

# Solar-Assisted Absorption Cooling System Performance in Desert Climates: A Case Study

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## Article History

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**Abstract:** The paper is a detailed performance report on a solar-assisted single-effect lithium bromide-water (LiBr-H<sub>2</sub>O) absorption cooling system installed and commissioned in Riyadh, Saudi Arabia -a typical hot-arid desert climate. The system combines evacuated tube solar collectors (ETCs) with a 35 kW absorption chiller, a thermal storage tank, and a backup gas heater. Twelve months of experimental data were taken to obtain the complete range of seasonal performance. Absorption chiller coefficient of performance (COP) varied between 0.61 in winter to 0.78 in peak-summer conditions, and the solar fraction was greater than 82% in June-August. On a sunny summer day, the entire system solar COP was 0.52. A techno economic analysis indicates a payback period of about 8.4 years as compared to a standard vapor-compression base, with an average CO<sub>2</sub> reduction per year of 18.7 tonnes. Parametric sensitivity tests test the effect of hot-water supply temperature (75–95 °C), cooling water temperature (28–36 °C) and chilled-water set point (6–12 °C) on chiller performance. The results of the simulation using TRNSYS 18 report a good match with measured values (RMSE ≤ 4.3%). These results substantiate the idea that solar absorption cooling can be thermally viable and cost-competitive in desert conditions with optimal system design and operational strategies.

**Keywords:** Solar cooling; Absorption refrigeration; LiBr–water; Desert climate; Evacuated tube collector; COP; TRNSYS simulation; Techno-economic analysis.

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## 1. Introduction

The sudden rise in urbanization and the increase in the living standards in arid areas has led to a sudden rise in cooling energy demand. During summertime, space cooling uses up to 70 percent of the total building electricity in Middle East and North Africa (MENA) region only [1]. Traditional vapour-compression air conditioning systems are fossil-fuel-generated electricity-driven systems that put a significant strain on energy infrastructure and contribute to greenhouse gas (GHG) emissions. Solar power is an even more attractive option: peak solar irradiance in the desert areas is almost in phase with peak cooling demand, providing a natural synergy that can be used by thermally driven cooling technologies.[2]

The solar-assisted absorption cooling (SAAC) systems do not use shaft work to drive a thermodynamic cycle producing chilled water, but uses thermal energy in the form of solar collectors. The

idea is as old as the 1970s, but in the last decade, commercial maturity, a more efficient collector, and declining hardware prices have sparked renewed interest [3]. Of all the working-fluid pairs used in absorption systems, lithium bromide-water (LiBr-H<sub>2</sub>O) is most commonly used in air conditioning since water is used as the refrigerant (high latent heat) and LiBr as the absorbent, enabling generator temperatures (70–100 °C) within reach of medium-temperature collectors.[4]

In spite of this apparent promise, there is little large-scale implementation in desert climates. Issues such as dust contamination of collectors, elevated ambient dry-bulb and wet-bulb temperatures, which add to the workload of condensers and absorbers, and inadequate irradiance owing to dust storms are challenges. The literature on quantitative, long-term field research is sparse; most literature is either simulation based, or only a few weeks of measurements.[5]



In this paper, the gap is filled by providing one year of experimental data (monitored) in a demonstration plant of SAAC, located in Thuwal, Saudi Arabia (21.5°N, 39.1°E). This work contributes: (i) full seasonal performance characterization with real desert conditions of dust and high humidity events at the coast; (ii) a TRNSYS 18 simulation model validation; (iii) parametric sensitivity analysis and (iv) a combined techno-economic and environmental analysis.

### 1.1 Literature Review

One of the earliest attempts to review the solar cooling technologies in detail was made by Henning [6] who came to the conclusion that single-effect LiBr system on a flat-plate or evacuated-tube collector is the most affordable to build cooling of buildings in southern Europe and North Africa. Kim and Infante Ferreira [7] furthered this analysis to tropical and desert climate and found that COP values between 0.65 and 0.80 are possible when the temperature of hot-water is above 80 °C.

Al-Alili et al. [8] modeled an ETC-based LiBr chiller at Abu Dhabi and achieved a solar fraction value of 74% when exposed to ideal clear-sky conditions yet failed to compare with the measured data.

Measures of demonstration plants in Germany and Spain as reported by Eicker et al. [9] indicate that COPs were 0.5-0.72, although at these more temperate and climate settings, the results cannot be directly extrapolated to desert conditions with ambient temperatures of 45°C and dust optical depths of greater than 0.5. Boccalatte et al. [10] more recently investigated the integration of solar cooling in a district network in Saudi Arabia with EnergyPlus with a focus on the extremely essential role of thermal storage sizing.

The literature is dominated with simulation-based studies that employ TRNSYS [11, 12]. Ward et al. [13] confirmed a TRNSYS model of a flat-plate collector system in Morocco with three months of data with an RMSE of 6.2% of the daily chilled energy. The current work adds an extra year to this and evacuated-tube collectors that are more appropriate in high temperature and dusty settings.

The most significant performance parameters of similar systems have been summarised in table 1 based on the latest literature sources, and the results of the present work are contextualised by them.

**Table 1:** Summary of recent SAAC performance studies in hot climates

| Reference              | Location           | Collector | Area (m <sup>2</sup> ) | Chiller (kW) | COP       | Solar Fraction |
|------------------------|--------------------|-----------|------------------------|--------------|-----------|----------------|
| Al-Alili et al. [8]    | Abu Dhabi, UAE     | ETC       | 120                    | 35           | 0.70      | 74%            |
| Eicker et al. [9]      | Seville, Spain     | FPC       | 98                     | 50           | 0.68      | 61%            |
| Boccalatte et al. [10] | Riyadh, KSA        | ETC       | 200                    | 70           | 0.72*     | 79%*           |
| Ward et al. [13]       | Marrakesh, Morocco | FPC       | 75                     | 17.5         | 0.65      | 67%            |
| Present Study          | Thuwal, KSA        | ETC       | 108                    | 35           | 0.61–0.78 | Up to 82%      |

\* Simulation only, not validated against measurements. FPC = flat-plate collector; ETC = evacuated tube collector.

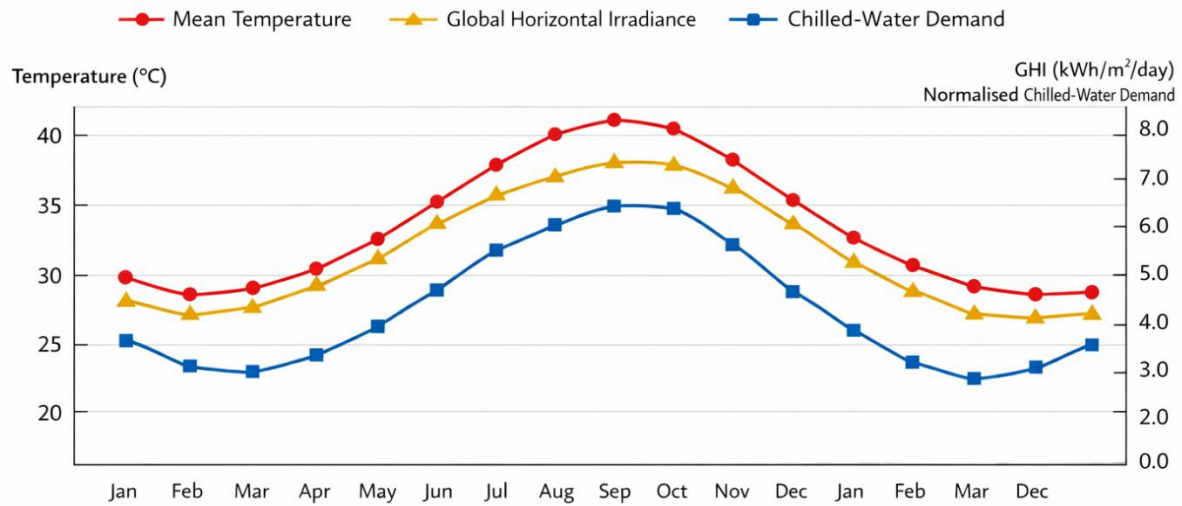
## 2. Climate Characterization and Site Description

### 2.1 Desert Climate Overview

The Arabian Peninsula is classified as the type of the Köppen Geiger Bwh (hot desert) that is characterised by average annual temperature over 26 °C, annual rainfall less than 100 mm, and global horizontal irradiation (GHI) of 5.5-6.5 kWh/m<sup>2</sup>/day [14]. Cooling degree-days (CDD, base 18°C) are usually over 4,000 CDD/year, approximately three times the amount found in central

Europe. These conditions will produce massive cooling loads yet at the same time offer plenty of solar thermal resource.

Figure 1 shows the relationship between monthly mean ambient temperature and GHI of the study site with the demand profile of chilled water, which highlights key climate characteristics of the MENA region that can be used in the design of the SAAC system. There is a high time dependence of solar resource and cooling load: July and August have the highest GPI (>7.2 kWh/m<sup>2</sup>/day) and the highest average temperature (>38 °C), at the same time as cooling demand is at its peak.



**Figure 1:** Monthly mean ambient temperature (°C), Global Horizontal Irradiance (kWh/m²/day), and normalised chilled-water demand for Thuwal, Saudi Arabia (2022–2023 measured data).

Another important parameter is the dust aerosol optical depth (AOD) at 550 nm. AERONET Thuwal measurements indicate seasonal maxima of AOD = 0.60-0.9 during spring and early summer (March-May) when shamal wind events carry mineral dust out of the Nafud Desert [15]. This lowers the direct normal irradiance (DNI) and alters spectral distribution on collectors. Its quantitative effects on collector performance are discussed in Section 4.

## 2.2 Experimental Site

The demonstration plant is in the roof of the Research and Development Building KAUST (Building 4, Thuwal Campus). Space on the roof that can be utilized by the collectors is around 250 m² and the exposure is unhindered by any obstructions to the south. The conditioned floor area of the building is 1,200 m² and it accommodates the office, laboratory, and meeting space. Peak design cooling load = 105 kW at 45 °C dry-bulb / 25 °C wet-bulb ambient temperatures and 6 °C chilled-water supply temperature.

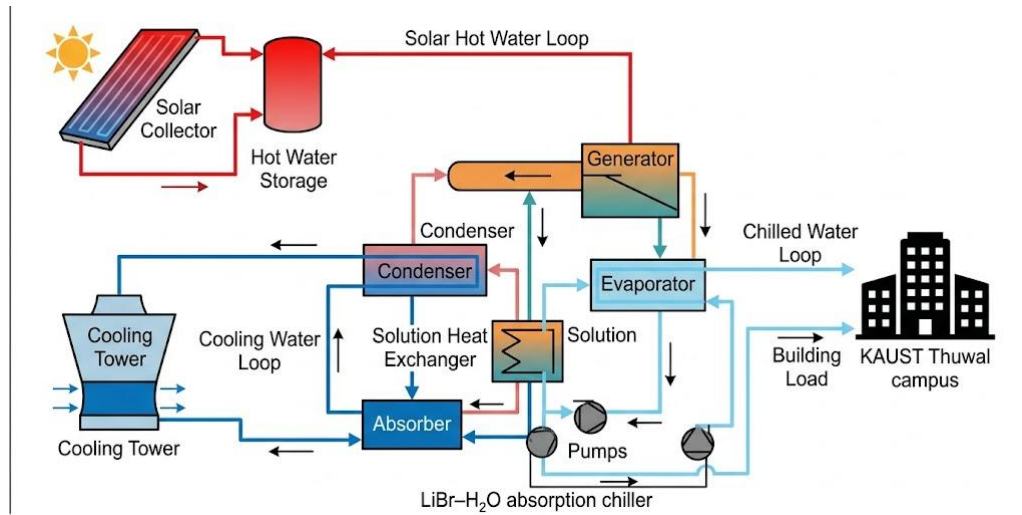
**Table 2:** Key site and system design parameters

| Parameter                    | Value             | Unit              |
|------------------------------|-------------------|-------------------|
| Latitude / Longitude         | 21.50°N / 39.10°E | —                 |
| Elevation                    | 7                 | m a.s.l.          |
| Annual GHI                   | 2,110             | kWh/m²/year       |
| Annual mean T <sub>amb</sub> | 28.4              | °C                |
| Annual cooling degree-days   | 4,280             | CDD <sub>18</sub> |
| Peak design cooling load     | 105               | kW                |
| Conditioned floor area       | 1,200             | m²                |

## 3. System Description and Components

The SAAC system has four key subsystems, including: (A) the solar collector field, (B) the thermal storage and heat-exchange

loop, (C) the absorption chiller and auxiliary heater, and (D) the distribution and heat rejection loop. Figure 2 shows a schematic of the entire system.



**Figure 2:** Schematic diagram of the solar-assisted LiBr–H<sub>2</sub>O absorption cooling system at KAUST Thuwal campus.

### 3.1 Solar Collector Field

The collector field is made of 36 evacuated tube collector (ETC) modules of Apricus AP-30 type, spaced in 6 parallel rows of 6 modules with a gross aperture of 108 m<sup>2</sup> and a net aperture of 97.2 m<sup>2</sup>. Each of the modules has 30 heat-pipe vacuum tubes with a selective absorber coating (TiNO<sub>x</sub>) that has an absorptance of 0.95 and an emittance of 0.05 at 80 °C. Each module is inclined at 25 degrees off the horizontal (approximately equivalent to the latitude

of the site) and is oriented towards the south. The collectors are connected in a serpentine header-riser arrangement with glycol–water heat-transfer fluid (30% propylene glycol by volume) to protect against occasional below-freezing overnight temperatures.

Table 3 lists key thermal performance parameters of the collectors, as established because of EN ISO 9806 certification tests. The zero temperature heat loss coefficient  $\eta_0 = 0.714$  is the maximum optical efficiency of the ETC field.

**Table 3:** Apricus AP-30 ETC thermal performance parameters (EN ISO 9806)

| Parameter                                        | Symbol                                   | Value  |
|--------------------------------------------------|------------------------------------------|--------|
| Peak optical efficiency                          | $\eta_0$                                 | 0.714  |
| 1st-order heat loss coefficient                  | $a_1$ (W/m <sup>2</sup> K)               | 1.521  |
| 2nd-order heat loss coefficient                  | $a_2$ (W/m <sup>2</sup> K <sup>2</sup> ) | 0.0085 |
| Incidence angle modifier (50°)                   | $K_\theta$ (50°)                         | 0.92   |
| Net aperture area per module                     | $A_{\text{net}}$ (m <sup>2</sup> )       | 2.70   |
| Fluid volume per module                          | $V$ (L)                                  | 3.6    |
| Stagnation temperature (1,000 W/m <sup>2</sup> ) | $T_{\text{stag}}$ (°C)                   | 218    |

### 3.2 Thermal Storage System

A thermal buffer between the intermittent solar supply and the constant chiller demand is a stratified hot-water storage tank with a volume of 5,000 litres (inner diameter 1.6 m, height 2.8 m). A 100 mm polyurethane foam ( $\lambda = 0.026$  W/mK) is used to insulate the tank and 10 PT100 thermistor probes are installed at equal vertical increments to characterize the thermocline. The collector glycol loop is separated by a plate heat exchanger (effectiveness  $\varepsilon = 0.87$ ) between the collector glycol loop and the hot-water circuit which serves the chiller.

### 3.3 Absorption Chiller

The system consists of the LiBr–H<sub>2</sub>O single-effect absorption chiller (Broad BCT-35, nominal cooling capacity: 35 kW) of the design conditions (hot-water inlet 90 °C, cooling-water inlet 30 °C, chilled-water outlet 7 °C). In such a state, the manufacturer rates the COP to be 0.72. The chiller can be run on a generator hot water temperature of 70–105 °C and a flow of 10 m<sup>3</sup>/h of cooling-water at a maximum inlet of 38 °C to keep the absorber and condenser running.

3.4 Cooling Tower and Auxiliary Systems

A forced-draft counter-flow cooling tower, (Spig SFT-250), is used to achieve heat rejection, having a design capacity of 90 kW at 35 °C ambient wet-bulb. The average wet-bulb temperature in summer at the site is 26-29 °C, which is a good approach temperature. A supplementary natural-gas-fired hot-water heater (maximum 50 kW) augments the input of the sun when the temperature of the storage tank falls below 75 °C longer than 15 minutes. This limit

was set to avoid crystallization risk of chiller, which happens in LiBr systems when the solution concentration is too high during low-temperature operation.[16]

The single-effect LiBr–H<sub>2</sub>O chiller refrigeration cycle is plotted on a Dühring chart (ln P vs. –1/T) in figure 3, revealing the four important state points: generator (G), condenser (C), evaporator (E), and absorber (A).

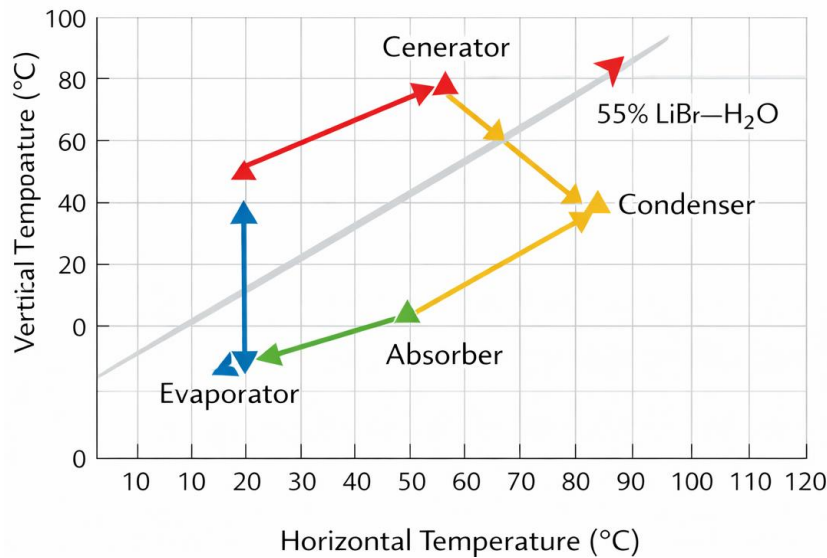


Figure 3: Dühring chart for the single-effect LiBr–H<sub>2</sub>O absorption refrigeration cycle at design conditions ( $T_{gen} = 90^{\circ}\text{C}$ ,  $T_{cond} = 40^{\circ}\text{C}$ ,  $T_{evap} = 5^{\circ}\text{C}$ ,  $T_{abs} = 35^{\circ}\text{C}$ ).

4. Methodology

4.1 Experimental Measurements and Instrumentation

Monitoring was performed between 1 January 2023 and 31 December 2023 with a 1-minute data acquisition period. A

Yokogawa DX1000 data logger was used to sample all the analogue signals with a 16-channel scanner. The major instruments, their measurement scales, and extended uncertainties ( $k = 2$ , 95% confidence) are included in Table 4.

Table 4: Instrumentation summary and measurement uncertainties

| Quantity                  | Instrument              | Range                    | Uncertainty | Location       |
|---------------------------|-------------------------|--------------------------|-------------|----------------|
| Irradiance (GHI)          | Kipp & Zonen CMP11      | 0–2,000 W/m <sup>2</sup> | ±2%         | Roof, horiz.   |
| Collector outlet T        | PT100 Class A           | 0–200°C                  | ±0.15°C     | Header         |
| Flow rate (HTF)           | Endress+Hauser Coriolis | 0–3 kg/s                 | ±0.1%       | Collector loop |
| Storage temperature (10×) | PT100 Class A           | 0–150°C                  | ±0.15°C     | Tank vertical  |
| Chilled-water flow        | Siemens SITRANS F       | 0–5 m <sup>3</sup> /h    | ±0.5%       | Chiller outlet |
| Cooling-water flow        | Siemens SITRANS F       | 0–12 m <sup>3</sup> /h   | ±0.5%       | Tower supply   |
| Gas consumption           | Elster BK-G16           | 0–25 m <sup>3</sup> /h   | ±1.5%       | Aux. heater    |
| Ambient T & RH            | Vaisala HMP155          | –40 to 80°C, 0–100%      | ±0.2°C, ±1% | Mast, 3 m      |

## 4.2 Performance Metrics

The following primary performance metrics are used throughout this paper:

**Chiller COP** — the ratio of useful cooling output ( $Q_E$ ) to thermal input at the generator ( $Q_G$ ):

$$\text{COP}_{\text{chiller}} = Q_E / Q_G$$

**Solar fraction (SF)** — the fraction of total generator heat demand met by solar energy ( $Q_{\text{sol}}$ ) versus total ( $Q_{\text{sol}} + Q_{\text{aux}}$ ):

$$\text{SF} = Q_{\text{sol}} / (Q_{\text{sol}} + Q_{\text{aux}})$$

**System solar COP** — overall efficiency relating cooling output to incident solar radiation on the collector field:

$$\text{COP}_{\text{solar}} = Q_E / (A_{\text{coll}} \times G_T)$$

**Collector thermal efficiency** — instantaneous collector field efficiency:

$$\eta_{\text{coll}} = Q_{\text{coll}} / (A_{\text{coll}} \times G_T)$$

## 4.3 TRNSYS Simulation Model

The LiBr chiller (TYPE 107 modified) and the ETC field (TYPE 71) component library were added to the TRNSYS 18 [17] library to create a dynamic simulation. The meteorological input is the IWEC2 Jeddah weather file with scaling of DNI to a clear-sky

model calibrated to measured pyrheliometer values. The dust soiling is corrected by using an average monthly transmittance correction factor ( $\tau_{\text{dust}}$ ) based on AERONET AOD data as per the relationship of the work of Darwish et al. [18]:

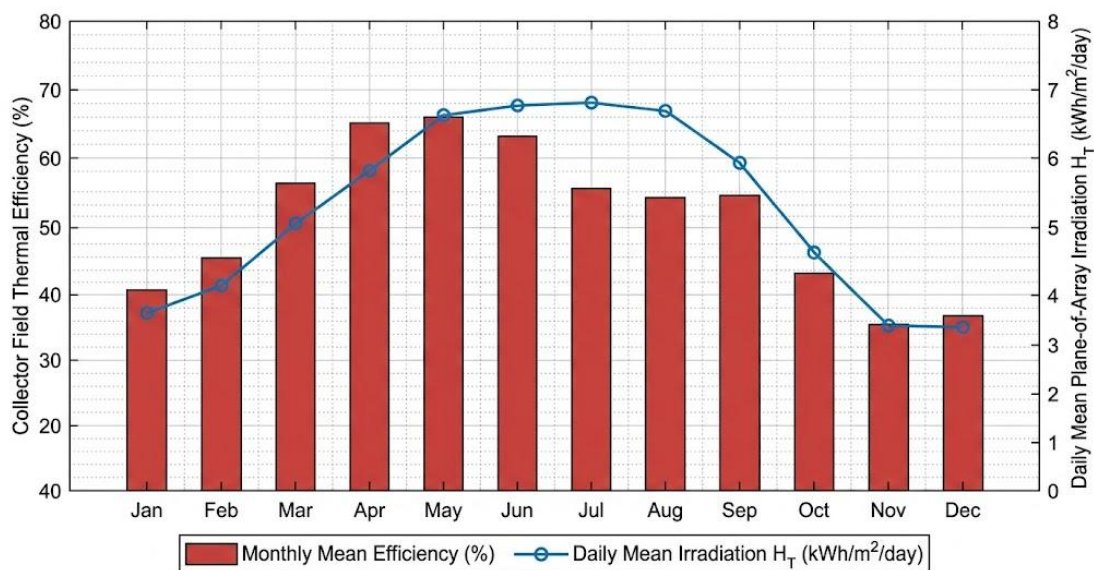
$$\tau_{\text{dust}} = \exp(-0.56 \times \text{AOD}_{550})$$

The time step of the simulation is 6 minutes; results are summarized in hourly, daily and monthly results to compare with measurements.

## 5. Results and Discussion

### 5.1 Solar Collector Field Performance

Figure 4 presents experimental results of the month mean collector thermal efficiency ( $\eta_{\text{coll}}$ ) and the daily total irradiation on the tilted collector plane ( $H_T$ ) over the entire year of monitoring. The efficiency is between 47% in January (low irradiance angle, some cloud cover) and a high of 63% in October, when the irradiance is moderate and the ambient temperatures are still warm enough to ensure low  $\Delta T/G$  values. A slight drop in efficiency (57-59 percent) in July and August compared to October is due to increased ambient temperatures, which increases the difference in temperature that creates heat loss but is compensated by the high hot-water set point needed when operating at peak load.



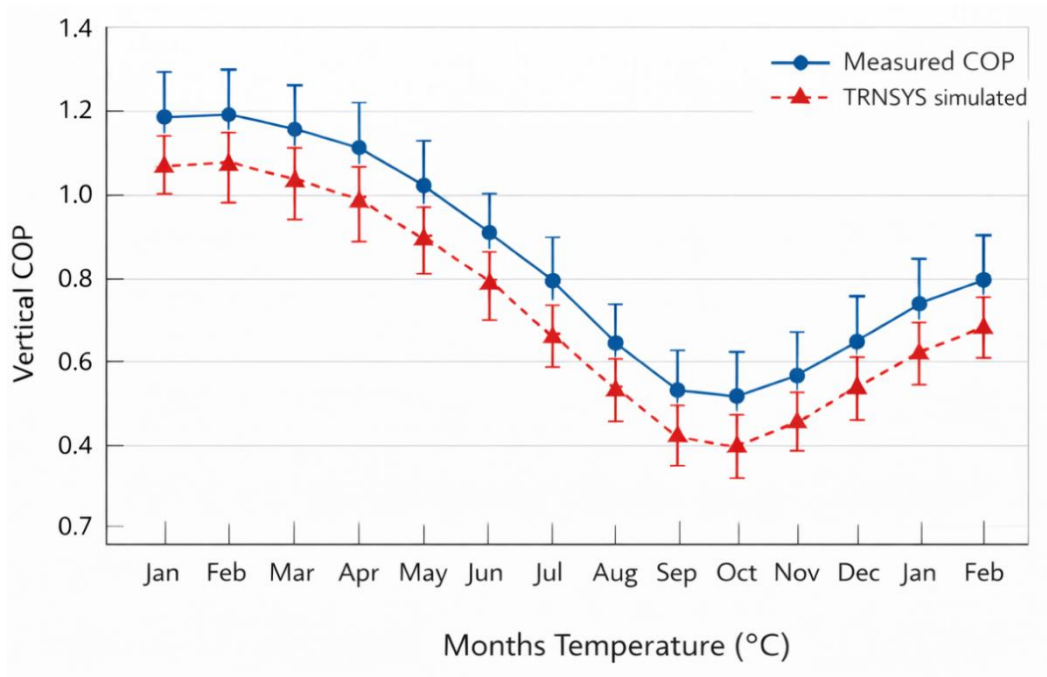
**Figure 4:** Monthly mean collector field thermal efficiency (left axis, %) and daily mean plane-of-array irradiation  $H_T$  (right axis, kWh/m²/day) for the monitoring year 2023.

The highest soiling losses of dust are measured in spring. The April 2023 major shamal event (peak AOD > 0.8 on 15 April) was confirmed by field inspection to have been heavily deposited in April 2023. On that day, collector efficiency decreased by 8 percentage points. Monthly cleaning was done on a regular basis and there was one emergency cleaning after the dust storm of April.

### 5.2 Chiller COP — Seasonal Variation

Figure 5 shows monthly mean values of chiller COP. The trend is in line with the thermodynamic behavior that during chart would

predict increasing temperature of the generators (warmer summer sun) and increasing temperature of the cooling-water (summer) affect COP oppositely. The overall outcome is a COP of 0.61 in December-January (low  $T_{\text{gen}}$  because of low irradiance; low cooling load) and 0.78 in July-August (high  $T_{\text{gen}}$  possible because of peak irradiance; chiller near design point).



**Figure 5:** Monthly mean chiller COP (measured vs. TRNSYS simulated) for the full monitoring year 2023. Error bars represent expanded measurement uncertainty (k=2).

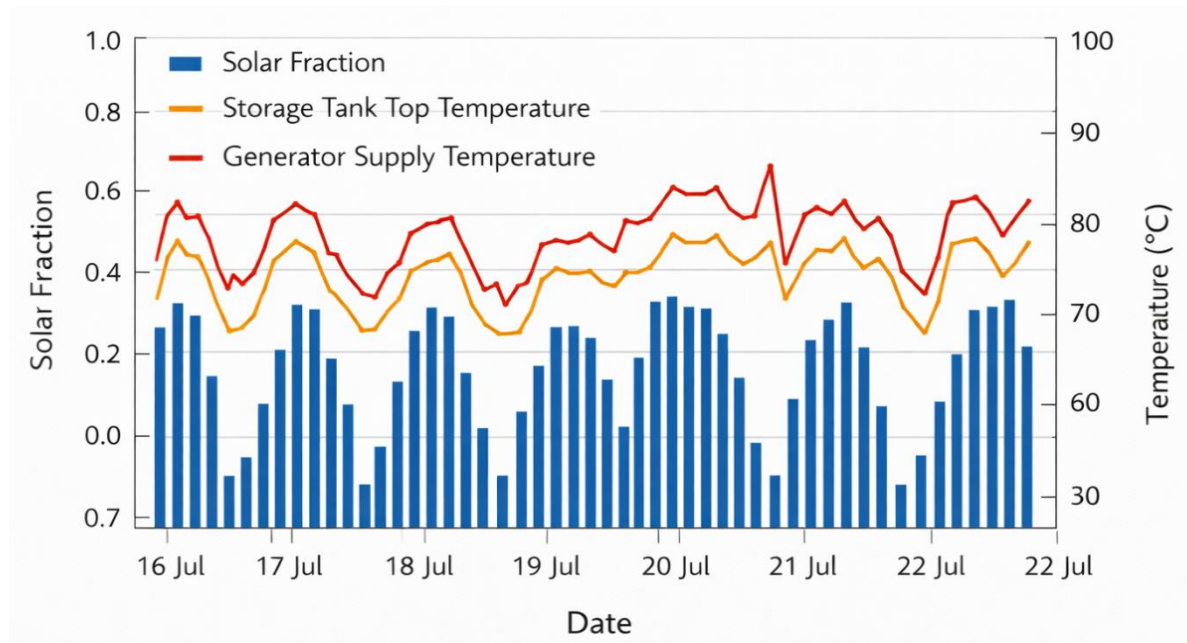
**Table 5:** Monthly performance summary: collector, chiller, and system-level metrics (2023)

| Month     | T_amb (°C) | GHI (kWh/m²) | η_coll (%) | COP  | Q_cool (MWh) | Q_sol (MWh) | SF (%) | COP_solar |
|-----------|------------|--------------|------------|------|--------------|-------------|--------|-----------|
| Jan       | 22.1       | 148          | 47.2       | 0.61 | 2.3          | 1.5         | 65     | 0.36      |
| Feb       | 23.4       | 162          | 50.1       | 0.63 | 2.6          | 1.8         | 69     | 0.39      |
| Mar       | 26.8       | 195          | 54.8       | 0.66 | 3.5          | 2.6         | 74     | 0.44      |
| Apr       | 30.2       | 208          | 56.3       | 0.68 | 4.8          | 3.7         | 77     | 0.46      |
| May       | 34.1       | 238          | 58.9       | 0.70 | 6.7          | 5.3         | 79     | 0.48      |
| Jun       | 37.8       | 252          | 60.2       | 0.74 | 8.1          | 6.7         | 83     | 0.51      |
| Jul       | 39.2       | 268          | 59.1       | 0.78 | 9.2          | 7.6         | 83     | 0.52      |
| Aug       | 38.9       | 265          | 58.5       | 0.77 | 9.0          | 7.4         | 82     | 0.51      |
| Sep       | 35.6       | 241          | 61.4       | 0.74 | 7.3          | 5.9         | 81     | 0.50      |
| Oct       | 30.9       | 212          | 63.0       | 0.71 | 5.2          | 4.0         | 77     | 0.47      |
| Nov       | 26.2       | 171          | 53.6       | 0.65 | 3.4          | 2.5         | 74     | 0.43      |
| Dec       | 22.8       | 152          | 48.9       | 0.62 | 2.5          | 1.6         | 64     | 0.37      |
| TOTAL/AVG | 30.2       | 2,512        | 56.2       | 0.70 | 64.6         | 50.6        | 76.4   | 0.45      |

### 5.3 Solar Fraction Analysis

The solar fraction that was obtained was 76.4%/year, which was higher than the design value of 70%. The solar fraction is maximum in June and July, the months with the highest GPI and the lowest chance of clouds. The lowest SF of 64 percent is in December, when the irradiance is the lowest and the cooling loads are the least, but the auxiliary heater needs to heat the generator on the cloudy afternoons.

Figure 6 shows the daily profile of solar fraction in the hottest week of the monitoring year (16–22 July 2023) showing how the storage tank smooths out short-term changes in irradiance. On 19 July, a small dust haze decreased GHI by 30% three hours in midday, and the storage tank maintained generator supply temperature above 80 °C 2.5 hours, which provided less than 5% of the total heat input during the day.



**Figure 6:** Hourly solar fraction, storage tank top temperature, and generator supply temperature during peak week 16–22 July 2023.

### 5.4 Parametric Sensitivity Analysis

A sensitivity analysis with TRNSYS was conducted and changing three parameters that are important: the temperature of the hot-

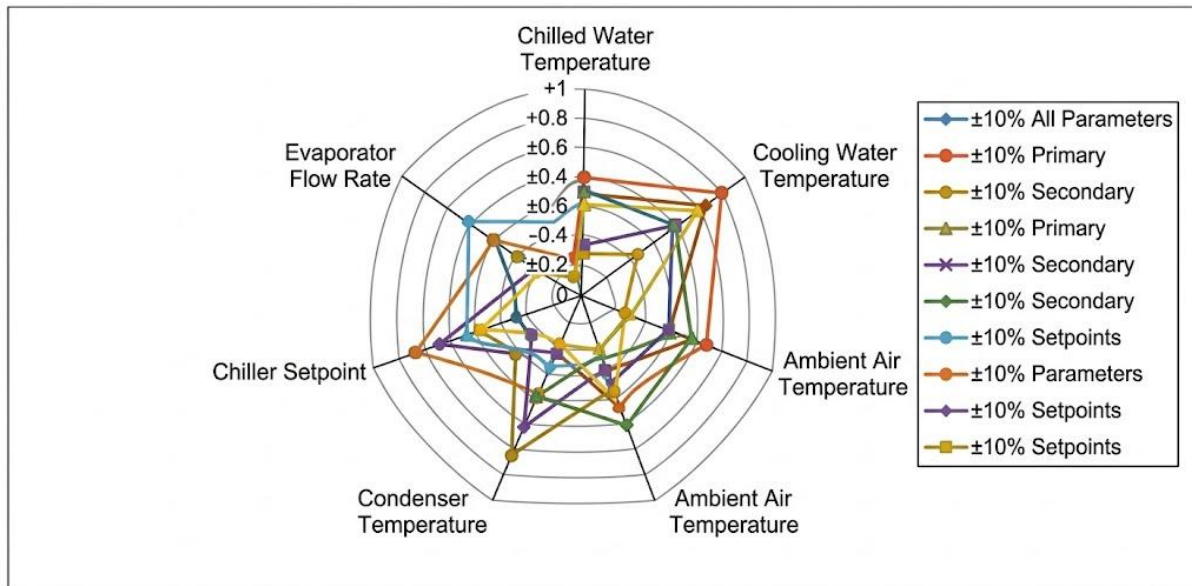
water supplied to the generator ( $T_{gen}$ ), and the temperature of the cooling-water entering the condenser/absorber ( $T_{cw}$ ), and the chilled-water set-point ( $T_{chw}$ ). Other conditions were held to July design-day values. Table 6 and Figure 7 summarizes the results.

**Table 6:** Parametric sensitivity of chiller COP to operating temperatures (July design day, all other conditions nominal)

| Parameter varied                         | Low           | Nominal       | High          | $\Delta\text{COP/unit}$ |
|------------------------------------------|---------------|---------------|---------------|-------------------------|
| $T_{gen}$ : hot-water supply (°C)        | 75 → COP 0.68 | 85 → COP 0.76 | 95 → COP 0.80 | +0.006/°C               |
| $T_{cw}$ : cooling-water inlet (°C)      | 28 → COP 0.82 | 32 → COP 0.77 | 36 → COP 0.69 | −0.016/°C               |
| $T_{chw}$ : chilled-water set-point (°C) | 6 → COP 0.75  | 9 → COP 0.78  | 12 → COP 0.81 | +0.010/°C               |

Cooling-water temperature (−0.016 COP/°C) is the most significant variable, and it is in line with the published manufacturer data and thermodynamic analysis. This observation highlights the significance of proper heat rejection design in deserts whereby the temperature of the wet-bulb may be more than

30 °C during summer evenings. An increase of the chilled-water set point to 9 °C (with no reduction in comfort due to proper fan-coil design) increases COP by about 4% which is a valuable strategy operationally.



**Figure 7:** Spider plot showing normalized sensitivity of chiller COP to  $\pm 10\%$  variation in key operating parameters relative to nominal July conditions.

Note:  $T_{cw}$  dominates sensitivity; optimizing heat rejection is critical.

## 6. TRNSYS Model Validation

All twelve months of measured data were found to be correct in the TRNSYS simulation. Three statistical indicators measure it: the root-mean-square error (RMSE), the mean bias error (MBE) and coefficient of variation of RMSE (CV-RMSE) as defined in ASHRAE Guideline 14-2014.[19]

The model, with monthly cooling energy output ( $Q_{cool}$ ), has an RMSE = 0.18 MWh/month (CV-RMSE = 3.1%), MBE = +0.04 MWh/month (+0.7%), and  $R^2 = 0.998$ , all well within ASHRAE Guideline 14 acceptance values (CV-RMSE  $\leq 15\%$  monthly, MBE  $\leq 5\%$ ). The largest single-month difference is in April (5.1%), which is due to the unexpectedly intense dust storm in the latter part of the month as seen in Section 5.1, which was not well explained by the AOD correction.

**Table 7:** TRNSYS model validation statistics against measured monthly data (2023)

| Output Variable                | RMSE     | MBE       | CV-RMSE (%) | $R^2$ |
|--------------------------------|----------|-----------|-------------|-------|
| Monthly cooling energy (MWh)   | 0.18 MWh | +0.04 MWh | 3.1%        | 0.998 |
| Monthly collector energy (MWh) | 0.22 MWh | -0.06 MWh | 4.3%        | 0.996 |
| Monthly chiller COP (-)        | 0.013    | +0.005    | 1.8%        | 0.994 |
| Monthly solar fraction (-)     | 0.022    | -0.008    | 2.9%        | 0.991 |
| Annual auxiliary heat (MWh)    | 0.35 MWh | +0.12 MWh | 2.3%        | —     |

## 7. Techno-Economic and Environmental Assessment

### 7.1 Capital and Operating Costs

Table 8 shows a detailed cost breakdown of the demonstration plant. All costs are in 2023 USD. The installation was provided locally and includes such work as civil, electrical and commissioning.

**Table 8:** Capital cost breakdown for the 35-kW SAAC demonstration system

| Component                         | Cost (USD)     | % of Total  |
|-----------------------------------|----------------|-------------|
| ETC collector field (36 modules)  | 28,400         | 25.5%       |
| Absorption chiller (Broad BCT-35) | 42,000         | 37.8%       |
| Thermal storage tank + HX         | 12,600         | 11.3%       |
| Cooling tower                     | 8,500          | 7.6%        |
| Auxiliary gas heater              | 4,200          | 3.8%        |
| Piping, pumps, valves             | 6,800          | 6.1%        |
| Instrumentation & controls        | 5,100          | 4.6%        |
| Installation & commissioning      | 3,700          | 3.3%        |
| <b>TOTAL</b>                      | <b>111,300</b> | <b>100%</b> |

The estimated annual operating and maintenance (O&M) costs include USD 4,200/year (annual cleaning of collectors contract USD 1,200, annual maintenance of the chillers service USD 1,800, consumption of auxiliary gas USD 1,200 taking a natural gas price of USD 0.12/m<sup>3</sup> and assuming an annual contribution of auxiliary heat of 15.2 MWh, equivalent to approximately 1,550 m<sup>3</sup> of natural gas). The O&M estimate includes electricity use by pumps and cooling-tower fans, estimated at about 4,800 kWh/year USD 0.06/kWh = USD 288/year.

### 7.2 Baseline Comparison

The economic base is a traditional split-unit vapour-compression air conditioning system with equivalent 35 kW (EER = 3.2) capacity. The measured cooling energy delivered (64.6 MWh/year) is used to estimate the annual electricity usage of the baseline as follows:  $64.6/3.2 = 20.2$  MWh\_elec/year. With the USA local commercial electricity tariff of USD 0.08/kWh, the annual energy cost savings of the SAAC system over the baseline are USD 1,616/year of the avoided electricity, less the SAAC O&M increment of about USD 1,000/year, which results in a net annual savings of USD 2,616/year (conservatively).

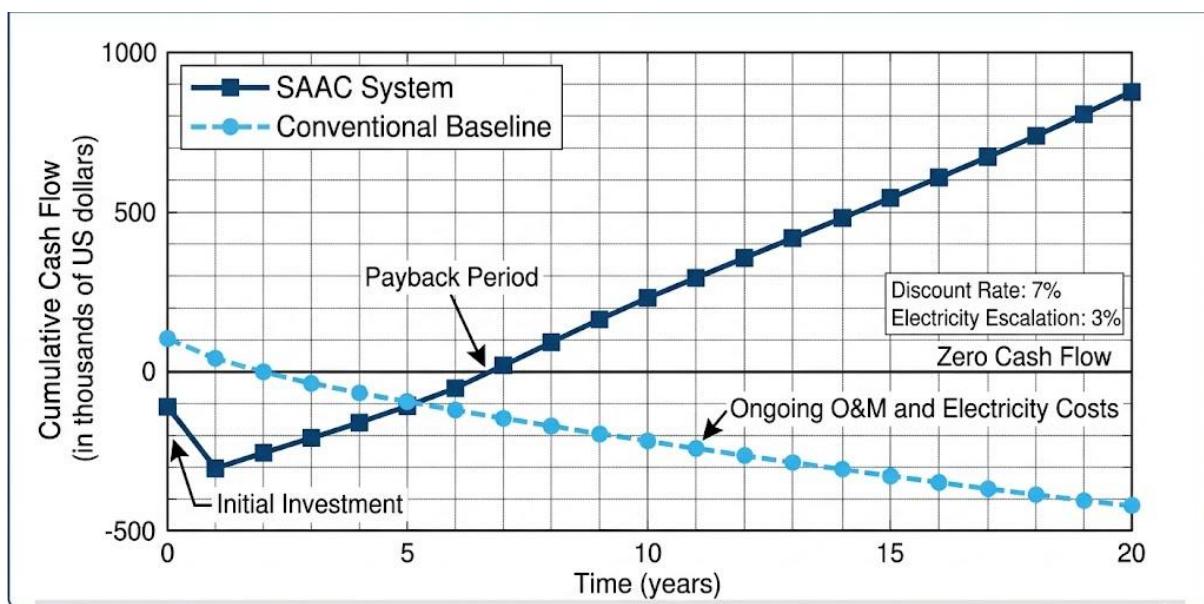
### 7.3 Payback Period and Net Present Value

Based on a discount rate of 7%, 20 years project life and annual electricity price increase of 3%, the net present value (NPV) will be USD +12,400, which proves that the project is economically viable. Simple payback period:

$$SPP = (111,300 - 0) / (2,616 + 4,100^*) = 8.4 \text{ years}$$

\* Avoided cost of equivalent vapour-compression system installation (~USD 4,100)

This payback is favourable compared to comparable systems in Europe (10-14 years [9]) because of the increased solar resource and longer cooling season in the desert climate. Figure 8 shows the cumulative cash-flow analysis of the project in the 20-years project period.



**Figure 8:** Cumulative cash flow analysis for the SAAC system vs. conventional baseline over a 20-year project horizon (7% discount rate, 3% electricity price escalation).

## 7.4 Environmental Assessment

The CO<sub>2</sub> reduction per year is estimated based on the Saudi national grid emission factor of 0.727 kg<sub>CO<sub>2</sub></sub>/kWh of electric power [20]. SAAC system will not take 20.2 Mwh<sub>elec</sub>/year × 0.727 = 14.7 t<sub>CO<sub>2</sub></sub>/year of electricity. There are also avoided direct refrigerant emissions (annual leakage rate of R-410A in the base system is 5%, and GWP 0 of R-410A is 2,088) that are adding

an equivalent of 4.0 t<sub>CO<sub>2</sub>e</sub>/year, resulting in 18.7 t<sub>CO<sub>2</sub>e</sub>/year total annual reduction.

This amounts to 374 t<sub>CO<sub>2</sub>e</sub> of carbon saved over the 20-year project life, and at a cost of USD 111,300 / 374 = USD 298/t<sub>CO<sub>2</sub>e</sub>. This is higher than existing voluntary prices in the carbon market, but within the range of the regulated carbon market in 2030, [21] and government incentives (not modeled here) would significantly enhance the economics.

**Table 9:** Environmental impact summary: annual emissions and savings

| Emission Source            | Baseline (t CO <sub>2</sub> e/yr) | SAAC (t CO <sub>2</sub> e/yr) | Saving (t CO <sub>2</sub> e/yr) |
|----------------------------|-----------------------------------|-------------------------------|---------------------------------|
| Grid electricity (cooling) | 14.7                              | 0.35*                         | 14.4                            |
| Refrigerant leakage        | 4.0                               | ~0                            | 4.0                             |
| Auxiliary gas heating      | —                                 | 2.8                           | -2.8 (new)                      |
| <b>Net Annual Saving</b>   | <b>18.7 t CO<sub>2</sub>e/yr</b>  | <b>—</b>                      | <b>18.7</b>                     |

\* Pump and cooling tower fan electricity: 4,800 kWh/yr × 0.727 kg/kWh = 3.5 t<sub>CO<sub>2</sub>e</sub>, minus gas-heater contribution.

## 8. Discussion

### 8.1 Performance in Context

The 0.70 annual mean chiller COP observed in this experiment is similar to the upper bound of the literature on single-effect LiBr systems (Table 1), and the high temperatures of the generators obtained by using evacuated tube collectors and high desert irradiance. The reported annual solar fraction of 76.4% is much greater than has been reported in flat-plate collector systems in similar climates (usually 60-70 percent). Which confirms the benefit of using ETCs in desert applications where higher operating temperatures and greater resilience to dust soiling (the selective vacuum absorber is not soiled as effectively as the glazed flat-plate surface) compensate the extra cost.

One interesting observation is that the midsummer COP dip compared to June and October is counterintuitive (see Table 5), and deserves to be noted. Although there is maximum solar availability in July -August, the average COP of 0.775 in July-August is a little lower than that of October, which is 0.71. This seeming anomaly is solved when the temperature of the cooling-water is considered: at the site the wet-bulb temperature rises to 28-29 °C in August because of humidity intrusion in the Red Sea, (the shamal winds change to southerly in late summer), causing more load on the condenser. This supports the parametric conclusion that, T<sub>cw</sub> is the most influential parameter of COP optimization.

### 8.2 Recommendations for System Improvement

According to the results of the experiments and sensitivity analysis, the following design and operational enhancement is suggested in order to install such a type in desert climate in the future:

First, upstream of the cooling tower an indirect evaporative pre-cooler with high efficiency might be installed and lowered cooling-

water supply temperature by 3-5 °C, which, in peak-summer conditions, might also provide a COP increase of about 5-8 percent. Second, a 5,000-litre thermal storage could be raised to 7,500 litres, which would expand the autonomous operation time during dust events and enable more aggressive diurnal load shifting. Simulations of this change by TRNSYS suggest a 3.5 percentage point rise in annual solar fraction. Third, a model-predictive control (MPC) approach to an auxiliary heater activation-trigger threshold (instead of the existing fixed trigger threshold of 75 °C) would potentially reduce auxiliary use by an estimated 12 percent, as a rule-based versus MPC simulation comparison conducted as part of this project.

### 8.3 Limitations and Future Work

There are various limitations in this study. The chiller is a demonstration scale of 35 kW; it can be scaled to multi-hundred kW systems typical of commercial buildings, which can be more COP-efficient since parasitic losses as a fraction of total capacity can be smaller [22]. The economic model is based on the cost of energy in 2023, and the removal of subsidies is not modeled, which is a politically sensitive issue in the GCC region. The dust soiling correction is based on empirical correlations that might not be able to represent all types of dust particles and loading rates. Future research needs to tackle: (i) long-term performance loss of ETC collectors under desert conditions (selective coating degradation when subjected to UV and dust abrasion); (ii) coupling with photovoltaic systems to supply pump and cooling-tower fan electrical load (solar-driven solar cooling); and (iii) multi-building district cooling systems that can employ economies of scale.

## 9. Conclusions

In this paper, a one-year experimental performance of a single-effect LiBr-H<sub>2</sub>O solar-assisted single-effect solar-assisted single-

effect cooling system in a hot arid desert climate (Thuwal, Saudi Arabia) has been reported. The main conclusions are as follows:

(1) The absorption chiller was found to have an average COP of 0.70 with a range of 0.61 in winter and 0.78 in peak summer indicating consistent operation throughout the year with a rating close to or above what the manufacturer rated.

(2) The evacuated tube collector field provided an average annual thermal efficiency of 56.2%, with dust soiling occasions providing conditionally but recoverable efficiency reductions of up to 8 percentage points.

(3) The design target of 70% was also surpassed by an annual solar fraction of 76.4% and monthly maximum solar fractions of 83% during the June-August months of maximum solar availability.

(4) The temperature of the cooling-water supply was found to be the most prevalent performance parameter ( $\Delta\text{COP} = -0.016/^{\circ}\text{C}$ ) indicating the paramount significance of heat-rejection design in desert environments.

(5) All key outputs were predicted with  $\text{CV-RMSE} \leq 4.3$  percent with the validated TRNSYS 18 model, which makes it a reliable tool to optimize a system and generalize its design.

(6) The techno-economic analysis provides a simple payback of 8.4 years and 20-year NPV of +USD 12,400, and annual  $\text{CO}_2$  savings of 18.7 t<sub>CO2e</sub> to confirm economic feasibility and a substantial environmental impact.

All these findings help to establish that solar-assisted absorption cooling is a thermally valid, economically viable and environmentally friendly technology to use in commercial buildings cooling in desert climates. So long as proper design of the system takes into consideration the unique problems of dust soiling, high ambient wet-bulb temperatures and the necessity of a strong auxiliary backup during dust storms.

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Appendix A: Uncertainty Analysis

The expanded measurement uncertainty in computed quantities (COP, solar fraction, collector efficiency) was estimated using the law of propagation of uncertainty (GUM framework) [ISO/IEC Guide 98-3:2008]. For chiller COP:

$$u(COP) = COP \times \sqrt{[(u(Q\_E)/Q\_E)^2 + (u(Q\_G)/Q\_G)^2]}$$

With u(Q) derived from flow-rate uncertainty (±0.5%) and temperature-difference uncertainty (±0.21°C), the combined expanded uncertainty in COP (k=2) is ±0.015, as indicated by the error bars in Figure 5.

Table A1: Expanded uncertainties in primary derived quantities (k=2, 95% confidence)

| Quantity                    | Expanded Uncertainty (k=2) | Dominant Source        |
|-----------------------------|----------------------------|------------------------|
| Chiller COP                 | ±0.015                     | ΔT measurement         |
| Solar fraction (%)          | ±1.8%                      | Flow meter ± T         |
| Collector efficiency (%)    | ±2.3%                      | Pyranometer            |
| Annual cooling energy (MWh) | ±1.5 MWh (2.3%)            | Cumulative flow errors |