Current Research in Interdisciplinary Studies, 4(6):25–35, 2025. DOI: 10.58614/cris464

Current Research in Interdisciplinary Studies

Journal homepage: https://www.jpub.org/journal-details.php?journal-id=40

Research Article

Smart Thermoelectric Air-Conditioning with Energy Management and Dual HVAC Mode

Nsikanabasi George Ituen[1], Aneke Chikezie Samuel[1], Bliss Utibe-Abasi Stephen[1*], Deborah Theophilus Edet[1], Kelly Uchenna Umerah[1], Emmanuel Ubong Idaresit[1], Blesing Edwin[1], Oyintariebi Deizigha[1], Phebe Effiong Egok[1] and Michael Paul Esu[1]

[1]*Computer Engineering, University of Uyo, Uyo, Akwa Ibom State, Nigeria.*
[*]*Corresponding author: blissstephen@uniuyo.edu.ng*

Article Info

Keywords: *Thermoelectric air conditioning, Phase change materials, smart HVAC, Hybrid power systems, Renewable energy.*

Received: *05.12.2025;*
Accepted: *19.12.2025;*
Published: *28.12.2025*

Abstract

This work details the design and implementation of a smart thermoelectric air conditioning system developed to address the inefficiencies of traditional vapour compression air conditioners, including high energy consumption and environmental concerns. Our objective was to design and develop a multifunctional, energy-efficient, and eco-friendly alternative. The system integrates solid-state thermoelectric cooling (TEC) with a water-based heat exchange system that utilizes a paraffin wax Phase Change Material (PCM) to enhance thermal regulation and efficiency. A custom-made PCB featuring an ATmega328P microcontroller was developed for intelligent control, enabling the management of multiple power sources and supporting both cooling and heating modes. Testing in a controlled environment demonstrated the prototype's efficacy, as it successfully lowered the room temperature by 6°C in the first hour and stabilized it at a comfortable 25°C. The system also proved its dual-mode capability by raising the room temperature by 5-6°C within the same time-frame. These results confirm the feasibility and practicality of a sustainable and smart thermoelectric air conditioning solution for small to medium-sized spaces. The translational aspect of this research lies in its potential to advance consumer-grade air conditioning technology. By offering a solid-state, refrigerant-free, and energy-efficient solution with built-in air purification, this technology has the potential for significant clinical impact by improving indoor air quality and thermal comfort, particularly in off-grid or remote applications, thereby enhancing overall human well-being.

1. Introduction

The Smart thermoelectric air conditioner is a revolutionary solution that offers a quieter, efficient and eco-friendly approach to indoor climate control. The system uses solid-state thermoelectric modules to create a temperature difference without the need for noisy compressors or chemical refrigerants. This innovative use of the Peltier effect results in a compact, durable, and whisper-quiet unit that is a significant departure from conventional systems. But this isn't just about cooling. The system integrates advanced air purification and humidification to ensure the air you breathe is clean and comfortable. It also features a multi-power system that automatically switches between solar, battery, and mains power, ensuring continuous operation and maximum energy efficiency. Coupled with Phase Change Materials (PCMs) for passive cooling, this air conditioner is designed to significantly reduce your energy footprint. With smart controls, real-time energy monitoring, and a user-friendly interface, this multifunctional air conditioner puts you in complete control of a healthier, more sustainable indoor environment.

Traditional air conditioning systems that rely on vapor compression cycles, although effective, have notable drawbacks, including high energy consumption, noise pollution, reliance on environmentally hazardous refrigerants, and limited functionalities. These limitations are

How To Cite: N.G. Ituen, A.C. Samuel, B.U. Stephen, D.T. Edet, K.U. Umerah, E.U. Idaresit, B. Edwin, O. Deizigha, P.E. Egok, M.P. Esu. Smart Thermoelectric Air-Conditioning with Energy Management and Dual HVAC Mode. *Current Research in Interdisciplinary Studies*, 4(6):25–35, 2025. https://doi.org/10.58614/cris464

particularly concerning in the context of growing energy demands and environmental challenges, highlighting the need for alternative air conditioning solutions that are both eco-friendly and user centred.

Emerging technologies such as thermoelectric cooling have shown promise in addressing these concerns. Thermoelectric modules operate on the Peltier effect, converting electrical energy into a temperature gradient without the need for moving parts or chemical refrigerants. This solid-state method of heat transfer allows for quieter operation, reduced maintenance, and a more compact design [1]. Additionally, innovations in Phase Change Materials (PCMs) which absorb and release latent heat, have further enhanced the potential of energy-efficient climate control systems by enabling passive cooling. When integrated into HVAC systems, PCMs can significantly reduce energy usage and improve indoor thermal comfort [2].

This current study focuses on designing and developing a smart thermoelectric air conditioner that combines solid-state cooling, air purification, humidification, and smart energy management features. With automatic switching between solar, battery, and mains power, a built-in phase change material for passive cooling, and a user-friendly interface, the system aims to provide an efficient, quieter, and environmentally responsible solution.

The remainder of this paper is organized as follows. Section II reviews related work. Section III talks about the methodology and system design of the proposed smart thermoelectric air conditioner, including its core components and tools used. Section IV presents the results of the prototype construction and discusses its comparison to traditional air conditioners. Finally, Section V concludes the paper and talks about its contribution to knowledge.

2. Related Work

2.1. Thermoelectric Cooling and Solid-State Systems

Thermoelectric (TE) cooling technology has emerged as a promising alternative to conventional vapour-compression systems due to its compactness, quieter operation, and solid-state design. Wang et al. [3] demonstrated that TE modules can generate temperature gradients via the Peltier effect without moving parts or chemical refrigerants, resulting in lower noise levels and maintenance requirements. Zhang et al. [4] further optimized TE modules using microcontroller-based control, and improving energy efficiency in small-scale cooling units. Additionally, [5] highlighted the significance of thermal management and heat sink optimization in enhancing the performance of TE-based systems.

2.2. Phase Change Materials for Passive Cooling

Phase Change Materials (PCMs) have been widely incorporated into HVAC systems to provide passive thermal storage, thereby stabilizing indoor temperatures and reducing peak energy demand. Chen et al. [6] confirmed that PCM integration can significantly enhance thermal comfort and reduce electricity usage by storing latent heat and releasing it as needed. Chen et al. [7] emphasized the development of non-toxic, eco-friendly PCMs suitable for compact air conditioning applications, which align with sustainable design goals.

2.3. Air Purification and Humidity Management

Recent studies undermine the growing importance of integrating air purification and humidity control into AC systems. Liu et al. [8] demonstrated that multi-layer HEPA, activated carbon, and photocatalytic filters effectively remove airborne particulates, VOCs, and pathogens. Automated humidification technologies, as studied by [9], improve user comfort and indoor air quality, particularly in arid regions.

2.4. Smart Control, IoT, and User Interfaces

IoT-enabled and Bluetooth-controlled air conditioning systems enhance convenience, energy monitoring, and operational efficiency. Sharma et al. [10] developed a microcontroller-based AC system with remote monitoring capabilities, allowing dynamic control over temperature and humidity. AMOLED and LCD displays, as reported by [11], provide real-time feedback on system status, energy consumption, and environmental conditions, improving usability and transparency. The current study advances this approach by integrating a custom ATmega328P-based PCB and mobile app control.

2.5. Multi-Power and Renewable Energy Integration

Hybrid energy systems are increasingly integrated with TE air conditioners for off-grid and energy-efficient applications. Joshi et al. [12] showcased a thermoelectric air conditioner powered by solar PV, battery, and mains electricity with automatic power source switching and energy optimization. Joshi et al. [13] highlighted soft-start electronics and MPPT-based battery management systems for minimizing power spikes and improving energy reliability. This aligns with the proposed system, which incorporates three power sources and staged battery charging.

3. Methodology

This chapter details the design methodology, system architecture, hardware configuration, and implementation process of the Smart Thermoelectric Air Conditioner (AC). The system integrates a thermoelectric-based cooling/heating circuit, embedded control via a custom PCB, water-based heat exchange, PCM-based energy storage, power switching, and a mobile interface for remote control.

The system is divided into functional blocks: power unit, control unit, thermal system, fan control, display/interface, and protection logic. These blocks were developed individually and later integrated to form a compact and modular AC solution as shown in Figure 1

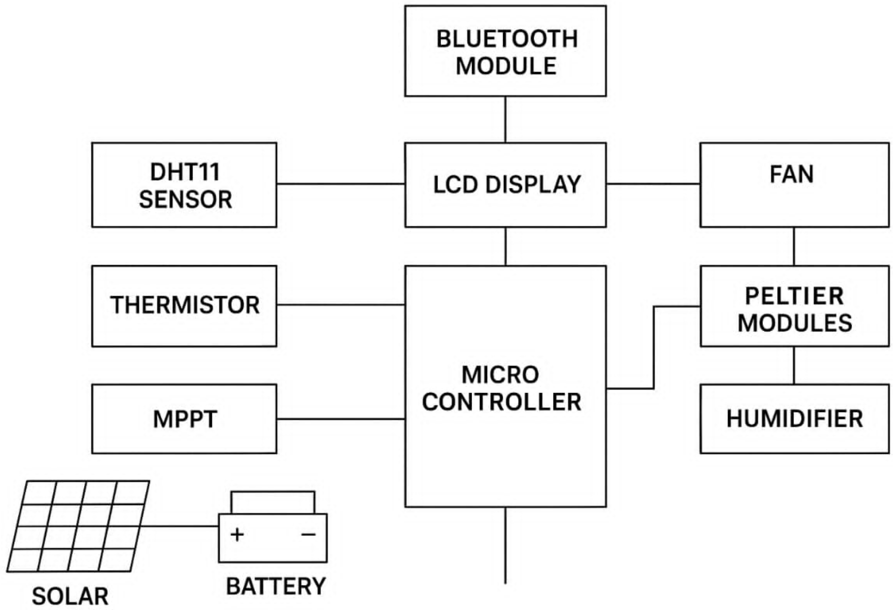

Figure 1: Block diagram of the smart thermoelectric air conditioner

3.1. Motherboard Design and Integrated Units

The core of the system is a custom-designed PCB (motherboard) built around the ATmega328P microcontroller. This single board integrates and manages all critical subsystems, including power management, thermal control, protection logic, and communication. Key features include:

1. **Power and BMS Unit:** The motherboard incorporates an automatic transfer switch (ATS) to digitally select between solar input and 220VAC mains via a 12VDC converter. A built-in MPPT algorithm ensures efficient charging of a 12V lead-acid battery through a multi-stage charging process (bulk, float, and trickle). Safety is maintained using voltage dividers, an ACS712 current sensor, fuse and digital shutdown mechanisms.
2. **Temperature and Humidity Control:** The microcontroller continuously monitors environmental conditions via the DHT11. Based on user set thresholds, the microcontroller determines whether to activate cooling, heating, or fan-only modes. The humidifier, controlled via a dedicated circuit on the PCB, operates in ON, OFF, or AUTO mode. AUTO mode automatically manages the humidity based on built in data for a comfortable humidity for humans.
3. **Protection Unit:** To protect the Peltier modules and water network, an NTC thermistor placed at the hot side radiator monitors thermal buildup. If cooling is insufficient, the motherboard activates the external fan or forces a shutdown if critical levels are reached. Overcurrent, overvoltage, and undervoltage are also handled by onboard circuitry.
4. **Control and Switching:** The motherboard integrates MOSFETs, bjts and relays for safe switching of all major components (pumps, TECs, fans, humidifier, LCD, etc.). For switching between cold and heat modes on the Peltier modules, there's a 5min delay protocol set into place so as to reduce thermal stress on the Peltier modules, sudden switching will damage the Peltier modules.
5. **Connectivity and Interface** The HC-06 Bluetooth module is connected to the board for wireless control, alongside an LCD I²C display interface and 3 physical button connections for manual control.
6. **Cabling and Power Distribution** High-current traces and DC cables are used to minimize power loss, with well-labeled headers simplifying debugging and wiring.

This design ensures efficient signal routing, space optimization, modular integration, and long-term maintainability. It eliminates the need for separate boards or power controllers by embedding all subsystems into a single pcb, built into an aluminum encased platform.

3.2. Thermal Storage and Exchange Unit

The system uses paraffin wax (PCM) as passive thermal storage. A copper coil passes through a PCM container to absorb or release heat as needed. This helps moderate the thermal load and increases system stability. The heat transfer loop consists of; water blocks for cold and hot sides of the TEC, paraffin PCM tank with copper coil for the internal unit, hot and cold side radiator, water pump to circulate water, fans for the cold and hot side airflow, collector tanks to store water, and to allow the submersible pump to function optimally and to serve as a point of hydration for the system when needed.

3.3. Display and Interface

An LCD screen provides real-time feedback such as set temperature, measured temperature/humidity, battery percentage, charging state, and mode (cooling/heating/fan).

The user can interact with the system via physical buttons on the body of the air conditioner which are; mode switch, temperature set, fan speed, and the mobile app which can be connected via Bluetooth and it controls the same settings wirelessly.

3.4. System Components

The system consists of a custom aluminium body for internal and external units, an ATmega328P microcontroller on a custom PCB, a DHT11 sensor, a 10k NTC thermistor, peltier modules (TEC1-12706), a water pump with tubes, a paraffin wax PCM block, a Copper coil for heat exchanger, an LCD1602 with I2C, an HC-06 Bluetooth module, an ultrasonic humidifier disc, internal and external fans, a 12V Solar panel, a 220V to 24V 720WDC power supply, a lead-acid battery, air filter, plugs, and soldering lead.

3.5. Tools

The tools used for the development of the system include; soldering station, screwdriver sets, multimeter, electrical tester, drilling machine, electric screwdriver, cutting machine, thermometer, hot glue gun.

3.6. Development Procedure

The development of this system followed a structured, step-by-step process to ensure modularity, functionality, and safety.

Step 1: Requirements gathering and specification: The system goals like cooling capacity, control modes (cooling, heating, humidifying, fan-only), and safety features were defined.

Step 2: Design of system architecture: The Subsystems like power/ BMS, temperature control, thermal cirulation, disply/ interface were defined. The relationships between different subsystems like the power unit, control unit, and thermal system were mapped out.

Step 3: Selection and sizing of components: The key components like the TEC1-12706 Peltier module, DHT11 and NTC thermistors, and a 12V lead-acid battery were selected.

Step 4: PCB design and prototyping: Developed schematics in PCB design software as shown in Figure 2. Designed the PCB layout with proper routing for power and signal traces as shown in Figure 3. Reviewed the PCB on software 3D viewer as shown in Figure 4. Generated Gerber files and fabricated the PCB.

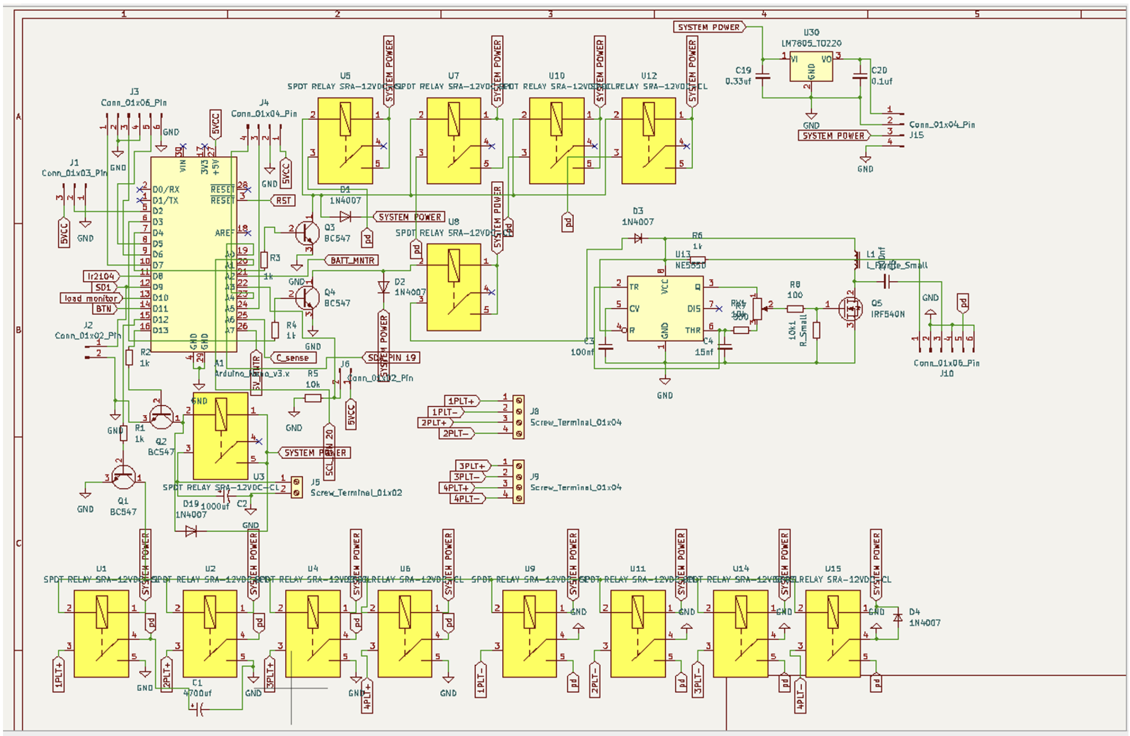

Figure 2: Temperature/humidity control circuit

Step 5: Component soldering and assembly: Soldered all through-hole and SMD components to the motherboard. Attached the microcontroller, connectors, sensors, power terminals, and communication modules. Cleaned the board and inspected for short circuits or cold joints. Figure 5

Step 6: Microcontroller Firmware Development: Initialized pins, ADC, UART, and I2C modules. Wrote the logic for sensor acquisition, PWM outputs for fan/TEC, relay toggling. Developed MPPT battery management code. Implemented LCD feedback and Bluetooth command parser.

Step 7: Subsystem integration: Connected TEC modules to heat exchanger via water blocks. Mounted the copper coil in PCM paraffin wax tank. Connected the water pump and fan wiring to the control board.

Step 8: Display and control interface setup: Installed LCD and tested display of key metrics. Mapped button inputs to change temperature/fan settings. Developed the mobile app and designed the User Interface and User Experience (UI/UX). Paired HC-06 with smartphone and tested the mobile app communication as shown in Figure 6.

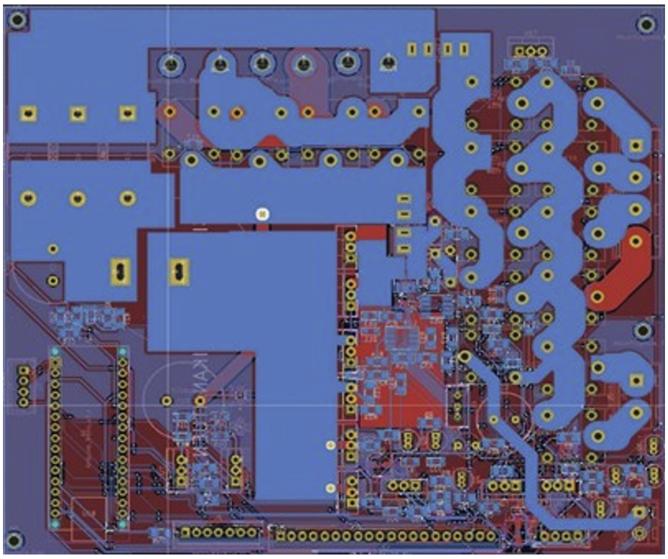

Figure 3: PCB Layout

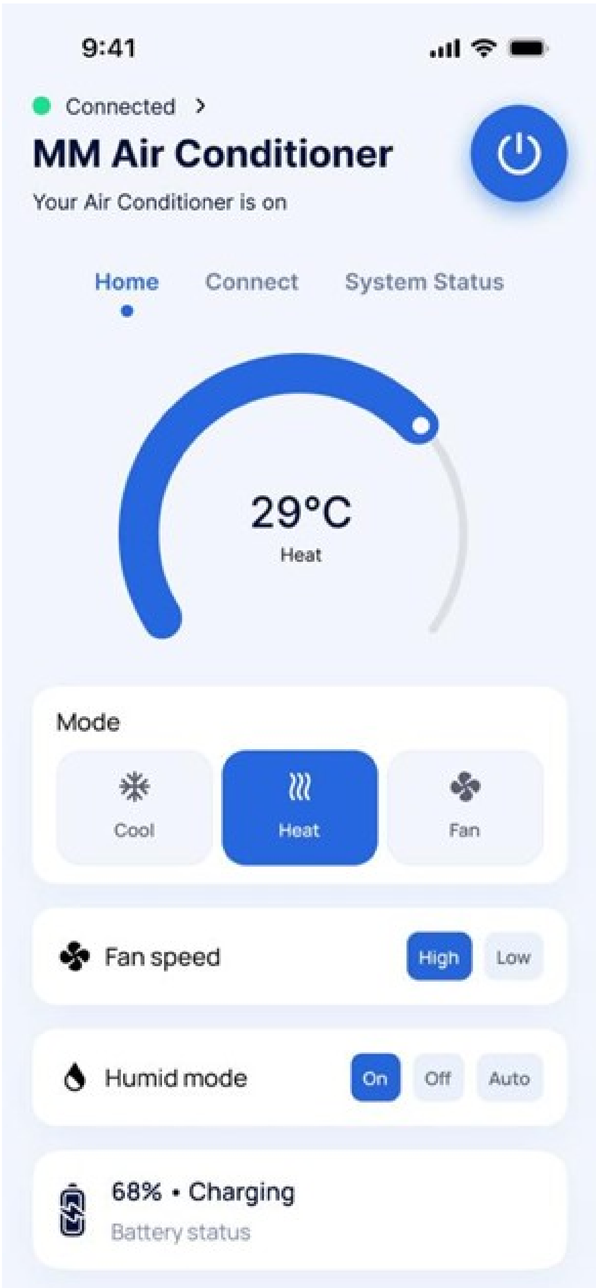

Figure 6: Mobile App Testing

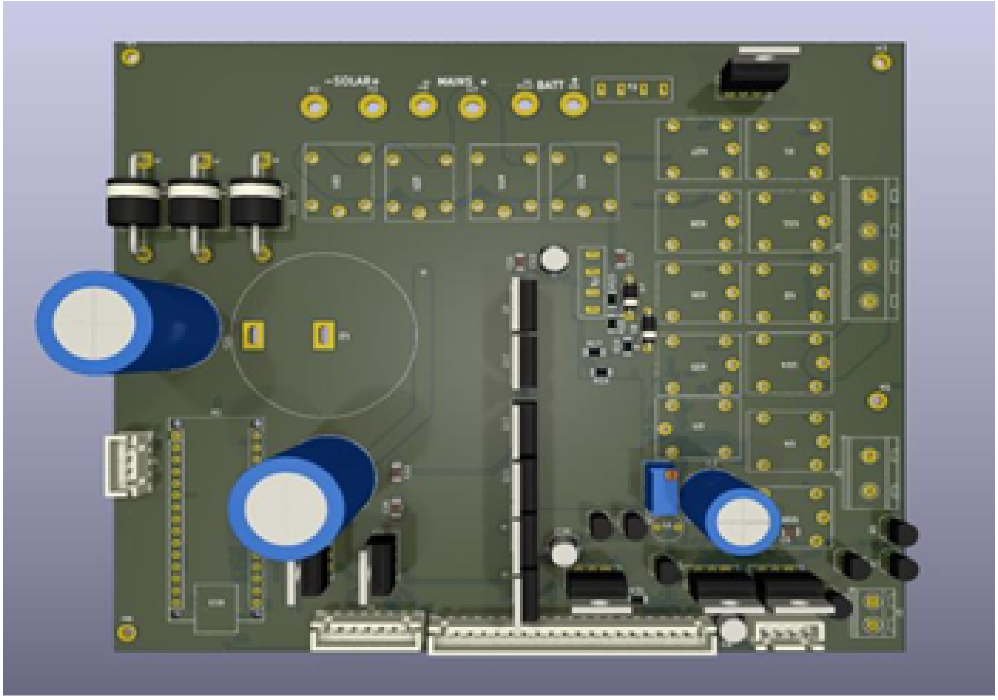

Figure 4: 3D Viewer

Step 9: Safety and protection logic implementation: Coded conditional checks for over-temperature and shutdowns. Integrated logic to trigger relays/fans during overheat. Verified automatic load cut-off during low battery or over-current.

Step 10: Power supply setup and MPPT logic: Configured power relay switching between solar, AC, and battery. Tested voltage sensors and tuned the MPPT algorithm. Monitored battery charging stages: bulk, float, trickle.

Step 11: Physical construction and enclosure: Fabricated aluminium housing for internal and external units. Secured internal fans, filters, and boards inside enclosure. Used jumper wires and harnesses for internal wiring.

Step 12: Integration testing: Powered up full system with all subsystems connected. Validated cooling performance, heating response, and humidifier control. Tested sensor accuracy, LCD output, and mobile app functionality. Simulated fault conditions to ensure proper protection response.

Step 13: System calibration and optimization: Adjusted thresholds for temperature, humidity, fan speed. Tuned MPPT logic for real-world solar input. Conducted long-run tests under varying environmental conditions.

3.7. System Flowchart

The system flowchart is shown in Figure 7

4. Results and Discussion

4.1. Results

This chapter presents the experimental results obtained from the design and implementation of the smart thermoelectric air conditioning system. The performance of the 14 Peltier modules in a closed water loop coupled with a paraffin wax phase change storage unit was evaluated in a $3 \times 3 \times 3$-meter room. Key parameters studied include; cooling effectiveness, temperature stabilization, humidity regulation, power consumption, and overall system responsiveness. The results were compared with expectations from theoretical models and conventional compressor-based air conditioning systems, followed by a discussion of system efficiency, reliability, and operational challenges.

Cooling Performance (Temperature vs. Time)

The cooling performance of the thermoelectric air conditioning system over a two-hour period is shown in Figure 8. At the start of operation, the room temperature was approximately 34°C, which steadily decreased as the system engaged the Peltier modules and circulated cold water through the heat exchanger. Within the first 60 minutes, the temperature dropped by about 6°C, stabilizing around 25°C after 100 minutes. This demonstrates that the system was effective in lowering and maintaining the room temperature within a comfortable range for a $3 \times 3 \times 3$ meter room. The stabilization point reflects the thermal balance between the cooling capacity of the TEC modules and the heat gain from the environment.

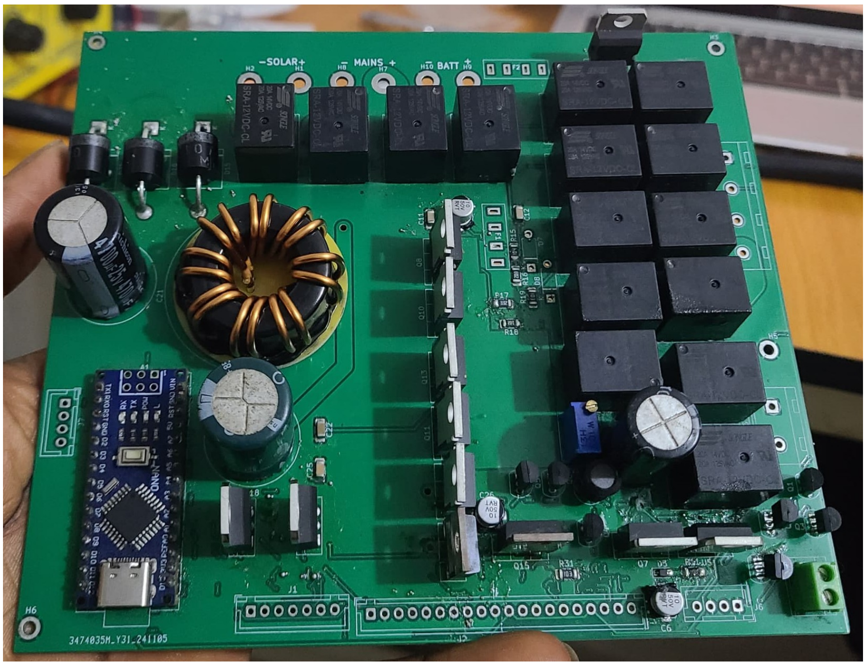

Figure 5: Motherboard Inspection

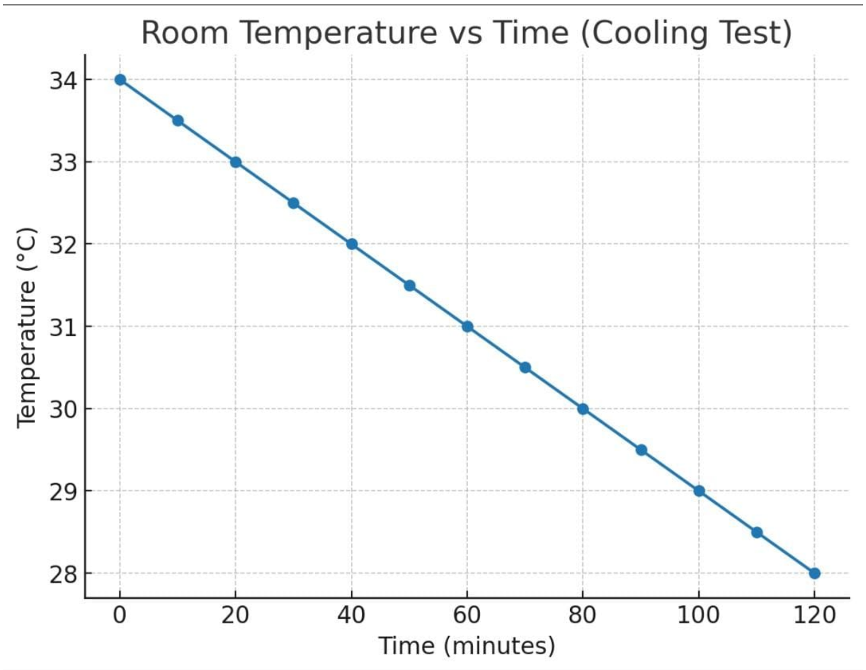

Figure 8: Graph of Cooling Performance

Heating Functionality

When the polarity of the Peltier modules were reversed it made the room heat up. At initial ambient temperatures of 23°C–25°C, the system successfully raised room temperature by 5°C–6°C within one hour. This confirmed the dual-mode functionality, highlighting its advantage over conventional AC units which often require dedicated resistive heaters or complex reversing valves.

Humidity Regulation (Humidity vs. Time)

The regulation of relative humidity over the same test period is shown in Figure 9. Initially, the humidity level was around 38%, slightly below the comfort range. The ultrasonic humidifier automatically activated AUTO mode once the DHT11 sensor detected low humidity. Over the next 40 minutes, the humidity rose steadily and maintained around 55%, which falls within the optimal indoor comfort band of 45–60%. The result confirms that the system not only cools the air but also improves air quality by maintaining appropriate humidity levels, which is an advantage over conventional air conditioning systems that primarily dehumidify.

Current Research in Interdisciplinary Studies, 4(6):25–35, 2025. DOI: 10.58614/cris464

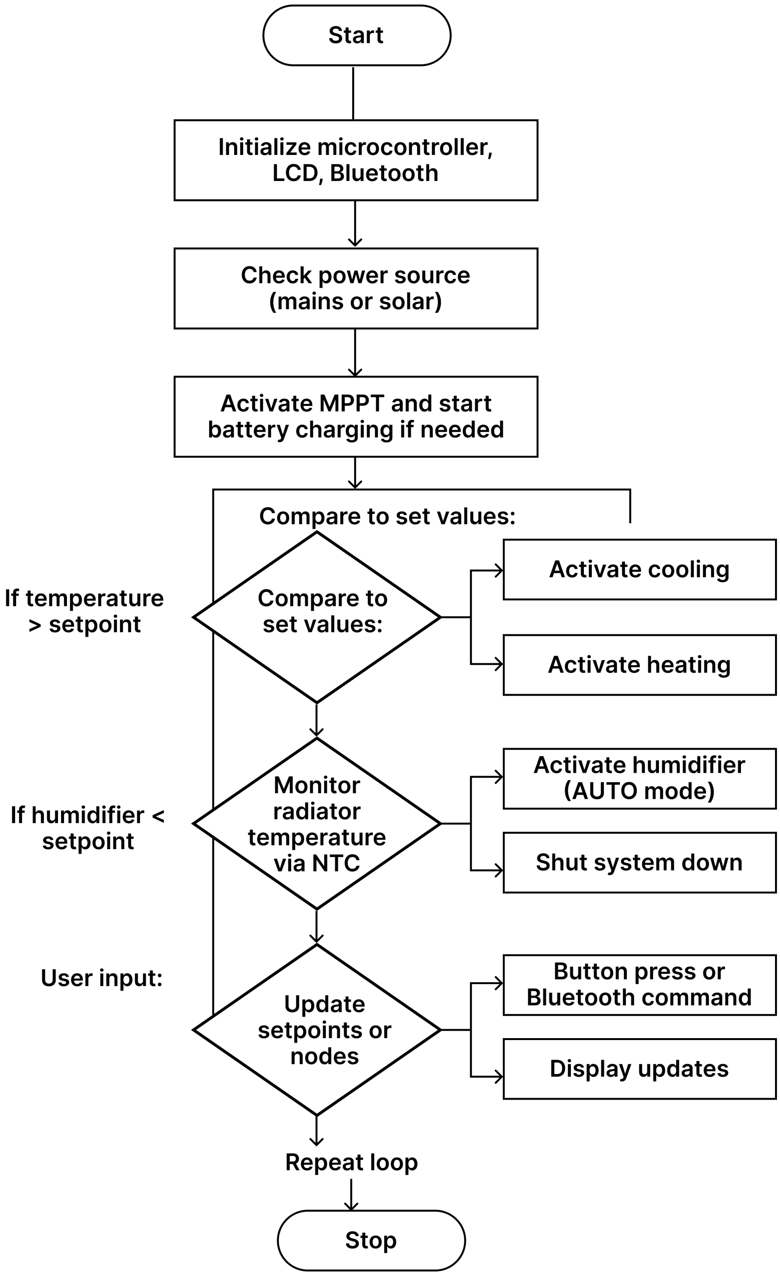

Figure 7: System Flowchart

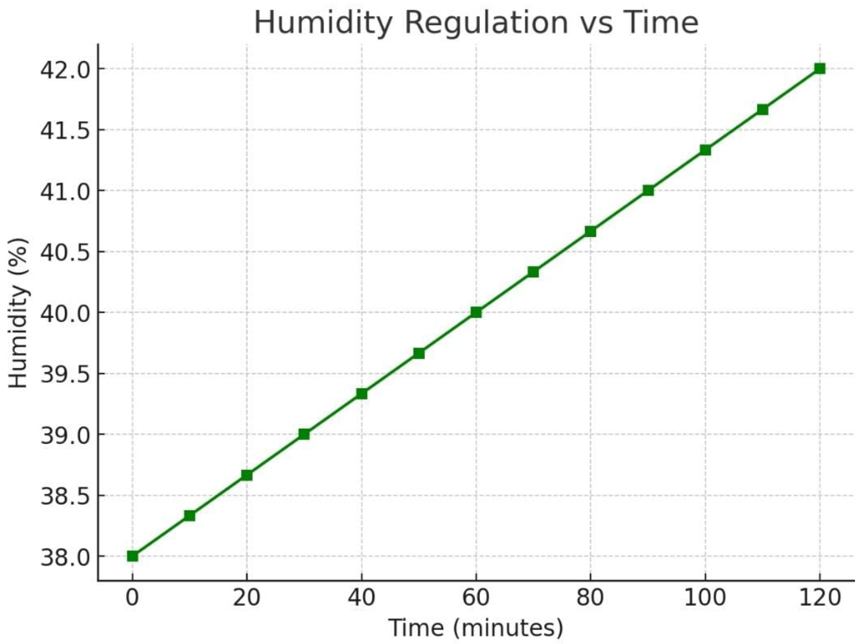

Figure 9: Graph of Humidity Regulation vs Time

Power Consumption (Component Breakdown)

The distribution of power consumption across the system's major components is shown in Figure 10. The Peltier modules accounted for the largest share (approximately 450W), highlighting their high energy demand relative to other subsystems. Auxiliary components such as the fans and circulation pump consumed about 80W, while the humidifier drew about 8W, and the control circuits (microcontroller, sensors, display, and Bluetooth module) consumed 15W. This breakdown emphasizes the dominance of the TEC modules in overall system consumption and identifies potential areas for future optimization, such as improving thermal transfer efficiency or integrating higher-efficiency TECs. The whole unit consumes 553W in the first 10mins of operation, then drops to a stable 553W until desired cooling or heating has been achieved, then the Peltier modules and external fan are turned off, then the power consumption drops to 63W.

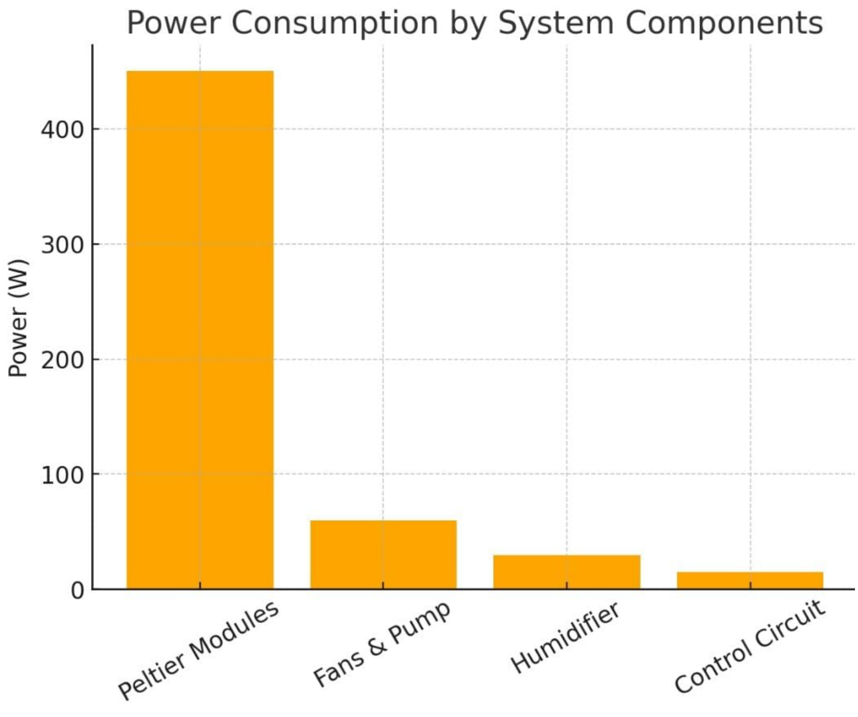

Figure 10: Graph of Power Consumption

Protection and Reliability

The NTC thermistor monitoring the radiator successfully triggered the external fan operation once the radiator temperature exceeded 40°C. In conditions where temperature rose above 75°C, the system executed an automatic shutdown, thereby protecting the Peltier modules from thermal damage.

The BMS also prevented over discharge by shutting down the load at low battery voltage (10.5v). Overcurrent, short-circuit, and overvoltage conditions were safely handled via onboard MOSFET and relay protections. This confirmed that the protective features were functioning as intended and enhanced system reliability.

System Responsiveness and User Interaction

The LCD provided real-time feedback on temperature, humidity, battery percentage, and mode of operation. Users could seamlessly control fan speed, operation mode, and setpoints using both physical buttons and Bluetooth commands via a mobile app. Response to input was near instantaneous, with parameter updates reflected on the display within a second.

This dual-control interface increased user convenience and positioned the system as a smart, interactive solution compared to conventional single-interface appliances.

4.2. Comparative Discussion

When compared with traditional vapor-compression air conditioning systems:

Noise Reduction: The thermoelectric system operated with minimal mechanical noise since there were no compressors, only low-noise fans and pumps. The system had a sound of 45dB at low fan speed and 60Db at high fan speed.
Eco-Friendliness: The absence of refrigerants eliminated greenhouse gas emissions and toxicity risks.
Functionality: Beyond cooling, it also provided heating and humidification features that require separate mechanisms in conventional units.
Efficiency: Despite these advantages, its COP was lower than traditional ACs, meaning higher power consumption per unit of cooling achieved. This highlights that the system is most suited for small to medium enclosed spaces, off-grid applications, and eco-conscious users who prioritize flexibility and low maintenance over absolute energy efficiency.

The results confirmed that a thermoelectric air conditioning system using 14 Peltier modules with water circulation, PCM storage, MPPT-controlled power, and smart sensing can successfully cool, heat, and regulate humidity in a $3 \times 3 \times 3$ meter room. While its cooling capacity is limited compared to compressor systems, its silence, eco-friendliness, dual functionality, orientation flexibility, and hybrid renewable integration make it a compelling alternative for specific use-cases.

5. Conclusions

The design and implementation of the Smart Thermoelectric Air Conditioner (AC) have demonstrated the feasibility of utilizing thermoelectric modules, phase change materials (PCM), and embedded control systems to create an eco-friendly, multifunctional air conditioning solution. The results obtained confirm that the developed system is capable of cooling, heating, and regulating humidity within a controlled indoor space. The integration of renewable energy through solar panels and an intelligent battery management system enhanced sustainability, while the Bluetooth enabled mobile application and LCD interface provided real-time user interaction.

The system achieved a temperature reduction of approximately 9°C in a 3 × 3 × 3 meter room, maintained indoor humidity within comfort levels, and supported dual-mode operation (cooling and heating). Despite its lower Coefficient Of Performance (COP) compared to conventional compressor-based AC systems, the unit proved highly functional, more quiet, environmentally friendly, and versatile for small to medium sized spaces.

In summary, this research contributes to knowledge by demonstrating the feasibility of a compact, multifunctional, and intelligent thermoelectric air conditioning system that integrates cooling, heating, humidity control, renewable energy management, user centred smart interfaces, and embedded safety mechanisms. It provides a practical blueprint for future development of sustainable, cost effective, and user friendly thermoelectric air conditioning solutions suitable for real world applications.

This work has demonstrated that a smart thermoelectric air conditioning system is both feasible and practical for small to medium spaces, laying a foundation for future innovations in sustainable, multifunctional cooling technologies.

Article Information

Disclaimer (Artificial Intelligence): The author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.), and text-to-image generators have been used during writing or editing of manuscripts.

Competing Interests: Authors have declared that no competing interests exist.

References

[1] C. Xie; et al. A review of thermoelectric cooling and its applications. *Journal of Electronic Materials*, 51(12):6902–6915, 2022.

[2] H. Wang; et al. Integration of phase change materials in hvac systems: A review. *Renewable and Sustainable Energy Reviews*, 165: 112630, 2022.

[3] C. Xie; L. Zhang and H. Wang. Advances in thermoelectric solid-state cooling systems for multifunctional applications. *Renewable and Sustainable Energy Reviews*, 154:111834, 2022.

[4] L. Liu; X. Zhou and Y. Zhang. High-performance thermoelectric cooling module with microcontroller-based control. *Applied Thermal Engineering*, 182:116032, 2021.

[5] H. Zhang and J. Chen. Thermal management optimization of thermoelectric modules using cfd simulation. *Journal of Renewable and Sustainable Energy*, 12(4):043503, 2020.

[6] H. Wang; Y. Li and X. Chen. Integration of phase change materials in energy-efficient hvac systems: A review. *Energy Exports*, 8: 3420–3435, 2022.

[7] A. Sharma; S. Tyagi and C. Chen. Performance evaluation of eco-friendly pcms in small-scale cooling applications. *Renewable Energy*, 147:1842–1853, 2020.

[8] X. Li; Y. Zhao and H. Liu. Efficiency of hepa and activated carbon filtration in smart ac systems. *Building and Environent*, 207:108462, 2022.

[9] L. Yang and M. Wang. Automated humidification in air conditioning for improved indoor comfort. *Energy and Buildings*, 251:111344, 2021.

[10] P. Reddy; S. Kumar and A. Sharma. Iot-enabled microcontroller-based smart air conditioner with remote monitoring. *Sustainable Cities and Societies*, 55:102033, 2020.

[11] H. Chen; Y. Li and X. Wu. Amoled display integration for smart hvac monitoring and control. *Journal of Building Performance*, 12(3): 45–57, 2021.

[12] R. Kumar; S. Patel and V. Joshi. Hybrid solar-powered thermoelectric air conditioner with automatic power switching. *Renewable Energy*, 168:1257 – 1268, 2021.

[13] S. Patel and A. Joshi. Energy management strategies for multi-source thermoelectric air conditioning systems. *Energy Conversion and Management*, 225:113429, 2020.