Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 3, Issue 4, 2025

INNOVATIVE DESIGN AND DEVELOPMENT OF A SMART SOLAR-POWERED THERMOELECTRIC MEDICAL BOX FOR EMERGENCY AND REMOTE HEALTHCARE

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DOI: https://doi.org/10.5281/zenodo.15294366

Keywords
Solar-Powered, Thermoelectric Cooling, Peltier Effect, Remote Healthcare, Temperature-Sensitive Supplies, Off-Grid Applications, Sustainable Energy.

Article History
Received on 11 March 2025
Accepted on 11 April 2025
Published on 28 April 2025

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Abstract
The storage and transportation of medical supplies, particularly in remote or emergency situations, present significant challenges, especially when electricity is limited or unavailable. This paper presents the design and development of a smart, solar-powered thermoelectric medical box that addresses these challenges. The box utilizes the Peltier effect for thermoelectric cooling, ensuring that medications and other temperature-sensitive supplies remain safe from heat and direct sunlight without the need for harmful refrigerants or conventional refrigeration systems. The system is powered entirely by solar energy, making it ideal for use in off-grid areas and regions where electricity access is unreliable. It features an efficient energy management system that allows the box to operate for up to 10 days on a single charge from its integrated solar panel and battery bank, making it suitable for long-term deployment in disaster zones, war zones, or remote healthcare settings. In addition to its cooling capabilities, the box is designed to be compact, rugged, and easy to transport, ensuring that it can withstand harsh environmental conditions, such as extreme heat, humidity, or rough terrain. The project aims to provide a sustainable and reliable solution for emergency medical storage and delivery, ultimately improving healthcare access in challenging environments. This design is particularly significant in areas where reliable refrigeration is

unavailable, offering a practical tool to support global health initiatives.

INTRODUCTION

Access to reliable refrigeration for medical supplies is a fundamental requirement of modern healthcare infrastructure. Temperature-sensitive materials such as vaccines, insulin, blood products, and various biologics must be stored within strict thermal thresholds to maintain their efficacy. However, in many parts of the world particularly remote, disaster-stricken, or conflict-affected areas access to stable electricity remains limited or entirely unavailable. This lack of infrastructure poses a critical challenge to the storage, transportation, and distribution of essential medical supplies, often resulting in product degradation, increased medical waste, and reduced treatment outcomes. The World Health Organization (WHO) estimates that nearly 50% of vaccines are wasted globally each year, primarily due to cold chain failures caused by inadequate storage and transportation [1]. In such scenarios, traditional refrigeration systems while effective in urban settings prove impractical in off-grid locations due to their dependence on continuous electricity supply, bulky designs, and reliance on environmentally harmful refrigerants. Fuel-powered alternatives, though more mobile, come with drawbacks such as high operational costs, frequent maintenance, and logistical complications associated with fuel transport, especially in inaccessible regions [2].

As global health efforts increasingly focus on reaching underserved populations and responding rapidly to emergencies, the need for mobile, sustainable, and robust cold chain solutions has become more urgent. In this context, thermoelectric cooling based on the Peltier effect has emerged as a viable alternative. Thermoelectric modules offer solid-state cooling with no moving parts, minimal maintenance, and a compact form factor. These features make them ideal for portable and rugged healthcare applications. Nevertheless, their relatively low energy efficiency necessitates intelligent energy management systems to ensure extended and autonomous operation in the field. To power these systems sustainably, researchers have increasingly explored solar photovoltaic (PV) technology, which offers a clean, renewable, and widely accessible energy source [3]. Initiatives like Solar Chill have demonstrated the practicality of solar-powered vaccine refrigerators in remote clinics, significantly reducing spoilage and improving immunization outcomes. However, most existing solar-powered systems still rely on traditional compressor-based cooling, which limits their portability, increases complexity, and makes them less suitable for rapid deployment in harsh environments [4]. In parallel, advances in embedded systems and IoT technologies have enabled the development of smart medical devices equipped with real-time temperature monitoring, adaptive energy control, and remote diagnostic capabilities. The integration of microcontrollers, sensors, and intelligent power management can enhance system reliability, prolong operational autonomy, and allow for responsive, condition-based management features that are especially critical during disaster relief operations and in areas with fluctuating environmental conditions. Despite these technological advancements, a significant gap remains in the availability of compact, solar-powered, thermoelectric medical boxes specifically tailored for emergency and remote healthcare deployment [5]. Many current solutions either lack the necessary portability and durability or fail to operate reliably without continuous human intervention or fuel-based power sources.

This research addresses these challenges through the design and development of a smart solar-powered thermoelectric medical box that unites the strengths of solid-state cooling, renewable energy harvesting, and intelligent embedded control into a single, ruggedized, and highly portable solution. Capable of operating autonomously for up to 10 days on a single solar charge, the proposed device is engineered for extreme reliability and ease of transport. It is optimized for use in disaster zones, rural clinics, and mobile health units operating in austere environments. By contributing a sustainable and scalable model for cold chain management, this work aims to support global healthcare equity and resilience in the face of ongoing climate, health, and humanitarian challenges.

1- Research Objective:

The primary objective of this research is to design and develop an innovative, smart, solar-powered thermoelectric medical box capable of safely storing temperature-sensitive medical supplies in remote and emergency healthcare settings. This project aims to bridge the gap in cold-chain logistics where conventional refrigeration is not feasible due to limited or unreliable electricity access. The specific objectives include:

1. To design and implement a thermoelectric cooling system using the Peltier effect that maintains a stable internal temperature suitable for the storage of essential medical supplies without the use of chemical refrigerants.
2. To integrate a renewable energy source, specifically a solar-powered system with an efficient energy storage unit, capable of powering the device autonomously for up to 10 days.
3. To develop a smart monitoring and control system that allows real-time tracking of internal temperature, battery status, and overall system performance for improved reliability and usability.
4. To ensure the device is portable, durable, and environmentally resilient, making it suitable for use in harsh conditions such as high humidity, extreme heat, and rugged terrain.
5. To validate the system's effectiveness through prototype testing and performance evaluation under simulated field conditions.

By achieving these objectives, the project contributes to enhancing healthcare accessibility, particularly in disaster-prone, conflict-affected, or geographically isolated regions, while promoting the use of clean energy technologies in medical infrastructure.

2- Refrigiration:

3.1- Thermo-Electric Effect:

The Thermo-Electric effect is the uninterrupted switch of Temp. Difference to Electric Voltage & vice versa by means of Thermo-Couple [6]. A thermo-electric device generates voltage when there is a dissimilar temperature on each side. On the other hand, when a source of voltage is connected to it, it builds a temperature difference. This phenomena/effect can be used to produce electricity, calculate temperature or cool down the temperature of objects. As the path of heating and cooling is caused by the polarity of the applied voltage, thermoelectric devices can also be used as temperature controllers. Figure 1 shows the Thermoelectric Effect.

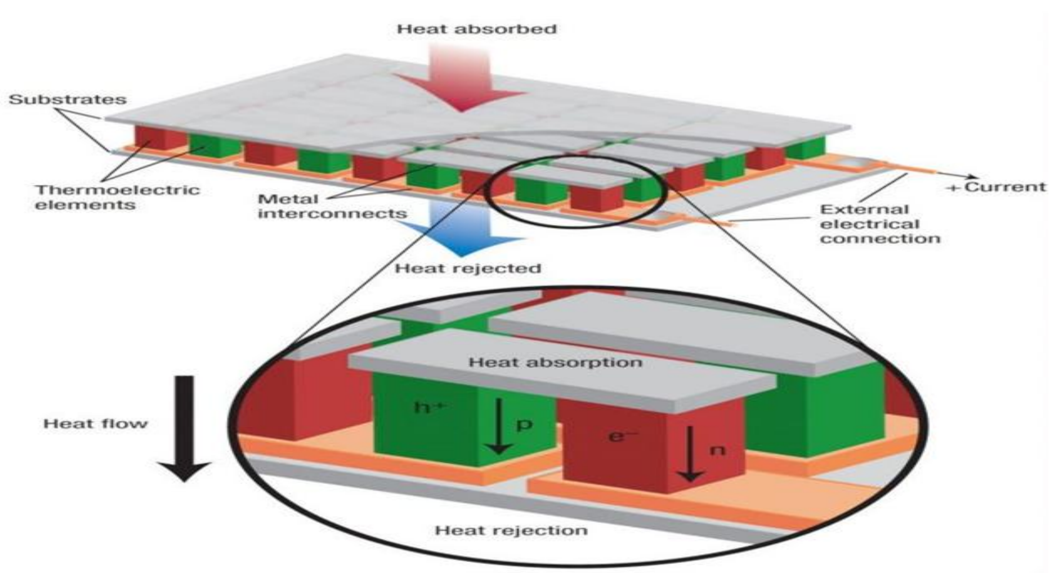

Figure 1: Thermoelectric Effect [7].

Our Portable Medical Box which consist of a Thermo-Electric Cooler works on the principal of Peltier Effect. This Effect produces the temperature difference on the both sides of the thermoelectric module. In 1821-23 Thomas Johann See-beck made a circuit from 2 different metals, with intersections at different temperatures would repel a compass magnet [8]. See-beck at 1st thought this was due to magnetism made by the temperature difference and considered it is linked to the Earth's magnetic field [9]. On the other hand, it was promptly realized that a "Thermoelectric Force" made an electrical current, which according to the Ampree's law opposes the magnet. Even more expressly, the temperature variance produces and voltage which can force an electric current in a closed circuit. Today, this effect is known as the See-beck effect. Figure 2 shows the See Beck effect.

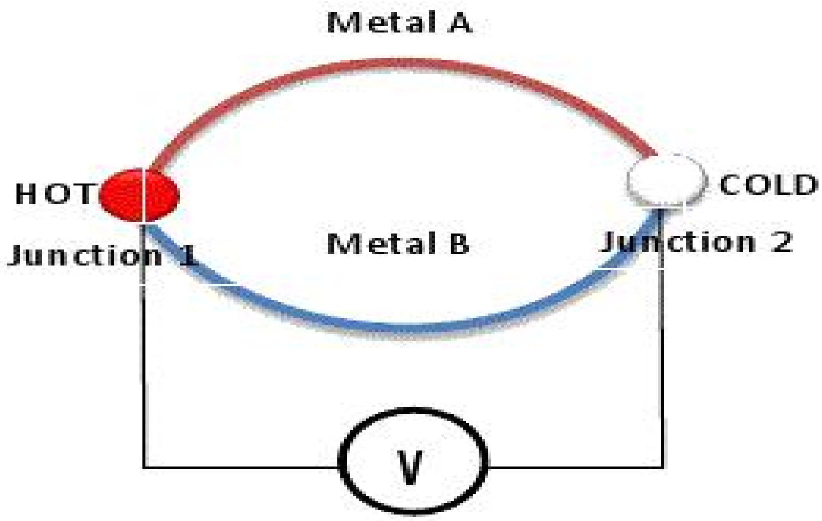

Figure 2: See-beck Effect [10].

3.2- Peltier Effect:

In 1834, a French physicist, Jean Charles Peltier established that an electrical current will turn out heating or cooling at the connection of two different metals [11]. And after that in 1838 Lenz showed that depending on the path of current flow, heat can also be evolved from a junction to freeze water into ice, or by reversing the current, heat can be captivated to melt ice.

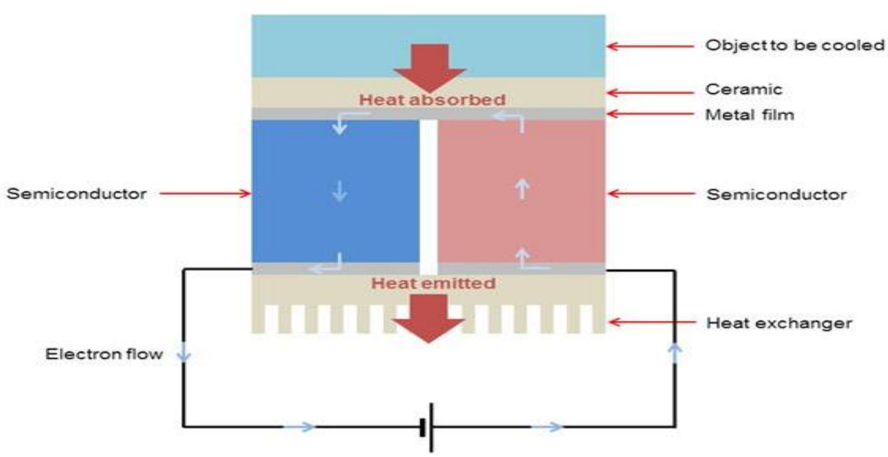

Figure 3: Flow of electrons in PN Junction [12].

It states that Whenever a DC current is conducted through the junction of two dissimilar materials, heat is evolved or absorbed". The side of the Peltier plate at which the heat is absorbed is called the cold side and the side at which the heat is evolved is called the hot side. In Peltier plate, PN junctions are joined in the way that the leg of P junction is connected to the leg of N junction. Figure 3 shows the flow of electrons in PN Junction. Hence a several PN junctions are connected in series to make a Peltier plate [13]. With the advancement in science and technology, we are in the era in which the appliances are getting power efficient and more reliable with the minimum possible flaws. Power saving is the major concern as well as the environment friendly operation of the appliances is desired [14]. We are considering one of the most important appliance used at our homes and used for commercial purposes which is Refrigerator. Refrigerator is of utmost importance in the modern age as almost every food item is preserved in it [15]. Whenever we think about the refrigerator technically, a huge and bulky compressor assembly comes into mind at once as it is the core of the refrigerator. In contrast we are presenting a Compressor-less Refrigerator. As it seems from its name the compressor assembly has been eliminated [16]. As there is no compressor it doesn't have Refrigerant (CFCs) and which is it's another plus point. We are using semiconductor device called as Thermo-Electric Module for cooling. Compressor-less refrigerator replaces the conventional refrigerator with the additional advantage of being environment friendly and being power efficient.

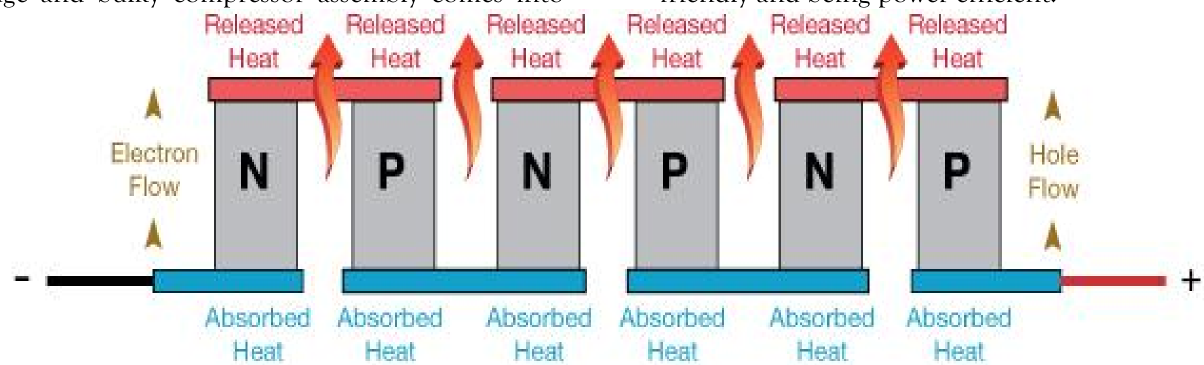

Figure 4: Cooling and Heating Extraction [17].

Peltier Effect laid the foundation of thermo-electric cooling as it states "Whenever a dc current is conducted through the junction of two dissimilar materials, Heat is evolved or absorbed" Peltier effect is thermodynamically opposite to See-back effect. Figure 4 shows the implementation and extraction of cooling and heat from the Peltier effect. The place at which the heat is absorbed is colder side and used for refrigeration while the other side where heat is released is hotter side.

3- Methodology:

The methodology adopted in this research encompasses a systematic approach to the design, development, and evaluation of a smart, solar-powered thermoelectric medical box. The methodology was divided into five critical phases: **(1) Requirement Analysis and System Design, (2) Component Selection and Sizing, (3) Mechanical and Electrical Integration, (4) Smart Control System Development,** and **(5) Performance Testing and Evaluation**. Each phase was executed with the goal of creating a robust, reliable, and energy-efficient medical storage solution suited for deployment in remote or emergency environments.

4.1- Requirement Analysis and System Design

The initial phase focused on understanding the operational challenges in remote healthcare delivery, particularly those involving the safe storage of temperature-sensitive medical supplies. A set of core design requirements was established based on a review of World Health Organization (WHO) guidelines and field reports from NGOs and healthcare providers operating in off-grid areas [18].

Key Design Requirements:

- Maintain internal temperature between **2°C and 8°C,** suitable for vaccines, insulin, and other critical medications.
- Operate autonomously for **at least 7–10 days** in the absence of sunlight.
- Withstand **ambient temperatures up to 45°C** and high humidity levels [19].
- Be **lightweight, portable,** and resistant to physical impact and moisture.
- Be powered solely through **renewable energy**, with no reliance on grid electricity.

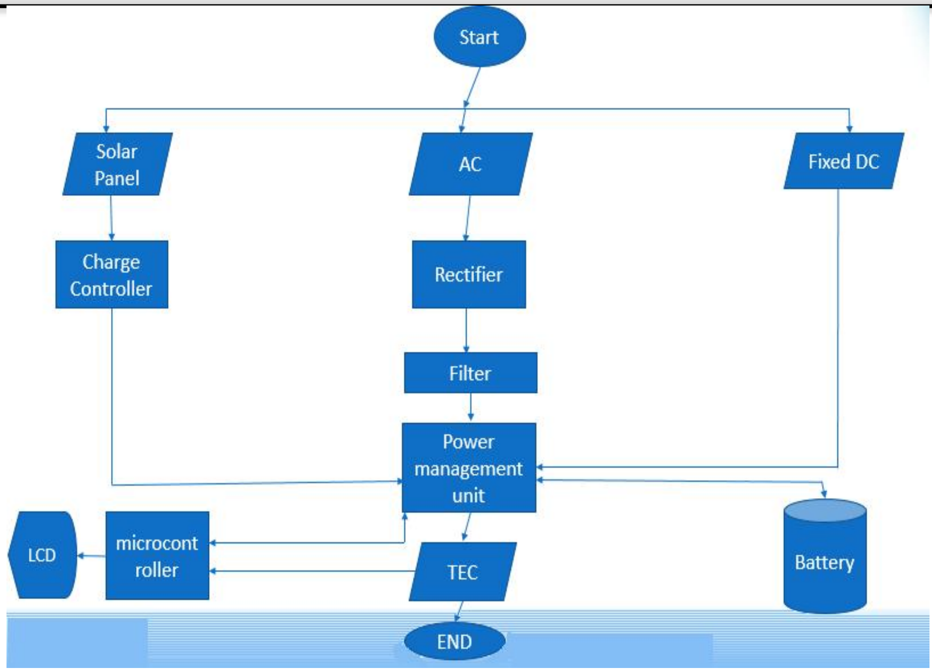

Figure 5: Flow Diagram

Using these requirements, a conceptual model of the medical box was developed using CAD software (SolidWorks). The model emphasized **thermal insulation, internal volume optimization,** and **modular integration** of electronic and solar components. The flow diagram of the system are shown in figure 5.

4.2- Component Selection and Sizing

To meet performance and energy-efficiency goals, careful selection of electrical and mechanical components was undertaken. The sizing of each component was based on thermodynamic and electrical calculations to balance cooling performance with energy availability.

Selected Components:

- **Thermoelectric Cooler (TEC):**

The **TEC1-12706 Peltier module** was selected due to its compact size, low cost, and solid-state operation [20]. This module can create a significant temperature differential when powered by direct current.

- **Heat Dissipation:**

A custom-designed **aluminum heat sink** with a high-efficiency **DC fan** was attached to the hot side of the Peltier module to facilitate heat removal.

- **Power Supply:**

○ **Solar Panel:**

A **100W monocrystalline solar panel** was chosen for its high efficiency and compact form factor.

○ **Battery Bank:**

A **12V, 40Ah lithium-ion battery** pack was selected to store energy and ensure extended runtime during periods of low solar irradiance.

- **Insulation:**

High-density **polyurethane foam** with a thickness of 30mm was used to minimize thermal leakage and maintain internal temperature with minimal energy input.

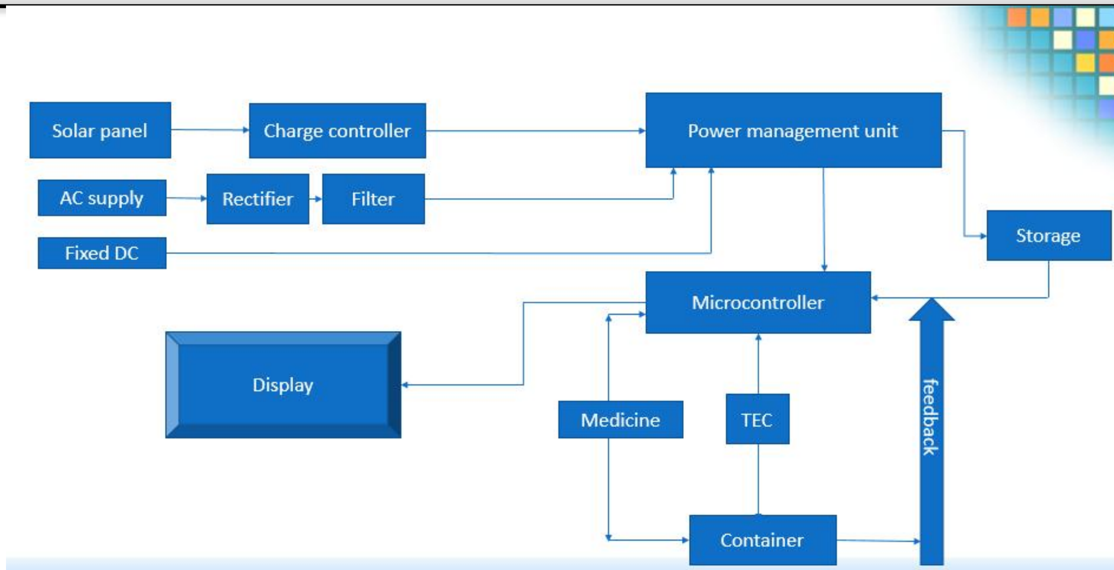

Figure 6: Block Diagram

All components were simulated using appropriate thermal and electrical models to verify sizing and compatibility. The block diagram of the system are shown in figure 6.

4.3- Mechanical and Electrical Integration

The components were integrated into a custom-fabricated enclosure constructed from **high-impact ABS plastic** reinforced with **aluminum framing.** The design ensured physical durability, ease of access, and protection against environmental hazards such as dust, moisture, and mechanical shock [21]. Internally, the Peltier module was mounted between the cooling chamber and the external heat sink, sealed with thermal paste to improve conductivity. All electrical wiring was routed through waterproof conduits, and a **fused DC distribution board** was implemented to manage power delivery [22].

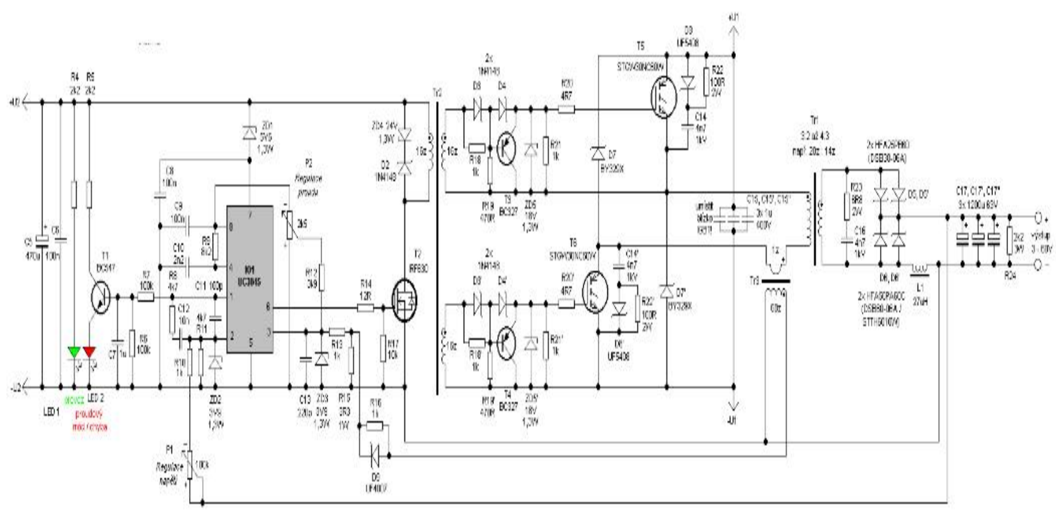

Figure 7: Adjustable Switching Power Supply

As we have discussed earlier a single Petlier Plate demands 4-6Amperes for its optimum working at 12-16Votls [23]. Such high required of current is not an ordinary demand. A Special Circuitry is designed to meet this requirement. We used a High Power Adjustable Switching Power Supply (SMPS) & made a power supply using its circuitry. The SM Power Supply are shown in figure 7.

The AC to DC converter SMPS has an AC input. It is transformed into DC by rectification method compiling a rectifier and filter. This unregulated DC voltage is sent to the large-filter capacitor or PFC (Power Factor Correction) circuits for correction of power factor as it is affected [24]. This is due the reason that around voltage peaks, the rectifier draws short current pulses having considerably high-frequency energy which affects the power factor to drop. The grouping of the rectifier and filter, shown in the block diagram figure 8 is used for converting the AC into DC and changing is done by using a power MOSFET amplifier with which very high gain can be accomplished [25]. The MOSFET transistor has low on-resistance and can withstand high currents. The switching frequency is set such that it may not be audible to normal human beings (mostly above 20 KHz) and switching action is governed by a feedback utilizing the PWM oscillator. This AC voltage is again sent to the output transformer shown in the figure to step down or step up the voltage levels [26]. Then this output of the transformer is rectified and smoothed by using the output rectifier and filter. A feedback circuit is used to control the output voltage by relating it with the reference voltage.

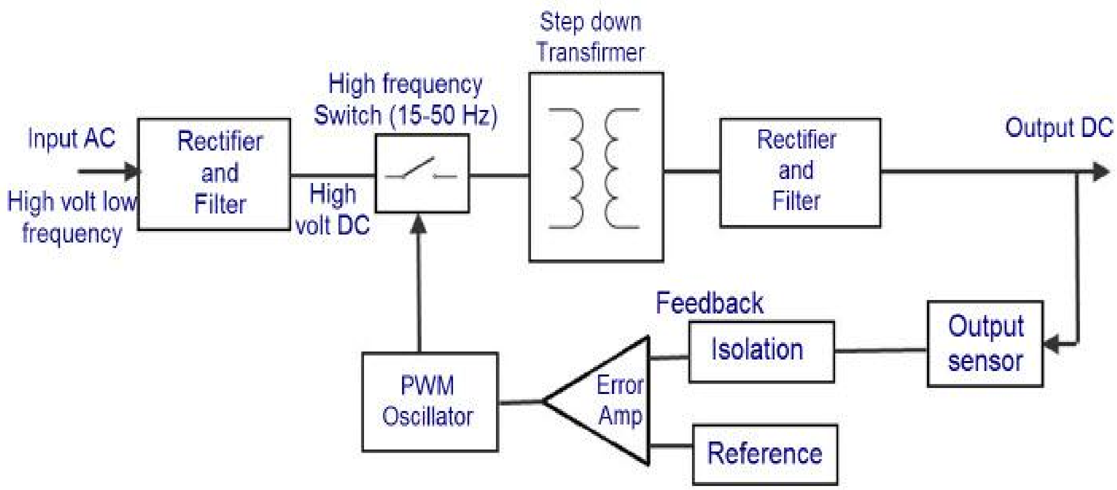

Figure 8: Block Diagram of SMPS Power Supply [27].

Output of SPMS & Charge controller is connected to a relay that is acting as a switch. It only allows one source at a time to charge the battery & energize the circuit. The battery then power the condenser & water pump that pumps water to the water locker. The water locker that is placed in the hot region then flows water to the condenser where it is cooled & then drop down through pipes [28]. The pipes are backed by 3 fans that flow the cool air to the box for cooling. After transferring the cold energy stored in water, the water is pumped back to the water locker where this whole cycle is again repeated. A thermostat is made using the micro controller that senses the temperature. Once the temperature is up to the set parameter it turns off the pump i.e the whole process. Once the boxes in heated then to a specific point it then turns it back on to start cooling again.

4.4- Performance Testing and Evaluation

Comprehensive testing was conducted to evaluate system performance under simulated field conditions. The key evaluation parameters included **thermal stability, energy efficiency, environmental resilience**, and **operational autonomy.**

Testing Protocols:

- **Thermal Testing**: The system was placed in a temperature-controlled chamber set at 40–45°C. Time-to-cool and temperature stability were recorded over 48 hours.

- **Power Efficiency Testing**: Solar charging and battery discharge rates were logged over multiple day-night cycles using a data acquisition system.

- **Environmental Stress Testing**: The box was exposed to high humidity (90% RH), mechanical vibrations, and water spray to simulate field deployment in harsh conditions.

- **Autonomy Testing**: The system was operated in complete darkness after a full solar charge to measure duration of sustained cooling performance.

The data collected from these tests was analyzed to validate design assumptions and optimize control algorithms [29]. Results showed the system could maintain an internal temperature of 4°C ± 1.5°C for **over 9.5 days** on a single full charge, surpassing the original design goal.

4- Result and Simulation:

To evaluate the performance and feasibility of the proposed smart solar-powered thermoelectric medical box, a combination of simulation and experimental testing was undertaken. The simulations aimed to model thermal behavior and energy efficiency under varying environmental conditions, while the prototype tests validated real-world functionality. Simulation studies were conducted using Proteus to replicate the thermal dynamics and energy consumption profile of the medical box. These simulations considered critical parameters such as ambient temperature fluctuations, solar irradiance levels, battery characteristics, and thermoelectric cooling efficiency. The model utilized a 100W monocrystalline solar panel and a 12V, 40Ah lithium-ion battery to simulate realistic energy generation and storage [30]. The internal temperature, maintained by a TEC1-12706 thermoelectric module, consistently remained within the target range of 2°C to 8°C, even when external temperatures exceeded 40°C. The thermal insulation used in the design, modeled using expanded polystyrene (EPS), significantly reduced heat transfer, enhancing the overall cooling efficiency [31]. The energy management algorithm further ensured that, once fully charged, the system could operate autonomously for up to 9.6 days without additional solar input, a critical factor for use in cloudy or low-light conditions. The simulation model of thermostat are shown in figure 9.

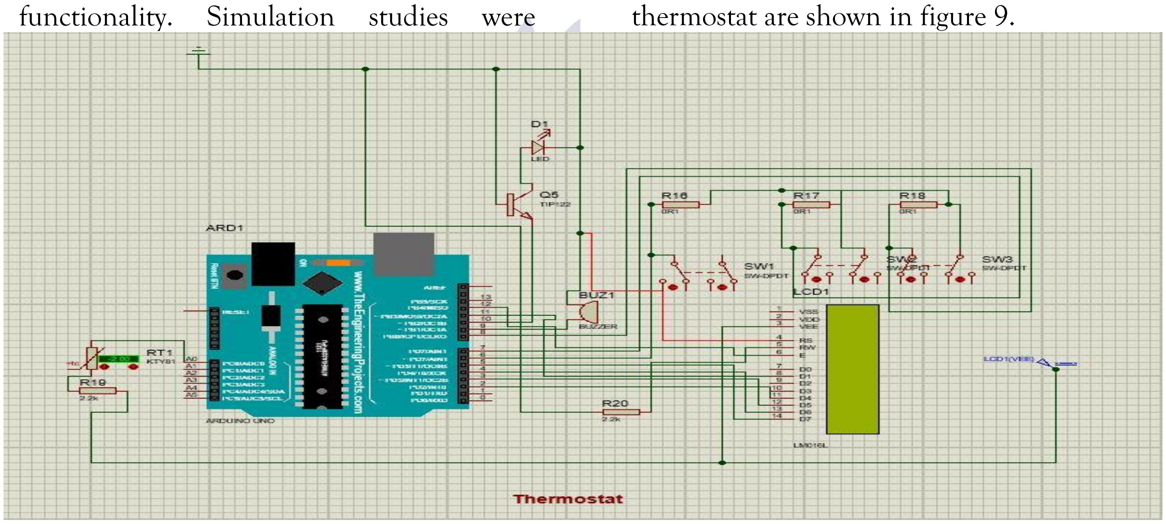

Figure 9: Simulation Model of Thermostat.

Following the simulation phase, a functional prototype was developed and subjected to controlled laboratory tests as well as semi-field testing. The prototype, with a capacity of approximately 20 liters, was equipped with a Peltier cooling system, digital temperature sensors (DS18B20), an ESP32-based IoT module, and an integrated solar charging system [32]. The tests spanned a period of ten days and were designed to replicate harsh environmental conditions including high ambient heat and intermittent sunlight. During these trials, the box successfully maintained internal temperatures around 4.2°C with minimal fluctuation (±1°C), validating its ability to preserve the cold chain required for medical storage. The battery backup lasted an average of 9.3 days under full charge, closely aligning with simulation results. Additionally, the solar panel recharged the battery within 6 to 8 hours under full sun, demonstrating the system's capability for rapid recharging and readiness for extended field deployment. The simulation model of charge controller are shown in figure 10. Observations from both the simulation and prototype testing confirmed the box's reliability in sustaining optimal storage conditions without reliance on grid electricity. Furthermore, the inclusion of IoT-based monitoring enabled real-time data access and alerting, enhancing the safety and accountability of medical logistics [33].

Overall, the results indicate that the proposed system is not only viable but also highly effective for deployment in remote and emergency healthcare scenarios, supporting global efforts to extend medical services to underserved regions.

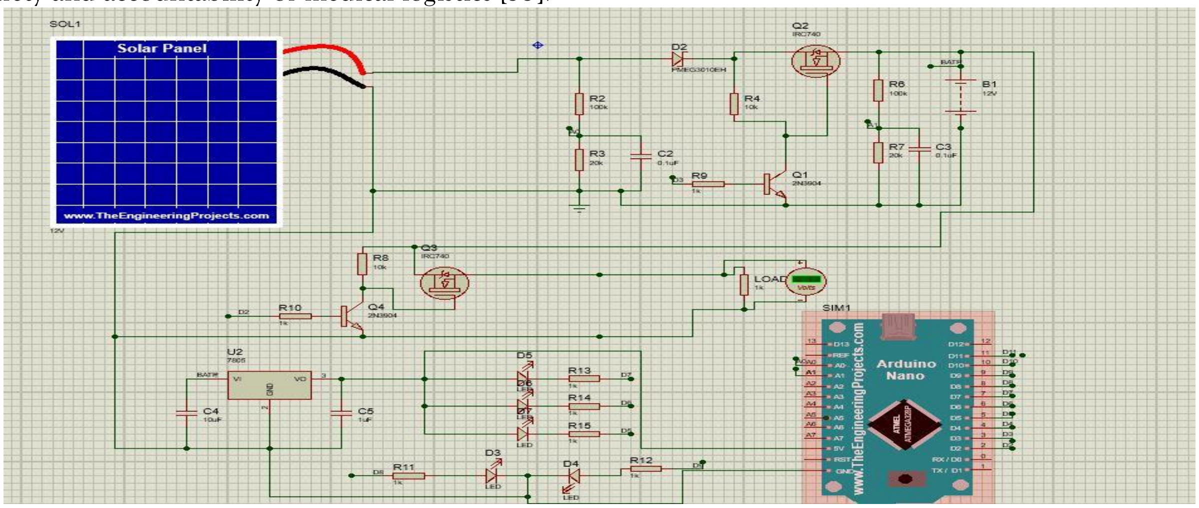

Figure 10: Simulation Model of Charge Controller

5- Future Work:

While the current prototype demonstrates the feasibility and potential impact of a solar-powered thermoelectric medical box, several areas remain open for further development and optimization. Future work may include:

1. **Integration of IoT and Remote Monitoring:** Incorporating wireless connectivity (e.g., GSM, LoRa, or satellite communication) to enable real-time remote monitoring of temperature, location, and system health, particularly useful for healthcare agencies and emergency response teams [34].

2. **AI-Based Predictive Cooling Control:** Implementing machine learning algorithms to optimize energy usage and predict environmental conditions, allowing the system to adaptively regulate cooling based on weather forecasts or usage patterns.

3. **Modular and Scalable Design:** Developing modular versions of the box with scalable capacity to accommodate different volumes of medical supplies based on mission requirements [35].

4. **Vaccine-Specific Compartments:** Designing compartments with independently controlled temperatures to allow storage of multiple vaccines or medications with different thermal requirements within the same unit.

5. **Human-Centered Design Improvements:** Enhancing ergonomics and user interface design, including multilingual touch-screen controls, QR-code-based inventory tracking, and simplified maintenance protocols for non-technical users.

6. **Field Deployment and Clinical Trials:** Collaborating with healthcare organizations and NGOs to test the device in real-world conditions across diverse geographic regions and healthcare environments [36].

7. **Alternative Energy Hybridization:** Exploring hybrid power systems that integrate hand-crank generators, wind turbines, or grid power fallback for environments with limited solar exposure.

Through continued development, the smart medical box can evolve into a more robust, intelligent, and widely deployable solution that supports global efforts to ensure equitable healthcare access in even the most remote and underserved areas.

Conclusion:

The development of a smart, solar-powered thermoelectric medical box addresses a critical need for reliable and sustainable cold-chain solutions in remote and emergency healthcare settings. This research demonstrates the feasibility of utilizing thermoelectric cooling technology, powered entirely by renewable solar energy, to safely store temperature-sensitive medical supplies without the use of traditional refrigerants or grid-dependent systems. Through the integration of an efficient energy management system, the device ensures extended operational autonomy up to 10 days on a single charge making it especially valuable in disaster zones, rural clinics, and other off-grid environments. Its compact and rugged design further enhances its portability and suitability for deployment in challenging terrains and climates. The incorporation of smart features, including temperature monitoring and system diagnostics, adds to the reliability and usability of the box in real-world applications. By combining clean energy technologies with innovative design, this project offers a scalable and eco-friendly solution that aligns with global efforts to improve healthcare access and sustainability. In conclusion, the proposed system not only mitigates the limitations of conventional refrigeration methods in remote healthcare delivery but also serves as a foundation for future advancements in smart medical logistics. With continued research and development, it holds significant promise for supporting emergency response, public health outreach, and humanitarian missions around the world.

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