

Performance Analysis of a Solar-Powered DC System toward Sustainable Cooling and Heating in a Hot Arid Climate: A Madinah Case Study

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ABSTRACT

As global temperatures rise and energy demands intensify, innovative climate-control solutions are essential for sustaining comfort in extreme environments. However, most existing Air-Conditioning (A/C) systems in hot-arid regions still rely on conventional Alternating-Current (AC) power, leading to significant conversion losses and limiting solar integration. This highlights the necessity for efficient, fully Direct-Current (DC)-powered alternatives. This study evaluates the performance and energy efficiency of a variable-speed DC A/C and heating system installed in Madinah, Saudi Arabia, during the summer of 2024 (June, July, August) and the winter of 2025 (January). The experimental investigation analyzes cooling and heating capacities, power consumption, ambient and indoor temperatures, and the Coefficient of Performance (COP). The system maintained an average indoor temperature of approximately 24 °C in summer and 25 °C in winter, ensuring thermal comfort despite outdoor temperatures exceeding 45 °C in summer and dropping to around 10 °C in winter. The peak cooling capacity reached 2261.4 W in July, accompanied by a 3% increase in total energy consumption compared to June. The highest cooling COP of 3.08 was recorded in June. This value decreased to 2.81 in July and recovered to 2.91 in August. During winter heating operation, the system achieved a COP of 5.72, delivering 10.19 kWh of heat with minimal energy input and demonstrating strong seasonal performance. The variable-speed operation enabled efficient adaptation to fluctuating conditions, confirming its suitability for extreme climates. The findings encourage future optimization through improved insulation, advanced control strategies, and renewable energy integration to enhance overall efficiency and promote sustainable building technologies.

Keywords-solar-powered A/C; DC air conditioning; energy efficiency; heating technology

I. INTRODUCTION

As global temperatures rise due to climate change, the demand for energy-efficient solutions has become critical, particularly in regions with extremely hot climates. A/C plays a vital role in maintaining indoor comfort, yet it accounts for a significant portion of global electricity consumption [1]. In Saudi Arabia, where summer temperatures frequently exceed

45°C, A/C is essential for daily life [2]. However, the growing reliance on conventional A/C systems presents serious challenges, including high energy consumption, increased peak electricity demand, and environmental concerns. As energy demand rises, addressing the inefficiencies of traditional cooling methods becomes imperative. These traditional A/C systems operate on AC electricity and are widely used in extreme climates to maintain indoor comfort. However, they

are energy-intensive and rely heavily on fossil fuel-based power generation, contributing to environmental degradation. In Saudi Arabia, A/C alone accounts for over 70% of total electricity consumption in residential and commercial buildings, particularly during peak summer months [3]. Globally, buildings consume a significant portion of energy, and in hot, humid regions, cooling can account for up to 50% of a building's total use. Studies in tropical climates, such as Makassar, Indonesia, show that energy-efficient A/C strategies can reduce consumption while maintaining thermal comfort [4]. The increasing dependence on conventional A/C systems in high-temperature areas exacerbates electricity shortages and raises concerns over energy security and sustainability [5, 6]. Sustainable and energy-efficient cooling solutions have been explored to address these challenges. One promising alternative is to integrate A/C systems with Photovoltaic (PV) panels. Unlike conventional A/C systems, which require inverters to convert DC electricity from renewable sources into AC power, DC powered A/C systems operate directly on DC power, eliminating conversion losses and improving efficiency. DC-based cooling systems can achieve up to 30% higher efficiency than traditional A/C systems due to reduced power conversion losses and optimized operation [7]. Furthermore, combining these systems with solar PV panels reduces grid reliance, while integrated battery storage ensures continuous nighttime cooling and stable operation in off-grid or energy-intensive applications.

Solar energy's potential for A/C has been extensively investigated, with PV-driven systems emerging as a practical alternative to solar thermal technologies due to their simplicity and ease of implementation. Authors in [8] examined a hybrid PV-grid A/C system in a Mediterranean climate, combining PV panels with grid backup to power a conventional AC unit. Their study, conducted over a summer, reported a solar contribution of 65%, reducing grid electricity use significantly. The system's performance was bolstered by high solar irradiance, suggesting applicability in hotter climates. However, the reliance on AC components highlights a gap that DC systems could address by eliminating inverter losses. Authors in [9] evaluated a PV-powered chiller system in a large tertiary building, focusing on its annual performance in a subtropical climate. The system achieved a solar fraction of 52%, with cooling primarily active during warmer months, demonstrating a strong correlation between solar availability and demand. A detailed energy balance model was employed, revealing that PV output covered over half the chiller's needs without winter operation, implying higher potential in consistently hot climates. These studies establish PV-driven cooling as feasible, setting the stage for DC-specific advancements.

DC A/C systems, which directly couple PV panels to DC compressors, bypass inverter-related energy losses (typically 10–20%) and enhance efficiency in solar applications. Authors in [10] explored a PV-powered DC A/C system designed for automotive use, integrating PV panels and batteries to drive a DC motor. Their experiments under dynamic load conditions showed reduced power consumption and stable cooling compared to AC equivalents, with the results being attributed to direct energy transfer and variable-speed compressors. This

design's success in mobile contexts suggests scalability to stationary applications in hot climates. Authors in [11] conducted an experimental study on a PV-driven DC A/C in Shanghai, integrating PV panels, a DC compressor, and battery storage. Their results indicated daytime grid savings of over 67% and a comprehensive energy efficiency ratio 4.6 times higher than conventional AC units, with batteries enabling 77% savings at night. The system's COP reached 0.289 under moderate solar radiation (18.2 MJ/m² daily), outperforming some solar thermal systems.

In [12], a hybrid PV-grid DC A/C in Kumasi, Ghana, a hot and humid region, was assessed over a year. The system maintained stable daytime cooling with PV panels, supplemented by batteries for nighttime use, reducing grid dependency by leveraging Ghana's high solar irradiance (averaging 5 kWh/m²/day). The authors emphasized battery sizing as critical for consistent performance, a key insight for hot climates. Authors in [13] analyzed a PV-driven heat pump in Jeddah, Saudi Arabia, whose performance was enhanced with radiative cooling. Their system lowered indoor temperatures by 10°C below ambient, achieving a higher COP through passive cooling integration. Tested under extreme summer conditions (up to 50 °C), the setup demonstrated resilience and efficiency, suggesting that such hybrid enhancements could bolster DC systems. These studies affirm the systems' potential in hot climates, though local conditions, like humidity and temperature extremes, influence the outcomes. In [14], a variable-speed DC solar cooler was evaluated in Ethiopia, focusing on its ability to adjust compressor speed to solar input. Experiments showed improved energy utilization and cooling consistency compared to fixed-speed systems, with a COP exceeding that of traditional AC units under high solar radiation. The effective design of PV-powered DC systems requires the optimization of components like PV panels, compressors, and storage. Authors in [15] investigated a solar-driven heat pump with a variable-speed compressor in a cold climate, but their findings on energy matching are relevant to hot regions. Adjusting compressor speed to PV output improved efficiency by 15–20%, an approach that could enhance performance in hot climates. Authors in [16] optimized a PV-driven liquid desiccant system for hot, humid climates, integrating PV panels with a desiccant cooling cycle. Their analysis found that balancing PV collector area with building constraints reduced regeneration heat needs by 30%, boosting efficiency. Battery storage is important for nighttime operation in hot climates. In [17], a system integrating thermoelectric cooling with PV panels improved output by 10–15% in high temperatures up to 50 °C but added complexity and cost, limiting scalability.

Authors in [18] examined the impact of dust accumulation on PV performance in arid climates, finding a 20–30 % efficiency drop without cleaning. In [19], the economics of solar-powered cooling in off-grid settings were analyzed, estimating a payback period of 5–7 years despite high upfront costs. Authors in [20] reviewed various solar-assisted air-conditioning technologies, mainly focusing on solar-thermal systems such as absorption and adsorption chillers, where the reported COP values typically ranged from 0.6 to 1.2. In contrast, the present work investigates a PV-powered,

electrically driven DC heat-pump system, which belongs to a different technology class and achieves significantly higher COP values (2.8–6.0) consistent with modern inverter-type systems.

The present study addresses the need for sustainable cooling and heating in extreme climates, such as in Madinah, Saudi Arabia. By experimentally evaluating a fully DC-powered A/C and heating system integrating with PV panels and battery storage, this research contributes to Saudi Arabia's Vision 2030 [21]. The study focuses on reducing electricity use, improving security, and minimizing environmental impact. The system, operating on a 48 V PV-battery setup, was tested in Madinah's hot desert climate. Its performance was assessed based on key metrics – cooling capacity, energy consumption, and COP – under varying conditions. Conducted at the Renewable Energy Laboratory of the Islamic University of Madinah, the experimental work provides real-world data on the system's efficiency and operational feasibility. The study examines whether the system can sustain comfort while minimizing energy use, offering insights into practicality and scalability. The novelty of this work lies in the comprehensive experimental evaluation of a fully DC, 48 V A/C and heating system that operates directly from PV power without inverters, eliminating conversion losses common in conventional inverter-based units. Unlike traditional systems that rely on on/off control or require multiple power conversions (AC–DC–AC), the proposed system features a fully variable-speed DC compressor driven directly by low-voltage DC, enabling smoother modulation and higher overall efficiency. The testing was conducted under the harsh hot conditions of Madinah, where summer temperatures exceed 45 °C and winter temperatures drop to around 10 °C, making this dual-mode (cooling and heating) seasonal assessment both original and highly relevant. These distinctive characteristics demonstrate a promising solution for sustainable climate control in regions facing extreme temperature variations.

II. STUDY AREA

Madinah, Saudi Arabia, was selected for this study due to its characteristic hot desert climate (Figure 1), with frequent summer temperatures above 40°C and high solar irradiation ranging from 2200 to 2400 kWh/m² annually. Its latitude near the Tropic of Cancer ensures abundant sunlight, making it an ideal location for testing the efficiency and reliability of solar-powered A/C.

III. EXPERIMENTAL SETUP

The experiment evaluated a 12,000 BTU fully DC A/C system under the extreme climate of Madinah over the summer of 2024 (June, July, August) and the winter of 2025 (January). Figure 2 shows Madinah's monthly temperature variation [22]. The DC unit had a rated input of 930 W and an EER of 12.9 BTU/W·h. Tests were conducted around solar noon using direct solar power from a 48 V PV array without batteries or inverter conversion. The array comprised six JA Solar JAM72S20-455/MR modules configured as two parallel strings of three panels in series, each rated at 455 W, V_{mp} 41.82 V, and I_{mp} 10.88 A. The panels were fixed at a 24° tilt facing south and cleaned weekly to minimize dust accumulation.

Figure 3 illustrates the experimental setup and thermocouple placements.



Fig. 1. Geographic location of Saudi Arabia, Madinah City. © NASA, Google, Mapa GISrael.

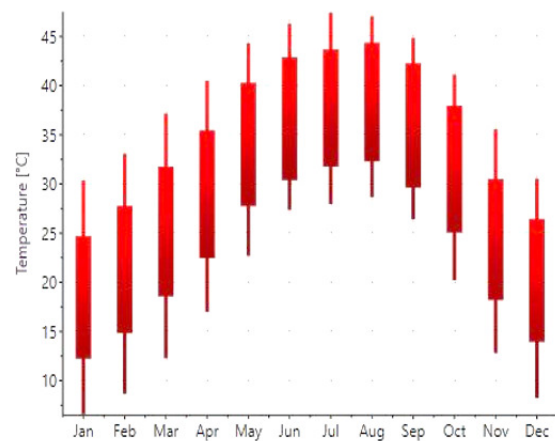


Fig. 2. Monthly average temperature variation in Madinah, Saudi Arabia (Meteonorm data [22]).

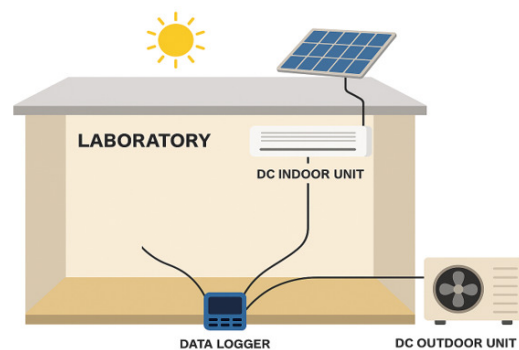


Fig. 3. Schematic diagram of the experimental setup.

The tests were conducted in a dedicated zone within the Renewable Energy Laboratory at the Islamic University of Madinah. The test chamber had a volume of 100 m³ (4.2 × 6 × 4 m) and was constructed with insulated wall and roof panels. During testing, internal heat gains and air infiltration were minimized, and the space was unoccupied. For cooling experiments, a heater was utilized briefly to pre-condition the

space, raising the indoor temperature to a standardized initial condition of 33 °C before each test run. No such pre-heating was applied for heating tests. A flowchart outlining the experimental methodology is presented in Figure 3.

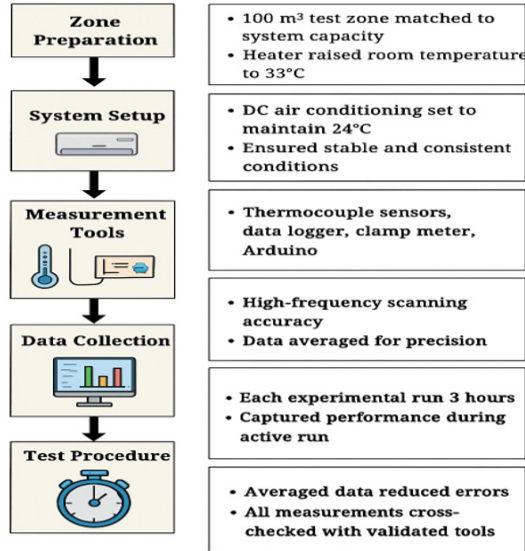


Fig. 4. Overview flowchart of the experimental methodology.

IV. UNCERTAINTY ANALYSIS

The uncertainty is the difference between actual and measured values, estimated using the instrument's data book or calibration report. The accuracy, range, and standard uncertainty for each measurement instrument are provided in Table I. Precautions were taken during testing to reduce the errors arising from changing conditions. The uncertainty, Δf , for any derived parameter f (e.g., energy) can be calculated by [23]:

$$\Delta f = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 \Delta x^2 + \left(\frac{\partial f}{\partial y}\right)^2 \Delta y^2} \quad (1)$$

where Δx and Δy are the uncertainties of the measured values.

The averaged performance parameters of the DC A/C system for the summer and winter test period are summarized in Table II. Accordingly, the maximum COP error was $\pm 7.61\%$ in June 2024, $\pm 6.56\%$ in July, and $\pm 6.92\%$ in August. For the heating COP measured in January, the maximum calculated error was $\pm 11\%$.

TABLE I. THE ACCURACY AND UNCERTAINTIES OF THE MEASURING SYSTEM.

Instrument	Accuracy	Range	Standard uncertainty
Thermocouple	$\pm 0.1^\circ\text{C}$	$-100 - 500^\circ\text{C}$	0.08°C
DC sensor	$\pm 0.5 \text{ A}$	$0 - 50 \text{ A}$	0.29 A
DC voltage sensor	$\pm 0.92 \text{ mV}$	$0 - 100 \text{ V DC}$	0.53 mV
Anemometer	$\pm(3\% + 0.20 \text{ m/s})$	$0.1 - 25.0 \text{ m/s}$	0.179 m/s

V. PERFORMANCE EVALUATION FORMULAS

This section presents formulas for evaluating the DC A/C system's thermal and energy performance. The calculations determine the air mass flow rate, sensible heat transfer, COP, and total energy consumption based on measured parameters such as air temperature, velocity, density, and specific heat:

$$\dot{m} = \rho \times V \times A \quad (2)$$

$$\dot{Q} = \dot{m} \times C_p \times (T_{\text{in_evap}} - T_{\text{out_evap}}) \quad (3)$$

The instantaneous COP evaluates the system's efficiency and is defined as:

$$\text{COP} = \frac{\dot{Q}}{\text{Energy Input}} \quad (4)$$

The overall COP ($\text{COP}_{\text{overall}}$) evaluates the DC system's performance over the full test period. Unlike on/off compressors, the variable-speed system continuously adjusts to the demand. The $\text{COP}_{\text{overall}}$ considers the total cooling delivered and total energy consumed, providing an accurate measure of efficiency under real-world conditions. It is defined as:

$$\text{COP}_{\text{overall}} = \frac{\text{Total heat absorbed (kWh)}}{\text{Total energy consumed (kWh)}} \quad (5)$$

The total electrical energy consumed during an operational period Δt , is calculated using:

$$E_{\text{total}} = \frac{\text{Power}_{\text{total}} \times \Delta t}{3600 \times 1000} \quad (6)$$

where $\text{Power}_{\text{total}}$ is the total power input into the DC system, including the compressor and auxiliary components (e.g., fans).

VI. RESULTS AND DISCUSSION

System performance was evaluated using the instantaneous COP for active cooling and the overall COP for the total test duration. Table II outlines the results, showing the DC system's ability to modulate compressor speed and adapt to varying cooling demands. Thermal comfort was clearly maintained, as the variable-speed compressor continuously adjusted its frequency to keep the indoor set-point temperature near 24 °C even under outdoor conditions exceeding 45 °C. This modulation principle, similar to Variable-Refrigerant-Flow (VRF) operation, minimized temperature fluctuations and cycling losses compared to on/off control, confirming both thermal comfort stability and energy efficiency.

The power use ranged from 593.39 W in heating to 775.8 W in cooling, with July showing the highest cooling capacity (2261.4 W) at a 45.2 °C ambient temperature. Indoor temperatures remained stable within a 22.3–25.0 °C range, confirming effective control. The COP peaked at 5.72 in heating and dropped to 2.81 during peak cooling, reflecting the compressor's operational adaptability. The COP decline in July corresponded to a higher condenser air outlet temperature and a greater condenser air $\Delta T_{\text{out-in}}$, signifying elevated condensing temperature and pressure. Consequently, compressor work and power input rose by 10.8% compared to June, while Q_{evap} increased only slightly (2.5%). To sustain the 24 °C set-point under hotter outdoor conditions, the compressor and fans operated at higher speeds. This marginal boost in capacity came at the cost of reduced efficiency due to the

increased lift, motor losses, and lower heat-rejection effectiveness. The reported total heat and energy values were calculated for a 3-h experimental duration. The following subsections provide a detailed monthly breakdown of these performance parameters.

A. System Performance in June 2024

In June, with an ambient temperature of 43.1°C, the system maintained a stable indoor temperature of 22.8°C against a set point of 24°C. The evaporator inlet and outlet temperatures averaged 25.2°C and 17.1°C, respectively, indicating efficient heat removal. The system consumed an average power of 700.1 W (2.1 kWh total over 3 h) to deliver a cooling capacity of 2206.8W, absorbing 6.6 kWh of heat. This resulted in an instantaneous COP of 3.08 and an overall COP (COP_{overall}) of 3.1. The continuous modulation avoided the cycling losses typical of on-off systems, leading to stable operation with minimal temperature fluctuations.

B. System Performance in July 2024

In July, with an ambient temperature of 45.2 °C, the DC system maintained an indoor temperature of 22.3 °C, close to the 24 °C setpoint. As shown in Figure 5, the temperature difference between the evaporator inlet (23.5 °C) and outlet (15.2 °C) indicates strong heat extraction and consistent cooling performance. The average power use was 775.8 W, resulting in a total energy consumption of 2.5 kWh (Figure 6). Figure 7 demonstrates that the system achieved a peak cooling capacity of 2261.4 W, with a COP of 2.81 and an overall COP of 2.7, reflecting higher compressor effort under extreme heat while sustaining comfort levels.

C. System Performance in August 2024

In August, with an ambient temperature of 43.5°C, the system maintained an indoor temperature of 22.8°C, near the 24°C setpoint. The evaporator inlet and outlet temperatures averaged 25.1°C and 17.0°C, respectively, indicating effective heat removal. The system consumed an average power of 745.6 W (2.2 kWh total energy), delivering a cooling capacity of 2222.1 W, which correspond to 6.6 kWh of absorbed heat over 3 h. This resulted in an instantaneous COP of 2.91 and an overall COP (COP_{overall}) of 3.0, reflecting improved efficiency compared to July.

D. System Performance in January 2025

In January, under an ambient temperature of 14.39 °C, the DC system maintained an indoor temperature of 25.01 °C, close to the heating setpoint. As depicted in Figure 8, the evaporator inlet (27.51 °C) and outlet (40.67 °C) temperatures indicate strong heat delivery and efficient operation. The average power consumption was 593.39 W, resulting in a total energy use of 1.69 kWh (Figure 9). Figure 10 shows that the system achieved a heating capacity of 3567.76 W. The corresponding COP was 5.72, with an overall COP (COP_{overall}) of 6.02, confirming high efficiency and stable thermal comfort through continuous variable-speed control.

TABLE II. SUMMARY OF AVERAGED DC A/C SYSTEM PARAMETERS FOR SUMMER 2024 AND JANUARY 2025

Parameter	Cooling case			Heating case
	June 2024	July 2024	August 2024	January 2025
Power (W)	700.1	775.8	745.6	593.39
Q _{evap} (W)	2206.8	2261.4	2222.1	3567.76
T _{amb} (°C)	43.1	45.2	43.5	14.39
T _{room} (°C)	22.8	22.3	22.8	25.01
T _{in,evap} (°C)	25.2	23.5	25.1	27.51
T _{out,evap} (°C)	17.1	15.2	17.0	40.67
T _{in,cond} (°C)	43.5	45.8	43.9	-
T _{out,cond} (°C)	50.4	55.0	52.1	-
COP	3.08	2.81	2.91	5.72
COP _{overall}	3.1	2.7	3	6.02
Total absorbed heat over 3h (kWh)	6.6	6.8	6.6	10.19
Total energy consumed over 3h (kWh)	2.1	2.5	2.2	1.69

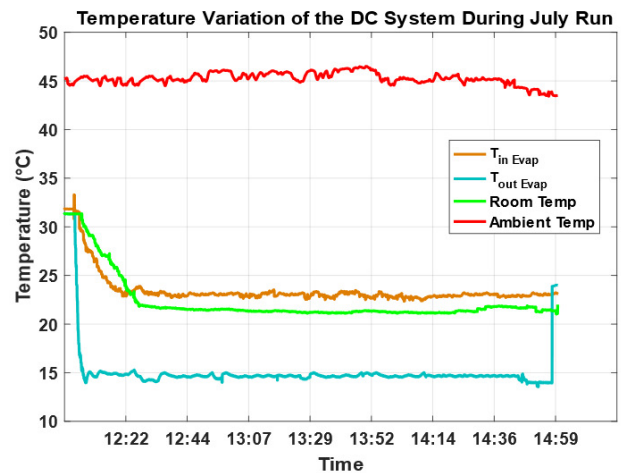


Fig. 5. Temperature variations for the cooling case.

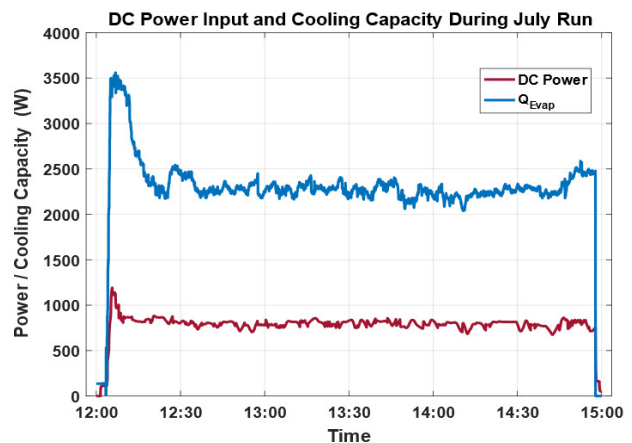


Fig. 6. Power consumption and cooling capacity for July 2024.

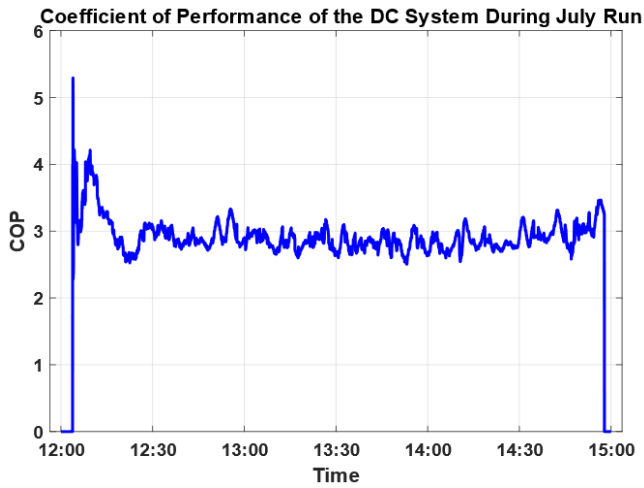


Fig. 7. COP variation on July 2024.

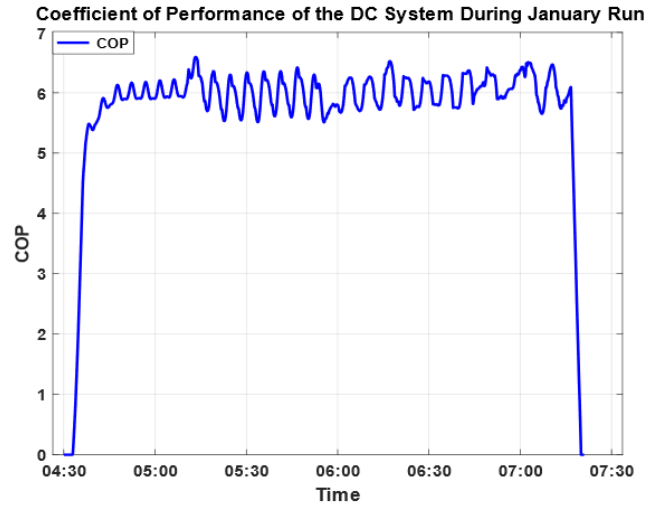


Fig. 10. COP variation on January 2025.

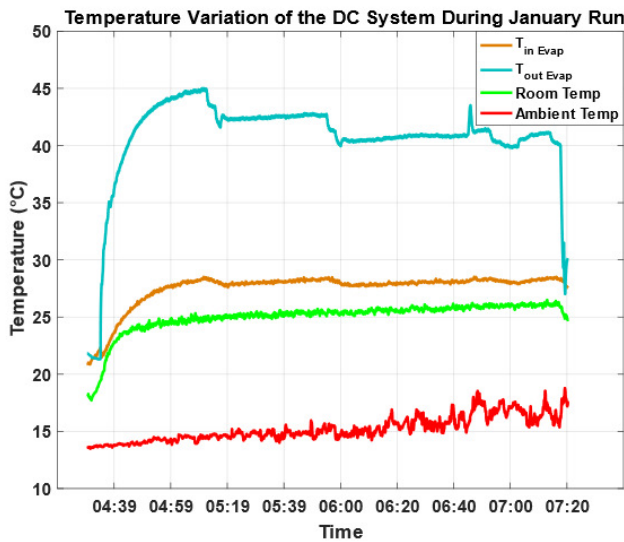


Fig. 8. Temperature variations for the heating case.

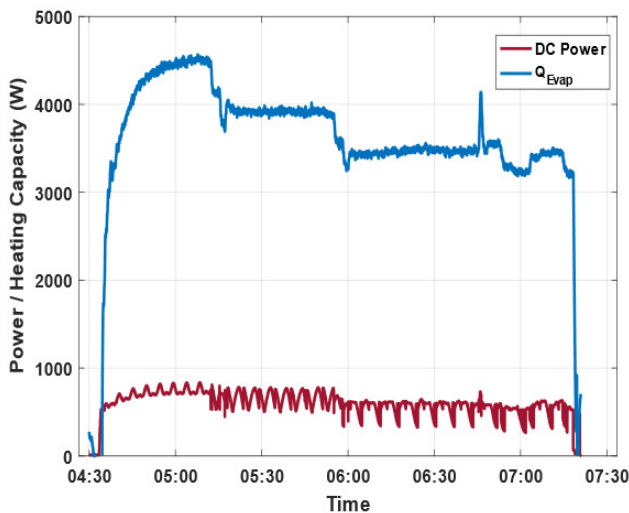


Fig. 9. Power consumption and heating capacity for January 2025.

VII. COMPARATIVE ANALYSIS

A. Power Consumption and Cooling Capacity

Power consumption increased from 700.1 W in June to 775.8 W in July – a rise of 10.8% – due to the higher cooling demand. It then decreased slightly to 745.6 W in August, which was still 6.4% above June. During January heating operation, power consumption was lower at 593.39 W (15.3% below the June cooling power). Cooling capacity peaked in July at 2261.4W (2.4% above June) and decreased slightly to 2222.1 W in August (0.6% above June). In contrast the heating capacity in January reached 3567.76 W, substantially exceeding the summer cooling capacities, demonstrating high winter performance (Figure 11).

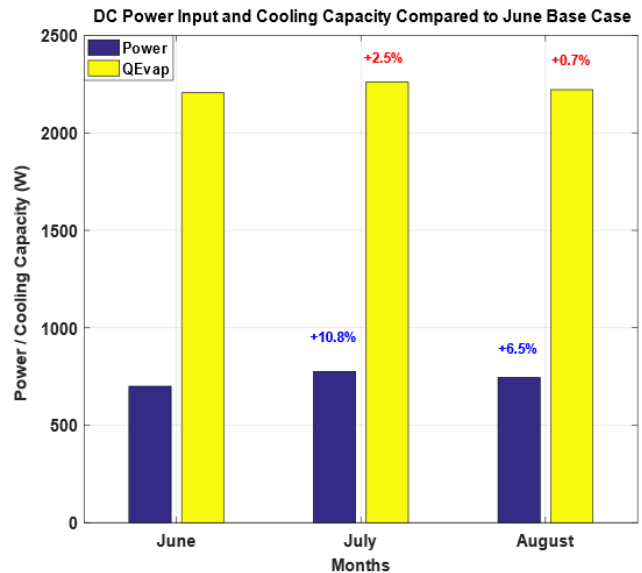


Fig. 11. Monthly power consumption, cooling and heating capacity.

B. Temperature Variations

The temperature graph (Figure 12) illustrates the following variations: ambient temperatures were 43.1 °C in June, rising to 45.2 °C in July (an increase of 4.8%), and 43.5°C in August (0.9% above June). Indoor temperatures remained stable at 22.8 °C in both June and August, with a slight drop to 22.3°C in July (3.2% lower than June/August), confirming effective cooling control. In January, with an ambient temperature of 14.39 °C, the system maintained an indoor temperature of 25.01 °C. The evaporator inlet and outlet temperatures reached 27.51°C and 40.67°C, respectively, demonstrating strong heating performance.

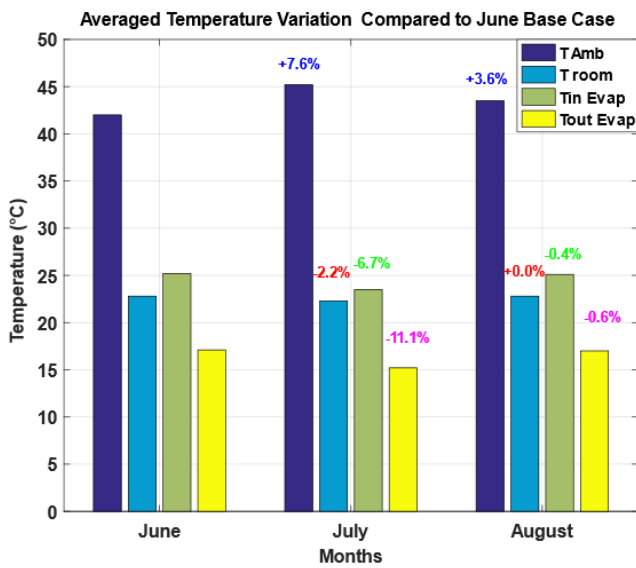


Fig. 12. Temperature variations across the studied months.

C. Overall Energy Consumption

Figure 13 shows the total energy consumption for cooling and heating. Consumption was 6.6 kWh in June, rising by 3% to 6.8 kWh in July, and then dropping slightly to 6.7 kWh in August (an increase of 1.5% compared to June). In January, energy use was at its lowest (1.69 kWh), while the system delivered 10.19 kWh of heat, demonstrating highly efficient heating with minimal energy.

D. Coefficient of Performance

The system achieved its highest COP (3.08) in June under moderate cooling loads. In July, the COP dropped by 8.8% to 2.81, due to higher ambient temperatures (45.2°C). It then recovered to 2.91 in August, representing an increase of 3.6% compared to July, as ambient conditions became cooler (43.5°C). In January 2025, during heating operation, the system demonstrated its peak efficiency. The COP reached 5.72, with an overall COP (COP_{overall}) 6.02, exceeding the summer values. This performance is attributed to the mild outdoor conditions and the efficient VRF DC operation of the system (Figure 14). The system's performance is strongly influenced by ambient temperature and thermal demand. High summer temperatures lowered the cooling COP, whereas the milder winter climate enabled a higher heating COP. The variable-speed DC system

outperformed conventional on-off ACs by dynamically adjusting to loads, which reduced energy consumption and maintained operational efficiency. Ongoing tests, which integrate PV power, demonstrate superior efficiency and sustainability. Future publications will detail the comparative performance, highlighting the benefits of renewable-powered AC systems in regions with extreme climates.

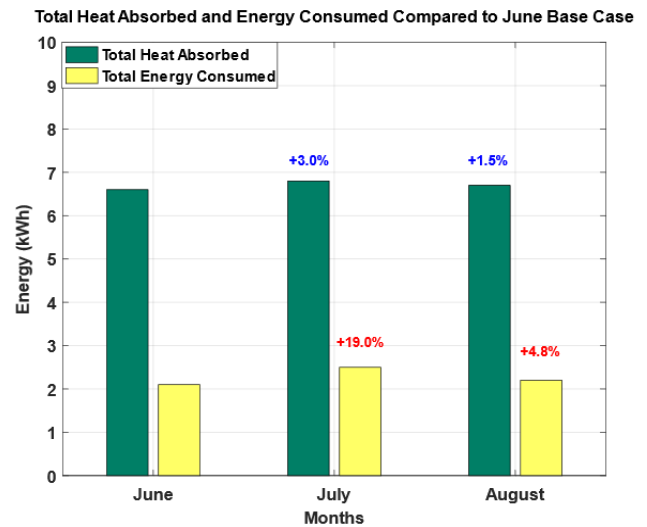


Fig. 13. Overall energy consumption across seasonal changes.

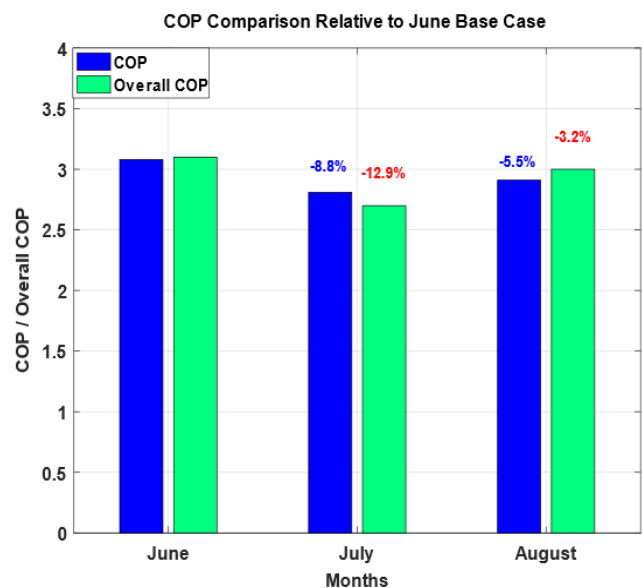


Fig. 14. Monthly comparison of the system COP for June, July, and August.

VIII. CONCLUSIONS

This study evaluated a fully Direct Current (DC)-powered Air Conditioning (A/C) and heating system with a 48 V Photovoltaic (PV)-battery setup under real conditions in Madinah, Saudi Arabia. The system maintained stable indoor temperatures around 24 °C in summer and 25 °C in winter, demonstrating strong seasonal adaptability.

The key findings of this study are: The cooling capacity peaked at 2261.4 W in July, with energy use rising 3% from June due to the higher load. The highest cooling Coefficient of Performance (COP) was 3.08 in June, dropping to 2.81 in July, then recovering to 2.91 in August. In January heating, the COP reached 5.72 and the overall COP (COP_{overall}) was 6.02, while the system consumed only 1.69 kWh to deliver 10.19 kWh of heat, showing high efficiency under mild winter conditions.

The system demonstrates the potential of variable-speed DC HVAC as a sustainable, efficient solution for extreme climates. Future work should explore optimization strategies such as advanced control algorithms, component scaling for larger capacities, and hybrid integration with emerging renewable technologies like solar-thermal or energy-storage systems. Further studies will also address PV-array sizing and battery-capacity sensitivity, the impact of dust accumulation on PV performance in arid environments, and long-term seasonal monitoring to assess durability. In addition, a comprehensive techno-economic analysis covering payback period and avoided grid-energy costs is proposed to evaluate scalability, reliability, and life-cycle performance.

This study fills a critical research gap in DC solar-powered HVAC for hot, arid regions and supports the development of sustainable climate control technologies aligned with Saudi Arabia's Vision 2030.

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