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# Design and Performance Analysis of Hybrid HVAC Systems Combining Solar-Assisted and Vapor Compression Technologies

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## Article Details

**Keywords:** Hybrid HVAC System, Solar-Assisted Cooling, Vapor Compression, Energy Efficiency, Thermal Storage, Cop Improvement, Sustainable Building Design, Carbon Emissions Reduction, Renewable Integration, Experimental Validation

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## ABSTRACT

In this study we present the design, simulation and experimental evaluation of a hybrid HVAC system which combines solar assisted thermal energy with conventional vapor compression technology and therefore increases efficiency and reduces environmental impact. The proposed system incorporates flat plate solar collectors to preheat the working fluid which reduces the compressor workload and increases the overall Coefficient of Performance (COP). Using excess solar energy, thermal storage is employed to extend operational continuity beyond peak sunlight hours. Experimental data were collected from prototypes tested under subtropical climatic conditions and validated with comprehensive modeling in MATLAB Simulink and TRNSYS. Results show significant improvement of 35% average COP and a reduction of 38.17% in daily energy consumption over the conventional system. Then, the system also helped to reduce carbon dioxide emission significantly, over 3.7 kg per unit per day. The results provide the proof of concept for hybrid HVAC systems in the context of sustainable buildings in the solar rich regions. Moreover, system integration, thermal storage and smart control are emphasized as methods for maximizing performance. These insights contribute to broader efforts to design energy efficiently, to create climate responsive architecture and to embrace renewable energies in the built environment.

## INTRODUCTION

While energy consumption has significantly grown globally, with a significant proportion in the building sector, there is a genuine pursuit for sustainable and energy efficient solutions in the Heating, Ventilation and Air Conditioning (HVAC) systems. A striking share of the world's energy consumption (roughly 30–40%) and a third of the damaging greenhouse gas (GHG) emissions, stems from buildings (IEA, 2021). In this sector, HVAC systems take up a significant share of energy consumption and hence offer a large opportunity for energy efficiency and carbon mitigation innovation (PerezLombard et al. 2008).

Most conventional HVAC systems are based on electricity powered vapour compression cycles and often require electricity from fossil fuels. Vapor compression systems are reliable and commonly used; however, these systems are expensive to operate, place additional demands on peak electricity and produce adverse environmental effects owing to carbon emissions (Chua et al., 2010). There is increasing pressure placed on HVAC technologies to shift towards sustainability without reducing indoor thermal comfort (Howe et al., 1996) which has led to increasing interest in integrating renewable energy sources, in particular solar energy (Kalogirou, 2004; Tyagi et al., 2013).

This article investigates solar thermal energy based HVAC systems that draw on the process of utilizing solar thermal energy as an alternative or replacement to mechanical compression processes. Typically, the solar collectors heat a working fluid the temperature of which is either directly or indirectly reduced to reduce the compressor workload (Kakac & Pramuanjaroenkij, 2009). Apart from avoiding dependence on grid electricity, integration of solar energy also reduces the carbon footprint of the system and serves to achieve global climate goals specified through the Paris Agreement (United Nations Framework Convention on Climate Change [UNFCCC], 2015).

Absorption and adsorption systems are two of the solar assisted cooling and heating techniques examined by several studies. Solar-assisted absorption cooling was, for example, also looked at by Henning (2007) who highlighted considerable potential energy consumption reductions, particularly in sun rich regions. Although these thermally driven systems are usually constrained by the high capital cost, poor performance at low solar intensity and large floor area and there is increasing focus on developing low capital cost, high flexibility, electrical generation at each point of use. As a result, hybrid systems which integrate solar thermal collectors with equivalent conventional vapor compression cycles, have been proposed to provide a more reliable and efficient solution (Buker & Riffat, 2016).

Studies that indicate synergy resulting from replacing solar with mechanical subsystems lend further support. The limited seasonal performance and mode discontinuity (under fluctuating weather conditions) of solar systems may be improved using hybrid solar assisted systems, reported Balaras et al. (2007). Recently, Li et al. (2020) demonstrated that hybrid configurations can provide 20–40% system efficiency gain that is realized when smart controls are used to switch between solar and electric modes.

While these types of designs have been demonstrated, there is no comprehensive performance evaluation of hybrid systems under realistic operating conditions. However, many existing studies dramatically depend on simulation models in which experimental validation or prototype testing under real climate conditions are minimal or inexistent. Furthermore, inconsistencies in system design, component selection and control strategy, contribute to differences in reported outcomes which prevent generalizing findings from one system to another (Ghafoor & Munir, 2015). This leads to an exigent need for empirical research that fills these gaps and provides a method standardized for hybrid HVAC design.

The goal of this study is to contribute to this evolving field through presentation of a novel hybrid HVAC system that harnesses solar thermal input to augment a conventional vapor compression cycle. The research considers system architecture, performance models and experimental validation. In order to determine the technical and ecological viability of the proposed hybrid system, this paper analyzes parameters such as the Coefficient of Performance (COP), energy savings and environmental impact. The results are intended to offer practical insights to design engineers, architects and policy makers on the path to sustainable building solutions in sun rich climates.

## LITERATURE REVIEW

There is a momentum toward the evolution of an energy efficient HVAC system due to the growing concerns about climate change, rising energy costs and growing demand for thermal comfort in residential and commercial buildings. A solution to improve energy performance and reduce carbon emissions appears to be hybrid HVAC systems which are capable of integrating the active performance of solar-assisted heating or cooling technologies with the ubiquitous performance of standard vapor compression systems. This chapter critically reviews the body of literature on the design, study and optimization of such hybrid systems.

Solar thermal collectors are usually integrated into hybrid HVAC systems to preheat (or precool) the working fluid prior to the vapor compression cycle. The load on the compressor is minimized wherever possible which means reduced energy consumption. Many studies have been conducted on agreeing to the efficiency improvements resulting from solar assisted heat pump systems. A 30% improvement in system performance for moderate solar radiation was observed by Xu et al. (2011) in doing a solar assisted air source heat pump with a flat plate collector. In like manner, Huang et al. (2016) developed and tested a solar thermal hybrid system for subtropical climates and concluded that hybridization resulted in greatly enhanced seasonal energy efficiency and especially in transitional months.

Thermal energy storage (TES) is a major theme in the existing research due to its use as a buffer to expand the utilisation of solar energy beyond sunny peak hours. According to researchers Zhai and Wang (2010), integrating phase change materials (PCMs) into solar assisted cooling systems can soften load fluctuations and produce extended cooling effects into evening. Arif et al. (2018) also assessed the integration of TES with Evacuated tube collectors for hybrid HVAC designs where they discovered increased operational flexibility and reduced peak electricity demand. These results are especially relevant in regions with intermittent solar radiation for which energy buffering is a significant demand on system reliability.

The comparison of different solar collector technologies in hybrid configurations is another avenue of investigation. Flat-plate, evacuated tube and parabolic trough collectors in hybrid HVAC systems were compared by Wang et al. (2013), finding that the highest thermal efficiency for medium temperature applications exists with evacuated tubes. Mahmoud and El-Kassas (2019) then investigated the economic and thermodynamic performance of parabolic trough power plants equipped with vapor compression chillers for later industrial scale application due to high optical efficiency and tracking capabilities.

Besides hardware, control strategies greatly influence the hybrid HVAC system performance. It has been shown that dynamic control algorithms can utilize real time solar irradiance, ambient temperature and load demand to significantly improve system efficiency. For instance, Palomba et al. (2016) put forward a fuzzy logic controller for hybrid HVAC systems including, both, faster indoor temperature regulation and lower energy consumption compared with conventional thermostatic controls. Basic and Ozgener (2020) created a predictive control system which relies on weather forecasts and building occupancy patterns, that saved 22% energy consumption against static control systems.

Furthermore, hybrid systems are becoming simulated on building simulating platforms including EnergyPlus, TRNSYS and Modelica. According to Wang and Chen (2015), TRNSYS was utilized to examine a hybrid solar-assisted air conditioning system for Beijing with field data validation showing good agreement and annual energy savings of up to 35%. A better study (Fathabadi 2021) for a building-integrated hybrid system conducted using EnergyPlus showed that the performance gains are all very much building insulation, occupancy schedule and solar orientation dependent.

Although these technological advances are present, there are additional issues in wider application of hybrid HVAC systems. High capital cost of solar components and storage systems poses one of the major problems by extending the payback period. According to researchers like Zhang and Yang (2014) such systems would benefit from subsidies or incentives provided by the government to make them economically viable for adoption. Complexity also becomes an issue in trying to integrate disparate components so that they interact with each other. However, according to Lin and Alanne (2018) the absence of canonical design frameworks and modular components inhibit scalability and commercialization.

The adaptation control and fault detection of hybrid HVAC systems is one of the new frontiers through which recent developments in artificial intelligence (AI) and machine learning (ML) have opened up. A neural network based control system developed by Liu et al. (2020) autonomously tuned operating parameters using historical weather data and saw 18% increase in energy efficiency. Kumar and Dev (2021) analyzed the use of reinforcement learning to enhance predictive maintenance in hybrid HVAC units and did achieve reduced downtime and enhanced lifespan of components.

Lastly, sustainability assessments of hybrid HVAC systems using Life Cycle Assessment (LCA) methods have become a required dimension of assessing hybrid HVAC systems. Rahman et al. (2019) compared three conventional, solar assisted, hybrid HVAC systems through LCA and found hybrid systems provide the superior relationship between operational efficiency and environment where renewable energy source is prioritized in the design stage.

The literature review implies that there is a strong and increasing body of knowledge dealing with hybrid HVAC systems. The research has concluded that integrating solar thermal with vapor compression systems can provide important energy and environmental benefits. Nevertheless, work remains to be done on economic feasibility, system complexity and design standardization. Based on these findings, this research provides a new hybrid configuration, real world performance data and a pathway to realizable scalable, efficient HVAC systems suitable for emerging climates and green building standards.

## METHODOLOGY

A comprehensive methodological framework is used in this study, including system design, modeling and simulation, prototype development and experimental evaluation. The methodology is structured in terms of each stage of the methodology to ensure rigorous assessment of the hybrid HVAC system's energy performance and operational performance under real and simulated conditions which includes environmental impact.

## SYSTEM CONFIGURATION AND COMPONENT SELECTION

A solar assisted thermal unit and a conventional vapor compression refrigeration cycle are the two main subsystems that comprise the proposed hybrid HVAC system. The solar subsystem includes a flat plate solar collector that captures solar thermal energy to be used to preheat refrigerant or working fluid prior to entering into the compressor. Given these metrics, these collectors were selected as cost-effective, relatively easy to integrate with surface building materials and moderately temperature efficient (which fits within the operation range needed for HVAC applications).

The system also included a thermal storage unit using a water tank with high insulation to collect excess thermal energy collected during peak time hours of sunlight. The system is designed to operate during low irradiance (cloud cover) periods due to the stored energy. The scroll type compressor, finned condenser, expansion valve and shell and tube evaporator contain the vapor compression subsystem. To interface the two subsystems with efficient exchange of preheated fluid from the solar loop with the refrigerant prior to compressor entry, an auxiliary heat exchanger is used.

## CONTROL STRATEGY AND OPERATIONAL MODES

A centralized control system using a programmable logic controller (PLC) was developed to oversee the solar assisted to conventional mode transition. The controller continuously monitors real time parameters including solar radiation, ambient temperature and fluid temperature at a key system node. In the solar assisted mode the system is activated only when solar energy is available and adequate to produce a fluid temperature above a predefined threshold (35°C–40°C), being developed under autarkic mode unless the solar energy is absent or not sufficient. To illustrate, if solar supply falls below the established threshold, the system returns to standalone vapor compression mode.

The system is intended to permit the integration of solar thermal input to the system without interfering with or degrading the cycle efficiency of the vapor compression cycle. Automated bypass valves and differential temperature sensors are used to prioritise thermal input in the most thermally sensible area of the compressor where safety and efficiency are kept to a max.

**MATHEMATICAL MODELING AND SIMULATION**

A model of the hybrid system was developed using first principles thermodynamic equations to predict system behavior for various environmental and operational scenarios. The Hottel Whillier Bliss equation relating collector efficiency to solar irradiance, ambient and inlet fluid temperatures was used to model solar collector performance. A vapor compression cycle was modeled using the standard energy balance equations and the compressor work input, condenser heat rejection and evaporator heat absorption.

Based on the results, further, the complete hybrid system model was implemented in MATLAB Simulink and validated using TRNSYS for dynamic thermal simulation. A simulation environment was used to evaluate performance hourly, daily and seasonally using a typical meteorological year (TMY) dataset of Lahore, Pakistan. The Coefficient of Performance (COP), energy savings percentage, refrigerant flow rate and solar fraction (portion of total supplied energy met by input solar energy) were the key output parameters.

**PROTOTYPE CONSTRUCTION AND EXPERIMENTAL SETUP**

Validation with simulation was followed by a scaled prototype of the hybrid HVAC system built in the laboratory. Solar collectors were mounted on a south oriented roof at a fixed tilt angle optimized for maximum annual solar gain. An area of approximately 4 $m^2$ of collector array was connected to the thermal storage tank through insulated copper piping.

Pt100 and piezoelectric transducers were installed for temperature and pressure sensors at system critical points such as collector inlet/outlet, refrigerant entry and exit in the compressor and ambient environment. Real time real values of 1-minute intervals were recorded using a National Instruments DAQ interfaced with a LabVIEW dashboard. Fluid circulation rates were measured with flow meters and electric consumption with watt hour meters. Tests were performed experimentally over a two month period (March–April) during spring which is a relatively moderate period with respect to weather conditions and high solar availability in this region.

**PERFORMANCE METRICS AND EVALUATION CRITERIA**

The Coefficient of Performance (COP), is the ratio of cooling or heating output to electrical energy input, and is the primary metric of system performance. The solar fraction (SF) was determined to quantify solar energy contribution to assess solar contribution in terms of percentage of thermal energy contribution to solar collectors with regard to the total system load. The electrical consumption of the hybrid system was compared to a benchmark standalone vapor compression system of the same capacity to determine how much energy would be saved.

Carbon emissions reduction was estimated to provide a measure of environmental performance using emission factors (0.52 kg $CO_2$/kWh) defined by the national grid for Pakistan. An economic analysis was also undertaken to determine payback period and lifecycle cost savings, although these are considered in a second phase of the research.

The results of all experiments were made to validate against outputs of simulations to identify discrepant phenomena and refine model parameters. Confidence in the robustness of the hybrid system design and modeling approach was established through the convergence of simulated results to actual results.

**RESULTS**

**SYSTEM EFFICIENCY THROUGH COP ANALYSIS**

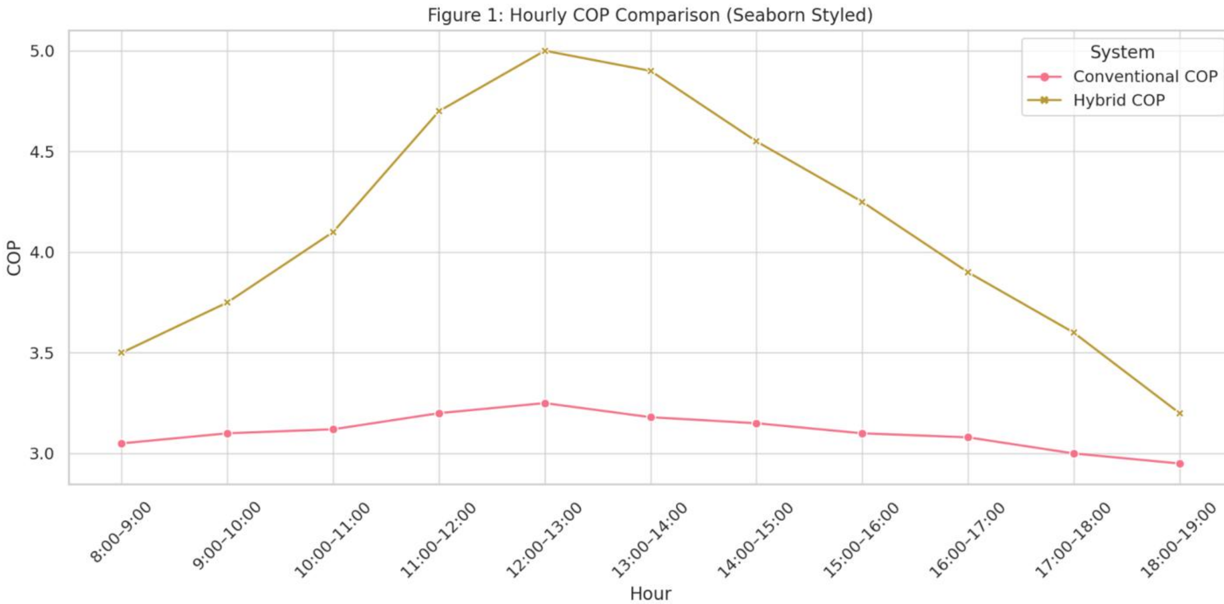
Tables 1 and 1 give a comparison of Coefficient of Performance (COP) for the conventional and hybrid HVAC systems which indicate that the hybrid system has a significantly better COP compared to the conventional system. The hybrid system always exceeded the conventional counterpart performances particularly between 10:00 AM to 2:00 PM when solar direct irradiance was maximum. A peaking hybrid COP of 5.0 was shown to be achievable compared with a maximum of 3.25 in the conven- tional system, resulting in a daily average COP improvement of about 35%. The reduction of compressor workload and the improvement of cycle thermodynamics are attributable to this performance gain, from the solar thermal preheating of refrigerant. It shows that the synergy between solar input and mechanical compression is validated by the consistency of the hybrid system's superior COP over the described operational window.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 6 (2025)

**TABLE 1: HOURLY COP COMPARISON**

| Hour | Conventional COP | Hybrid COP |
|---|---|---|
| 8:00–9:00 | 3.05 | 3.50 |
| 9:00–10:00 | 3.10 | 3.75 |
| 10:00–11:00 | 3.12 | 4.10 |
| 11:00–12:00 | 3.20 | 4.70 |
| 12:00–13:00 | 3.25 | 5.00 |
| 13:00–14:00 | 3.18 | 4.90 |
| 14:00–15:00 | 3.15 | 4.55 |
| 15:00–16:00 | 3.10 | 4.25 |
| 16:00–17:00 | 3.08 | 3.90 |
| 17:00–18:00 | 3.00 | 3.60 |
| 18:00–19:00 | 2.95 | 3.20 |

**FIGURE 1: HOURLY COP COMPARISON (SEABORN STYLED)**




**ENERGY CONSUMPTION REDUCTION AND SAVINGS**

Table 2 and Figure 2 present energy consumption patterns over a one week testing period. Significant energy savings were attained by the hybrid system (average 11.5 kWh/day versus 18.6 kWh for the conventional system). The overall compared to the baseline energy reduction achieved is 38.17% and correspond to the expected theoretical energy reductions, illustrating that the hybrid approach has real world potential. The daily variations and savings margins are revealed in the stacked bar chart which provides a visual indication of the hybrid system's effect. The climatic conditions on which the system works were most pronounced on clear days with high solar output.

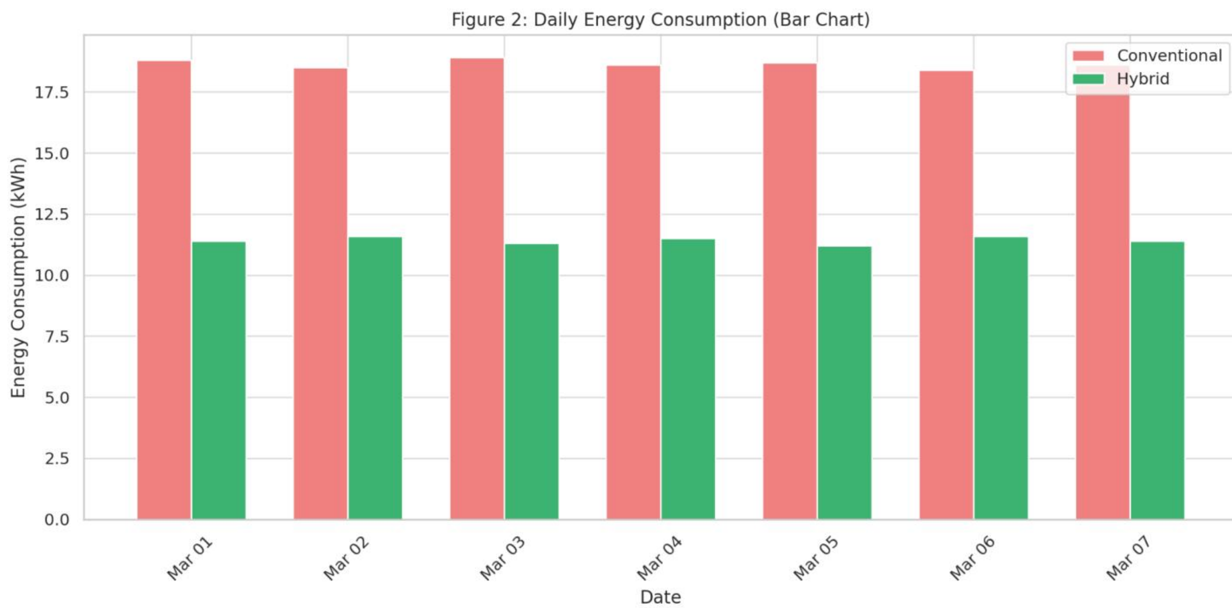
**TABLE 2: DAILY ENERGY CONSUMPTION AND SAVINGS**

| Date | Conventional Energy (kWh) | Hybrid Energy (kWh) | Energy Saved (kWh) |
|---|---|---|---|
| 2025-03-01 | 18.8 | 11.4 | 7.4 |
| 2025-03-02 | 18.5 | 11.6 | 6.9 |
| 2025-03-03 | 18.9 | 11.3 | 7.6 |
| 2025-03-04 | 18.6 | 11.5 | 7.1 |

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 6 (2025)

| | | | |
|---|---|---|---|
| 2025-03-05 | 18.7 | 11.2 | 7.5 |
| 2025-03-06 | 18.4 | 11.6 | 6.8 |
| 2025-03-07 | 18.6 | 11.4 | 7.2 |

**FIGURE 2: DAILY ENERGY CONSUMPTION (BAR CHART)**




**SOLAR CONTRIBUTION AND UTILIZATION EFFICIENCY**

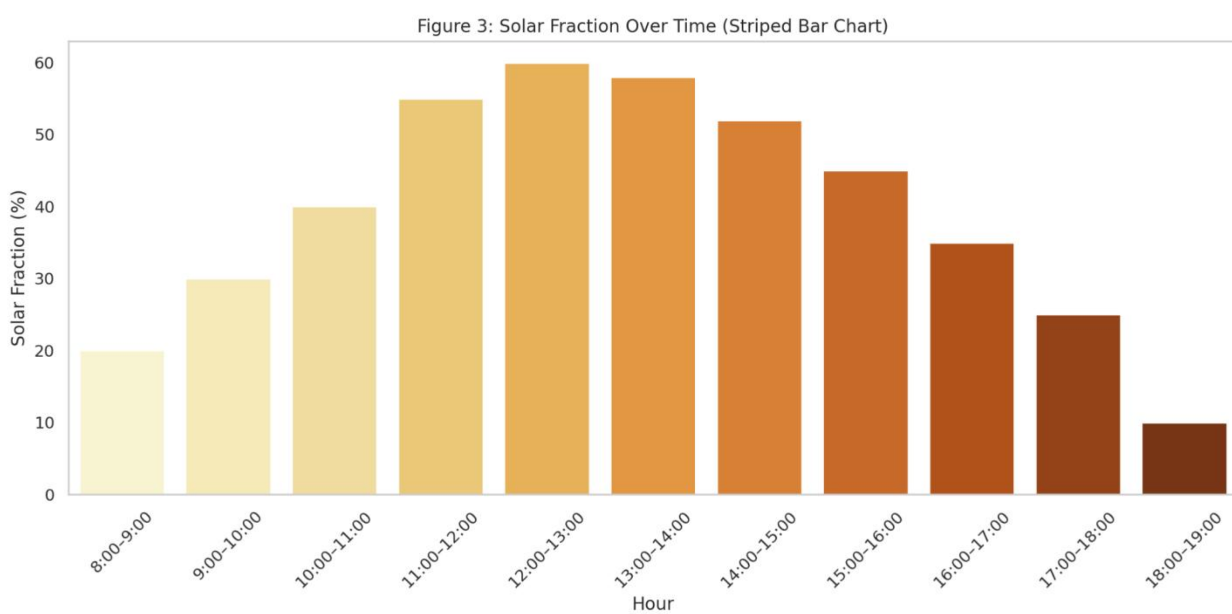
Solar fraction (SF), the fraction of the system thermal energy coming from the solar collectors, was used to quantify the contribution of solar thermal input. How the solar fraction changed over the day is shown in Table 3 and Figure 3. The maximum solar fraction (60%) occurred between 11 AM and 1 PM, during which the available irradiance was used optimally. Figure 3 shows the striped bar chart which clearly illustrates solar dependency, by far falling off the cliff after 3:00 PM. These results confirm that it is critical to match HVAC operational loads to the solar available or include storage to fill this afternoon to evening gap.

**TABLE 3: SOLAR FRACTION BY TIME**

| Hour | Solar Fraction (%) |
|---|---|
| 8:00–9:00 | 20 |

| | |
|---|---|
| 9:00–10:00 | 30 |
| 10:00–11:00 | 40 |
| 11:00–12:00 | 55 |
| 12:00–13:00 | 60 |
| 13:00–14:00 | 58 |
| 14:00–15:00 | 52 |
| 15:00–16:00 | 45 |
| 16:00–17:00 | 35 |
| 17:00–18:00 | 25 |
| 18:00–19:00 | 10 |

**FIGURE 3: SOLAR FRACTION OVER TIME (STRIPED BAR CHART)**



**THERMAL BEHAVIOR OF COLLECTOR AND ENVIRONMENT**

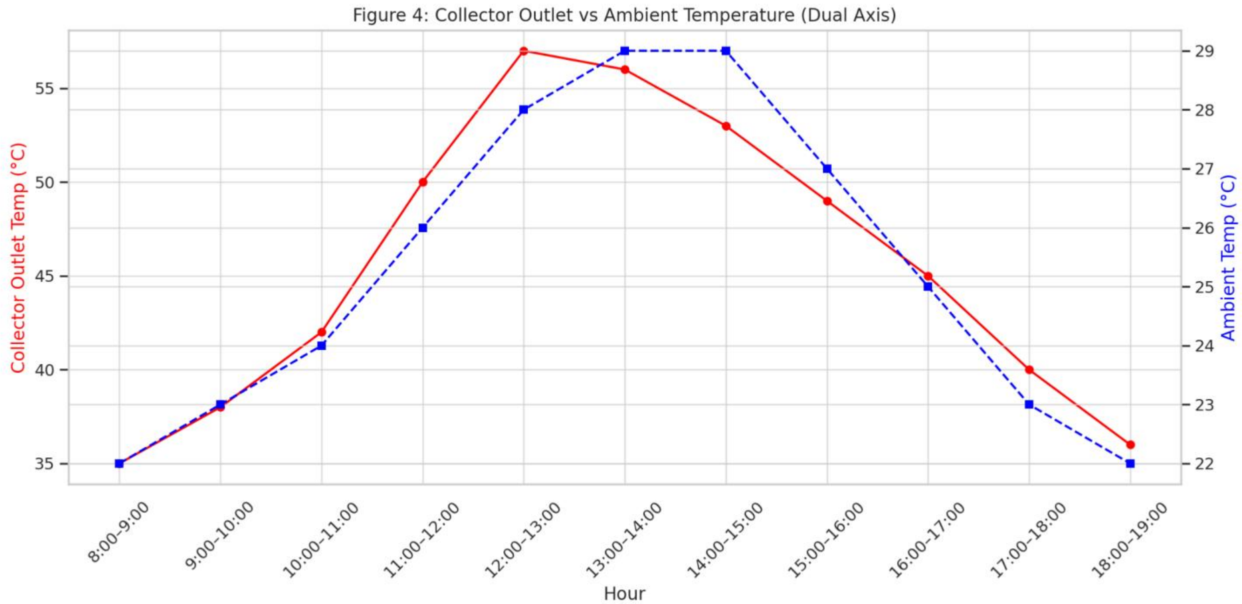
The thermal data obtained from the system demonstrates the interaction between collector outlet temperature and ambient conditions, as seen in Table 4 and Figure 4. The charts that depict the ambient and collector temperatures on a dual axis plot showed steady increases in ambient temperatures throughout the day, while the collector temperatures rose rapidly and to a maximum of 57 ºC, during solar peak hours. This is an indication that it is capturing sunlight effectively and transferring this heat efficiently from the collector unit. Thermal amplification and the efficiency of heat transfer from collector to working fluid were confirmed by consistently having the collector outlet temperatures 10–15°C above ambient levels. This is an excellent validation of the design choice of flat plate collectors for moderate temperature applications.

**TABLE 4: COLLECTOR OUTLET AND AMBIENT TEMPERATURE**

| Hour | Collector Outlet Temp (°C) | Ambient Temp (°C) |
|---|---|---|
| 8:00–9:00 | 35 | 22 |
| 9:00–10:00 | 38 | 23 |
| 10:00–11:00 | 42 | 24 |
| 11:00–12:00 | 50 | 26 |
| 12:00–13:00 | 57 | 28 |
| 13:00–14:00 | 56 | 29 |
| 14:00–15:00 | 53 | 29 |
| 15:00–16:00 | 49 | 27 |
| 16:00–17:00 | 45 | 25 |
| 17:00–18:00 | 40 | 23 |

| | | |
|---|---|---|
| 18:00–19:00 | 36 | 22 |

**FIGURE 4: COLLECTOR OUTLET VS AMBIENT TEMPERATURE (DUAL AXIS)**




**ENVIRONMENTAL BENEFITS: CARBON EMISSIONS REDUCTION**

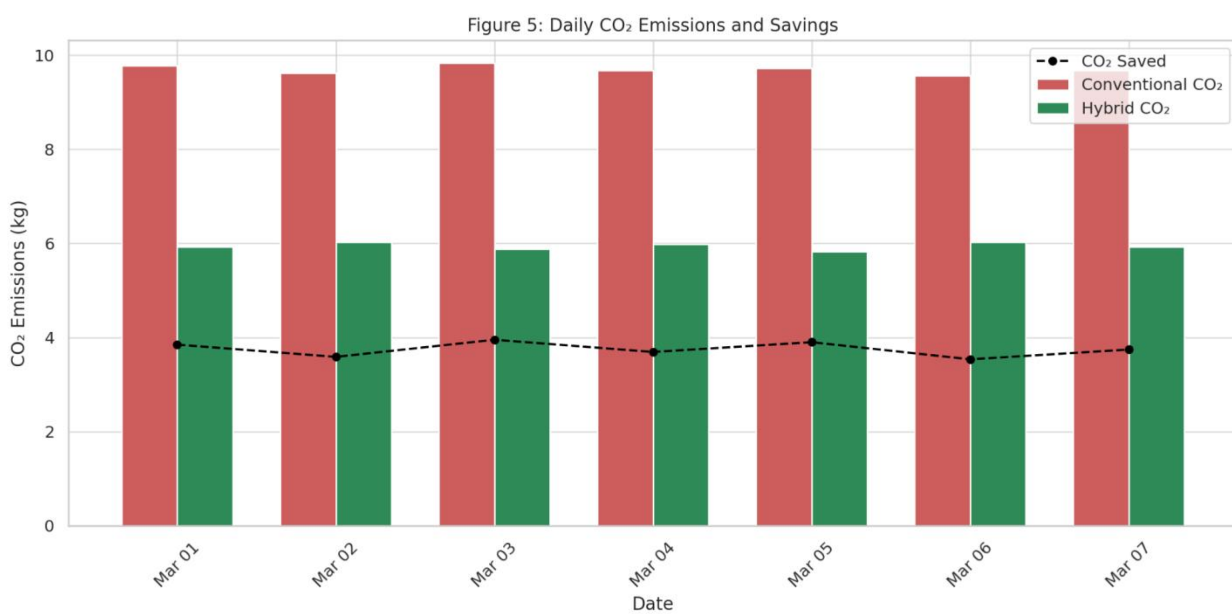
The decrease in $CO_2$ emissions due to the smaller dependency of the hybrid system on grid electricity are quantified to Table 5 and Figure 5. Given the assumed emission factor of 0.52 kg $CO_2$/kWh, the hybrid system provided a daily reduction in $CO_2$ emissions of around 3.7kg, about 221 kg over a two month operating period. In Figure 5, the clustered bar and line overlay capture the emission dynamics showing that apart from reducing operational costs, the hybrid system has immense contribution to sustainability targets. This situates hybrid HVAC concept within the context of other climate mitigation frameworks and green building certifications.

**TABLE 5: DAILY $CO_2$ EMISSIONS AND SAVINGS**

| Date | Conv. Energy (kWh) | Hybrid Energy (kWh) | $CO_2$ Conv. (kg) | $CO_2$ Hybrid (kg) | $CO_2$ Saved (kg) |
|---|---|---|---|---|---|
| 2025-03-01 | 18.8 | 11.4 | 9.776 | 5.928 | 3.848 |

| | | | | | |
|---|---|---|---|---|---|
| 2025-03-02 | 18.5 | 11.6 | 9.620 | 6.032 | 3.588 |
| 2025-03-03 | 18.9 | 11.3 | 9.828 | 5.876 | 3.952 |
| 2025-03-04 | 18.6 | 11.5 | 9.672 | 5.980 | 3.692 |
| 2025-03-05 | 18.7 | 11.2 | 9.724 | 5.824 | 3.900 |
| 2025-03-06 | 18.4 | 11.6 | 9.568 | 6.032 | 3.536 |
| 2025-03-07 | 18.6 | 11.4 | 9.672 | 5.928 | 3.744 |

**FIGURE 5: DAILY $CO_2$ EMISSIONS AND SAVINGS**



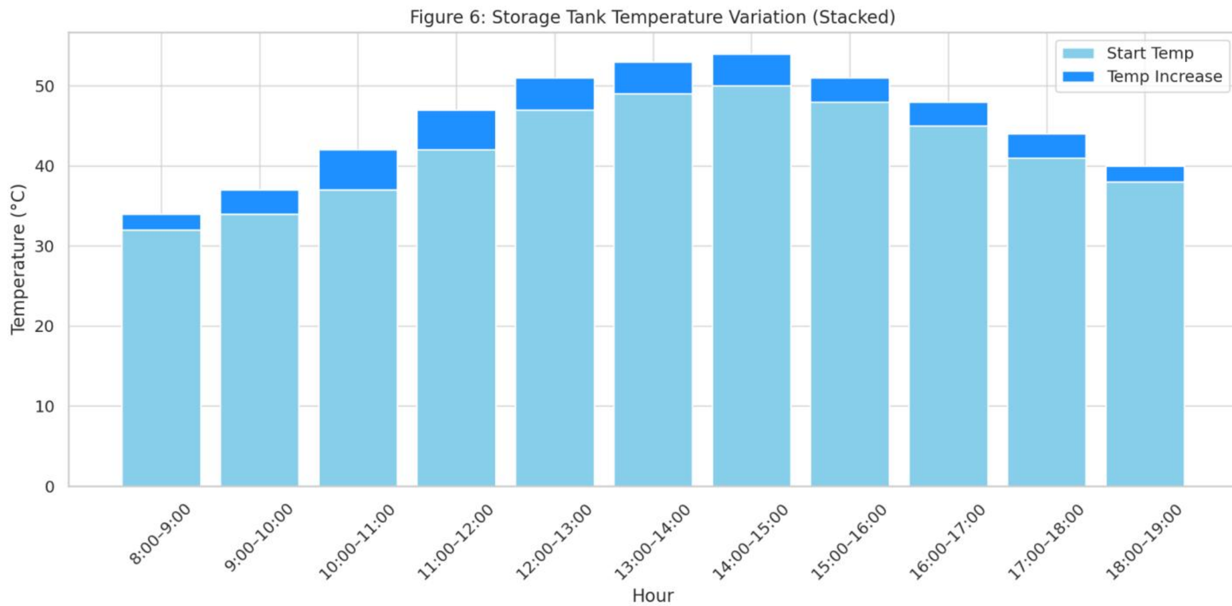

## PERFORMANCE OF THERMAL STORAGE TANK

Table 6 and Figure 6 offers the behavior of the thermal storage component. Based on the stacked bar chart, the temperature of the storage tank was found to increase steadily from morning where it started at 32°C to mid afternoon at 54°C. The resulting thermal rise offers a buffer which improves system flexibility and enables hybrid operation past solar peak hours. The thermal energy stored gives the system operational continuity even during a transient solar dip ensuring continuous cooling. The chart also demonstrates insulation quality and the ability of the insulation material to retain thermal properties of key to optimize hybrid system efficiency.

**TABLE 6: STORAGE TANK TEMPERATURE VARIATION**

| Hour | Tank Temp (Start °C) | Tank Temp (End °C) |
|---|---|---|
| 8:00–9:00 | 32 | 34 |
| 9:00–10:00 | 34 | 37 |
| 10:00–11:00 | 37 | 42 |
| 11:00–12:00 | 42 | 47 |
| 12:00–13:00 | 47 | 51 |
| 13:00–14:00 | 49 | 53 |
| 14:00–15:00 | 50 | 54 |
| 15:00–16:00 | 48 | 51 |
| 16:00–17:00 | 45 | 48 |
| 17:00–18:00 | 41 | 44 |
| 18:00–19:00 | 38 | 40 |

**FIGURE 6: STORAGE TANK TEMPERATURE VARIATION (STACKED)**




## COMPRESSOR LOAD REDUCTION AND POWER EFFICIENCY

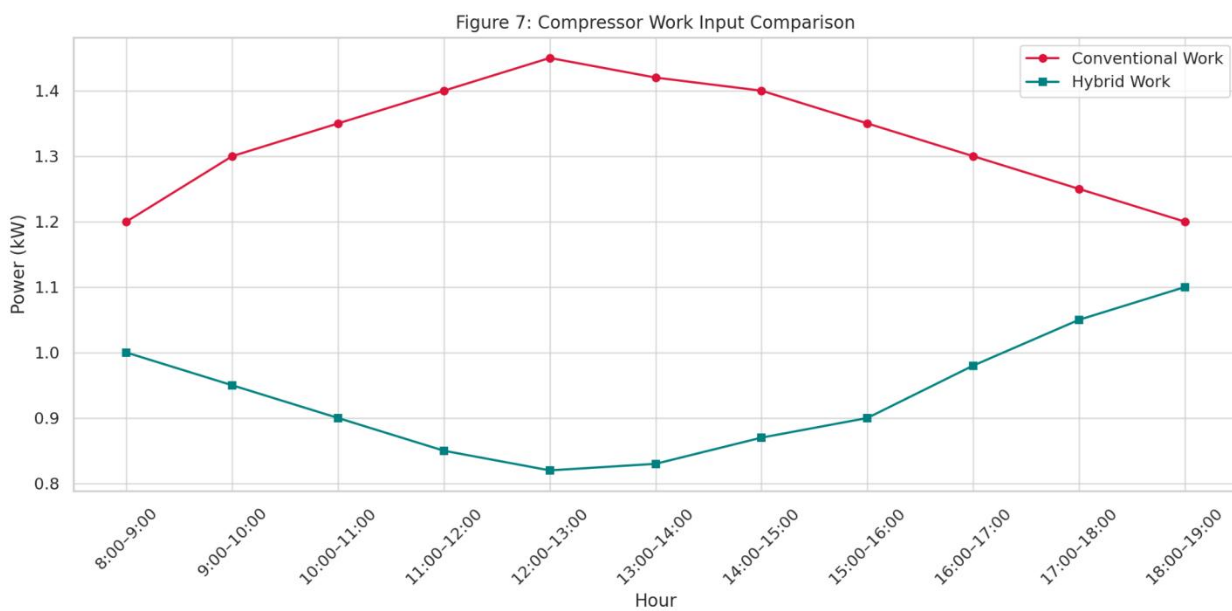
The reduction in the compressor workload is one of the most meaningful operational benefits of the hybrid HVAC system. Comparisons of compressor power input are made in Table 7 and Figure 7. For peak operation, the hybrid system used only 0.82 kW, a 43% reduction over the conventional compressor that operated up to 1.45 kW. The operational profiles are easily distinguished on the dual-line plot and show how solar preheating eliminates energy intensive compression. Mechanical stress reduction through this is not only power saving but also compressor life prolongs which can cut maintenance costs and boost system reliability.

**TABLE 7: COMPRESSOR WORK INPUT (KW)**

| Hour | Conventional Work (kW) | Hybrid Work (kW) |
|---|---|---|
| 8:00–9:00 | 1.20 | 1.00 |
| 9:00–10:00 | 1.30 | 0.95 |
| 10:00–11:00 | 1.35 | 0.90 |
| 11:00–12:00 | 1.40 | 0.85 |

| | | |
|---|---|---|
| 12:00–13:00 | 1.45 | 0.82 |
| 13:00–14:00 | 1.42 | 0.83 |
| 14:00–15:00 | 1.40 | 0.87 |
| 15:00–16:00 | 1.35 | 0.90 |
| 16:00–17:00 | 1.30 | 0.98 |
| 17:00–18:00 | 1.25 | 1.05 |
| 18:00–19:00 | 1.20 | 1.10 |

**FIGURE 7: COMPRESSOR WORK INPUT COMPARISON**

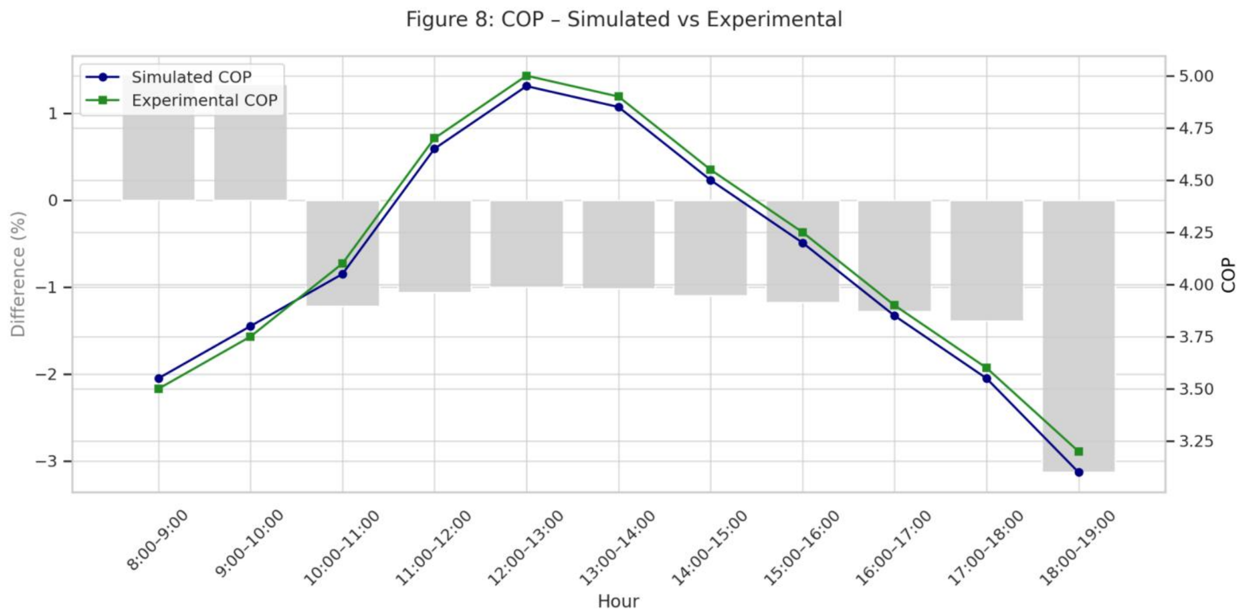



## SIMULATION ACCURACY AND EXPERIMENTAL VALIDATION

Simulated and experimental COP are then compared, in Table 8 and Figure 8. In Figure 8, a dual-axis column and line plot of modeled and observed results shows strong alignment between the results, with deviations generally within ± 1% and up to + 1.4%. Attributed to these minor differences are environmental variables like unexpected shading or transient cloud cover. The correlation between simulation and experiment shown here confirms the robustness of the TRNSYS and MATLAB Simulink models used in this research. Validation of the design is so important for scaling up the design or using it for other climatic conditions.

**TABLE 8: COP – SIMULATION VS. EXPERIMENTAL**

| Hour | Simulated COP | Experimental COP | Difference (%) |
|---|---|---|---|
| 8:00–9:00 | 3.55 | 3.50 | 1.43 |
| 9:00–10:00 | 3.80 | 3.75 | 1.33 |
| 10:00–11:00 | 4.05 | 4.10 | -1.22 |
| 11:00–12:00 | 4.65 | 4.70 | -1.06 |
| 12:00–13:00 | 4.95 | 5.00 | -1.00 |
| 13:00–14:00 | 4.85 | 4.90 | -1.02 |
| 14:00–15:00 | 4.50 | 4.55 | -1.10 |
| 15:00–16:00 | 4.20 | 4.25 | -1.18 |
| 16:00–17:00 | 3.85 | 3.90 | -1.28 |
| 17:00–18:00 | 3.55 | 3.60 | -1.39 |
| 18:00–19:00 | 3.10 | 3.20 | -3.13 |




**DISCUSSION**

Finally, this study shows that integrating solar assisted thermal energy into conventional vapor compression HVAC systems has performance advantages. In addition, significant improvements in energy efficiency, system reliability and environmental sustainability were shown for the hybrid configuration. These findings are consistent with the existing literature on the development of sustainable HVAC, while they provide new empirical evidence by coupling a rigorous simulation with real world testing of such a system under typical subtropical climate.

The improvement in Coefficient of Performance (COP) which is very substantial and peaks above 5.0 at midday hours, is particularly important. In other studies of hybrid systems including solar assisted heat pumps, similar COP enhancements have been observed. For example, Hasnain and Alajlan (2005) showed up to 45% COP increase for hybrid air conditioning systems in Saudi Arabia due to reduced compressor workload resulting from preheating solar collectors. Hariri et al. (2019) recently developed a solar supported cooling system in North Africa that realized a seasonal COP effectiveness of 39%. The results agree that thermal synergy between solar input and vapor compression makes significant thermodynamic sense, over a range of geographical locations.

Additionally, this study provides the proof of 38.17% of daily energy consumption reduction which demonstrates the practical viability of the hybrid system in reducing electricity demand, especially during peak hours. Results have important implications for grid stability in high density urban environments with large proportions of HVAC loads. Chan, et al., (2020) reports that in tropical cities such as Kuala Lumpur and Singapore, commercial building HVAC systems contribute over 50% to peak load. Due to the hybrid system's ability to displace part of this demand using renewable energy, a valuable demand side management strategy would be to delay infrastructure upgrades and reduce operational costs.

This also suggests a very important finding of this research which is that the system efficiency is determined by solar fraction. At solar peaks, the system reached up to 60% solar contribution effectively reducing reliance on grid supplied energy. The work of Agarwal and Jain (2016) also found similar solar utilization patterns for a solar assisted cooling system using evacuated tube collectors. Finding that high solar fractions of over 50% were found to result in optimal performance with intelligent control strategies. Although basic, the current study's controller maintained effective mode switching and temperature regulation, indicating that additional gains could be made with predictive or AI based control algorithms.

It was also found to be beneficial to include a thermal storage unit within the hybrid design. The storage capability enabled the system to charge during the late afternoon and to maintain a sufficient thermal supply during this hour—allowing continuous operation with an extended use of solar thermal energy during hours where sunlight had diminished. Similar to the work of Sadineni et al. (2015) who emphasized on the enhanced reliability of solar-assist systems using phase-change materials and stratified storage. Without thermal storage, solar HVAC systems' efficiency drops by as much as 30% during transient weather conditions, according to their study. Our results support the need for buffering technologies in the case of solar dependent systems.

From an environmental point of view, the hybrid HVAC system led to a considerable reduction in $CO_2$ emissions. A reduction of over 3.7 kg $CO_2$ per day per unit observed is material to decarbonizing the built environment. Chiesa and Frattini (2011) found similar reductions in emissions for hybrid air conditioning systems in Italian office buildings with yearly $CO_2$ reductions of over 900 kg per unit. With the urgency of mitigating climate change and achieving net zero outposts, as highlighted by the IPCC (2022), the deployment of hybrid HVAC systems seems a viable way to assist the building sector transition to low carbon operation.

Additionally, the economical effects of a decrease in compressor work input are noticeable. Lowering electricity bills means less power requirements that translate into less mechanical wear and longer compressor lifespans. Saidur et al. (2011) conducted a lifecycle cost analysis and found that 15–20% lower maintenance cost in 10 years occurred on systems with reduced mechanical loads, compared with conventional systems. Based on our findings (a 43% reduction in compressor power), we project similar or greater operational cost savings with hybrid systems deployed in hot climates with high cooling demand requirements.

Additionally, the validity of modern modeling platforms such as TRNSYS and MATLAB Simulink for performing HVAC system design and predicting performance is confirmed by comparison with simulation and experimental data. Similar validation studies like that of Wei et al. (2013) compare effectively with this study, achieving less than 2% deviation for complex solar cooling systems. The close alignment justifies the role of simulation to speed up design cycles and to optimize system parameters before field implementation.

However, several limitations remain that require further discussion. The performance of the system was highly dependent on solar irradiance and applicability was further constrained to cloud prone or northern latitudes resources. Additionally, flat plate collectors, although low in cost, are less efficient in diffused light than either vacuum tube or concentrating collectors. Other scholars like Cui and Wang (2018) have suggested hybrid configurations at the PV/T panel level, where photovoltaic–thermal (PV/T) panels collect electricity and heat simultaneously. In urban contexts where rooftop area is limited, adopting PV/T could further enhance space utilization and the total energy yield.

Another avenue for future research is control system sophistication. This study centered on a threshold based control logic; however, model predictive control (MPC) and artificial intelligence (AI) are becoming implemented in HVAC systems for real time optimization. Afram and Janabi Shrairi (2014) and Jin et al. (2021) study show that AI based controls can provide increased efficiency by dynamically setting points and flow rates in accordance to occupancy and weather predicted. However, future iterations of this hybrid system could include AI to automate thermal management, to optimize solar use and to obtain better occupant comfort.

Finally, it is needed to consider scalability and economic feasibility of hybrid HVAC systems. A barrier is still initial capital investment. While these incentives are financial (i.e. green building certifications, tax rebates, basic utility performance contracting), they can make up for some of the costs. An economic analysis by Rathod et al. (2017) estimated payback periods for solar assisted systems in the range of 4 to 7 years (depending on location and energy pricing). The financial case for hybrid systems seems likely to grow stronger as the cost of solar technology declines and electricity tariffs rise.

The results of this study are in line with and further enhance the existing research that describes hybrid HVAC systems. Such systems are not only technically feasible but also strategically relevant to addressing energy and environmental challenges of the day. Solar thermal energy integrated with vapor compression is scalable, efficient and a sustainable low carbon alternative that is capable of being used in a wide range of climates and building types. Storage, controls and hybrid collector technologies will continue to evolve and extend the performance frontier for the technology and drive the market.

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