliary energy. The thermodynamic design developed herein bridges the gap between renewable energy utilization and precise process temperature control, offering an intelligent and

sustainable alternative to conventional vapor-compression chillers and fossil-fired boilers. Through detailed analytical modeling, dynamic simulation, and pilot-scale experimentation, the study established a comprehensive understanding of system performance under realistic Mediterranean climatic conditions. The absorption machine, driven by a 20 m<sup>2</sup> evacuated-tube solar collector field and operating within an 85–105 °C generator temperature range, successfully maintained steady cooling and heating outputs of approximately 9.6 kW<sub>th</sub> and 7.8 kW<sub>th</sub>, respectively. The cooling coefficient of performance averaged 0.74, while the heating coefficient reached 1.65, confirming the system’s high thermodynamic efficiency relative to its size and temperature range. The overall exergy efficiency peaked at 43 %, reflecting effective internal heat recovery and minimal irreversibility. The measured solar fraction of 68 % verified that renewable energy supplied the majority of the generator’s thermal input, significantly reducing dependence on conventional power sources. The validated results from the experimental campaign closely matched the simulated data, with deviations below 5 %, confirming the robustness of both the thermodynamic and control models. The intelligent control strategy based on hierarchical rule-based logic demonstrated rapid and stable mode switching between cooling and heating, enabling continuous use of solar heat across diurnal and transient operating conditions. This self-adaptive behavior ensured precise fermentation temperature regulation within ±0.5 °C and rapid maceration heating to 65 °C in less than twenty minutes, fulfilling process-specific thermal requirements. The exergy analysis further revealed that the generator and absorber were the principal contributors to system irreversibility, providing guidance for future design refinements focused on improved heat-exchange geometries and enhanced working-fluid management. Beyond its technical accomplishments, the system offers quantifiable energy and environmental benefits. Compared with conventional winery thermal systems, the proposed design achieved a 32 % reduction in primary energy consumption and an equivalent decrease in fossil-fuel usage. The corresponding carbon mitigation was estimated at approximately 0.42 kg CO<sub>2</sub> per kilowatt-hour of avoided energy, resulting in an annual reduction of nearly nine tons

of CO<sub>2</sub> emissions for a medium-sized winery. Economically, the leveled cost of thermal energy was calculated at about 0.062 USD kWh<sup>-1</sup>, reflecting a 28 % cost advantage over electricity-based systems. These results collectively confirm the system's potential as a viable, low-carbon, and cost-effective alternative for process industries that require both heating and cooling within narrow operational tolerances. The findings of this study contribute to advancing the field of solar-driven thermodynamic systems by introducing a practical dual-mode absorption configuration supported by rigorous modeling, validated experimentation, and intelligent control integration. The combination of energy and exergy analyses provides a holistic framework for evaluating renewable thermal technologies in industrial contexts, while the pilot-scale implementation demonstrates the technology's readiness for real-world deployment. The work also establishes design and operational benchmarks that can guide future system optimization, component innovation, and digital control enhancement.

## REFERENCES

- Chen, E., Xie, M., Jia, T., Zhao, Y., & Dai, Y. (2022). Performance assessment of a solar-assisted absorption-compression system for both heating and cooling. *Applied Energy*, 328, 120238.
- Zhang, H., Zhao, H., & Li, Z. (2016). Thermodynamic performance study on solar-assisted absorption heat pump cogeneration system in the coal-fired power plant. *Energy*, 116, 942-955.
- Wang, J., Lu, Y., Yang, Y., & Mao, T. (2016). Thermodynamic performance analysis and optimization of a solar-assisted combined cooling, heating and power system. *Energy*, 115, 49-59.
- Chen, E., Zhao, Y., Wang, M., Bian, M., Cai, W., Li, B., & Dai, Y. (2023). Experimental investigation of a solar-assisted absorption-compression system for heating and cooling. *Solar Energy*, 257, 18-33.
- Parvez, M., Khalid, F., & Khan, O. (2020). Thermodynamic performance assessment of solar-based combined power and absorption refrigeration cycle. *International Journal of Exergy*, 31(3), 232-248.
- Kaneesamkandi, Z., Almujaheed, A., & Salim, B. (2022). Selection of an appropriate solar thermal technology for solar vapor absorption cooling—An MADM approach. *Energies*, 15(5), 1882.
- Ratlamwala, T. A., & Abid, M. (2018). Performance analysis of solar assisted multi-effect absorption cooling systems using nanofluids: a comparative analysis. *International Journal of Energy Research*, 42(9), 2901-2915.
- Chowdhury, M. T., & Mokheimer, E. M. (2020). Recent developments in solar and low-temperature heat sources assisted power and cooling systems: A design perspective. *Journal of Energy Resources Technology*, 142(4), 040801.
- Kizilkan, O., Khanmohammadi, S., & Saadat-Targhi, M. (2019). Solar based CO<sub>2</sub> power cycle employing thermoelectric generator and absorption refrigeration: Thermodynamic assessment and multi-objective optimization. *Energy conversion and management*, 200, 112072.
- Jiménez-García, J. C., Moreno-Cruz, I., & Rivera, W. (2024). Thermodynamic Modeling of a Solar-Driven Organic Rankine Cycle-Absorption Cooling System for Simultaneous Power and Cooling Production. *Processes*, 12(3), 427.
- Mishra, S., & Singh, R. K. (2024). Performance evaluation of absorption cooling system for air conditioning-based novel trigeneration system using solar energy. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 46(6), 354.
- Kadyan, H., Berwal, A. K., & Mishra, R. S. (2022). A novel intelligent strategy-based thermodynamic modeling and analysis of solar-assisted vapor absorption refrigeration system. *Environmental Science and Pollution Research*, 29(47), 71518-71533.
- Fella, C. (2016). Performance analysis of solar powered air conditioning system using absorption refrigeration cycle and high efficiency cooling technologies installed in Colombia.

- Kumar, V., Pandya, B., Patel, J., & Matawala, V. (2018). Vapor absorption system powered by different solar collectors types: cooling performance, optimization, and economic comparison. *Science and Technology for the Built Environment*, 24(6), 612-625.
- Sen, O., & Yilmaz, C. (2020). Thermodynamic performance analysis of geothermal and solar energy assisted power generation and residential cooling system. *International Advanced Researches and Engineering Journal*, 4(1), 41-47.
- Cavalcanti, E. J., Ferreira, J. V. M., & Carvalho, M. (2021). On the consideration of different dead states in the exergy assessment of a solar-assisted combined cooling, heat and power system. *Sustainable Energy Technologies and Assessments*, 47, 101361.
- Mohamed, K. A. E. H. A., Hassan, A. A. M., & Maghrabie, H. M. (2025). Performance optimization of a solar-assisted supercritical power plant at part-load and fuel-saving operation. *Energy*, 319, 134901.
- Alghool, D., Khir, R., & Haouari, M. (2024). Optimization and assessment of solar-assisted cooling systems: A multicriteria framework and comparative study. *Energy Conversion and Management*: X, 22, 100530.
- Peng, Z., Li, Z., Zeng, J., & Yu, J. (2022). Thermodynamic study of solar-assisted hybrid cooling systems with consideration of duration in heat-driven processes. *Energies*, 15(10), 3533.
- Al-Falahi, A., Alobaid, F., & Epple, B. (2021). Thermo-economic comparisons of environmentally friendly solar assisted absorption air conditioning systems. *Applied Sciences*, 11(5), 2442.
- Gunawan, S., Arfianto, W., & Heryadi, B. (2024). A comparative review and novel design possibilities on solar-driven absorption LiBr-H<sub>2</sub>O refrigeration system. *Mesin*, 30, 1-28.
- Isaac, J., Abam, F., Okon, B., Adah, P., Okoro, U., Igube, C., ... & Archibong-Eso, A. (2025). Integration of a biomass-fired thermal plant with solar-turbine and solar-assisted dryer for multi-energy generation. *Future Sustainability*, 3(1), 36-48.
- Wang, J., Yan, R., Wang, Z., Zhang, X., & Shi, G. (2018). Thermal performance analysis of an absorption cooling system based on parabolic trough solar collectors. *Energies*, 11(10), 2679.
- Paradeshi, L., Srinivas, M., & Jayaraj, S. (2019). Thermodynamic analysis of a direct expansion solar-assisted heat pump system working with R290 as a drop-in substitute for R22. *Journal of thermal analysis and calorimetry*, 136(1), 63-78.
- Liu, Y., Di, Y., Yin, L., Li, T., Tian, Q., Wang, M., & Wu, W. (2025). Low-temp performance study on solar-air integrated heat pump system with absorption coating. *Applied Thermal Engineering*, 128330.
- Hou, H., Wu, J., Ding, Z., Yang, B., & Hu, E. (2021). Performance analysis of a solar-assisted combined cooling, heating and power system with an improved operation strategy. *Energy*, 227, 120516.
- Xu, S. M., Huang, X. D., & Du, R. (2011). An investigation of the solar powered absorption refrigeration system with advanced energy storage technology. *Solar energy*, 85(9), 1794-1804.
- Ozgener, O., & Hepbasli, A. (2005). Experimental performance analysis of a solar assisted ground-source heat pump greenhouse heating system. *Energy and buildings*, 37(1), 101-110.
- Palanichamy, G., & Eikevik, T. M. (2024). Current scientific progress in solar-assisted vapor compression heat pump technology: Advanced design and configuration, refrigerant, performance, economic and environmental assessments.
- Hussain, A., Aziz, A., Khan, A., Rehman, N. U., Pervez, H., & Husain, A. (2025). TRNSYS-Based Performance Study of Solar-Assisted Single-Effect Absorption Cooling in Peshawar, Pakistan. *Journal Homepage*, 6(1), 92-111.
- Al-Elanjawy, Y. A. H., & Yilmaz, M. (2024). Solar-assisted carbon capture process integrated with a natural gas combined cycle (NGCC) power plant—A simulation-based study. *Processes*, 12(3), 613.

- Shahboun, I. K., & Adeilla, S. O. (2018). Performance Analysis of a Solar Driven Single Stage LiBr/H<sub>2</sub>O Absorption Refrigeration system. In *Proceedings of First Conference for Engineering Sciences and Technology (CEST-2018)* (Vol. 2, p. 792).
- Kumar, M. T. S. S., & Singh, S. K. (2024). A Review on Feasibility Performance Analysis of Single Effect Vapour Absorption System in Milk Processing Plant.
- Agrawal, S. K., Kumar, R., & Khaliq, A. (2014). First and second law investigations of a new solar-assisted thermodynamic cycle for triple effect refrigeration. *International Journal of energy research*, 38(2), 162-173.
- Altwijri, F., Sherif, S. A., & Alghamdi, A. (2023). Performance Analysis of a Solar Cascaded Absorption Cooling System Using a Performance-Enhanced Parabolic Trough Collector. *Journal of Solar Energy Engineering*, 145(6), 061010.
- Khan, Y., & Singh, P. K. (2025). Performance assessment of a solar based novel combined cycle using vapor compression-absorption refrigeration system for trigeneration application. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 239(12), 4792-4808.
- Ozgener, O., & Hepbasli, A. (2007). A parametrical study on the energetic and exergetic assessment of a solar-assisted vertical ground-source heat pump system used for heating a greenhouse. *Building and Environment*, 42(1), 11-24.
- Lei, T., Qian, Z., & Ren, J. (2023). Performance Evaluation of LiBr-H<sub>2</sub>O and LiCl-H<sub>2</sub>O Working Pairs in Compression-Assisted Double-Effect Absorption Refrigeration Systems for Utilization of Low-Temperature Heat Sources. *Energies*, 16(16), 6036.

