

Optimise a solar thermal cooling system using combined simulation TRNSYS and Genopt software for refrigeration demand in various African climates

Proc IMechE Part A:
J Power and Energy
2025, Vol. 0(0) 1–17
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DOI: 10.1177/09576509251404129
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Abstract

This study presents an optimisation simulation-based approach for the ideal solar absorption cooling system design, including a thermal storage tank and a solar thermal collector. The strategy aims to reduce the costs of solar chilling systems by determining the optimal collector area and storage capacity while minimising electricity consumption to operate system. A hybrid approach is used to achieve the optimal configuration by combining dynamic simulation with TRNSYS and an optimisation algorithm using Gen-Opt. The system's life cycle cost, over 20 years, serves as the optimisation goal. The study examines the effects of three economic factors: solar collector area, storage capacity, and electricity prices, on the design. The outcomes are analysed from technical and economic perspectives across various African locations. Additionally, techno-economic optimisation was conducted to identify the best set of system design parameters. The findings illustrate how electricity prices and climatic conditions influence the techno-economic feasibility of the system. Alkufra demonstrates and achieves the best techno-economic performance due to its high solar radiation and lower reliance on auxiliary power, which reduces electricity costs throughout the system's lifetime. Cairo achieves a fairly reasonable performance, providing satisfactory economic viability compared to Lagos or Accra, due to sun availability and electricity costs.

Keywords

Absorption chillers, absorption refrigeration, energy storage/ auxiliary systems, solar energy systems, solar thermal conversion

Introduction

Electricity consumption around the world is increasing dramatically due to high living standards, the use of appliances, and the need to meet people's demands. Cooling systems are more commonly used in urban areas, consuming nearly 40% of the total supplied electricity. The demand for cooling is currently being met by fossil fuels. However, the negative impact of burning fossil fuels on the atmosphere and the potential risk of shortages have prompted us to seek alternative energy resources. Renewable energy sources, such as solar energy for producing thermal energy, could reduce the reliance on fossil fuels for electricity consumption. Therefore, the transition toward renewable energy for cooling applications is both an environmental necessity and a strategic energy priority. Thermal solar energy can power an absorption chiller to satisfy cooling demand.

The global demand for energy to meet cooling needs is projected to rise dramatically by 2050, particularly in developing regions. As shown in Figure 1, energy use for cooling in Asia is expected to nearly double, reaching around 14,000 TWh, while significant increases are also anticipated in the Middle East, Africa, and Latin America. This growing demand reflects population growth, urbanisation, and rising living standards in hot climates. Figure 2 further illustrates that

by 2050, energy consumption will be dominated by air-conditioning and freezing applications, especially in Latin America and the Middle East. These trends highlight the urgent need for energy-efficient and renewable-based cooling technologies to mitigate future electricity demand and reduce associated environmental impacts.

In Africa, the demand for refrigeration and air-conditioning is projected to grow significantly due to population increase, urbanisation, and agricultural storage requirements. According to the International Energy Agency (IEA), electricity demand for space cooling is expected to triple by 2050, with the fastest growth occurring in hot-climate regions such as North and Sub-Saharan Africa. At present, fossil fuels dominate the energy mix in most African countries, with renewables contributing less than 20% on average. However, solar energy offers enormous potential: the continent receives some of the

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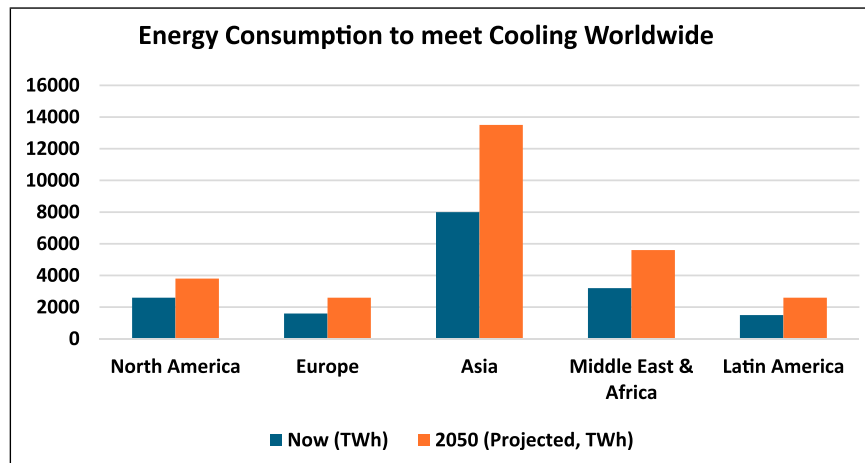


Figure 1. Energy consumption to meet cooling needs worldwide, now and in the future (IEA, EIA, WEO).

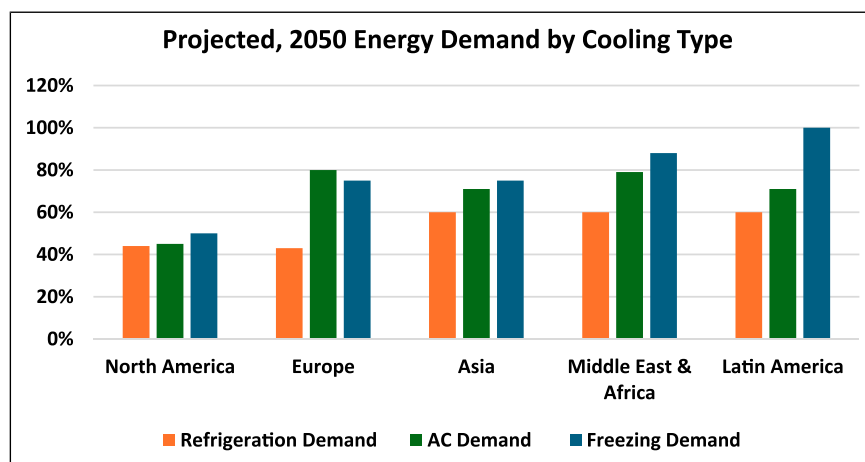


Figure 2. Projected, 2050 energy demand by cooling type (IEA, EIA, WEO).

highest solar irradiation levels worldwide, exceeding 2000 kWh/m² annually in regions such as Libya and Egypt. Incorporating solar energy into cooling systems can therefore reduce both electricity costs and environmental impacts.

Simulation tools are widely used to analyse or optimise the performance of cooling system parameters. They enable designers to modify and run simulations multiple times to assess the impact of each variable. To address issues more easily, this type of software can automatically run simulation-based optimisations for cooling systems, utilising exploration techniques that require minimal time and effort.^{1,2}

Peprah et al.^{1,2} proposed an optimal cooling schedule using a simulated annealing-based approach, while Hao et al.^{1,2} developed a machine-learning-enhanced design optimiser for urban cooling. Their work highlights how integrated optimisation and simulation methods can improve cooling system design performance and reduce computational effort.

Wetter³ developed the GenOpt optimisation tool, capable of minimising cost functions generated by simulation software. It is particularly useful when the cost function is mathematically expensive or difficult to express analytically. One advantage of GenOpt is that it can be integrated with simulation programs, such as TRNSYS, which can read and write input and output files in text format. Abdolmaleki and Berardi⁴ demonstrated the use of TRNSYS for modelling hydrogen-fuelled systems for zero-energy

buildings, confirming its flexibility in representing complex energy systems.

Calise⁴ performed a thermo-economic analysis and optimisation of solar heating and cooling systems for different Italian school buildings and climates, showing that optimal configurations can significantly reduce payback periods. Hang et al.⁵ optimised and developed a solar cooling system for a small office using linear regression-based modelling to link cost, energy use, and carbon emissions. Al-Alili et al.⁶ conducted a study on optimising a solar single-effect absorption chiller modified for Abu Dhabi's climate, where they formulated two single-objective optimisation problems: one minimising backup electricity use and the other minimising system cost. Lu et al.⁷ investigated a double-effect absorption chiller combined with evacuated tube collectors, identifying that collector efficiency strongly influences overall system economics. Berhane et al.⁸ used life cycle cost (LCC) and multi-objective optimisation to minimise both system cost and CO₂ emissions in a solar absorption chiller system. Hang et al.⁹ also applied stochastic and deterministic optimisation to analyse system uncertainties, concluding that stochastic optimisation better handles design risk.

Recent contributions between 2020 and 2024 have advanced the integration of optimisation and simulation in solar cooling applications. For instance, Li et al.¹⁰ developed a multi-objective TRNSYS–Genetic Algorithm framework for solar

cooling in subtropical climates, achieving a 23% reduction in system cost compared to manual optimisation. Hussein and El-Shaer¹¹ experimentally validated a TRNSYS model of solar-driven adsorption cooling for North-African cities, confirming higher coefficient of performance (COP) values in arid regions. Zhang et al.¹² introduced a deep-learning-assisted optimisation for evacuated-tube solar chillers, enhancing convergence speed of GenOpt by 40%. Rahman et al.¹³ compared PV-driven compression chillers and solar absorption systems and found absorption systems more cost-effective when electricity exceeds £0.06/kWh. Khalid and Rashid¹⁴ developed a hybrid PSO–Hooke-Jeeves algorithm for large-scale solar cooling in Middle Eastern climates, demonstrating that Hooke-Jeeves search provides faster local convergence for multi-dimensional problems.

These recent studies emphasise the importance of hybrid and AI-assisted optimisation methods. However, most available literature has concentrated on Asian and European climates, with limited research addressing the African energy context, where high solar potential coexists with variable electricity pricing and grid reliability. Moreover, there remains a lack of comprehensive techno-economic optimisation combining life-cycle cost, solar fraction, and primary energy savings within a unified framework.

Despite these contributions, the application of advanced optimisation frameworks to solar-assisted absorption chillers in African climates remains limited. Furthermore, most prior work has concentrated on parametric or deterministic optimisation approaches, which may not fully capture location-specific uncertainties in solar availability, electricity cost, and cooling demand. This study addresses these gaps by integrating TRNSYS simulations with GenOpt to optimise a solar thermal cooling system, focusing on life cycle cost and energy efficiency across four African locations with distinct climates: Alkufra (Libya), Cairo (Egypt), Accra (Ghana), and Lagos (Nigeria).

Materials and methods

The cooling system is powered by thermal energy harvested from the sun during the day through a thermal solar collector field. At night, the system first utilises the stored energy, and an electric boiler operates to run the absorption chiller when the

stored energy is insufficient. This system is designed to meet medium temperature refrigeration demands (2°C to 12°C) for storing fruits and vegetables in hot locations. The solar cooling system, which needs to be optimised for minimum cost and higher efficiency, is demonstrated below. It primarily consists of an absorption chiller, storage unit, evacuated tube collector, backup system, and pumps. The thermal energy is supplied by the thermal solar collector to be stored in the storage unit, providing the system with the necessary heat of approximately 85°C to 118°C. The solar absorption chiller was analysed in this research as it can initially be driven by thermal solar energy during the day. An electric boiler is utilised to supply the cooling system with the necessary inlet temperature when solar energy cannot meet the required temperature. The system consists of four cycles. In the first cycle, fluid flows from the heat source; the pump activates when the fluid temperature is higher than the ambient temperature, and the stored fluid temperature is lower than that of the fluid in the solar collectors. In the second cycle, the pump operates when the chiller is ON, controlled by a thermostat that monitors indoor temperature. If the fluid temperature does not meet requirements, the electric boiler will heat the liquid to the set point temperature, which is also regulated by a thermostat. The outlet fluid is managed by a mixer; if the fluid is hotter than that in the storage unit, it will be pumped to the boiler immediately; if it is not hot enough, it will go to the storage unit. In the third cycle, the fluid is directed to the cooling tower to cool down and then returned to the condenser in a closed loop. In the fourth cycle, whenever there is a demand for chilled energy, pump four activates to cool down the storage room, and the fluid is sent back to the chiller. Figure 3 and 4 demonstrates the solar cooling system in TRNSYS simulation software.

Figure 5 illustrates the interaction between GenOpt and a Simulation Program for optimisation and simulation processes. GenOpt controls the optimisation by inputting data into the simulation program and retrieving the outputs. The Simulation Program executes the simulations based on GenOpt's inputs, generates results (outputs and logs), and returns them to GenOpt for evaluation. This loop continues until the optimisation criteria are met, adjusting variables to enhance system performance based on the simulation outputs.

The optimisation process was carried out using TRNSYS software to simulate the system's performance, along with

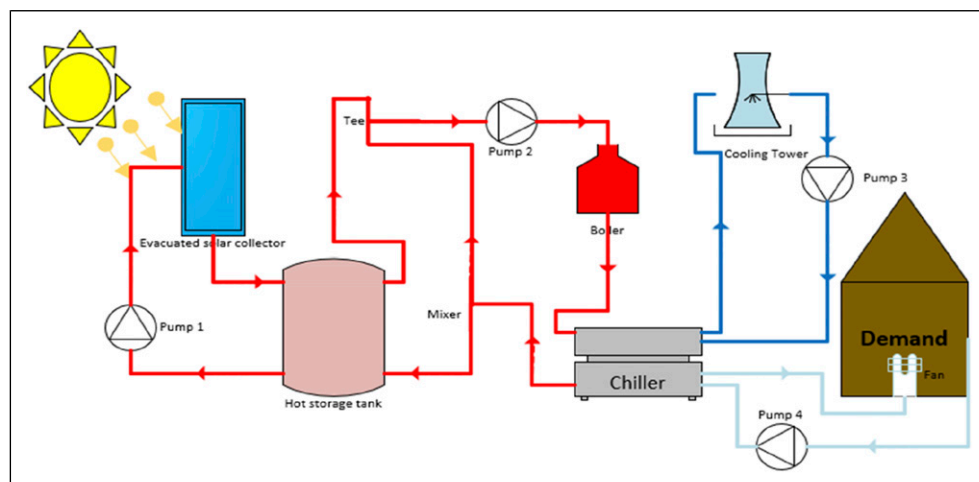


Figure 3. The schematic diagram of a solar absorption chiller cooling system.

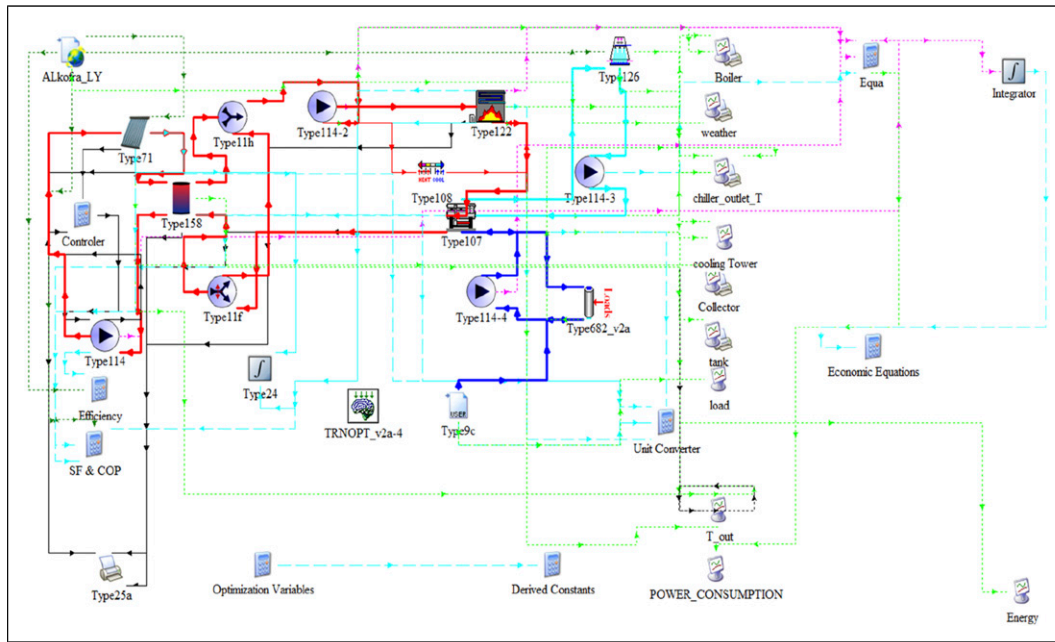


Figure 4. The solar thermal cooling system in the TRNSYS Software environment.

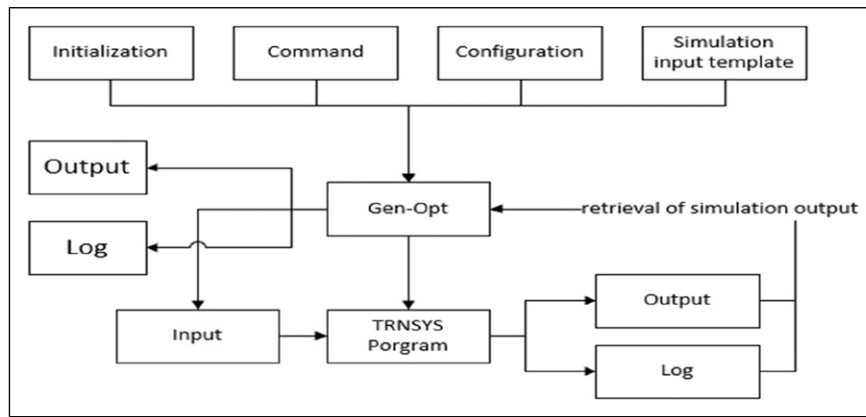


Figure 5. The interface between Gen-Opt and a simulation program Hasan et al.¹⁵

GenOpt to optimise variables such as collector area, slope angle of the collector, and storage capacity. The software was programmed to minimise costs while maximising cooling efficiency. Firstly, the TRN-build program serves as the interface to integrate TRNSYS and GenOpt. After combining both software programs, GenOpt could automatically run TRNSYS simulations hundreds of times, reducing the workload of the simulation. The process of both software programs is illustrated in Figure 5 above. GenOpt can repeatedly create building (.bui) and deck (.dck) files, run TRNSYS with those files, keep results, and restart.¹⁶

The thermal behaviour of the solar-assisted cooling system was characterised using fundamental energy balance equations. The net useful heat gain from the solar collector field is expressed as:

$$Q_{coll} = A_c \eta_c G_t \quad (1)$$

Q_{coll} is the represents the useful thermal energy collected (W). A_c is the collector surface area (m^2). η_c is the instantaneous collector efficiency. G_t is the incident global solar radiation (W/m^2).

The energy balance of the thermal storage tank is formulated as:

$$\frac{dUs}{dt} = mcp(T_{in} - T_{out}) - Q_{loss} \quad (2)$$

Us is the stored energy within the tank (J). m denotes the mass flow rate of the working fluid (kg/s). cp is its specific heat capacity (J/kg.K). Q_{loss} accounts for thermal losses to the surroundings (W). T_{in} is the inlet temperature. T_{out} is the outlet temperature.

Solar fraction

The solar fraction is the ratio between the extracted solar energy and the total energy required by the whole system; it varies between 0 and 1.

$$SF = \frac{Q_{solar}}{Q_{solar} + Q_{boiler}} \quad (3)$$

Coefficient of performance

The coefficient of performance is a crucial indicator of the performance of thermal solar cooling systems, depending on both output and input energy sources.

$$COP_{system} = \frac{Q_{cool}}{Q_{boiler} + Q_{solar}} \quad (4)$$

$$COP_{chiller} = \frac{Q_{eve}}{Q_{gen}} \quad (5)$$

Primary energy saving

The primary energy saving is the ratio of electricity consumption for a solar cooling system and a conventional compression chiller system, Equation below represents the relation between the total primary power consumed by the auxiliary boiler in a thermal solar cooling system to the total primary power consumed by a traditional air compressor chiller to cover the same cooling load, ϵ_{ele} is energy conversion factors was assumed to 0.4 according to Ayadi & Al-Dahidi.¹⁷

$$PER = \frac{Q_{cold}}{\left(\frac{Q_{boiler}}{\epsilon_{ele}}\right)} \quad (6)$$

Figure 6 below illustrates the optimisation process followed in this research for the solar-assisted absorption cooling system. The procedure begins with the input of climatic data and load profiles for each location, followed by defining the system components and initial design parameters in TRNSYS. The simulation is then executed to calculate key performance indicators such as the coefficient of performance (COP), solar fraction (SF), and primary energy ratio (PER). The resulting performance data are passed to GenOpt, which evaluates the cost function and initiates an iterative optimisation loop. Within this loop, the Hooke–Jeeves algorithm continuously adjusts the main design variables—collector area, storage volume, and collector slope angle—until the life-cycle cost (LCC) converges to its minimum value. On the system side, the solar field supplies heat to the thermal storage tank, which in turn powers the absorption chiller; the auxiliary power system provides backup energy under low-radiation conditions. A controller regulates energy flow among these subsystems to maintain stable operation. The process concludes with the output of the optimal configuration that minimises cost and maximises overall system

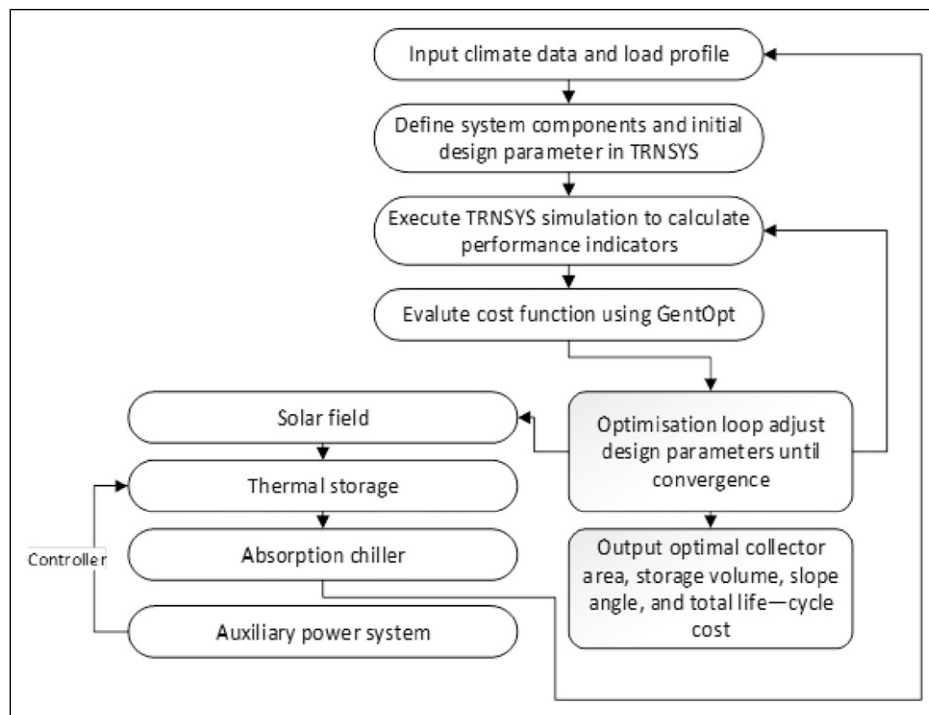


Figure 6. Flow chart showing the modelling and optimisation sequence of the solar absorption cooling system.

Table 1. Parameter values for the optimisation approach in TRN-opt.

	Slop angle (degree)	Collector area (m ²)	Storage capacity (m ³)
Minimum	10	1000	60
Maximum	45	2500	500
Initial value	15	1000	60
Step	5	50	25

efficiency. Table 1 below illustrates the optimisation approach for each parameter.

The interface between TRNSYS Software and Gen-opt (TRN-opt) requires the minimum, maximum, initial, and step values. Additionally, the cost object function is demonstrated in equations below:

$$\begin{aligned} COST_{SOLAR} = & ((AREA_{COLL1} * COST_{M2}) \\ & + (VOL_{TANK1} * COST_{M3})) \\ & + (LIFETIME * (Q_{-T} * COST_{KWH})) \end{aligned} \quad (7)$$

$$\begin{aligned} Q_{-T} = & Q_{-PUMP} + Q_{-PUMP1} \\ & + Q_{-PUMP2} + Q_{-PUMP3} + Q_{-boiler} \end{aligned} \quad (8)$$

Additionally, TRN-opt is a powerful add-on application in TRNSYS, as it offers the option to choose optimisation algorithm methods, such as the coordinator search method and the Hooke-Jeeves search method, among others.¹⁸

- The coordinator search method optimises by investigating a variable quantity at a time, near its decreasing step size, repetitively. It is simple; however, it could be slow for complex problems or high-dimensional scenarios.¹⁹
- The Hooke-Jeeves Search Method combines exploratory search along coordinate directions with pattern attempts for faster convergence. It is more effective and robust for multi-dimensional challenges. The Hooke-Jeeves Search Method was chosen for this research because it is more efficient and converges faster.¹⁸

The costs of the evacuated tube solar thermal collector, storage, and electricity in each country are presented in Table 2 below.

Results

Weather data for each location (temperature, humidity, and solar radiation) were input into the model to accurately simulate real conditions. The optimisation method employed search algorithms to achieve the most efficient configuration for each location. Figure 7 illustrates the 3D mapping of the African weather profile.

The figure above illustrates the 3D mapping of the African weather profile. The X-axis displays temperature in degrees Celsius (°C), ranging from 0°C to 50°C. The Y-axis shows humidity in percentage (%), spanning from 0% to 100%. The Z-axis represents radiation in watts per square meter (W/m²), varying between 0 and 2000 W/m². Each data point reflects a specific combination of humidity, temperature, and radiation readings. The points are color-coded according to a colour bar on the right, indicating the magnitude of radiation: Blue denotes low radiation values (around 200 W/m²), while Red indicates high radiation values (around 1800 W/m²). High radiation is observed at elevated temperatures (above 30°C) and is associated with lower humidity levels. Low radiation is noted at cooler temperatures (below 20°C) and tends to correspond with higher humidity levels. Mid-range radiation values are

Table 2. The cost of electricity and the main solar cooling system.

	Cost (£)
Collector area (m2)	400
Storage capacity (m3)	520
Feed-in-tariff (W)	
Libya	0.05
Egypt	0.047
Nigeria	0.045
Ghana	0.16

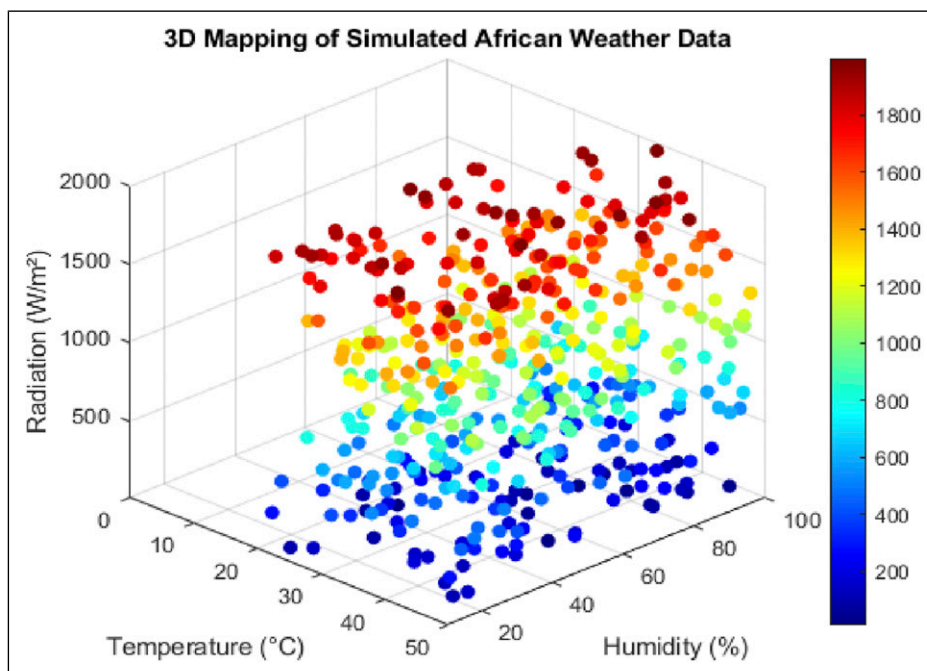


Figure 7. 3d mapping of the African weather profile.

found in the transition zones of temperature and humidity. This visualization supports analysing trends in weather data and examining how temperature and humidity affect solar radiation in a simulated African environment. Moreover, it illustrates where the system may be more advantageous or less effective in terms of technical and economic performance. In this study, four locations were selected to evaluate the system, each chosen for its unique weather profiles (temperature, humidity, and solar radiation).

Table 3 below shows the most optimised values of the primary design parameters alongside the minimum cost achieved for each location.

Figure 8 demonstrates the relationship between collector area, tank volume, and cost for a solar cooling system in Lagos. As the collector area increases to 2453.125 m², the cost initially drops, reaching an optimised cost of £7,128,871, before stabilizing. The tank volume remains consistent at 100 m³ throughout the optimisation process, indicating that varying the tank volume does not significantly impact the system's overall cost.

Figure 9 illustrates the relationship between collector area, tank volume, and cost. The optimisation process results in a minimum cost of £2,546,257 with a collector area

Table 3. The optimal values for system cost, collector slope angle, collector area, and storage capacity.

	Cost	Slop angle (degree)	Collector area (m2)	Storage capacity (m3)
Alkufra	1,493,918	10	2500	213
Cario	2,546,084	21	2500	100
Accra	6,607,349	10	2500	100
Lagos	7,131,090	10	2500	100

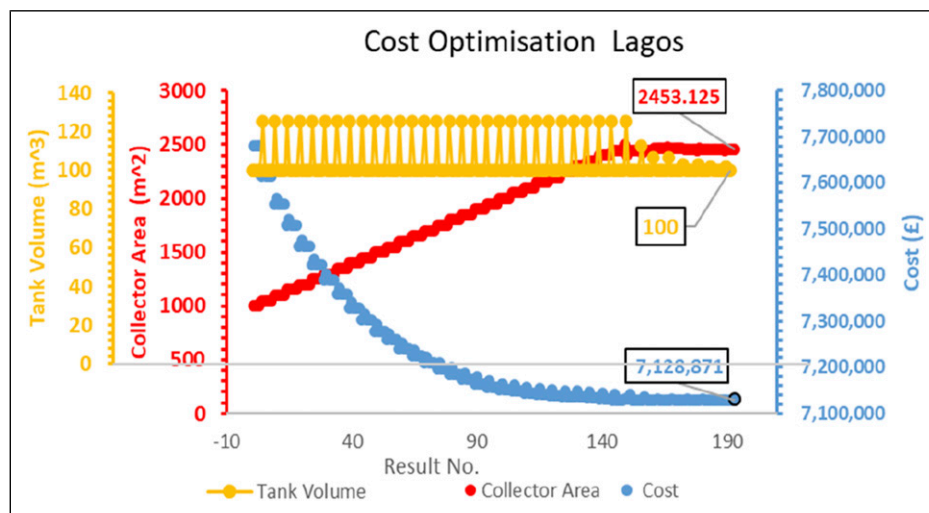


Figure 8. The cost analysis during the optimisation process for a solar cooling system in Lagos, Nigeria.

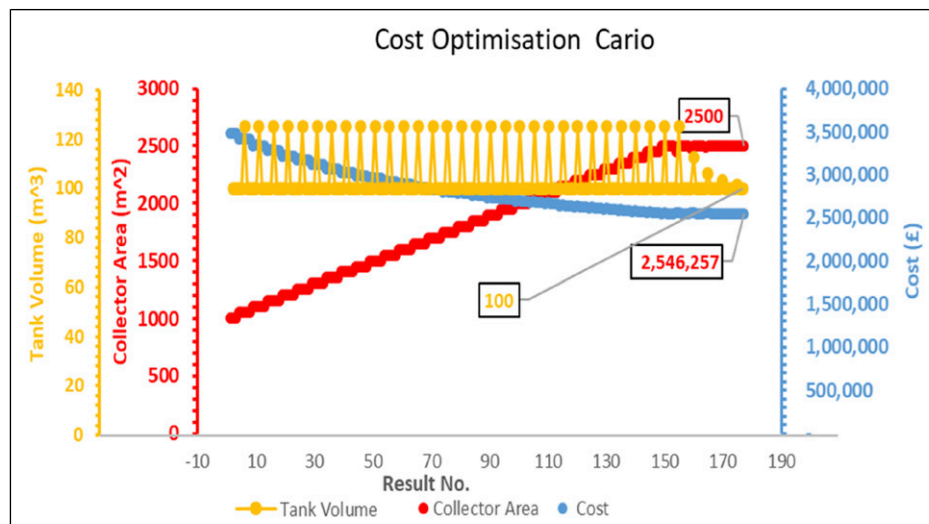


Figure 9. The cost analysis during the optimisation process for a solar cooling system in Cairo, Egypt.

of 2500 m², while the tank volume remains consistent at 100 m³ throughout the analysis. The collector area increases steadily, reducing costs until it reaches an optimised point, after which it stabilises.

Figure 10 illustrates the relationship between collector area (m²) and storage capacity (m³) with the cost (£) for a solar thermal cooling system in Alkufra. The chart shows how varying the collector area and tank volume impacts the overall system cost during optimisation. The price decreases because a larger collector area likely enhances the efficiency of solar energy collection, reducing reliance on auxiliary energy sources (like electricity or fuel). The lowest cost point is £1,493,932, corresponding to a collector area of approximately 2500 m² and a storage capacity of 213 m³.

Figure 11 illustrates the relationship between collector area, tank volume, and cost for a solar cooling system in Accra. The minimum cost reached is £6,600,224, with a collector area of 2106 m², while the tank volume remains constant at 100 m³ throughout the optimisation process. As

the collector area increases, the cost initially decreases, reaching the optimal point before stabilizing.

Weather data profile

Temperature. Figure 12 “Average Ambient Temperature” compares the monthly average temperatures for four locations: Accra, Alkufra, Cairo, and Lagos. Accra consistently records the highest average temperatures throughout the year, while Alkufra displays the most temperature variation, with cooler months early in the year and higher peaks in the summer. Cairo and Lagos show more moderate and relatively consistent temperatures. The temperature trends indicate distinct climate conditions in each area, influencing cooling system performance and energy requirements.

Humidity. Figure 13 “Average Humidity” compares the monthly average humidity percentages for Accra, Alkufra, Cairo, and Lagos. Accra and Lagos consistently

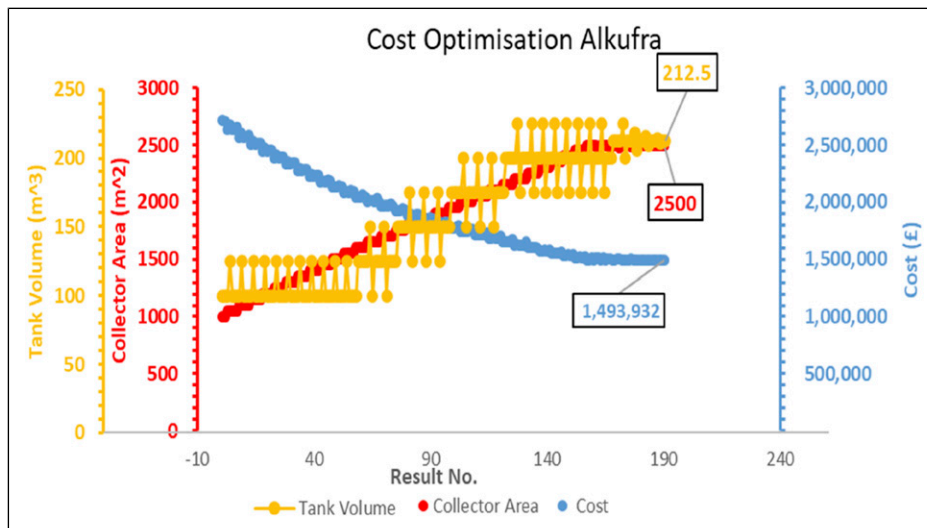


Figure 10. The cost analysis during the optimisation process for a solar cooling system in Alkufra, Libya.

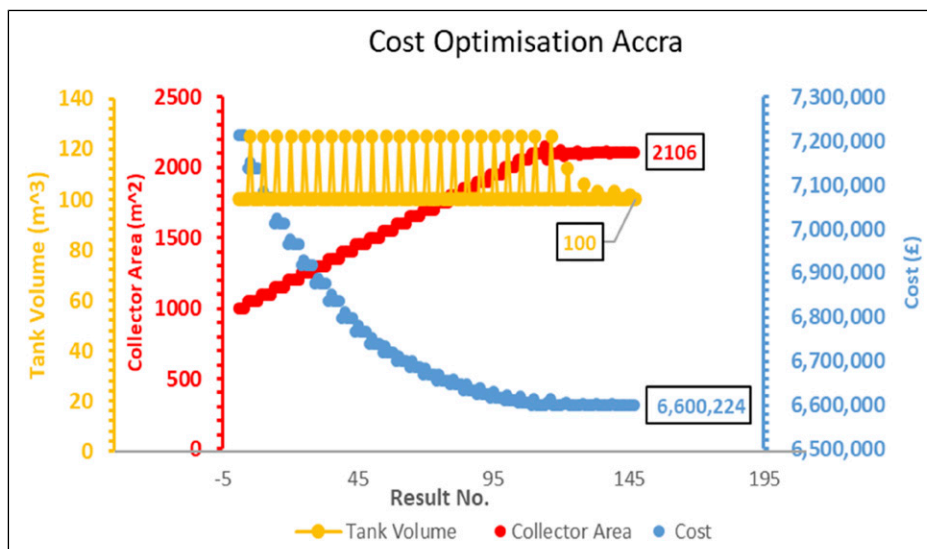


Figure 11. The cost analysis during the optimisation process for a solar cooling system in Accra, Ghana.

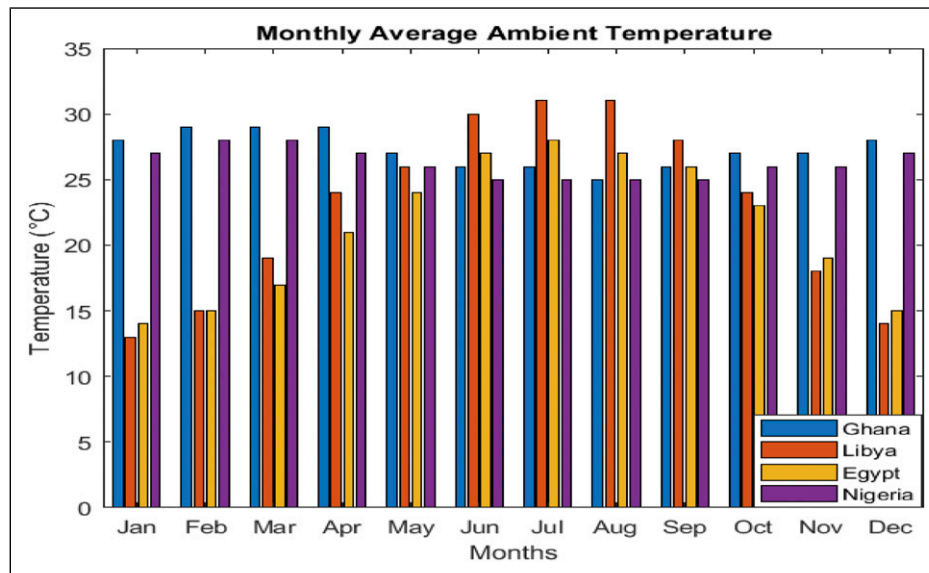


Figure 12. Monthly average temperature in various locations in Africa.

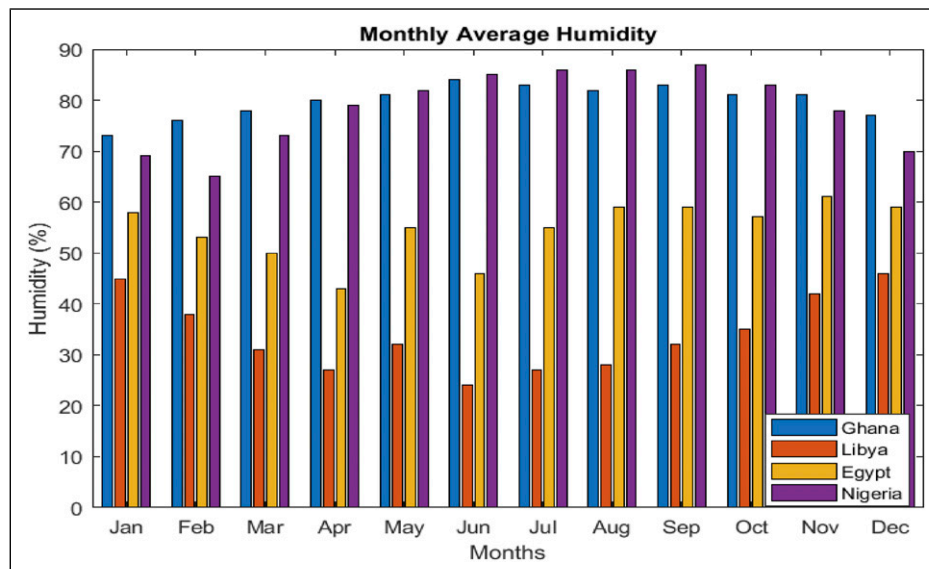


Figure 13. Monthly average humidity in various locations in Africa.

show high humidity levels, averaging around 70–80% throughout the year. In contrast, Alkufra consistently records the lowest humidity, indicating a much drier climate. Cairo exhibits moderate humidity, with fluctuations between 40% and 60%. These variations suggest that Accra and Lagos experience more humid conditions, while Alkufra remains arid.

Radiation. Figure 14 “Average Solar Radiation” compares the monthly solar radiation levels for Accra, Alkufra, Cairo, and Lagos. Alkufra consistently receives the highest solar radiation, exceeding 1000 units throughout the year, while Accra and Lagos experience lower radiation levels, ranging from 600 to 800 units. Cairo has moderate solar radiation, peaking at around 900 units. This indicates that Alkufra benefits from the most intense solar radiation,

supporting high solar energy generation, while the other locations receive comparatively less solar exposure.

Evacuated tube thermal solar collector efficiency. Figure 15 shows the efficiency of evacuated thermal solar collectors over 24 hours for four different locations: Accra, Alkufra, Cairo, and Lagos. The efficiency of the solar collectors increases around 8 a.m. and declines around 6 p.m. in most locations. Accra reaches its highest efficiency (0.75) between 11 a.m. and 2 p.m. Alkufra demonstrates a more gradual increase, attaining a peak efficiency slightly lower than Accra but sustaining it for a longer time. Cairo experiences a much steeper rise and falls in efficiency, peaking at about 0.55 for a shorter period. Lagos achieves its highest peak efficiency at 0.76,

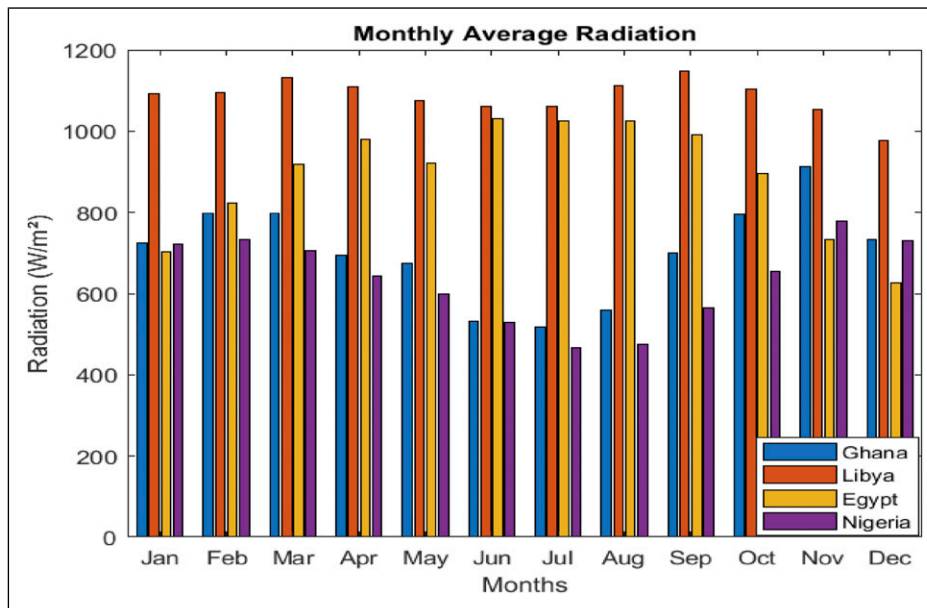


Figure 14. Monthly average solar radiation full-on in various locations in Africa.

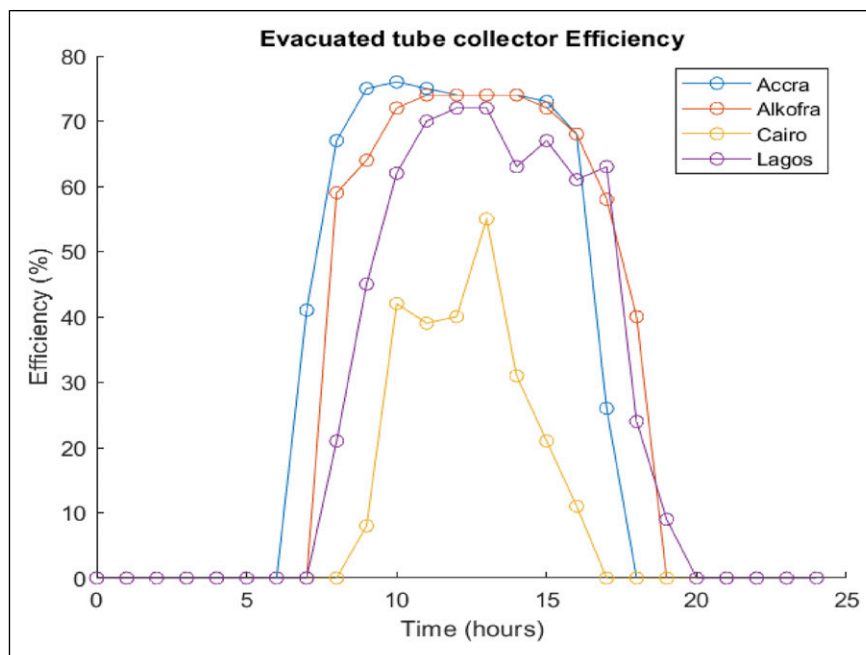


Figure 15. Evacuated Tube Solar Collector Efficiency in various locations in Africa.

but also undergoes fluctuations during the middle of the day.

Technical performance

Accra. Figures 16 and 17 below compare the system coefficient of performance, Solar Fraction, and Primary Energy Savings on a cloudy day versus a sunny day in Accra. On the cloudy day (first figure), the COP and SF remain lower and more stable, peaking briefly around 17:00, while the PER stays consistent and relatively low. On a sunny day (second figure), the COP and SF show higher peaks between 12:00 and 17:00, indicating better system performance due to increased solar energy availability. The

performance metrics, especially the SF and COP, are noticeably more responsive and higher on sunny days, demonstrating how the system relies heavily on solar radiation for optimal cooling efficiency.

Figure 18 shows energy data for Accra over 12 months, measured in kWh. The energy obtained from the solar collector varies throughout the year, with a significant rise in April. Following this, solar energy drops in May and gradually stabilizes between June and October. Solar energy declines in the colder months, which is expected due to reduced sunlight during these periods, but there is a notable increase again in November.

Figures 19 and 20 compare system performance in Alkofra on a cloudy day versus a sunny day, illustrating

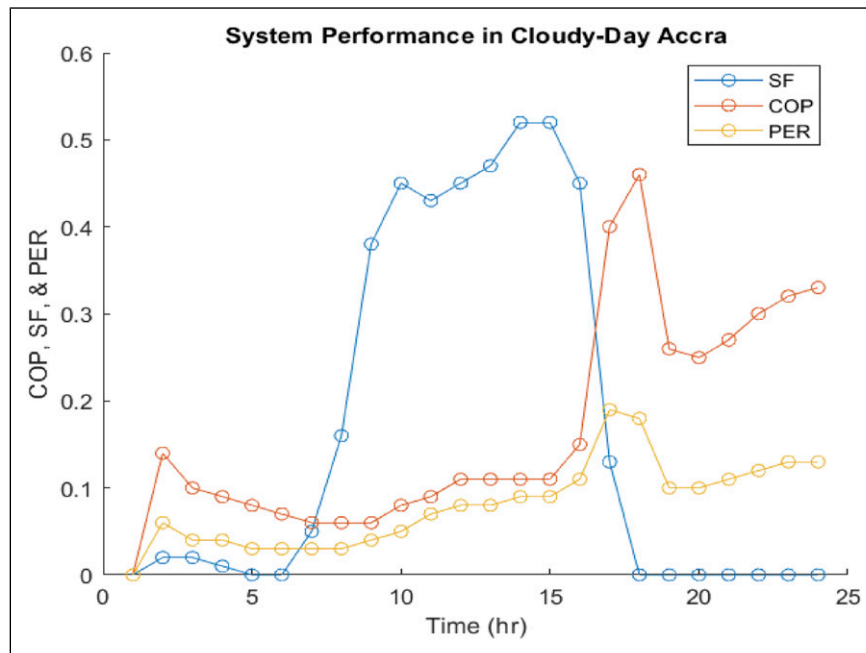


Figure 16. Solar Cooling System Performance on a cloudy day in Accra, Ghana.

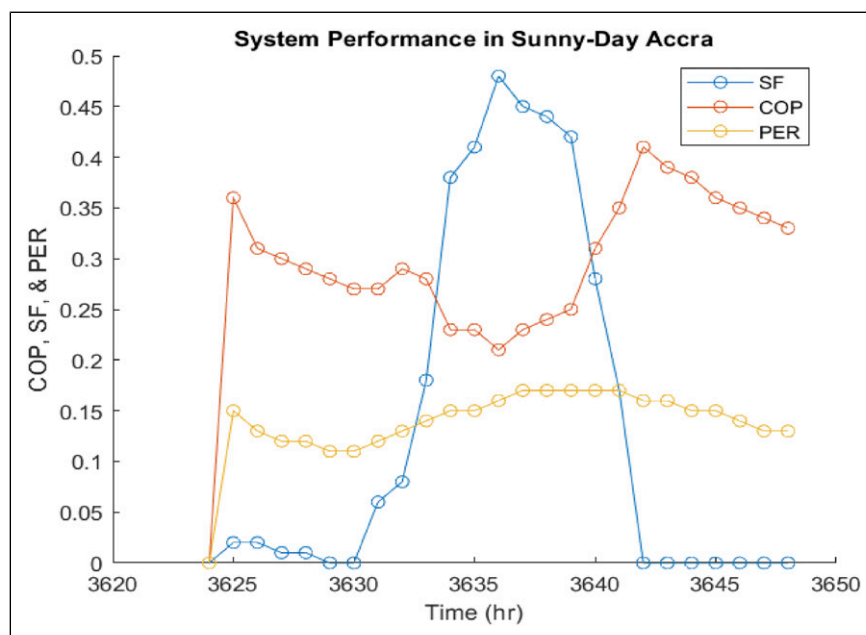


Figure 17. Solar Cooling System Performance on a sunny day in Accra, Ghana.

variations in Solar Fraction, Coefficient of Performance, and Primary Energy Savings. On a cloudy day, SF peaks around 3 p.m. and quickly declines after 4 p.m., while COP and PER steadily rise and reach their peaks between 4 p.m. and 6 p.m., with COP attaining 0.8. Conversely, on a sunny day, both SF and COP exhibit more gradual increases with higher peaks, with COP reaching 8.0 and SF approximately 0.7 between 2 p.m. and 5 p.m., indicating better system performance under clear conditions. The graph for the sunny day reveals more consistent and higher system efficiency compared to the cloudy day, where solar energy availability is restricted.

Figure 21 highlights the energy performance of a solar thermal cooling system in Akufra. The system performs

best during the spring and summer months when solar energy is abundant, resulting in higher chilled energy outputs. Solar energy fluctuates significantly throughout the year, peaking dramatically in April when it reaches its highest value. Other notable peaks occur in May, June, August, and September, with moderate values in the other months. Solar energy tends to be lower in January, February, October, November, and December, likely due to seasonal variations in sunlight availability. The contribution of boiler energy is consistently small across all months compared to solar energy and chilled energy values. There is a slight increase in boiler energy use from April to September, indicating that during these months, the boiler supports the solar system, but its

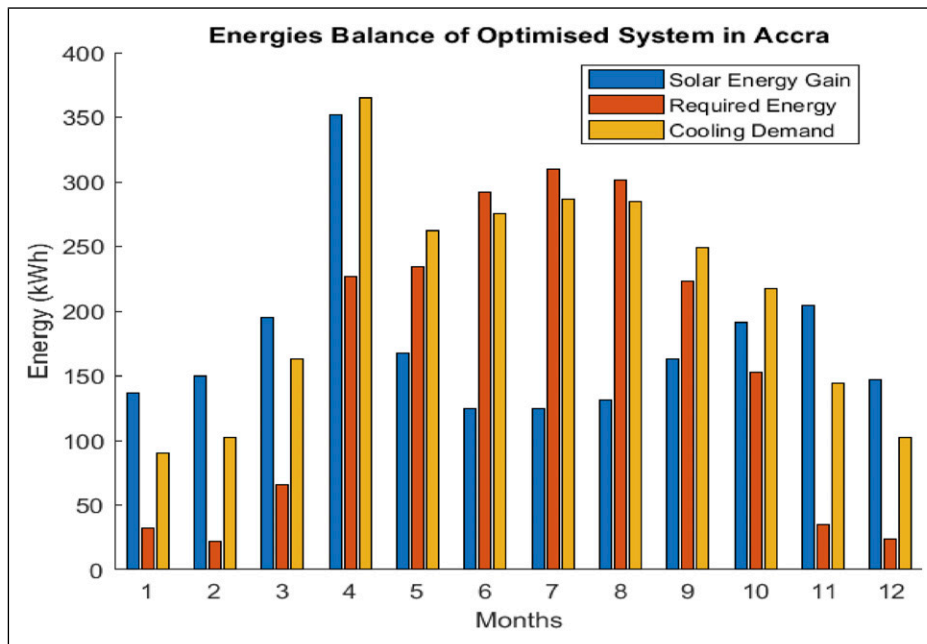


Figure 18. Output energies by optimised solar cooling system in Accra, Ghana.

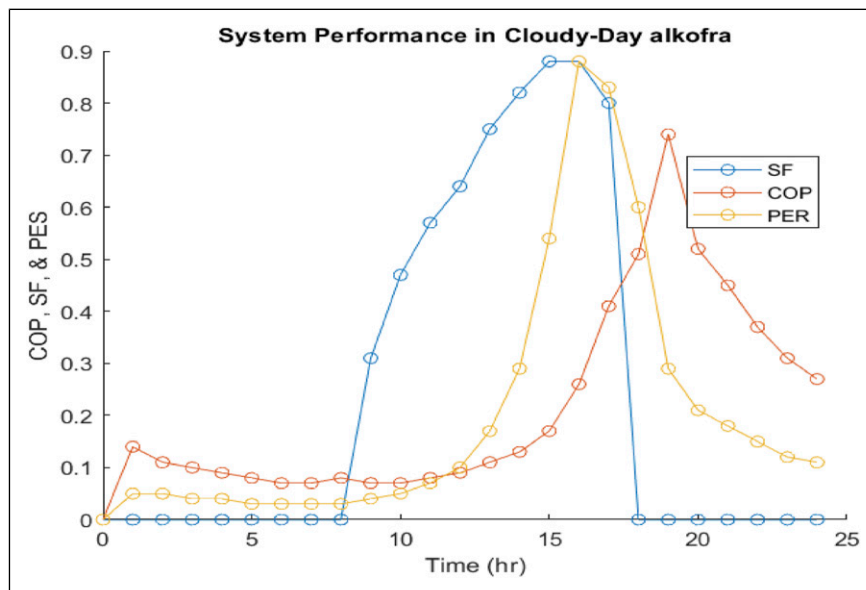


Figure 19. Optimised solar cooling system Performance on a Cloudy day in Alkufra, Libya.

contribution remains minimal compared to the solar energy value.

Figures 22 and 23 compare system performance in Cairo on a cloudy day (top) and a sunny day (bottom), illustrating Solar Fraction, Coefficient of Performance, and Primary Energy Savings. On a cloudy day, SF remains low, briefly peaking around noon, while COP peaks in the afternoon at approximately 0.5, and PER remains moderate yet stable. On a sunny day, SF, COP, and PER rise more gradually, achieving higher overall peaks (with COP reaching 1.0 and PER close to 0.9), indicating significantly better performance attributed to increased solar radiation. The sunny day reflects a more efficient system with greater energy savings and solar contributions compared to the cloudy day.

Figure 24 illustrates the energy contributions of the solar thermal system, including the energy produced by

the solar collector, the electricity required, and the total chilled energy demand of the cooling system in Cairo throughout the year. The system achieves peak performance during spring and summer, demonstrating reduced reliance on the boiler, and experiences the highest energy outputs when solar energy is most abundant. In the winter months, the solar contribution declines, necessitating a greater dependence on boiler energy to meet cooling demands.

Lagos. Figures 25 and 26 compare the system performance in Lagos on a cloudy day versus a sunny day, regarding Solar Fraction, Coefficient of Performance, and Primary Energy Saving. On a cloudy day, SF and PER rise sharply in the afternoon but quickly drop off after peaking, while COP remains low and fluctuates

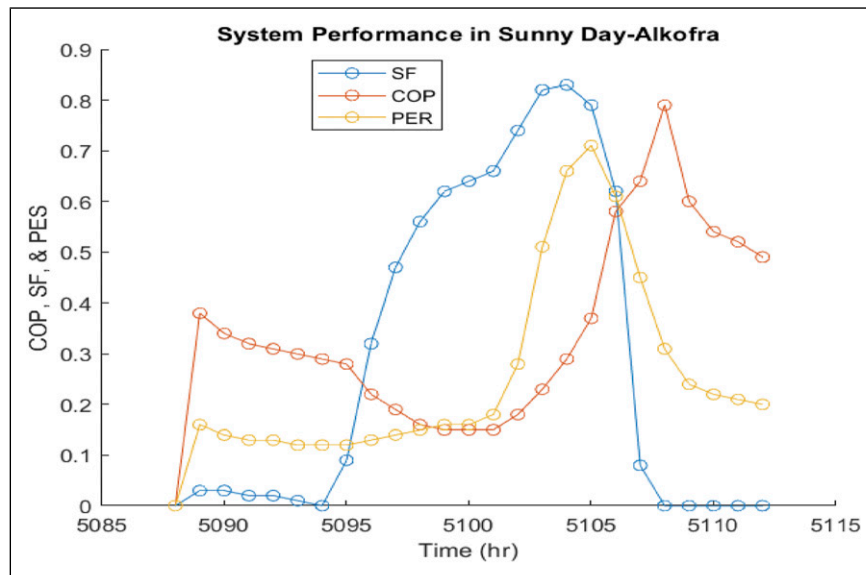


Figure 20. Optimised solar cooling system Performance on a sunny day in Alkofra, Libya.

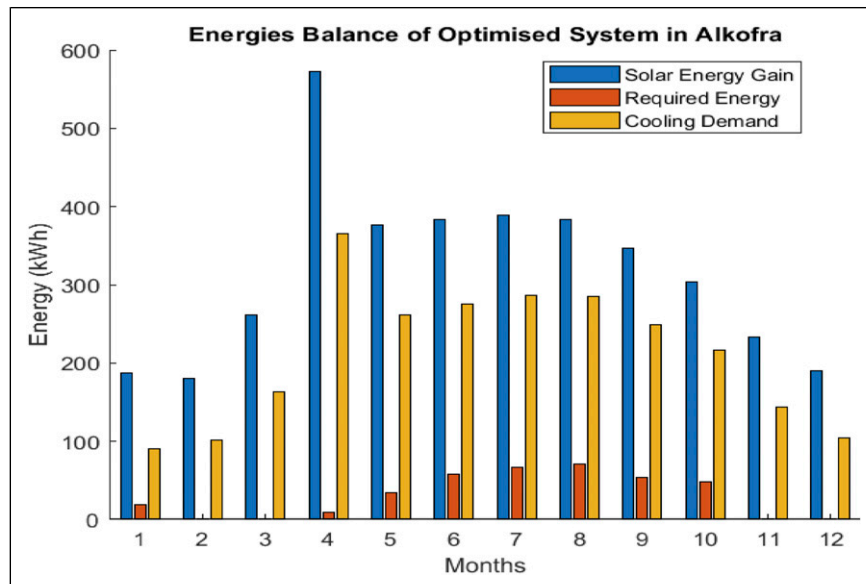


Figure 21. Output energies by optimised solar cooling system in Alkofra, Libya Cairo.

throughout the day. On a sunny day, SF, COP, and PER all exhibit a more gradual and stable rise, with higher peaks (SF 1, COP 0.9, PER 0.9), indicating improved system efficiency with consistent solar input. The results for the sunny day demonstrate significantly better and more stable system performance compared to the cloudy day, owing to higher solar energy availability.

Figure 27 illustrates the seasonal energy performance of the optimised cooling system in Lagos. The system relies significantly on solar energy during the spring and summer months, particularly in April, when both solar energy and cooling demand reach their peak. The boiler energy supplements the system during months with higher cooling loads, especially in July and August, when solar energy alone is insufficient. Overall, the system is designed to maximise solar energy usage but still requires auxiliary energy during peak cooling demand periods.

Discussion

The optimisation results were further examined to understand how different design parameters affected performance and cost in each location. The analysis showed that the collector area and electricity price had the strongest impact on the system's life-cycle cost (LCC). When the collector area increased, the need for auxiliary electricity decreased significantly. However, once the collector area exceeded about 2,500 m², the total cost stopped improving because the benefit of adding more collectors became small.

In Alkofra, the best design configuration—with a collector area of 2,500 m², storage volume of 213 m³, and slope angle of 10° achieved the lowest total cost of £1.49 million. Cairo followed with £2.55 million, while Accra and Lagos showed higher costs between £6.6–7.1 million. The higher costs in these two cities were mainly due to lower solar radiation and higher humidity. These findings agree with those of Calise⁴

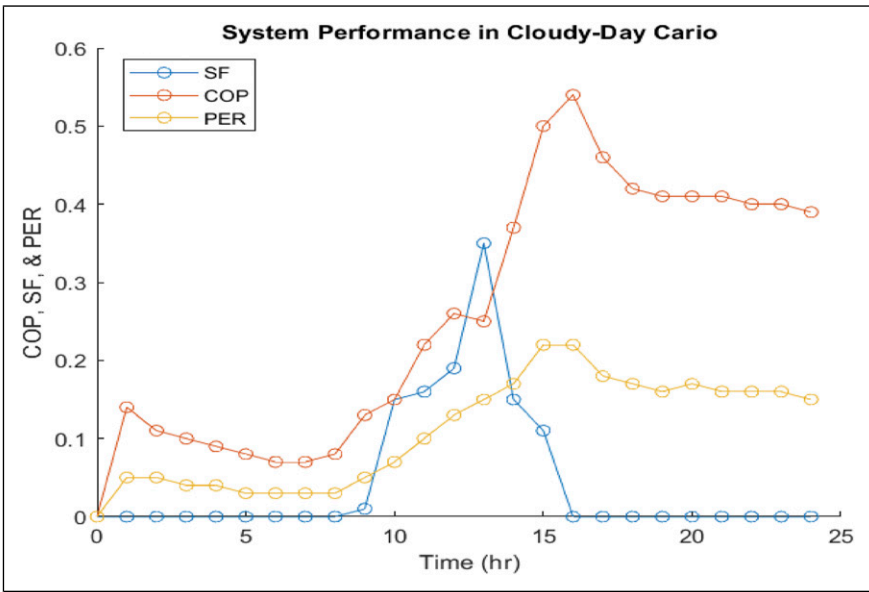


Figure 22. Optimised solar cooling system Performance on a cloudy day in Cairo, Egypt.

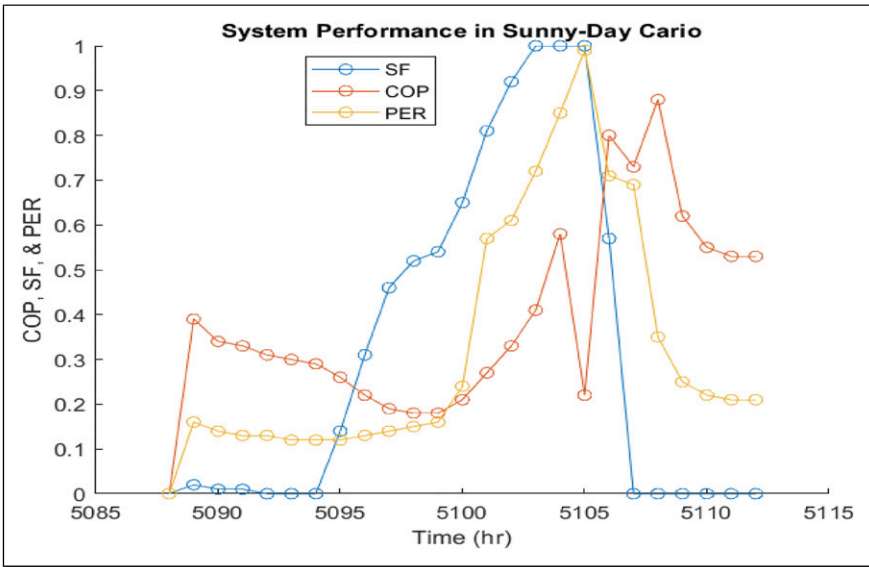


Figure 23. Optimised solar cooling system Performance on a sunny day in Cairo, Egypt.

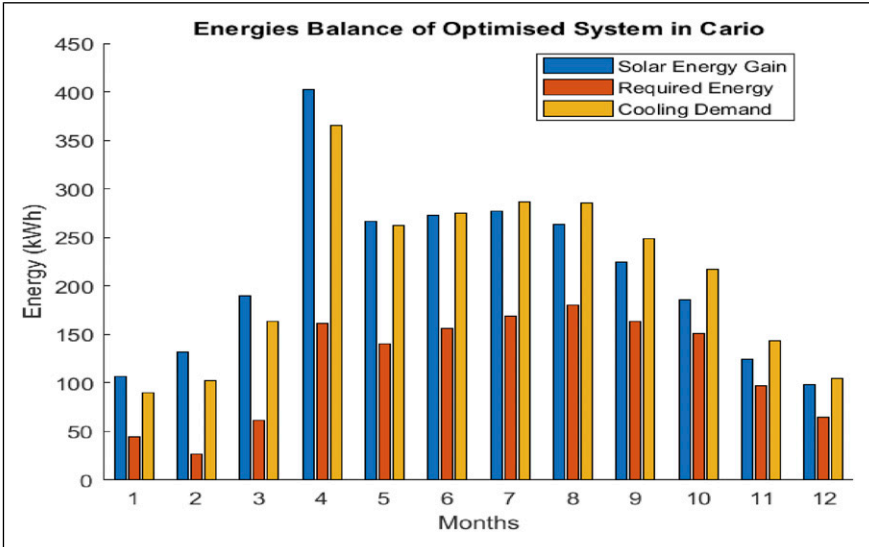


Figure 24. Monthly output energies by optimised solar cooling system in Cairo, Egypt.

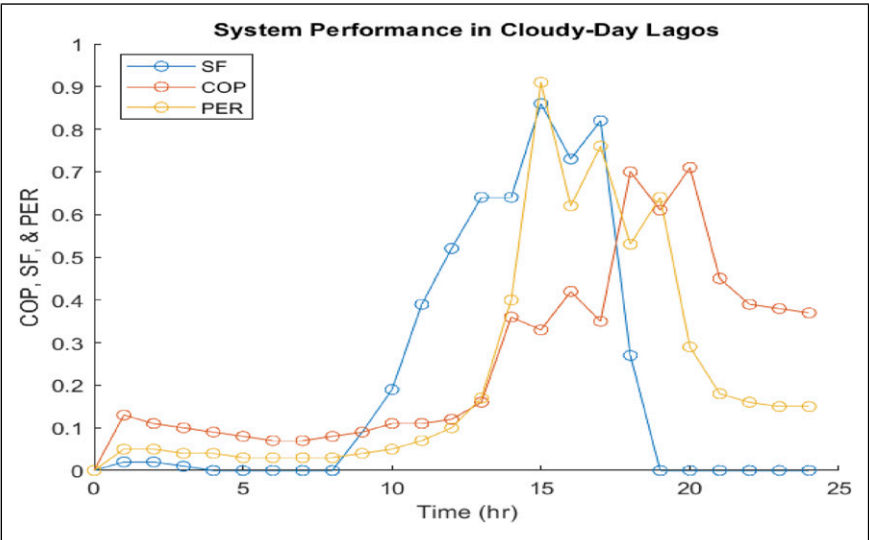


Figure 25. Optimised solar cooling system Performance on a cloudy day in Lagos, Nigeria.

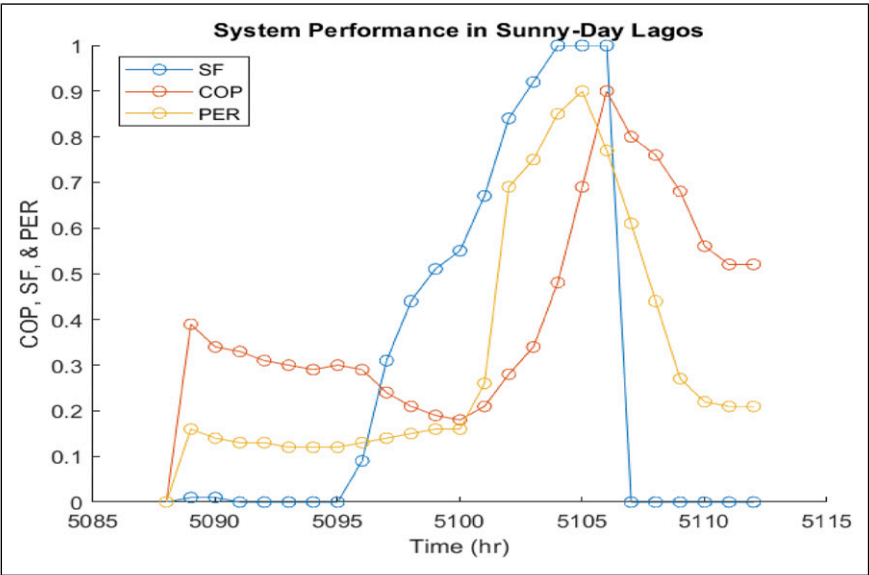


Figure 26. Optimised solar cooling system Performance on a sunny day in Lagos, Nigeria.

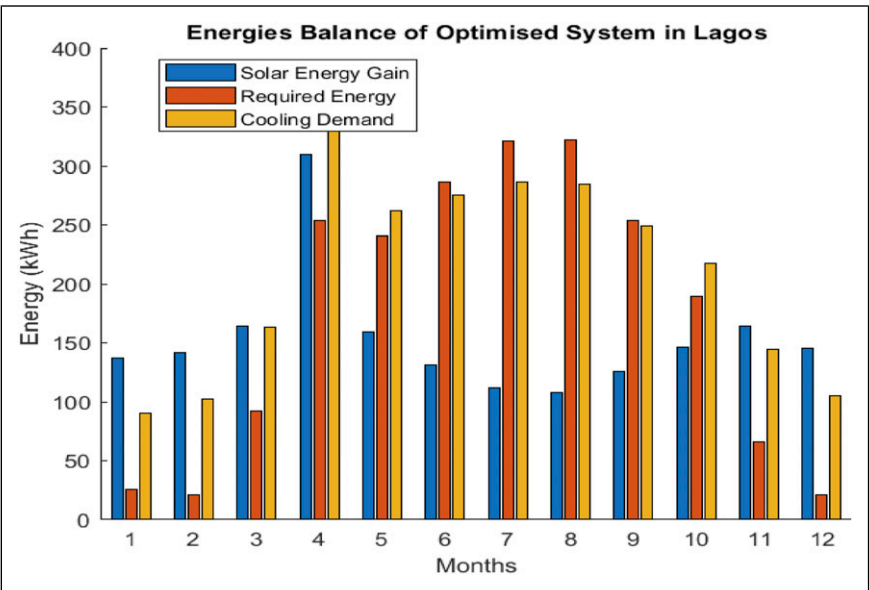


Figure 27. Monthly output energies by optimised solar cooling system in Lagos, Nigeria.

and Hang et al.,⁵ who found that collector area is the main factor influencing both energy output and total cost.

The sensitivity analysis showed that increasing the storage volume from 60 to 200 m³ reduced the use of auxiliary electricity by 8–12% in regions with strong solar radiation. However, this effect was much smaller in humid climates. The best collector slope angle was found between 10° and 25°, balancing efficient solar collection with practical installation size.

System performance in all four locations was strongly affected by solar availability. The Coefficient of Performance (COP) and Solar Fraction (SF) reached their highest values between 12:00 and 17:00 on sunny days, then dropped quickly after sunset when the stored energy was used up. In Alkufra, the COP reached 0.8 and SF 0.68, while in Lagos, lower solar radiation limited the COP to 0.5 and SF to 0.4.

Seasonal performance followed similar trends. Between April and September, solar contribution was at its highest and the use of auxiliary power was minimal, whereas in winter more backup electricity was required. These trends agree with the studies of Lu et al.⁷ and Hussein and El-Shaer,¹¹ confirming that evacuated tube collectors perform best in arid and semi-arid regions.

To validate the model, the simulation results were compared with published data from Al-Alili et al.,⁶ Hang et al.,⁵ and Li et al.¹⁰ The COP values (0.5–0.8) were within $\pm 10\%$ of those reported in the literature. The relationship between cost and collector area closely matched Calise,⁴ showing diminishing cost improvements beyond 2,500 m². Predicted primary energy savings (20–45%) were also similar to Li et al.,¹⁰ confirming the accuracy and reliability of the TRNSYS–GenOpt optimisation process. Minor differences (less than 8%) were likely due to different collector efficiencies and climate conditions.

Among all locations, Alkufra and Cairo provided the best techno-economic results because of their high solar potential and moderate electricity prices. In contrast, Accra and Lagos showed lower performance due to high humidity and electricity costs. These outcomes highlight the importance of designing solar cooling systems according to each region's specific climate.

From a broader perspective, national policies and incentives—such as feed-in tariffs, low-interest loans, and tax exemptions for solar equipment—could encourage wider adoption of these systems. The optimisation framework developed in this study, which combines TRNSYS dynamic simulation with GenOpt, can serve as a practical tool for engineers and policy-makers to design efficient and cost-effective solar-driven cooling systems for African climates.

Conclusion

This research demonstrates the feasibility and effectiveness of optimising solar-assisted cooling systems using a hybrid simulation-optimisation approach. By integrating TRNSYS simulations with GenOpt optimisation, the study identifies optimal system configurations that minimise life cycle costs while maximising energy efficiency across diverse African climatic zones. The

analysis highlights the significant influence of solar collector area and storage capacity on system performance, with location-specific variations dictated by solar radiation levels and electricity costs.

Key findings indicate that regions with higher solar irradiance, such as Alkufra, achieve the lowest life cycle costs. In contrast, areas with moderate or lower irradiance require larger collector areas and greater dependence on auxiliary energy sources. The study highlights the potential of solar cooling systems as a sustainable and economically feasible alternative for meeting cooling demands in Africa.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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References

1. Peprah AK, Appiah SK, Amponsah SK, et al. An optimal cooling schedule using a simulated annealing based approach. *Appl Math* 2017; 08(8): 1195–1210.
2. Hao T, Huang J, He X, et al. A machine learning-enhanced design optimizer for urban cooling. *Indoor Built Environ* 2023; 32(2): 355–374.
3. Wetter M. Design optimization with GenOpt. Available at: <https://simulationresearch.lbl.gov/>
4. Calise F. Thermoeconomic analysis and optimization of high efficiency solar heating and cooling systems for different Italian school buildings and climates. *Energy Build* 2010; 42(7): 992–1003.
5. Hang Y, Qu M and Zhao F. Economic and environmental life cycle analysis of solar hot water systems in the United States. *Energy Build* 2012; 45: 181–188.
6. Al-Alili A, Hwang Y, Radermacher R, et al. A high efficiency solar air conditioner using concentrating photovoltaic/thermal collectors. *Appl Energy* 2012; 93: 138–147.
7. Lu ZS, Wang RZ, Xia ZZ, et al. Study of a novel solar adsorption cooling system and a solar absorption cooling system with new CPC collectors. *Renew Energy* 2013; 50: 299–306.
8. Berhane HG, Gonzalo GG, Laureano J, et al. Design of environmentally conscious absorption cooling systems via multi-objective optimization and life cycle assessment. *Appl Energy* 2009; 86(9): 1712–1722.
9. Hang Y, Du L, Qu M, et al. Multi-objective optimization of integrated solar absorption cooling and heating systems for medium-sized office buildings. *Renew Energy* 2013; 52: 67–78.
10. Vahldiek K, Koltermann J, Pierl D, et al. Leakage localization in district heating networks based on real network and measurement data. *Energy Rep* 2021; 7: 508–516.
11. Obobisa ES. Achieving 1.5 °C and net-zero emissions target: the role of renewable energy and financial development. *Renew Energy* 2022; 188: 967–985.

12. Meiers J and Frey G. Interfacing TRNSYS with MATLAB for building energy system OptimizationInterfacing TRNSYS with MATLAB for building energy system OptimizationEnergies. *Energies* 2025; 18(2): 255.
13. Jalalizadeh M, Fayaz R, Delfani S, et al. Dynamic simulation of a trigeneration system using an absorption cooling system and building integrated photovoltaic thermal solar collectors. *J Build Eng* 2021; 43: 102482.
14. Joe Opoku D-G and Osei-Kyei Maria Rashidi R. Review of driving forces for digital twin adoption in the construction industry. In CIB World Building Congress. *Thesis*. 2023; 27–30.
15. Hasan A, Vuolle M and Sirén K. Minimisation of life cycle cost of a detached house using combined simulation and optimisation. *Build Environ* 2008; 43(12): 2022–2034.
16. Asadi E, da Silva MG, Antunes CH, et al. A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB. *Build Environ* 2012; 56: 370–378.
17. Ayadi O and Al-Dahidi S. Comparison of solar thermal and solar electric space heating and cooling systems for buildings in different climatic regions. *Sol Energy* 2019; 188: 545–560.
18. Robertson BL, Price CJ and Reale M. A hooke and Jeeves-CARTopt hybrid method for nonsmooth optimization. *AMO-Advanced Modeling and Optimization*. 2011; 13(3): 381–401.
19. Hong LJ. Discrete optimization via simulation using coordinate search. In: .Proceedings of the Winter Simulation Conference, 2005, Orlando, FL, USA, 04-04 December 2005.



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Optimise a solar thermal cooling system using combined simulation TRNSYS and Genopt software for refrigeration demand in various African climates

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2025-12-31

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<https://doi.org/10.1177/09576509251404129>

Abdelwanes A, King P, Wijayantha KGU, et al., (2025) Optimise a solar thermal cooling system using combined simulation TRNSYS and Genopt software for refrigeration demand in various African climates. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, Available online 27 November 2025