



Simulation-Based Performance and Economic Evaluation of a Solar Thermal Cooling System for a Warehouse in Alkofra, Libya

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Efficient cooling is crucial to avert the 30–50% postharvest losses of agricultural products in warm climates when temperature control fails, preserving food quality and the integrity of the supply chain. The need for energy to cool buildings is rising globally, especially in hot countries. Most of this increase is to meet medium- and large-scale refrigeration demands to keep agricultural produce fresh. A novel solar cooling system to meet such

demand is highly desirable to help meet the increased demand for energy, reduce CO₂ emissions, and cut electricity costs, especially in hot and arid areas. This research proposes a thermal solar cooling system to meet refrigeration demand. The proposed system was investigated for a hot and arid environment using TRNSYS 18 software. The main system variables, such as thermal solar collector area, collector slope angle, and storage capacity, were explored regarding solar fraction, coefficient of performance, and primary energy saving. The results demonstrate that a solar cooling system to cool a warehouse of 144-m² area used to store 112 tons of fruits and vegetables at 6–8 °C requires an evacuated tube solar collector of area 1173 m² supplied by TVP SOLAR with a claimed solar to thermal efficiency of 72%. Also, the solar panel gradient to achieve the highest values of solar fraction was 30 deg, with 60 m³ storage capacity and collector pump flowrate of 20.8 kg/s with a backup system (boiler 100 kWh capacity), to achieve the highest values of solar fraction, coefficient of performance of the whole system, coefficient of performance (COP) of absorption chiller, and primary energy saving 0.53, 0.24, 0.68, and 0.24, respectively. However, financial analysis showed that the investment cost of the proposed system is 45% higher than that of the traditional system, the vapor compressor chiller system, in terms of £/Wh. However, the solar thermal cooling system's ongoing (running) cost was 60% cheaper than a vapor compressor cooling system. Moreover, the investment payback period was nearly 10 years. Finally, CO₂ emissions would be reduced by nearly 35% per annum by utilizing the proposed system compared to a vapor chiller compressor system.

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1 Introduction

Natural gas and oil production is expected to decline in the next few decades, while global power consumption is expected to simultaneously increase sharply around the world [1]. It is well known that most of the global energy produced is consumed for cooling and heating purposes, with the highest proportion to meet demands for thermal comfort [2], which is generally achieved by mechanical cooling and heating systems [3].

Most energy consumed in hot locations is by air conditioning; for instance, as El-Sharkawy et al. [4] demonstrated, commercial buildings in Saudi Arabia can consume as much as 60% of the electricity generated. In Egypt, householders use almost a third of their electrical power consumption to meet cooling demand. According to Ayadi and Al-Dahidi [5], nearly 40% of the electrical power consumed in the United States and Australia, and between 25% and 30% in the EU and China, provides comfortable building conditions. Moreover, Andreou et al. [6] have estimated that there will be a considerable growth in the use of energy for cooling in European residential buildings, such that electrical consumption by air-conditioning systems will increase by 2.5 times by 2050. Therefore, significant attention is given to viable alternative energy resources instead of fossil fuels. Researchers have tested various clean technologies, and it has been concluded that switching to cleaner, sustainable energy production could lead to a

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substantial reduction in oil dependence and CO₂ emissions [6,7]. Many types of clean energy can be obtained using different technologies. Solar energy is the clear preferred option for countries in the Middle East [3].

The primary aim of this study is to evaluate the technical, economic, and environmental feasibility of a solar thermal cooling system for medium-scale cold storage in hot and arid climates. Specifically, the study seeks to: (i) quantify the cooling load for a 112-ton warehouse in Alkofra, Libya, (ii) model and validate a single-effect solar absorption cooling system in TRNSYS, (iii) analyze the influence of collector area, slope, and storage volume on system performance metrics such as solar fraction (SF), coefficient of performance (COP), and primary energy savings (PES), and (iv) assess the cost-effectiveness and CO₂ mitigation potential relative to a conventional vapor compression system.

Although numerous studies have investigated solar thermal cooling systems in Europe, Asia, and the Middle East, there is a lack of research addressing their application in North Africa, particularly in Libya. The major significance of this study lies in three aspects. First, it provides the techno-economic and environmental assessment of solar thermal cooling for a refrigerated warehouse in Libya, a country where agricultural postharvest losses exceed 30–50% due to inadequate cold storage. Second, it applies a validated TRNSYS model to explore the performance of a medium-scale absorption cooling system under local climatic conditions, providing results directly relevant to arid environments with high solar irradiance. Third, by linking technical performance metrics (SF, COP, PES) to both economic payback and CO₂ mitigation, the study offers a technical feasibility to demonstrate the broader socio-economic and environmental value of solar thermal cooling. Together, these contributions highlight the novelty and relevance of this work in bridging the gap between system modeling and real-world applications in Libya.

1.1 Solar Thermal Energy. Solar thermal energy gained by harvesting solar radiation and transforming it into heat is efficient, economical, and clean and can be used directly or stored for cooling and heating objectives. According to Tian and Zhao [8], there is increasing awareness of the potential for solar energy because of improved energy transformation capacity and increases achieved in storage intensity. The major components of a thermal solar energy application are the solar collectors and the energy storage system. Researchers have investigated the performance and optimization of both components for space cooling and heating purposes. Zhang et al. claimed this a decade ago [9]. The hottest objective in the energy sector was to capture solar power and store it as usable thermal power, and this remains the goal today. Of course, thermal solar energy can also be used to meet cooling demand, as demonstrated by Al-Yasiri et al. [10] with air conditioning.

1.2 Solar Cooling System. A solar cooling system uses electricity obtained from solar radiation by solar collectors such as photovoltaic (PV) panels to power conventional air-conditioning systems or by collecting thermal energy from the sun to run chillers. According to Song et al. [11], solar-driven cooling systems could reduce running costs, CO₂ emissions, and power consumption. The efficiency of a solar cooling system relies on the availability of solar radiation [10]. Absorption chillers use heat energy obtained from solar collectors to produce cooling or refrigeration and are efficient and effective technologies [12,13]. In an experimental study carried out in Madrid by Syed et al. [13] to investigate cooling systems driven by solar thermal energy, it was found that a solar absorption chiller is preferred for hot and dry weather. A similar study to test solar absorption chiller performance was performed in China, and the results clearly illustrated the efficiency of such systems on a hot, clear day at the location [14].

In the United Kingdom, tests of the operational performance of a solar absorption chiller on a hot sunny day showed that an average COP value of 0.58 could be achieved by adding cold storage [19]. An experimental study in Zaria, Nigeria, of a 3-kW solar absorption chiller with an inlet temperature of 95 °C provided by a gas burner achieved a maximum COP value of 0.47 [15]. A study conducted in Greece of a small-scale solar absorption chiller with a flat plate collector of a net area of 150 m² revealed that on a hot sunny day, the average COP could be as high as 0.44 [16]. In China, an experimental test conducted by Chen et al. [14] of a 5-kW single absorption chiller with an adiabatic absorber and flash evaporator demonstrated that the range of thermal COP was between 0.76 and 0.64. Further studies done in Greece by Ayadi et al. [17] and in Italy by Ali et al. [18] investigated the performance of a single absorption chiller to cool office buildings, obtaining, respectively, maximum COP values of 0.55 and 0.8.

Yin et al. [19] tested a micro-scale solar absorption chiller system experimentally under various cooling modes in Shanghai. The results illustrated that a maximum cooling of 4.5 kW could be enhanced by 23.5% by utilizing radiant cooling panels instead of fans. The comfort temperatures achieved were classified as level A. In addition, the performance of the integrated “free” cooling and solar absorption chiller was clearly shown to provide 25% of the cooling demand throughout the test. It could reach 70% in the summer months. Solar fraction and COP of the system per day varied between 0.33 and 0.4 and 0.37 and 0.8, respectively [18].

In Madrid, Lizarte et al. [20] tested the performance of a solar absorption prototype system, including an external plate heat exchanger, for residential use. The result showed that the thermal COP achieved was 0.53, with the solar fraction during the test period at 47%. Under similar climate conditions, Syed et al. [13] carried out a novel experimental study to provide standard data for verifying mathematical models. The findings showed a maximum capacity of COP at 0.6 and confirmed that solar absorption chillers operate best in hot and dry areas, with a solar fraction on hot, dry days ranging between 0.33 and 0.4.

Tests carried out by Li et al. [21] provided experimental results of the performance of solar chillers in Kunming, China. The efficiency of parabolic trough solar collectors varied from 0.35 to 0.45, chiller COP ranged from 0.11 to 0.27, and efficiency ranged from 0.25 to 0.70. In Thailand, the performance of a solar absorption chiller system was investigated experimentally by Pongtornkulpanich et al. [22]; the outcome demonstrated that the solar fraction ranged from 63% to nearly 100%, and the thermal energy provided by solar collectors had about 81% thermal efficiency.

MATLAB and TRNSYS software are the most used tools for modeling solar cooling systems [23], with TRNSYS applications operating according to ISO 9459-5:2007 (solar heating—domestic heating systems part 5: systems performance). This simulation software has an extensive library that contains proven models of components, such as solar collectors and energy storage, and can combine representative equations to simulate output or input [24]. Further, it has been shown that TRNSYS can be integrated with other software packages, for instance, MATLAB, EES, CDF, and VISUAL BASIC [25]. It also contains an unlocked source code option that enables users to validate and modify it. Its findings have been demonstrated to be authentic, and the accuracy of its results is within 10% of the corresponding experimental findings. Therefore, it was decided that TRNSYS is suitable software for investigating, analyzing, and optimizing the performance of solar cooling system components. Such as driving temperatures of main chiller parts (generator, absorber, condenser, and evaporator), area of the collector's field, consideration required to provide the energy necessary to run the system, the volume of the storage system, and backup system requirements, as well as evaluating COP and efficiency [10,26].

Within the UAE, a simulation evaluation was performed by Ssembatya et al. [28] using TRNSYS to assess the required area of

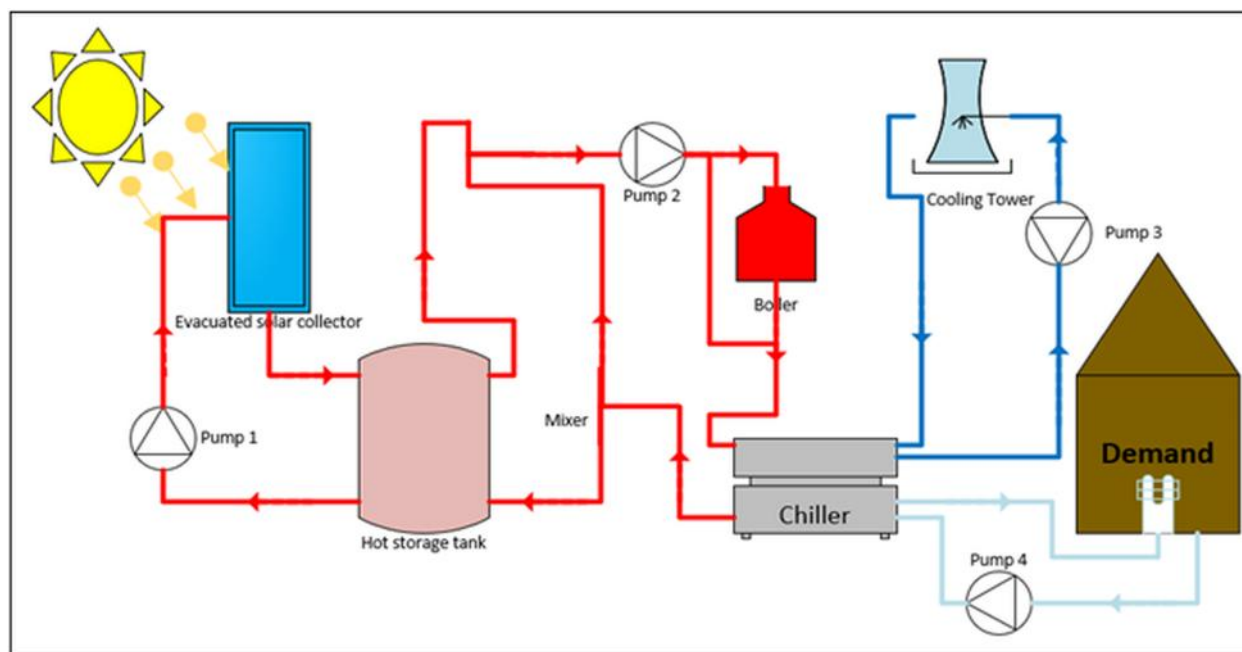


Fig. 1 Schematic diagram of the design of a thermal solar cooling system

the collector, and the COP of a 35.2-kW solar system to cool a building area of 116 m². The results showed that a low SF could be improved by increasing the area of the collector to 150 m²; this increase was significant for providing adequate monthly cooling. The chiller operated at optimum COP, and to provide the required chiller start temperature, a high degree backup system was required, with the author recommending the addition of a controller between the chiller and the storage tank.

A previous TRNSYS study assessed whether indoor comfort could be maintained in a family house in Peshawar (Pakistan) using a 3.5 kW solar absorption chiller and 12 m² of evacuated-tube collectors. With thermal storage, indoor temperature below 26 °C was achieved [29].

TRNSYS was used to evaluate the optimal performance of a 5-ton capacity solar absorption chiller in Tehran [5]. The outcomes of varying collector area, storage tank capacity, and mass flowrate of the solar system on the performance of the absorption chiller were reported. The results clearly showed that it was possible to enhance the performance by 28% with optimal values of chiller parameters (55 m² collector area, 1 m³ capacity of storage system, pack-up system start point of 77 °C, mass flowrate through collector of 1000 kg/h, and the slope angle of the solar collector of 33 deg).

The efficiency of a solar absorption chiller is assessed through its COP, which measures the ratio of useful cooling output to thermal energy input. In solar cooling systems, the SF is also important, representing the proportion of cooling energy provided directly by solar energy. Both COP and SF are influenced by factors like solar radiation levels, collector area and efficiency, thermal storage capacity, weather conditions, and the control strategies used in the system.

Thermal energy storage plays a vital role in bridging the gap between solar energy availability and cooling demands. By storing excess heat during sunny intervals and releasing it as needed, Thermal Energy Storage (TES) ensures the reliable and uninterrupted operation of the chiller system. Furthermore, supplementary systems, including gas burners or electric heaters, are often integrated to boost thermal input when solar radiation is insufficient.

Simulation tools like TRNSYS are commonly employed in the analysis and performance assessment of solar cooling systems. These tools combine intricate mathematical models of system

components (such as collectors, chillers, pumps, and control units) to evaluate system performance under diverse environmental and operational scenarios. Simulations enable parametric analyses, optimization of design parameters, and the correlation of theoretical performance with empirical findings.

In summary, the literature demonstrates that solar absorption cooling systems have been widely tested in Europe, Asia, and parts of the Middle East, with reported COP values ranging between 0.4 and 0.9 depending on configuration, climate, and collector type. However, several key gaps remain unaddressed. First, few studies have focused on North African climates, and none have provided a detailed case study for Libya, despite its high solar potential and urgent need for cold storage to reduce postharvest losses. Second, while experimental and simulation studies have evaluated performance metrics such as COP and solar fraction, there is limited work that integrates these technical outputs with economic and environmental assessment in a single framework. Third, although some parametric analyses have examined individual variables (e.g., collector area or slope), there is a lack of systematic evaluation of trade-offs among collector size, storage capacity, and performance outcomes under realistic operational constraints. This study addresses these gaps by developing a validated TRNSYS model for a medium-scale refrigerated warehouse in Alkofra, Libya, and linking the technical performance of the system directly to cost savings and CO₂ mitigation potential.

2 System Description

Figure 1 shows the proposed solar thermal cooling system used to evaluate the performance of a warehouse in Libya for the cold storage of fruit and vegetables.

2.1 Building Location and Size. The building chosen to investigate a solar cooling system was a medium-sized warehouse, 12 m long, 3 m high, and 12 m wide, in Alkofra, in the north-east of Libya, near the Egyptian border. Alkofra was selected as the case study location due to its dual relevance: (i) it is one of Libya's agricultural regions, with significant fruit and vegetable production requiring cold storage, and (ii) meteorological data indicate high annual solar irradiance, making it particularly suitable for solar thermal cooling applications. Compared to coastal regions such

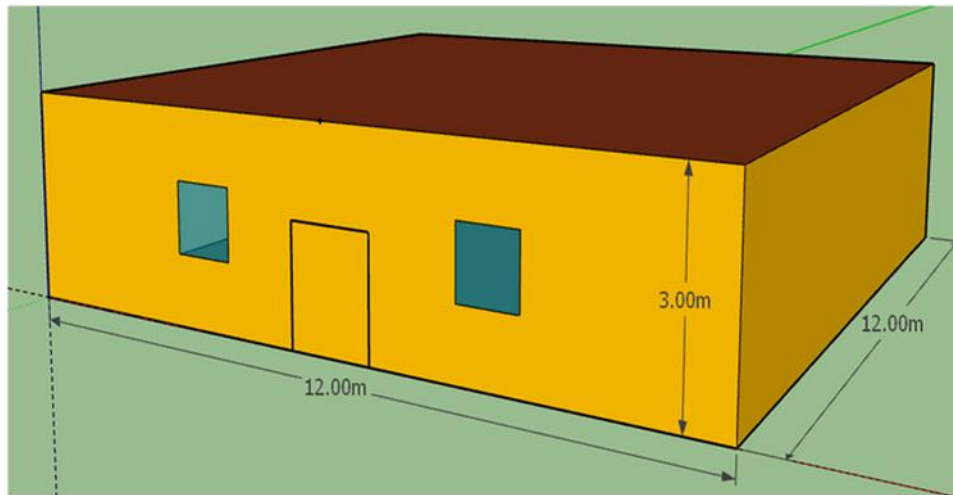


Fig. 2 Dimensions and shape of the proposed warehouse using SKETCHUP, the warehouse facing north

Table 1 Technical specifications of the main components, parameters, and inputs used in TRNSYS software

Component	Type	Parameter and input	Value	Unit
Solar collector	Type 71	Collector area	1173	m ²
		Slope angle	30	deg
		Efficiency	72	%
Absorption chiller	Type 107	Capacity	810	kW
		COP	0.53	—
		Fluid-specific heat	4.19	kJ/kg K
		Hot water (inlet–outlet)	95–85	°C
		Flowrate hot stream	52,524	kg/h
		Cold water (inlet/outlet)	37–32	°C
		Flowrate cold stream	182,375	kg/h
		Chilled water (inlet/outlet)	10.6–5.6	°C
Hot storage	Type 158	Flowrate chilled stream	77,327	kg/h
		Volume	60	m ³
		Loss coefficient	3.325	kJ/h m ² K
Auxiliary heater	Type 122	No. of nodes	10	—
		Capacity	1000	kW
		Efficiency	78	%
Data reader	Type 9c	Setpoint temperature	98.89	°C
		No. of value	2	—
Pump	Type 114	Efficiency	60	%
		Flowrate	75,000	kg/h
		Control signal	0.5	—

as Tripoli or Benghazi, Alkofra combines higher solar potential with greater distance from seaports, which amplifies the need for reliable local cold storage to reduce postharvest losses. These factors make Alkofra an appropriate reference case for evaluating the feasibility of solar thermal cooling in Libya.

The building has a single floor of 144 m², with a cold storage area, and the whole warehouse floor area is maintained at a temperature between 6 and 8 °C. The building faces north–south (see Fig. 2). The internal load assumptions were based on typical operating practices for medium-scale cold storage warehouses. A workforce of ten people for 3 h per day was assumed to account for fruit handling and packaging activities, consistent with American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) guidelines for occupancy gains. Lighting loads were set according to ASHRAE 90.1 recommendations for nonresidential storage spaces, with fluorescent lamps representing standard technology widely used in Libyan warehouses. Equipment gains reflect the operation of fan coil units derived from manufacturer data and validated against values reported in previous cold storage studies. These

assumptions ensure that internal loads realistically represent the conditions of a working warehouse in Alkofra.

and the thermal insulation is provided by a 0.113-m-thick layer of polyethylene enclosed by a 0.008-m-thick aluminum sheet inside and a 0.009-m-thick steel outside. The ceiling and doors are the same construction as the walls, and the windows (area 1 m²) are double-glazed. The warehouse work schedule is from 8:00 to 18:00 and is considered a single thermal zone. The cold storage capacity of the building is 112 tons of fruits. Ten people work inside the cold store for 3 h daily to handle the fruit. Ten fluorescent lamps illuminate the cold store during the product handling process. Eight fan coil units with a capacity of 14 kW are used to circulate the air.

2.2 Modeling in TRNSYS. This study evaluates a solar thermal cooling system's ability to fulfill refrigeration needs. The proposed system, centered on an 810-kW single-effect absorption chiller, is fully modeled in TRNSYS (version 18). Table 1 outlines the technical



The cooling demand was identified using weather data for Alkofra provided by TRNSYS software. Figure 4 shows the diagram of the solar cooling system under examination. Theoretical load and energy balance equations were also applied in parallel, not as an alternative to simulation, but to provide an independent cross-check of TRNSYS outputs and ensure methodological transparency.

$$SF = \frac{Q_{\text{solar}}}{Q_{\text{solar}} + Q_{\text{boiler}}} \quad (1)$$

Variable	Optical loss coefficient (a_0)	Loss coefficient (a_1), kJ/h m ² K	Loss coefficient (a_2), kJ/h m K	Incident angle modifier (IAM)
Value	0.802	5.4	0.00576	0.93 at 50 deg

$$\text{COP}_{\text{system}} = \frac{Q_{\text{cool}}}{Q_{\text{boiler}} + Q_{\text{solar}}} \quad (2)$$

$$\text{COP}_{\text{chiller}} = \frac{Q_{\text{eve}}}{Q_{\text{gen}}} \quad (3)$$

$$PER = \frac{Q_{\text{cold}}}{\left(\frac{Q_{\text{boiler}}}{\varepsilon_{\text{ele}}} \right)} \quad (4)$$

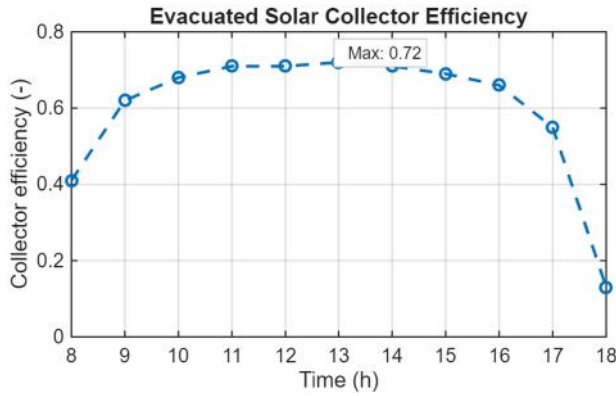



Fig. 5 Thermal efficiency of evacuated thermal solar collectors

3 Technical Analysis

3.1 Cooling Load Analysis. The total cooling load could be calculated using the equations below; however, in this article, TRNBUILD was used to calculate the total demand.

Cooling load:

$$Q_{\text{total}} = Q_{\text{walls and ceiling}} + Q_{\text{infiltration}} + Q_{\text{equipment}} + Q_{\text{lighting}} + Q_{\text{occupants}}S + Q_{\text{occupants}}S \quad (5)$$

Walls and ceiling load:

$$Q_{\text{walls and ceiling}} = A \times U \times (T_o - T_i) \quad (6)$$

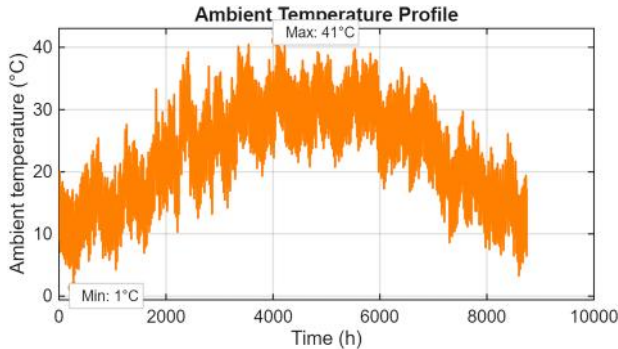


Fig. 6 Ambient temperature profile for Alkofra, Libya, throughout the entire year: TRNSYS weather file = Alkofra typical meteorological year; and simulation timestep = 1 h

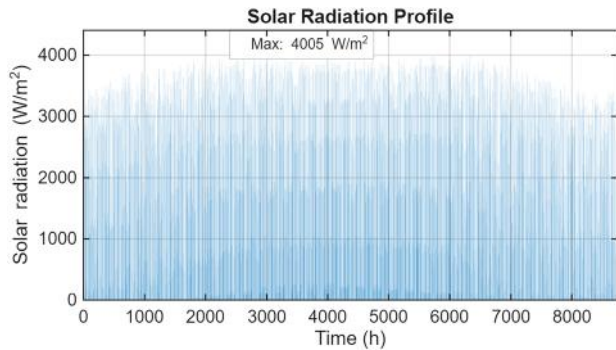


Fig. 7 Solar radiation in Alkofra, Libya, over a year: collector optical loss $a_0 = 0.802$; thermal loss $a_1 = 5.4 \text{ kJ/h m}^2 \text{ K}$; $a_2 = 0.00576 \text{ kJ/h m}^2 \text{ K}^2$; and IAM = 0.93 at 50 deg

Infiltration load:

$$Q_{\text{infiltration}} = 0.33NV(T_o - T_i) \quad (7)$$

Equipment load:

$$Q_{\text{equipment}} = \text{sum power} \quad (8)$$

Lighting load:

$$Q_{\text{lighting}} = 3.41 \times W \times Fu \times Fb \times CLF \quad (9)$$

Occupancy load:

$$Q_{\text{occupancy}}S = N \times SHG \times CLF \quad (10)$$

$$Q_{\text{occupancy}}L = N \times LHG \quad (11)$$

3.2 Product Load. According to Marchi et al., the typical cooling demand for refrigerated warehouses is approximately 270 kilowatt hours (kWh) per square meter per year. The high cooling demand for refrigerated warehouses must also account for the necessary temperature reduction of the fruits and vegetables in storage. This can be calculated as Tabassum et al. [30] stated:

$$Q_{\text{pro}} = m \times C_p \times (T_o - T_i) \quad (12)$$

where T_i and T_o represent the temperature of the fruit or vegetables when entering the warehouse and their storage temperature, respectively, m is the mass of fruit or vegetables, and C_p is their specific heat.

The product load calculated using Eq. (12) corresponds to the 112 tons of fruits and vegetables stored in the warehouse. For the simulation, the inlet temperature of the produce was assumed to equal the ambient temperature at the time of delivery, which means that Q_{pro} varies seasonally with weather conditions. This assumption ensures that the cooling energy required to reduce the produce from its entry temperature to the storage setpoint (6–8 °C) reflects realistic operational conditions. In TRNBUILD, this variable product load was combined with envelope heat gains (walls, ceiling, infiltration, equipment, and lighting) to define the

Table 3 Validation of chiller specifications and simulation results

	Parameters	Theoretical calculations	Simulation values	Error-values (%)
Chilled water	Chilled energy (kW)	450	445	1.1
	Inlet temperature (°C)	10.556	11	4.0
	Outlet temperature (°C)	5.556	6	7.4
Hot water	Hot input energy (kW)	611	662	7.7
	Inlet temperature (°C)	98	101	2.9
	Outlet temperature (°C)	88	93	5.3
Cold water	Cold energy (kW)	1061	1113	4.7
	Inlet temperature (°C)	32	34	5.8
	Outlet temperature (°C)	37	39	5.1
Storage energy capacity (kWh)		553	649	14.7
Auxiliary energy capacity (kWh)		262	277.78	5.6

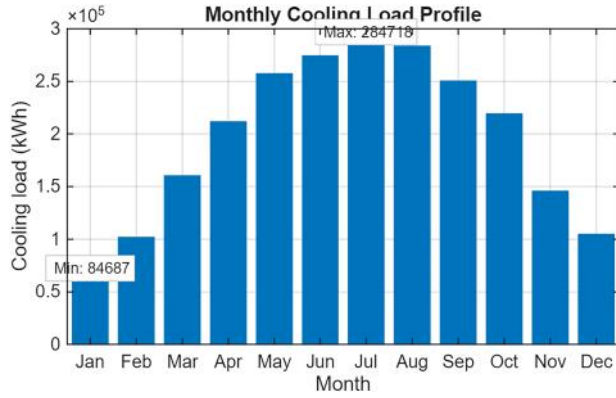


Fig. 8 Annual cooling load profile for the warehouse in Alkofra, Libya

hourly cooling demand profile. The total load profile was then linked to local weather data in TRNSYS, capturing both daily and seasonal variability. The 810-kW chiller capacity was therefore sized to meet the highest monthly cooling demand during peak summer conditions.

In this study, the specific heat capacity (C_p) of mixed fruits and vegetables was taken as 3.6 kJ/kg K, a representative average from literature for high-moisture produce. The cold storage capacity of 112 tons refers to the static storage capacity of the warehouse rather than daily throughput. The TRNBUILD simulations indicated a peak summer cooling demand of approximately 520 kW when combining product load, envelope heat gains, and occupancy/equipment loads.

4 Energy Analysis

The following equations were used to determine the energy required or produced by the system [31] and validate the output result from the TRNSYS software:

Hot water energy:

$$Q_{hw} = \frac{\text{rated capacity}}{\text{rated COP}} \times \text{fraction design energy input} \quad (13)$$

Chilled water energy:

$$Q_{chw} = m_{chw} \times C_{pchw} \times (T_{chwi} - T_{chwset}) \quad (14)$$

Cold water energy:

$$Q_{cw} = Q_{chw} + Q_{hw} = \text{kWh} \quad (15)$$

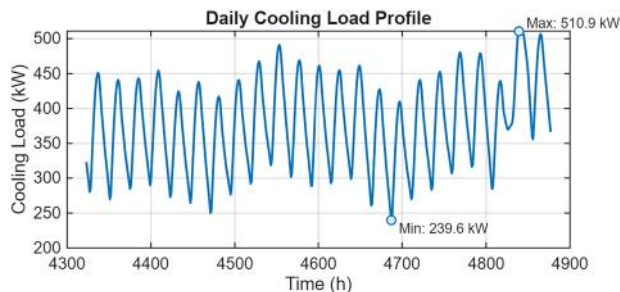


Fig. 9 Cooling load profile for August in the warehouse in Alkofra, Libya

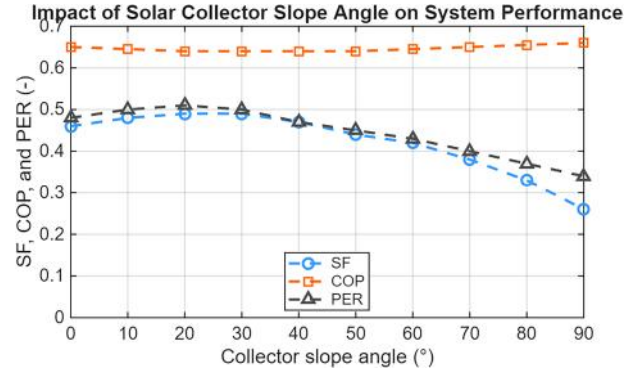


Fig. 10 Effect of slope angle on SF and COP: evacuated tube collector area = 1100 m²; storage = 60 m³; ambient $T = 30^\circ\text{C}$; collector efficiency = 72%; and mass flowrate = 52,524 kg/h (hot stream)

Boiler energy:

$$Q_{boiler} = mf \times C_{pf} \times (\Delta T) = \text{kWh} \quad (16)$$

Storage energy:

$$Q_{storage} = V \times C \times P \times (\Delta T) = \text{kWh} \quad (17)$$

5 Solar Collector Area

Solar collector area generally refers to the area of the solar collector necessary to meet a specific energy demand:

$$A = \frac{Q_{hw}}{k \times s} \text{ m}^2 \quad (18)$$

In this study, the primary power source is an evacuated tube solar collector used to drive a solar absorption chiller. Its efficiency can be determined using the following equation (see also Table 2):

$$\eta = a_0 - a_1 - \frac{(\Delta T)}{G} - a_2 \frac{(\Delta T)^2}{G} \quad (19)$$

The technical specifications of the evacuated tube solar collector are presented in Table 2, as stated by Khan et al.

The efficiency of an evacuated tube collector (ETC) can reach 72% on a hot sunny day in Libya (see Fig. 5). In the early morning, its value is 40%, continuously rising until it reaches its peak efficiency of 72% at midday and its lowest point at sunset.

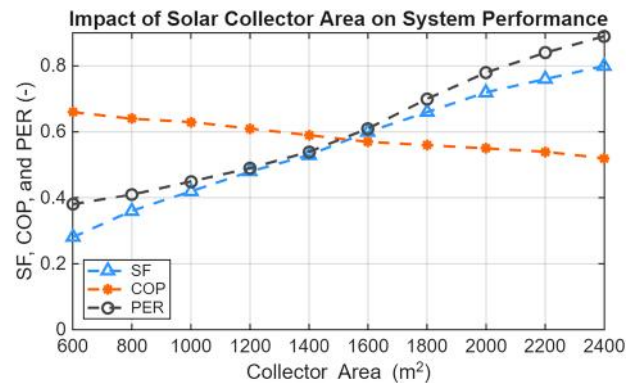


Fig. 11 Effect of collector area on SF, primary energy savings, and COP: slope = 30 deg; storage = 60 m³ and inlet/outlet temperatures = 95/85 °C (hot), 37/32 °C (cold), and 10.6/5.6 °C (chilled)

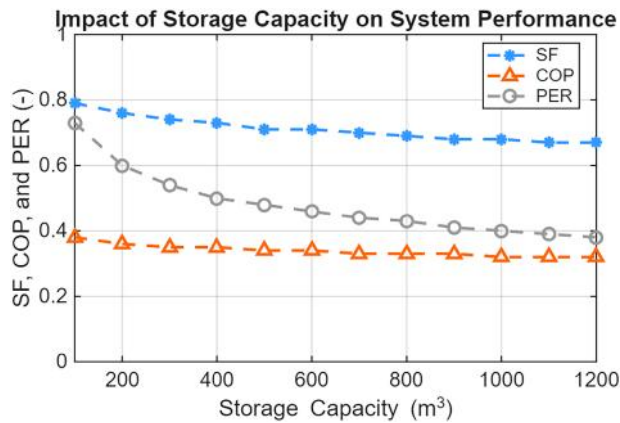


Fig. 12 Effect of storage capacity on the SF, PES, and COP: collector area = 1100 m²; slope = 30 deg; collector efficiency = 72%; and ambient $T = 30$ °C

Note that Fig. 5 of 72% is the maximum efficiency of the ETC according to data supplied by the manufacturer. The following equation was used to find the collector pump's mass flowrate:

$$\text{Collector pump flow rate} = \text{collector area} \times \text{collector test flow rate} \quad (20)$$

6 Results

6.1 Weather Data. The variation in ambient temperature and solar irradiation over 1 year (average values or for a specific year 2025) is shown in Figs. 6 and 7. The lowest ambient temperature occurs in January (2 °C), while the highest occurs in summer (41 °C). In the morning, the low temperature is due to the absence of sunlight. After dawn, the ambient temperature rises, reaching around 34 °C on average. The irradiation follows a similar trend, starting at a low of 115 W/m² at 7:00 a.m., then increasing to a maximum of nearly 4000 W/m² around noon.

6.2 Monthly and Annual Cooling Load Variation. Showing a peak demand of 520 kW during the summer months. The 810-kW absorption chiller was selected as the nearest available commercial size to cover this peak demand. As shown in Fig. 8, the annual (monthly) cooling load profile indicates that the peak cooling demand occurs during the summer months. A representative daily cooling load profile for August is shown in Fig. 9. The TRNSYS simulation results were validated against standard mathematical cooling load and energy balance equations, with differences below 15% (Table 3), which is within acceptable ranges for simulation-based studies. However, no experimental prototype was available at this stage to provide empirical validation. Instead, the model was against published experimental results from comparable systems in the literature, as referenced in Sec. 2, ensuring that key performance indicators such as COP and solar fraction fell within realistic ranges. Future work will focus on developing a pilot-scale demonstration to provide site-specific empirical data for Alkofra.

7 Parametric Analysis

It should be noted that the collector area of 1173 m², the storage volume of 60 m³, and the slope angle of 30 deg represent the initial design derived from standard load calculations and validated against mathematical equations. These values were not intended to represent an optimized configuration, but rather the baseline case against which the parametric variations were tested.

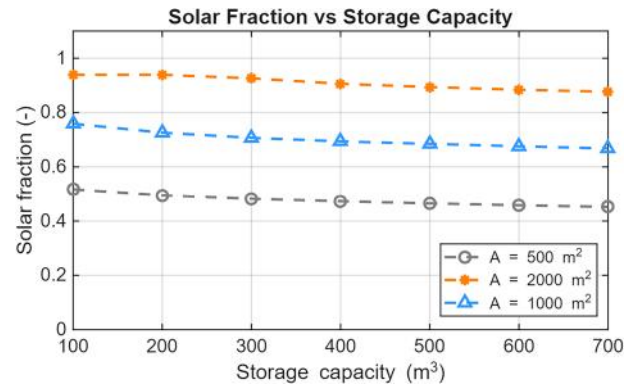


Fig. 13 Solar fraction at various storage capacities for three solar collector areas. Performance coefficients across various collector sizes and storage options: slope = 30 deg and collector efficiency = 72%.

7.1 Effect of Solar Collector Slope Angle. The angle of the slope greatly influences the performance of any solar system; therefore, system performance was tested at different slope angles. The results are shown in Fig. 10, with a fixed ETC area of 1100 m² and a storage capacity of 60 m³. Both the solar fraction and primary energy savings steadily increase with slope angle, reaching a maximum at 30 deg with values of 0.49 and 0.5, respectively. Beyond this point, both begin to decline continuously until they reach their lowest values of 0.21 and 0.33 at a slope of 90 deg. The COP of the system remained nearly constant at around 0.65.

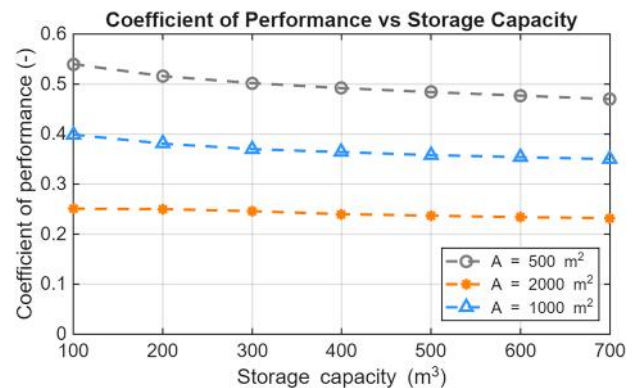


Fig. 14 Coefficient of performance at various storage capacities: slope = 30 deg; ambient $T = 30$ °C; chiller COP = 0.53; and storage temperature range = 95–85 °C

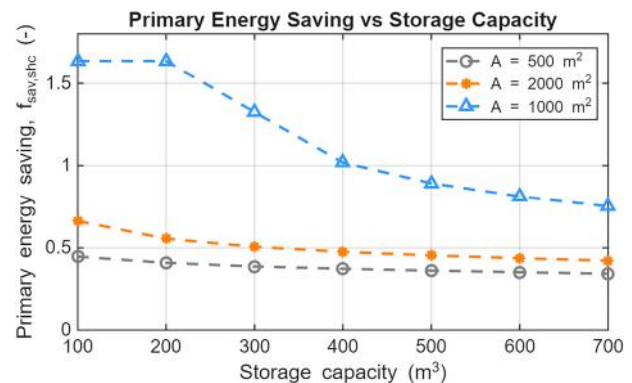


Fig. 15 Primary energy saving with storage capacity and collector area for a typical sunny day in Alkofra, Libya: slope = 30 deg; collector efficiency = 72%; system load = 810 kW; storage = 60 m³ baseline; and boiler efficiency = 78%

Table 4 Components cost: thermal solar cooling system and traditional vapor compressor cooling system

Item	Cost (source)
Absorption chiller	2328 RT £ [35]
Solar collectors	139 £/m ² [35]
Chilled water pump	413 £ [35]
Cooling water pump	620 £ [35]
Hot water pump	1190 £ [35,36]
Installation cost	5% of component cost [37]
Operation and maintenance cost	0.48 kWh/£
Water consumption cost	—
Electricity cost in Libya	0.053 kWh/£
Lifetime of the system	25 years [37]
Discount rate	10%
Cooling tower cost	44 £/kW [37]
Thermal storage cost	520 £/m ³ [37]
Boiler	1550 £ [38]
Compressor chiller	4651 £ [35]
Chilled water pump	413 £ [35]
Cooling water pump	620 £ [35]
Hot water pump	1020 £ [35]
Installation cost	60,000 £ [39]
Operation and maintenance cost	10.7 \$/kW [40]
Water consumption cost	—
Electricity cost in Libya	0.10 kWh/£

7.2 Effect of Solar Collector Area. The impact of the solar collector area on the proposed system performance was examined with a constant slope angle (30 deg) and constant storage capacity (60 m³). As shown in Fig. 11, the SF and primary energy savings increase as the collector area expands. The lowest SF value (0.2) was recorded when the collector area was set to 500 m², while the highest value (0.8) occurred at a maximum area of 2500 m². A similar trend was observed in primary energy savings, which grew from approximately 0.37 to nearly 1.0 at the maximum area. However, the COP of the system gradually decreased with increasing collector area, from 0.67 at the minimum area to 0.52 at the maximum area.

7.3 The Influence of Hot Storage Capacity on System Performance. The influence of storage capacity on the performance of the thermal solar cooling system was investigated, maintaining a constant collector area of 1100 m² and a slope angle of 30 deg (refer to Fig. 12). It was noted that an increase in storage capacity results in a reduction of the values of SF, COP, and PES.

7.4 Solar Fraction Varies With Collector Areas and Storage Capacities.. Figure 13 shows how changing storage capacity and collector area affects the system's solar fraction, with a fixed slope angle of 30 deg. As the collector area grows, the solar fraction increases. Conversely, increasing storage capacity slightly results in a lower solar fraction.

Figure 14 illustrates the effect of changing both storage capacity and collector area values on the system's COP with a constant slope angle of 30 deg. We observe that a smaller collector area results in a higher COP. However, increasing storage capacity slightly reduces the COP value.

Table 5 Annual electrical consumption of traditional and thermal solar cooling systems

Electricity consumption, traditional cooling system (kW) per year	Electricity consumption of the thermal solar cooling system (kW) per year
5,078,480	3,291,053

Table 6 Results of financial analysis and CO₂ emissions

System	Vapor compressor system	Solar cooling system	Reduction (%)
Annual CO ₂ emissions (kg/year)	3,605,720	2,336,647	35.1
Capital cost (£/w)	0.48	0.91	47
Ongoing cost (£/w)	0.16	0.07	56

7.5 Variation of Primary Energy Savings for Various Collector Areas and Storage Capacities. The influence of changing the values of both storage capacity and collector area on the system's primary energy savings with a constant collector slope angle of 30 deg is shown in Fig. 15. We observe that the smaller the collector area, the lower the PES, and increasing the storage capacity decreased the value of COP. When the collector's area was less than 1000 m², the decrease was slight, but for a collector's area of 2000 m², there was a sharp decline in PES with an increase in storage capacity.

8 Economic Analysis

The economic analysis of thermal cooling systems requires further investigation, with greater emphasis on minimizing the costs of solar collector areas and storage systems. However, the literature does not provide sufficient data on the pricing of thermal solar cooling systems. Table 4 summarizes typical values for water-lithium bromide absorption chiller pricing. Annual electrical consumption of traditional and thermal solar cooling systems, results of financial analysis and CO₂ emissions obtained in this study is shown in Tables 5 and 6 below.

The costs are derived from various sources, including expert consultations and vendor information [34].

To investigate the economic feasibility, the following equations were used:

$$C_{\text{solar system}} = \text{costs of(chiller + collector + pump + installation + cooling tower + storage)}(\text{£}) \quad (21)$$

$$C_{\text{traditional system}} = \text{costs of(chiller + pump + installation)}(\text{£}) \quad (22)$$

$$\begin{aligned} \text{Power consumption cost}_{\text{traditional system}} &= \text{chiller consumption cost} + \text{pumps consumption cost} \\ &+ \text{fans consumption cost} = (\text{£}) \end{aligned} \quad (23)$$

$$\begin{aligned} \text{Power consumption cost solar system} &= \\ \text{consumotion costs(chiller + pumps + fans + cooling tower} &+ \text{boiler)}(\text{£}) \end{aligned} \quad (24)$$

$$\text{Payback period} = \frac{\text{capital cost}(\text{£})}{\text{net saving}(\text{£})} \quad (25)$$

$$\text{Net saving} = \text{running costs TCS} - \text{running costs TSCS} \quad (26)$$

$$\begin{aligned} \text{Running cost per year} &= \text{maintenance cost} \\ &+ \text{power consumption cost} \end{aligned} \quad (27)$$

$$\begin{aligned} \text{Total saving} &= \text{system lifetime(years)} \times (\text{net saving} \\ &- \text{running cost TSCS} - \text{capital cost TSCS} \end{aligned} \quad (28)$$

The CO₂ emissions were calculated by multiplying the annual electricity consumption of each system by the Libyan grid emission factor, assumed to be 0.71 kg CO₂/kWh based on International

Energy Agency (IEA) and regional electricity mix data. The 35% reduction in annual CO₂ emissions is directly linked to the economic performance of the system. Since both emissions and operating costs scale with grid electricity use, the solar fraction (SF = 0.53) translates simultaneously into environmental benefits and reduced energy bills. For example, the decrease from 5,078,480 kWh/year [vapor compression cooling system (VCC)] to 3,291,053 kWh/year (solar thermal cooling system) results in both a 1.27-million kg/year CO₂ reduction and a 35% decrease in electricity costs. These combined effects highlight the reported payback period of approximately 10 years, showing that environmental and economic gains are inherently connected in this system. In other words, the same mechanism that reduced reliance on grid electricity drives both carbon mitigation and financial savings, highlighting the dual value of adopting solar thermal cooling.

9 Discussion

This study aimed to design, model, and analyze the performance of a solar thermal cooling system tailored for a medium-sized warehouse in Alkofra, Libya, using TRNSYS software. The simulation was validated with standard mathematical equations, yielding an overall error of 5.8% in output energy, which is well within acceptable margins for similar energy simulations.

The system utilized a single-effect absorption chiller and ETCs, achieving a collector area of 1173 m² and a slope angle of 30 deg, with an SF of 0.53, an overall COP of 0.24, and a chiller-specific COP of 0.68. These findings place the system's performance within the mid-to-upper range compared to related systems. For example, Said et al. [32] in Saudi Arabia reported a COP of 0.69 for a small-scale ETC-based refrigeration system (10.1 kW), and Khan et al. [41] achieved a COP of 0.8 using a similar setup. In Germany, Al-Falahi et al. [43] recorded a COP range of 0.5–0.9 in a hybrid parabolic trough/ETC system for a 700-kW application, suggesting that scale and collector type can significantly influence performance.

Additionally, Liu et al. observed a COP of 0.67 in a 350 kW ETC-based system in China, closely mirroring the chiller-specific COP of this study. Other systems using flat plate collectors (FPCs), such as Syed et al. in Spain (COP 0.42) and El Hassani et al. in Morocco (COP 0.53), exhibited lower efficiencies than ETC-based systems under similar climatic conditions.

Studies such as Mohanraj et al. and Calise et al. further reinforce the viability of solar-assisted absorption systems. Mohanraj et al. demonstrated that in hot climate regions like India, ETCs coupled with LiBr–H₂O chillers consistently outperform compression systems in terms of long-term cost-effectiveness. Similarly, Calise et al. analyzed integrated solar cooling systems in Mediterranean climates and found SF values ranging from 0.45 to 0.6, with economic payback periods nearing 10 years, consistent with this study's estimate.

The parametric analysis conducted in this work indicated that expanding the collector area improved the solar fraction and primary energy savings (PES), achieving maximum values (SF = 0.8; PES = 1) at a collector area of 2500 m². However, the COP slightly increased up to a collector area of 500 m² before leveling off, consistent with findings by Wang et al., who used 958 m² of collectors for a 150-kW system in Shanghai and recorded a COP of 0.6.

Regarding the collector slope angle, optimal performance was achieved at 30 deg, beyond which both SF and PES began to decline—a trend also reported by Ghafoor and Munir, who highlighted that slope angles above 35 deg in hot-arid regions tend to result in reduced annual energy yield due to misalignment with peak solar angles.

The system's storage capacity analysis indicated that increasing thermal storage volume (beyond 100–200 m³) decreased COP, SF, and PES. This reflects similar trends reported by Gabbar et al., where large-scale storage volumes increased system inertia and

energy losses. Supporting studies by Farjana et al. [33] also indicate that for systems under intermittent solar gain, smaller, optimally matched storage capacities enhance responsiveness and reduce thermal losses. An important design consideration is the role of the storage system in addressing solar intermittence. The 60-m³ thermal storage tank in the baseline system was sized to buffer daily variations in solar input, enabling the chiller to operate more continuously even during short-term cloud transients or after sunset. However, the parametric analysis showed that increasing storage capacity beyond 100–200 m³ reduced overall system performance (lower COP, SF, and PES). This reduction is due to higher thermal inertia, which delays system response, and greater surface area for heat losses, which wastes stored energy before it can be effectively used by the chiller. These findings illustrate the trade-off inherent in storage design: while storage is essential for mitigating solar intermittence, oversizing the tank leads to diminishing returns and higher costs. Therefore, optimal system design requires balancing storage volume against collector area and load profile to maximize both efficiency and reliability.

The parametric analysis highlighted clear trade-offs between design parameters. Increasing collector area enhances the solar fraction and primary energy savings but simultaneously reduces the overall COP, as the chiller receives more heat input relative to cooling output. This illustrates that a larger field size may maximize renewable contribution but at the cost of efficiency. Similarly, increasing thermal storage capacity beyond 60–100 m³ reduced COP, SF, and PES due to increased thermal inertia and higher heat losses across the larger tank surface area. Physically, this occurs because stored energy is wasted before it can be effectively transferred to the chiller, leading to diminishing returns.

These results suggest that the most effective design cannot be identified by varying one parameter at a time. Instead, a multivariable optimization framework is required to balance collector size, slope, storage volume, and cost simultaneously. While this study focused on validating the baseline configuration and examining single-parameter sensitivity, the integration of multiobjective optimization will form the next step of this research.

It should be emphasized that the auxiliary boiler in this system is electrically powered rather than gas-fired, meaning that both costs and CO₂ emissions are consistently calculated based on electricity consumption. As such, the reported 35% annual CO₂ reduction is entirely attributable to reductions in grid electricity use, with no hidden gas emissions excluded. The achieved solar fraction of 0.53 implies that just over half of the cooling demand was supplied directly by solar energy, which in turn lowered electricity purchases and contributed to the calculated payback period of approximately 10 years. The COP obtained in this study (0.24 for the overall system and 0.68 for the chiller) is lower than the 0.5–0.9 range reported by Khan et al. [40] for hybrid systems. This discrepancy is primarily due to three factors: (i) the larger scale of the warehouse case, which increases pump and auxiliary losses, (ii) the reliance on an electrically powered auxiliary boiler that reduces overall primary energy savings, and (iii) climatic variability in Alkofra compared to higher-irradiance locations investigated in the literature. Nonetheless, the performance values remain within the expected range for single-effect absorption chillers in hot, arid climates and align with similar large-scale TRNSYS simulations. These findings demonstrate how technical performance metrics, particularly solar fraction, translate directly into both economic outcomes and environmental benefits.

On the economic front, the system's initial cost is 45% higher than that of conventional systems, but this is offset by operational costs that are 60% lower and a projected payback period of 10 years. These findings align with Desideri et al., who reported a similar trend in Italy, and Shahsavar et al., who noted that solar thermal systems reach economic break-even points in 8–12 years, depending on load profile and collector type. Additionally, the study's reported 46% annual CO₂ emissions reduction mirrors data from studies by Khosravi et al. and Calise et al.,

which attribute solar thermal systems with 40–60% emissions savings over traditional cooling systems in warm climates.

While the proposed system demonstrates promising technical and economic feasibility, several limitations should be acknowledged. In arid regions like Alkofra, dust accumulation on evacuated tube collectors can significantly reduce optical efficiency and therefore lower the solar fraction over time. Regular cleaning and maintenance strategies are thus essential for reliable long-term performance. Water availability, often a limitation for absorption chillers due to cooling tower demand, is less critical in the Libyan context since water is abundant and provided at minimal cost; nevertheless, water management practices would still be required to prevent fouling and scaling. Furthermore, this study adopted a single-effect absorption chiller configuration due to its commercial maturity, lower investment cost, and suitability for medium driving temperatures achievable with evacuated tube collectors. Double-effect chillers, while capable of achieving higher COP values, require higher driving temperatures and more complex operation, making them less practical under the studied conditions. These limitations highlight the importance of considering site-specific constraints when scaling solar thermal cooling solutions.

It should also be recognized that while the present study relied on simulation and mathematical validation, experimental validation through a prototype system remains a crucial next step. A pilot plant in Alkofra would enable direct measurement of COP, solar fraction, and reliability under local climatic and operational conditions, as well as provide empirical data on collector performance under dust exposure. This would further strengthen confidence in the scalability of the system.

In summary, the findings of this study strongly align with the existing literature on performance and feasibility. The system's COP, SF, and PES metrics fall within the expected range for ETC-based solar thermal cooling systems, and its economic viability, despite the high upfront cost, is consistent with global benchmarks. Collectively, these findings reinforce the applicability of solar thermal cooling systems for medium-scale refrigeration in hot, arid environments like Alkofra and support broader transitions toward low-carbon, energy-efficient cooling technologies.

10 Conclusion

This study demonstrates that a solar thermal cooling system is a viable and sustainable option for meeting medium-scale refrigeration needs in hot and arid regions like Alkofra, Libya. Such a system not only provides an effective cooling solution but also offers significant environmental and economic benefits.

To assess its performance, the system was examined with a solar collector area of 1173 m², a slope angle of 30 deg, and a thermal storage capacity of 60 m³. The results for SF, COP, and PES were 0.53, 0.24, and 0.68, respectively. Increasing the collector area enhances both the solar fraction and primary energy savings. The highest SF value obtained was 0.8, and the highest PES value was observed at 0.9 when the collector area was at its maximum setting of 2500 m². The peak values of COP, SF, and PES were reported when the slope angle was set at 30 deg. Increasing storage capacity resulted in a decrease in SF, PES, and COP.

The economic analysis revealed that the initial cost of the thermal solar cooling system is 45% more expensive than the traditional system. However, the long-term advantages are significant: the ongoing cost of solar thermal cooling systems (STCs) is 60% less than that of VCCs. The payback period for the proposed solar thermal cooling system is approximately 10 years. Additionally, the system could cut CO₂ emissions by about 46% compared to the traditional system. Beyond technical and economic performance, the broader impact of such systems should be underscored: by providing reliable cold storage in hot climates, solar thermal cooling can directly reduce the losses of fruits and vegetables reported in developing regions, thereby improving food security and supply chain resilience in Libya and similar arid countries.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the article.

Nomenclature

m	= mass flowrate, kg/h
A	= area, m ²
C	= specific heat capacity, kJ/kg/°C
G	= solar radiation, W/m ²
K	= thermal conductivity, W/(m K)
N	= number of occupants
Q	= heat energy, kW
S	= average solar radiation, W/m ²
T	= temperature, °C
U	= overall heat transfer coefficient (U-factor), W/(m ² K)
V	= volume, m ³
W	= power, W
a_0	= optical loss coefficient
a_1	= heat loss coefficient, kJ/h m ² K
a_2	= heat loss coefficient, kJ/h m ² K
C_p	= specific heat, kJ/kg K
Q_{boiler}	= energy provided by boiler, kW
Q_{ceiling}	= heat transfer through ceiling, kW
Q_{chw}	= chilled water energy, kW
Q_{cool}	= chilled energy, kW
Q_{cw}	= cold water energy, kW
$Q_{\text{equipment}}$	= heat gain from appliances, kW
Q_{eve}	= energy provided by evaporator, kW
Q_{gen}	= energy provided by generator, kW
Q_{hw}	= hot water energy, kW
$Q_{\text{infiltration}}$	= heat gain from infiltration, kW
Q_{latent}	= latent load of occupants, kW
Q_{lighting}	= heat gain from lighting, kW
Q_{people}	= occupant load, kW
Q_{pro}	= product load, kW
Q_{sensible}	= sensible heat of occupants, kW
Q_{solar}	= useful solar energy gain, kW
Q_{walls}	= heat transfer through walls, kW
T_a	= ambient temperature, °C
T_{chwi}	= inlet chilled water temperature, °C
T_{chwset}	= set chilled water temperature, °C
T_i	= inlet temperature, °C
T_o	= outlet temperature, °C
F_b	= blast factor allowance
F_u	= light use factor
LHG	= latent heat gain, kW
PES	= primary energy saving
RT	= refrigeration tons, RT

Greek Symbols

ε	= electric ratio (primary energy conversion factor)
η	= thermal efficiency of solar collector

Abbreviations

a	= ambient
£	= pound Sterling
ASHRAE	= American Society of Heating, Refrigeration, and Air-Conditioning Engineers
boiler	= boiler
ceiling	= ceiling
chw	= chilled water
CLF	= cooling load factor
CO ₂	= carbon dioxide

cool = cooling or chilled energy
 COP = coefficient of performance
 cw = cold water
 CW = cold water
 ETCs = evacuated tube collectors
 eve = evaporator
 gen = generator
 H₂O = water
 hw = hot water
 i = inlet
 IAM = incidence angle modifier
 latent = latent load
 LiBr = lithium bromide
 lighting = lighting load
 o = outlet
 people = occupant load
 pro = product load
 sensible = sensible load
 set = setpoint temperature
 SHG = sensible heat gain
 solar = solar gain
 VCCs = vapor compression cooling system
 walls = wall

References

- [1] Bentley, R. W., 2002, "Global Oil and Gas Depletion: An Overview," *Energy Policy*, **30**(3), pp. 189–205.
- [2] Yin, H., Jawadwala, H., Kohanoff, J., Qu, M., Holmes, N., Tian, R., Liu, X., and Jani, R., 2021, "Thermal Comfort: Radiant Systems—A Review of Experimental-Based Thermal Comfort Research in Radiation Systems," Proceedings of the ACSA 109th Annual Meeting: Expanding the View, St. Louis, MO, Mar. 24–26, 2021, pp. 16–20. <https://www.acsa-arch.org/proceedings/Annual%20Meeting%20Proceedings/ACSA.AM.109/ACSA.AM.109.2.pdf>
- [3] Omer, A. M., 2008, "Green Energies and the Environment," *Renewable Sustainable Energy Rev.*, **12**(7), pp. 1789–1821.
- [4] El-Sharkawy, I. I., AbdelMeguid, H., and Saha, B. B., 2014, "Potential Application of Solar Powered Adsorption Cooling Systems in the Middle East," *Appl. Energy*, **126**, pp. 235–245.
- [5] Ayadi, O., and Al-Dahidi, S., 2019, "Comparison of Solar Thermal and Solar Electric Space Heating and Cooling Systems for Buildings in Different Climatic Regions," *Solar Energy*, **188**, pp. 545–560.
- [6] Andreou, A., Barrett, J., Taylor, P. G., Brockway, P. E., and Wadud, Z., 2020, "Decomposing the Drivers of Residential Space Cooling Energy Consumption in EU-28 Countries Using a Panel Data Approach," *Energy Built Environ.*, **1**(4), pp. 432–442.
- [7] Chidambaram, L. A., Ramana, A. S., Kamaraj, G., and Velraj, R., 2011, "Review of Solar Cooling Methods and Thermal Storage Options," *Renewable Sustainable Energy Rev.*, **15**(6), pp. 3220–3228.
- [8] Tian, Y., and Zhao, C. Y., 2013, "A Review of Solar Collectors and Thermal Energy Storage in Solar Thermal Applications," *Appl. Energy*, **104**, pp. 538–553.
- [9] Zhang, H., Baeyens, J., Cáceres, G., Degève, J., and Lv, Y., 2016, "Thermal Energy Storage: Recent Developments and Practical Aspects," *Prog. Energy Combust. Sci.*, **53**, pp. 1–40.
- [10] Al-Yasiri, Q., Szabó, M., and Arıcı, M., 2022, "A Review on Solar-Powered Cooling and Air-Conditioning Systems for Building Applications," *Energy Reports*, **8**, pp. 2888–2907.
- [11] Song, A., Lu, L., and Ma, T., 2017, "Life-Cycle Evaluation of Different Types of Cooling Systems in Buildings," *Energy Procedia*, **142**, pp. 1743–1748.
- [12] Sokhansefat, T., Mohammadi, D., Kasaeian, A., and Mahmoudi, A. R., 2017, "Simulation and Parametric Study of a 5-Ton Solar Absorption Cooling System in Tehran," *Energy Convers. Manage.*, **148**, pp. 339–351.
- [13] Syed, A., Izquierdo, M., Rodríguez, P., Maidment, G., Missenden, J., Lecuona, A., and Tozer, R., 2005, "A Novel Experimental Investigation of a Solar Cooling System in Madrid," *Int. J. Refrig.*, **28**(6), pp. 859–871.
- [14] Chen, J. F., Dai, Y. J., Wang, H. B., and Wang, R. Z., 2018, "Experimental Investigation on a Novel Air-Cooled Single Effect LiBr-H₂O Absorption Chiller With Adiabatic Flash Evaporator and Adiabatic Absorber for Residential Application," *Sol. Energy*, **159**, pp. 579–587.
- [15] Ahmadu, T. O., 2019, "Experimental Evaluation of a 3 kW Absorption Chiller Prototype," *Niger. J. Technol.*, **38**(2), pp. 334–341.
- [16] Tsekouras, P., Drosou, V., Tzivanidis, C., and Antonopoulos, K.A., 2014, "Experimental Results of a Solar Absorption Cooling Plant in Greece," *Int. J. Sustain. Energy*, **35**(4), pp. 309–322.
- [17] Ayadi, O., Mauro, A., Aprile, M., and Motta, M., 2012, "Performance Assessment for Solar Heating and Cooling System for Office Building in Italy," *Energy Procedia*, **30**, pp. 490–494.
- [18] Ali, A. H. H., Noeres, P., and Pollerberg, C., 2008, "Performance Assessment of an Integrated Free Cooling and Solar Powered Single-Effect Lithium Bromide-Water Absorption Chiller," *Solar Energy*, **82**(11), pp. 1021–1030.
- [19] Yin, Y. L., Song, Z. P., Li, Y., Wang, R. Z., and Zhai, X. Q., 2012, "Experimental Investigation of a Mini-Type Solar Absorption Cooling System Under Different Cooling Modes," *Energy Build.*, **47**, pp. 131–138.
- [20] Lizarte, R., Izquierdo, M., Marcos, J. D., and Palacios, E., 2012, "An Innovative Solar-Driven Directly Air-Cooled LiBr-H₂O Absorption Chiller Prototype for Residential Use," *Energy Build.*, **47**, pp. 1–11.
- [21] Li, M., Xu, C., Hassanien, R. H. E., Xu, Y., and Zhuang, B., 2016, "Experimental Investigation on the Performance of a Solar Powered Lithium Bromide-Water Absorption Cooling System," *Int. J. Refrig.*, **71**, pp. 46–59.
- [22] Pongtornkulpanich, A., Thepa, S., Amornkitbamrung, M., and Butcher, C., 2008, "Experience With Fully Operational Solar-Driven 10-Ton LiBr/H₂O Single-Effect Absorption Cooling System in Thailand," *Renewable Energy*, **33**(5), pp. 943–949.
- [23] Christopher, S. S., Santosh, R., Ponrajan Vikram, M., Prabakaran, R., Thakur, A. K., and Xu, H., 2021, "Optimization of a Solar Water Heating System for Vapor Absorption Refrigeration System," *Environ. Prog. Sustainable Energy*, **40**(1), p. e13489.
- [24] British Standards Institution (BSI), 2007, "System Performance Characterization by Means of Whole-System Tests and Computer Simulation," British Standards Institution, pp. 1–4.
- [25] Shrivastava, R. L., Kumar, V., and Untawale, S. P., 2017, "Modeling and Simulation of Solar Water Heater: A TRNSYS Perspective," *Renewable Sustainable Energy Rev.*, **67**, pp. 126–143.
- [26] Asim, M., Dewsbury, J., and Kanan, S., 2016, "TRNSYS Simulation of a Solar Cooling System for the Hot Climate of Pakistan," *Energy Procedia*, **91**, pp. 702–706.
- [27] Ssematya, M., Pokhrel, M. K., and Reddy, R., 2014, "Simulation Studies on Performance of Solar Cooling System in UAE Conditions," *Energy Procedia*, **48**, pp. 1007–1016.
- [28] Butt, I. B., Tan, J., Waqas, A., Ali, M., Javed, A., and Ali, A. Y., 2020, "Effect of Modified Flow Schemes of Heat Transfer Fluid on the Performance of a Solar Absorption-Cooling System for an Educational Building in Pakistan," *Appl. Sci.*, **10**(9), p. 3327.
- [29] Tabassum, T., Akter, F., and Uddin, M. N., 2023, "QPRO: Quantum Nanotechnology for Data Storage Using Programmable Read Only Memory," *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, LNICTS*, Vol. 491, pp. 447–459. https://link.springer.com/chapter/10.1007/978-3-031-34622-4_36
- [30] Khan, M. S. A., Badar, A. W., Talha, T., Khan, M. W., and Butt, F. S., 2018, "Configuration Based Modeling and Performance Analysis of Single Effect Solar Absorption Cooling System in TRNSYS," *Energy Convers. Manage.*, **157**, pp. 351–363.
- [31] Better Buildings Initiative, 2024, "Combined Heat and Power Technology Fact Sheet: Absorption Chillers for CHP Systems," Better Buildings Initiative.
- [32] Said, S. A. M., Spindler, K., El-Shaarawi, M. A., Siddiqui, M. U., Schmid, F., Bierling, B., and Khan, M. M. A., 2016, "Design, Construction and Operation of a Solar Powered Ammonia-Water Absorption Refrigeration System in Saudi Arabia," *Int. J. Refrig.*, **62**, pp. 222–231.
- [33] Farjana, S. H., Huda, N., Mahmud, M. A. P., and Saidur, R., 2018, "Solar Process Heat in Industrial Systems – A Global Review," *Renewable Sustain. Energy Reviews*, **82**, pp. 2270–2286.
- [34] Narayanan, R., Harilal, G. K., and Golder, S., 2021, "Feasibility Study on the Solar Absorption Cooling System for a Residential Complex in the Australian Subtropical Region," *Case Stud. Therm. Eng.*, **27**, p. 101202.
- [35] Anchorpumps, 2025, "Buy TP 50-120/2 A F A BQQE 0.75 kW Single Stage Single Head In Line 2 Pole 415v," Anchorpumps.
- [36] Roshanzadeh, B., Asadi, A., and Mohan, G., 2023, "Technical and Economic Feasibility Analysis of Solar Inlet Air Cooling Systems for Combined Cycle Power Plants," *Energies*, **16**(14), p. 5352.
- [37] Yuandaboiler, 2025, "Yuanda Factory 60 100 120 180 240 290 360 480 580 700 1050 kW Electric Hot Water Boiler—China Hot Water Boiler and Electric Water Boiler."
- [38] Modern Building Services, 2011, "Bringing Old Chillers up to New Standards," https://modbs.co.uk/news/fullstory.php/aid/8895/Bringing_old_chillers_up_to_new_standards_html
- [39] Sebzali, M. J., Ameer, B., and Hussain, H. J., 2012, "Economic Assessment of Chilled Water Thermal Storage and Conventional Air-Conditioning Systems," *Energy Procedia*, **18**, pp. 1485–1495.
- [40] Agservicestx, n.d., "How to Increase Air Cooled Chiller Life Expectancy," Agservicestx, <https://agservicestx.com/increase-air-cooled-chiller-life-expectancy/>.
- [41] Khan, M. M. A., Ibrahim, N. I., Saidur, R., Mahbulul, I. M., and Al-Sulaiman, F. A., 2016, "Performance Assessment of a Solar Powered Ammonia-Water Absorption Refrigeration System with Storage Units," *Energy Convers. Manage.*, **126**, pp. 316–328.
- [42] Rahman, S., Said, Z., and Issa, S., 2020, "Performance Evaluation and Life Cycle Analysis of New Solar Thermal Absorption Air Conditioning System," *Energy Rep.*, **6**, pp. 673–679.
- [43] Al-Falahi, Adil, Alobaid, Falah, and Eppe, Bernd, 2020, "Design and Thermo-Economic Comparisons of Large Scale Solar Absorption Air Conditioning Cycles," *Case Stud. Therm. Eng.*, **22**, p. 100763.



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