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SunCool: Solar Powered Thermoelectric Mini Cooling System for Vaccine Preservation

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Abstract - *With the growing worldwide demand for dependable cold-chain solutions in medical and vaccine storage, energy usage has surged significantly. To address this challenge, the Sun-Cool Smart Solar Powered Thermoelectric Mini Cooling System was designed and developed. The system combines photovoltaic solar energy harvesting with Peltier module-based thermoelectric cooling, utilizing a microcontroller alongside a temperature sensor to precisely regulate the internal temperature within the critical 2°C – 8°C range essential for vaccine integrity. A 12V lead-acid battery, continuously charged via solar panels, serves as the primary power source, while an LCD screen and buzzer provide real-time status updates and threshold alerts. Experimental results confirm that the prototype reliably sustains the target temperature range with minimal upkeep. Its compact design, affordability, and environmentally conscious operation position it as a practical solution for remote healthcare settings and emergency relief operations.*

Key Words: Solar Cooling System, Thermoelectric Cooling, Peltier Effect, Vaccine Preservation, Renewable Energy, Smart Healthcare

1. INTRODUCTION

As the world continues to evolve technologically, the need for dependable cooling solutions has become increasingly critical across domains including medicine, food preservation, and electronics. Yet, the escalating demand for refrigeration brings with it a significant rise in energy consumption and a reliance on chemical refrigerants that are harmful to the climate and the ozone layer. This highlights an urgent requirement for sustainable, energy-efficient alternatives capable of functioning independently from conventional power infrastructure.

Among the sectors most dependent on consistent refrigeration is immunization. Vaccines require strict temperature control generally within a 2°C to 8°C window to retain their efficacy and therapeutic value. In rural and geographically isolated communities where power supply is inconsistent or entirely absent, sustaining this cold chain presents a formidable challenge. Power outages and inadequate storage infrastructure frequently lead to vaccine degradation, significant wastage, and declining immunization rates.

Conventional refrigeration systems depend heavily on uninterrupted electricity and compressor-driven mechanisms, rendering them impractical for off-grid deployment. Such systems tend to be cumbersome, costly, and demand frequent servicing. Consequently, there exists a clear and growing demand for a lightweight, affordable, and energy-conscious cooling alternative capable of ensuring dependable vaccine storage under these conditions.

Recent progress in both renewable energy and thermoelectric technology has paved the way for innovative cooling solutions. Thermoelectric cooling, which operates on the principle of the Peltier effect, presents a compact, silent, and refrigerant-free approach to temperature regulation. Furthermore, microcontroller-integrated systems enable accurate real-time temperature monitoring and automated operational control, greatly improving overall reliability and system performance.

Driven by these technological advancements, this project introduces SunCool: Solar Powered Thermoelectric Mini Cooling System. The system harnesses solar energy to drive a thermoelectric cooling unit, enabling efficient and environmentally responsible operation. Engineered to be portable, lightweight, and low-maintenance, SunCool is particularly well-suited for rural health centers, mobile vaccination campaigns, and disaster response situations. A built-in microcontroller ensures continuous temperature oversight and dynamic control.

Through the convergence of renewable energy and intelligent automation, SunCool advances both public health goals and environmental responsibility. It guarantees safe vaccine storage while diminishing reliance on traditional energy sources contributing meaningfully to the creation of accessible, affordable, and sustainable healthcare infrastructure.

2. LITERATURE SURVEY

Adedeji et al. [1] developed a solar-powered refrigerator using solar energy as the primary power source for refrigeration. Their work demonstrated the feasibility of integrating solar power with refrigeration systems and highlighted the benefits of compact and relatively low-cost solar-powered cooling for applications where conventional electricity may be limited.

Roopa et al. [2] investigated medicine refrigeration for rural and flood-affected areas using a solar-based dual-mode battery charging approach. The study emphasized the importance of maintaining refrigeration during situations where grid electricity is unreliable, making solar generation and battery-supported operation valuable for healthcare applications.

Field et al. [3] presented a photovoltaic/thermoelectric refrigerator specifically intended for medicine storage in developing countries. The proposed system used direct-current thermoelectric cooling together with photovoltaic power and battery storage, demonstrating the suitability of this combination for portable medical refrigeration in locations without reliable electricity.

Dhawde et al. [4] reviewed portable solar thermoelectric refrigerator and air-cooling technologies. Their work examined solar thermoelectric cooling as a comparatively low-cost and environmentally friendly alternative to conventional cooling systems and highlighted its potential for portable applications.

Awasthi et al. [5] investigated the design and development of a thermoelectric refrigerator based on the Peltier effect. The study contributes to the understanding of thermoelectric refrigeration as a compact cooling technology and demonstrates its potential as an alternative to conventional refrigeration for small-scale applications.

Raj et al. [6] studied the design and fabrication of a solar-powered thermoelectric refrigerator. Their work combined solar energy with thermoelectric cooling, demonstrating the potential of renewable energy to operate compact refrigeration systems while reducing dependence on conventional electrical power.

Venkatesh et al. [7] experimentally investigated a solar-powered thermoelectric refrigerator. The study focused on the practical performance of thermoelectric cooling when powered using solar energy and contributed to the development of renewable-energy-based refrigeration systems.

Patel et al. [8] presented a solar-based thermoelectric refrigerator, examining the use of solar energy for operating a thermoelectric cooling system. The work supports the use of Peltier-based refrigeration for applications requiring compact and renewable-energy-powered cooling.

Singh et al. [9] investigated the performance of a thermoelectric cooling system for vaccine storage. The study is particularly relevant to medical cold-chain applications because maintaining an appropriate and stable temperature is essential for preserving vaccines and other temperature-sensitive medical materials.

Kumar et al. [10] examined optimization of a thermoelectric cooler using solar power for medical cold storage. Their work highlights the importance of improving the energy utilization and cooling performance of thermoelectric systems when they are used for healthcare-related storage applications.

Sharma et al. [11] studied a portable solar thermoelectric refrigerator. The work demonstrates the potential of combining portability, solar energy, and thermoelectric cooling to develop refrigeration systems suitable for locations where conventional power infrastructure is limited.

Ali et al. [12] developed a solar thermoelectric refrigerator for vaccine storage. Their work demonstrates the application of solar-powered thermoelectric technology to medical refrigeration and emphasizes the need for reliable cooling for vaccine preservation.

Patel et al. [13] investigated the design and testing of a thermoelectric cooler using a Peltier module. The study contributes to understanding the practical operation and performance of Peltier-based cooling systems and supports their application in compact refrigeration systems.

Sharma et al. [14] evaluated the performance of a Peltier-based cooling system powered by solar energy. Their work further demonstrates the feasibility of using renewable solar power with thermoelectric cooling and emphasizes performance evaluation for practical cooling applications.

Mehta et al. [15] investigated a thermoelectric solar refrigerator intended for rural health centers. The study is relevant to the development of refrigeration systems for healthcare facilities in rural areas, where dependable electrical infrastructure may not always be available.

Gupta et al. [16] studied the design and simulation of a smart portable solar refrigerator incorporating IoT monitoring. This work is particularly relevant to intelligent refrigeration because IoT-based monitoring can provide continuous information about system operating conditions and temperature, improving the ability to monitor temperature-sensitive storage.

Patel et al. [17] investigated a solar-powered thermoelectric vaccine storage system. The work combines renewable energy, thermoelectric cooling, and vaccine storage, reinforcing the suitability of solar-powered refrigeration for maintaining cold-chain requirements in locations with limited electricity access.

Singh et al. [18] evaluated a portable solar-based thermoelectric cooling system. The study further supports the use of solar energy and thermoelectric technology for portable cooling applications and demonstrates the continuing development of compact renewable-energy-based refrigeration systems.

Based on the reviewed studies, solar-powered and thermoelectric refrigeration technologies provide a promising approach for portable and off-grid cooling. However, the existing literature also indicates the need for reliable temperature control, battery-supported operation, thermal management, and continuous monitoring when such systems are intended for medical and vaccine storage. Therefore, the proposed SunCool system combines solar charging, battery backup, thermoelectric cooling, temperature sensing, microcontroller-based control, LCD monitoring, and IoT-based remote monitoring to provide a compact cooling solution for rural and off-grid healthcare applications.

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3. OBJECTIVE

The primary goal of the "SunCool: Solar Powered Thermoelectric Mini Cooling System" project is to engineer a dependable, portable, and environmentally conscious solution for vaccine preservation in rural and off-grid communities where access to stable electricity remains limited. The system is designed to consistently sustain the critical temperature range of 2°C to 8°C through thermoelectric cooling leveraging the Peltier effect, entirely eliminating the reliance on traditional refrigeration equipment and environmentally damaging refrigerants.

A microcontroller-based control unit is embedded within the system to facilitate continuous real-time temperature monitoring and precise regulation. To guarantee uninterrupted operation regardless of grid availability, the system is equipped with a solar power harvesting mechanism supported by a dedicated battery backup. Furthermore, the project places strong emphasis on delivering a cost-efficient, minimal-maintenance, and user-friendly cooling solution tailored for a range of healthcare scenarios including mobile vaccination campaigns, rural medical facilities, and emergency disaster relief operations. In doing so, it aims to strengthen cold chain integrity and significantly reduce vaccine spoilage and wastage.

4. BLOCK DIAGRAM

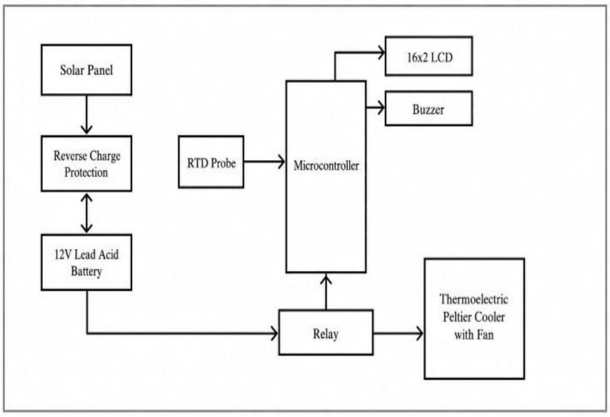

Fig. 1: Block diagram

5. PROPOSED SYSTEM

Hardware Components

ESP32 Microcontroller:

The ESP32 serves as the brain of the entire system. It continuously reads input data from the temperature sensor, processes it, and sends control signals to the relay module to manage the cooling operation. It also oversees the LCD display output and coordinates overall system functionality.

Solar Panel:

The solar panel functions as the primary energy source, converting incoming solar radiation into usable electrical energy. This generated power is directed toward charging the battery and running the system, enabling fully eco-friendly and grid-independent operation.

Lead-Acid Battery:

The battery acts as the energy reservoir, storing power captured by the solar panel. It delivers a consistent and stable power supply to the system during periods of reduced sunlight or nighttime, ensuring that cooling remains uninterrupted at all times.

Peltier Module (Thermoelectric Cooler):

The Peltier module constitutes the primary cooling element of the system. Functioning on the principle of the thermoelectric (Peltier) effect, it generates a thermal gradient across its two surfaces the cold side of which is utilized to actively lower the temperature within the storage chamber.

RTD Temperature Sensor:

The RTD temperature sensor is tasked with continuously measuring the internal temperature of the cooling chamber. The collected readings are transmitted to the ESP32, enabling precise and responsive temperature regulation throughout system operation.

Relay Module:

The relay functions as an electronically controlled switch, operating under direct command from the ESP32. It governs the activation and deactivation of both the Peltier module and the cooling fan in response to real-time temperature conditions.

Cooling Fan and Heat Sink:

The cooling fan and heat sink work in tandem to expel thermal energy from the hot side of the Peltier module. This thermal management mechanism enhances the overall cooling efficiency and ensures stable, sustained performance of the thermoelectric unit.

LCD Display:

The LCD display presents real-time system data including internal temperature readings, battery charge status, and operational state offering users a straightforward and accessible means of monitoring the system at a glance.

Buzzer:

The buzzer serves as an audible alert mechanism, triggered whenever abnormal temperature fluctuations or system irregularities are detected. This feature ensures user awareness and enables prompt corrective action when needed.

6. FLOW OF THE SYSTEM

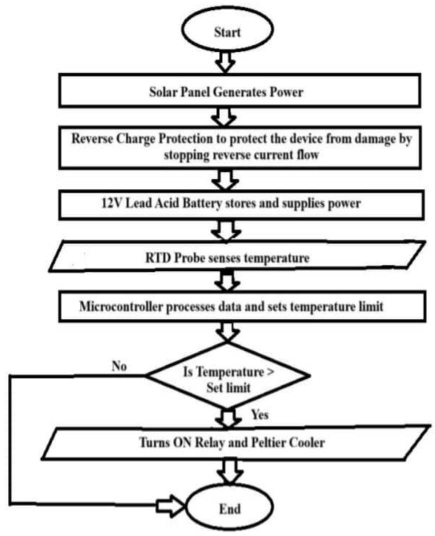

Fig 2: Flow Chart

7. RESULTS AND DISCUSSION

The SunCool Solar Powered Thermoelectric Mini Cooling System integrates a range of carefully selected components, including an ESP32 microcontroller, a TEC1-12726 Peltier module, an RTD temperature sensor, an LCD display, a relay module, a DC cooling fan, a solar panel, a lead-acid battery, and a thermally insulated cooling chamber. The system is engineered to deliver portable, sustainable, and grid-independent refrigeration tailored for medical and vaccine storage needs in rural and remote environments. The figures presented below illustrate the outcomes recorded during system implementation and experimental testing.

1. Prototype Hardware Setup

As depicted in Figure 3, the fully assembled hardware prototype of the SunCool system was successfully fabricated and subjected to comprehensive testing. The setup comprises the thermally insulated cooling chamber, thermoelectric cooling module, solar panel assembly, LCD display unit, and an IoT-based monitoring interface linked to a laptop for continuous real-time observation and performance evaluation.

Fig 3: Complete Hardware Prototype of SunCool System

2. Thermoelectric Cooling Unit

As illustrated in Figure 4 below, the TEC1-12726 Peltier module was successfully assembled together with an aluminium heat sink and a DC cooling fan to deliver effective thermal dissipation and reliable cooling performance. The cooling fan operates continuously to draw heat away from the hot side of the Peltier module, thereby sustaining stable and consistent cooling conditions within the storage chamber.

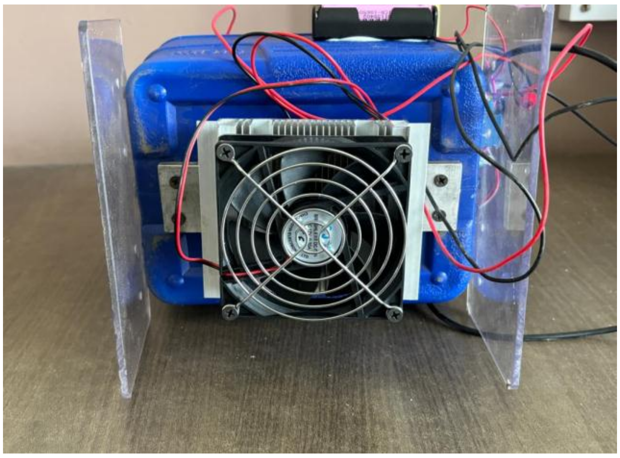

Fig 4: Thermoelectric Cooling and Heat Sink Arrangement

3. LCD Temperature Monitoring System

As depicted in Figure 5 below, the LCD display provided continuous real-time readouts of both temperature and voltage levels throughout system operation. The ESP32 microcontroller successfully established communication with the temperature sensor and the display module, enabling intelligent and automated system monitoring at all times.

Fig 5: Real-Time Temperature and Voltage Monitoring

4. Solar Power Integration

As illustrated in Figure 6 below, the solar panels delivered a continuous supply of renewable energy to the cooling system while simultaneously charging the battery backup. This solar-driven mode of operation significantly reduced reliance on conventional grid electricity, facilitating fully independent off-grid refrigeration.

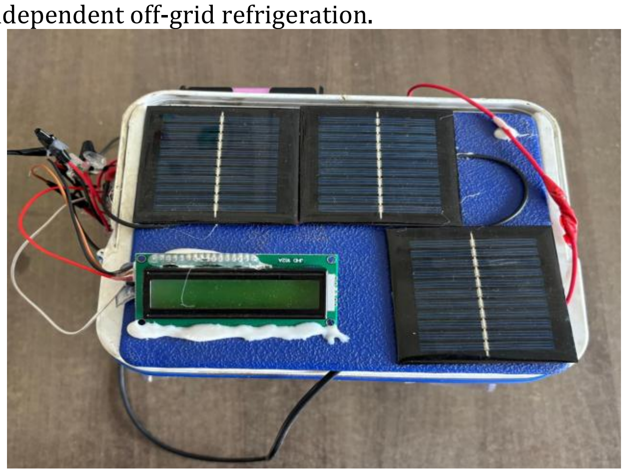

Fig 6: Solar Panel Power Supply Setup

5. Cooling Chamber Internal Arrangement

As depicted in Figure 7 below, the internal arrangement of the cooling chamber incorporates the cold side of the Peltier module along with a temperature sensing probe, both positioned within the thermally insulated enclosure. This configuration successfully sustained a sufficiently low internal temperature, making it well-suited for the storage of medical supplies and vaccines.

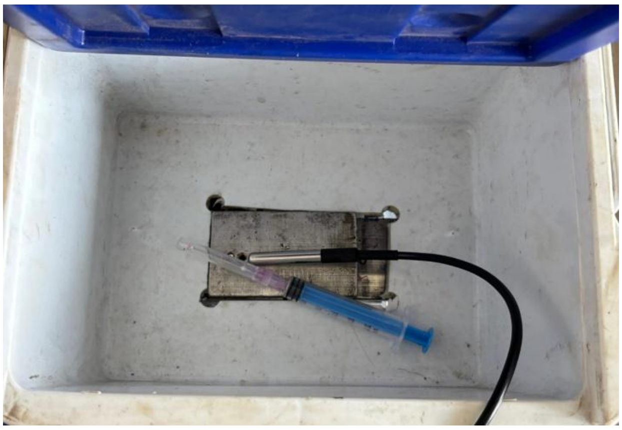

Fig 7: Internal Cooling Chamber Setup

6. IoT Cloud Monitoring System

As illustrated in Figure 8 below, the developed system successfully transmitted live temperature and voltage data to the ThingSpeak cloud platform via IoT connectivity. The graphical monitoring dashboard facilitated continuous remote observation of the system's cooling performance and overall operational status in real time.

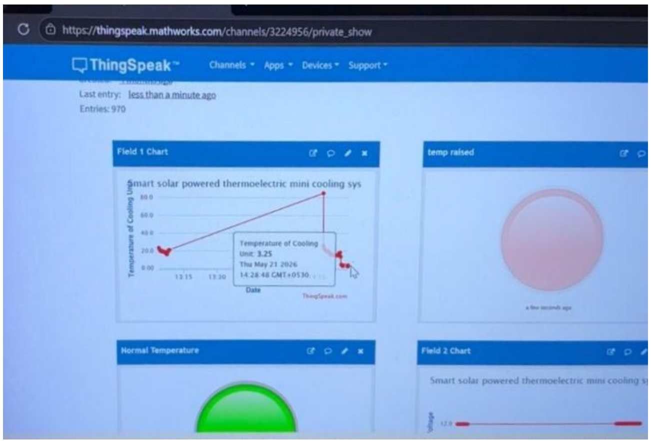

Fig 8: IoT-Based Thing-Speak Monitoring Dashboard

8. CONCLUSION

The SunCool: Solar Powered Thermoelectric Mini Cooling System represents a forward-thinking and environmentally responsible approach to vaccine preservation, particularly in rural and remote communities where reliable electricity access remains a persistent challenge. By harnessing solar energy in conjunction with thermoelectric cooling technology, the system delivers consistent and precise temperature control without any dependence on harmful chemical refrigerants. Its clean, silent, and virtually maintenance-free operation makes it exceptionally well-suited for healthcare deployments in underserved and resource-limited settings.

The incorporation of intelligent control capabilities further strengthens the system's dependability and operational efficiency, ensuring that stored vaccines retain their safety and potency throughout the storage period. This project demonstrates the transformative potential of combining renewable energy with contemporary technology to address pressing real-world healthcare challenges. It sets the foundation for future innovations in sustainable medical devices, contributing to global aspirations for environmentally conscious development and broader healthcare accessibility.

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