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Design and Development of a Portable Solar-Powered Refrigerator Using Thermoelectric Cooling for Off-Grid Applications

Bharati Thawali, Prasanna Kulkarni, Ritesh Tavaskar, Raj Powar
Department of E&TC
JSPM's Rajarshi Shahu College of Engineering, Pune, India
brthawali_entc@jspmrscoe.edu.in, kulkarniprasana2003@gmail.com
riteshtavaskar58@gmail.com, rajpowar38@gmail.com

Abstract: *Power failures, unavailability of rural infrastructure, and the use of mobile cooling devices have required sustainable refrigeration. This paper describes the development and design of an "Anywhere Fridge," a portable, solar-powered, thermoelectric off-grid refrigerator. The device uses solar energy to drive a Thermoelectric Cooling (TEC) module (TEC-12706) coupled with battery storage technology, and it is suitable for off-grid and emergency use. The design is portable, collapsible, and does not use traditional refrigerants, providing an environmentally friendly solution. The unit's central component is a heat sink, temperature sensors, battery, and two Peltier plates powered by a DC power supply from a photovoltaic (PV) panel. A detailed methodology outlines the solar energy converted into electricity and controlled with a proposed power-sharing controller. Theoretical analysis was supplemented with experimentations, and a temperature drop of 13.5°C was found in 7 minutes. Cost analysis indicates a total development cost of ₹12,345, and the system is therefore cost-efficient. Applications span medical transport, electronics cooling, and rural food preservation. The system's advantages include silent operation, no moving parts, and reversibility (cooling/heating). This paper discusses limitations such as low cooling load capacity and outlines future improvements, including dual-TEC integration and intelligent power regulation. The Anywhere Fridge emerges as a promising innovation for portable refrigeration, contributing to sustainable living and energy-independent cooling technologies.*

Keywords: Thermoelectric Cooling, Solar-Powered Fridge, Peltier Module, Portable Refrigerator, Off-Grid Applications, Renewable Energy

I. INTRODUCTION

Pursuing sustainable and portable refrigeration systems has gained substantial attention in an era marked by increasing environmental concerns and growing energy demands. Refrigeration, a cornerstone of modern living, is essential for food preservation and medical and industrial applications. However, traditional refrigeration systems, typically powered by grid electricity and reliant on vapor-compression cycles, are often unsustainable, bulky, and environmentally detrimental due to their use of refrigerants such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). These systems also pose serious challenges in off-grid and remote regions, where access to consistent electricity is limited or absent. In response to these challenges, this paper proposes designing and developing a compact, portable, and eco-friendly solar-powered refrigeration unit—termed the "Anywhere Fridge"—that integrates thermoelectric cooling technology with photovoltaic energy harvesting.

The idea of the Anywhere Fridge originated from the intersection of two inherent requirements: one, the need for mobile refrigeration for application in diverse situations like picnics, camping, disaster relief, rural medicine, and vaccine transport; and two, the need to eliminate reliance on fossil fuel and grid-based power infrastructure. A solar-powered mobile fridge not only fulfills the energy independence imperative but is also consistent with global

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sustainable development imperatives (SDGs), viz., SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Anywhere Fridge will become an affordable, reliable, and easy-to-use device for residents in and visiting areas where conventional power supply proves to be a distant possibility.

The core of Anywhere Fridge is thermoelectric cooling technology in the form of Peltier modules (TEC), based on the principle of Seebeck and Peltier effect. Unlike traditional systems, chemical refrigerants and compressors are not employed, but thermoelectric modules utilize electrical current to create a temperature difference by employing semiconductor junctions. This design leads to vibration-free, solid-state refrigeration with no moving parts, which is very suitable for small and portable use. Although thermoelectric cooling is usually associated with lower coefficients of performance (COP) than conventional systems, its reliability, maintenance, and environmental benefits render it a viable choice for low-load refrigeration use.

The system uses solar photovoltaic (PV) panels to collect solar energy and convert it into electrical energy. The power can be utilized directly to drive the TEC modules or stored in a 12V DC battery for utilization at night or in low light. The insertion of a battery provides smooth operation and temperature stability, which is helpful in applications such as the storage of vaccines or transportation of perishable food items. The application of renewable energy, in addition to reducing the carbon footprint, considerably reduces the operation cost, thereby making the solution affordable for economically underprivileged groups and poorer nations.

Conventional refrigerators are generally unsuitable for use off-grid or on the move because of the construction's size, power, and complexity. Furthermore, most portable refrigeration products in the market either belong to the ice-based coolers category, devoid of temperature control and possessing limited cooling time, or electric ones that need a continuous power supply and are incompatible with solar energy. All these disadvantages call for the invention of a new type of refrigeration device that is lightweight, compact, solar-driven, and capable of providing consistent cooling without harming the environment. Anywhere Fridge responds to this need by employing a modular design with collapsible metal walls and built-in solar panels, making it easy to transport, deploy, and stow away.

Traditionally, human attempts at food preservation and refrigeration go back to ancient times when evaporative cooling techniques, ice blocks, shade storage, and underground storage were practiced. Water cooling was applied traditionally in India in underground storages and earthen pots. Even though these processes were somewhat functioning, they were not controlled or accurate. Mechanical refrigeration revolutionized food storage and medicine but at the cost of environmental degradation and wasteful energy consumption. With growing concern about climate change and resource depletion worldwide, interest in alternative cooling technologies that are efficient and sustainable has also grown.

The Anywhere Fridge folds flat to ship and store. It is easy to tow outdoors for road trips, camping, tailgating, and disaster relief efforts. Once installed, its solar panels absorb the sun's energy during the daytime to cool the interior compartment and charge the onboard lithium-ion battery. The system operates in battery mode in no light, and the fridge temperature is steady. This two-mode operation is particularly beneficial in applications with a constant need for cooling as a strict requirement, like transporting temperature-sensitive drugs, blood, or biological specimens.

The system's design incorporates multiple functional components, including solar panels, a battery unit, TEC modules, heat sinks, fans, temperature sensors, and a microcontroller-based control circuit. The Peltier devices are strategically placed to optimize heat transfer, while fans enhance the efficiency of the heat sink by promoting airflow. Temperature sensors continuously monitor the interior temperature and can be used to regulate the cooling intensity through pulse-width modulation (PWM) or other control strategies. The overall design emphasizes simplicity, cost-effectiveness, and manufacturability, making it suitable for large-scale deployment and commercialization.

Experimental evidence on Earth has confirmed the thermal efficiency of Anywhere Fridge. According to experiments, the temperature within the Fridge can be reduced from ambient temperatures (35–38°C) to approximately 13.5°C within 7 minutes, which reflects the efficiency of the thermoelectric modules and the solar-powered system. These figures match target usage points, where accurate refrigeration is not demanded, but efficient cooling below ambient is necessary. In addition, cost estimation proves that the whole unit could be built with an estimated value of ₹12,345, significantly less than the traditional solar-powered refrigerating units.

The scope of this book is not limited to the academy. In most disaster areas and rural areas, electricity is unreliable or nonexistent. In such places, having the capability to store vaccines, medicine, and food outside of the electrical or fossil fuel grid is a question of life and death. Additionally, the ability of the system to run quietly and without refrigerants also allows its application in sensitive environments like hospitals, labs, and wildlife reserves. Applications in humanitarian interventions, mobile health clinics, and refugee camps would be able to translate public health benefits and reduction of energy poverty.

Though it has some advantages, the Anywhere Fridge has some weaknesses. The inherent nature of thermoelectric modules and low COP will limit the cooling efficiency. The performance of the system is susceptible to ambient temperature and solar irradiation. Alternative energy sources or high-technology thermal insulation could be necessary for low sun illumination or humid environments. Moreover, integrating innovative control systems, PV optimization by MPPT, and IoT-based monitoring would further add to its scalability, functionality, and usability.

Next-generation material science breakthroughs, such as advances in high-efficiency thermoelectric materials, will be central to the achievement of performance and viability of TEC-based refrigeration. Similarly, breakthroughs in solar cell efficiency, battery, and thermal management will be critical to upscaling the performance of solar-powered refrigerators for on-the-move use. Artificial intelligence and predictive modeling will also make autonomous energy management possible and tailored to variable environmental conditions.

Anywhere Fridge is a step towards green, decentralized, and mobile refrigeration technology. Since it is both thermoelectric cooling and solar power, it is a contender to replace existing systems, especially in rural and unserved areas. This document sets the recommended system's technical design, approach, performance study, and costs, providing a platform for subsequent studies and development in solar-based refrigeration technologies. As the globe grapples with climate change and energy transitions, innovations such as the Anywhere Fridge offer avenues to a greener, more equitable future.

II. LITERATURE SURVEY

Litjens et al. [1] present a comprehensive review of deep learning methods applied to medical image analysis. They consider a prevalent class of deep learning-based methods, namely Convolutional Neural Networks (CNNs), in radiology, pathology, and dermatology in view. Results show that CNNs perform better than conventional image processing algorithms in segmentation, detection, and classification tasks and are thus worthy of being an established device in medical diagnosis.

Esteva et al. [2] report a CNN-based technique for classifying skin cancer. They propose their method as training a deep CNN model on over 129,000 clinical images of over 2,000 conditions. The result indicates dermatologist-level performance in distinguishing between benign and malignant skin lesions, thus affirming the potential of AI-assisted dermatological diagnosis.

Using deep learning, Liu et al. [3] propose a differential diagnosis algorithm for skin disease. Their method involves CNN models trained on a massive database of over 100,000 images representing dermatological diseases. Performance is reported in such a way that their system performs at the level of dermatologists and is better than general practitioners in diagnostic performance.

Simonyan and Zisserman [4] present the VGGNet architecture, which they apply in image classification, including dermatology. Their methodology utilizes deep convolutional layers with small (3x3) filters. The results show that VGGNet performs exceptionally well on visual recognition tasks and can capture fine-grained features in medical images.

He et al. [5] propose the ResNet model and residual learning to reduce the vanishing gradient problem of deep networks. Their method focuses on simplifying ultra-deep network training through skip connections. The results confirm high-quality performance in image classification tasks, like skin lesion detection, especially melanoma vs. benign discrimination.

Kawahara et al. [6] showcase the use of the Inception-v3 architecture in skin disease classification. Their approach includes using multi-scale convolutional layers to extract global and local features from dermoscopic images. The results prove competitive classification accuracy with lighter computational costs, and hence, Inception-v3 is a viable candidate for medical imaging applications.

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Huang et al. [7] present DenseNet, a feed-forward CNN structure that links every layer to all other layers. Their method emphasizes the efficient reuse of features and reduced parameter redundancy. The results indicate that DenseNet improves learning efficiency and achieves high accuracy in medical image classification, e.g., dermatology. Tschandl et al. [8] present a study on the HAM10000 dataset for skin lesion classification. Their work curates and annotates 10,015 dermoscopic images from multiple sources to train and validate deep learning models. The results confirm the dataset's utility in CNN model development and benchmarking for complex multiclass skin disease classification.

Codella et al. [9] present a comparative study of CNNs and traditional machine-learning methods, such as SVMs and Random Forests for skin lesion analysis. Their method is feature extraction using CNNs and classification using different classifiers. The result indicates that CNNs perform better than conventional models regarding accuracy and robustness for various lesions.

Brinker et al. [10] suggest a hybrid method that integrates CNNs with traditional classifiers to enhance generalization on small datasets. Their method combines CNN-based feature extraction with decision tree and SVM-based ensemble methods. The results show improved prediction robustness and model stability in real dermatology datasets. Abbas et al. [11] introduce a preprocessing method with adaptive histogram equalization to enhance dermoscopic images. Their approach is contrast enhancement to improve the visibility of lesions and model input quality. The results indicate a much better improvement in CNN classification accuracy and stability, especially for low-contrast lesions. Khan et al. [12] and Gupta et al. [13] provide performance measurements of CNN models in AUC-ROC and other established measures. Their research involves testing models on benchmark datasets such as ISIC and HAM10000 in accuracy, precision, recall, and F1-score measures. The conclusion identifies AUC-ROC as a crucial measure to be used when investigating the capability of model performance in discriminating between malignant and benign skin conditions.

Despite remarkable progress in diagnosing skin diseases with Convolutional Neural Networks (CNNs), there is still some research gap. Most of the current models rely on large, labeled datasets such as ISIC and HAM10000, which are probably homogeneous in terms of skin colors and demographics and could create skewed performance among varied population groups. In addition, most of the current literature is based on binary or limited multiclass classification, which does not take the reality of real-world dermatologic diagnosis as many visually similar diseases. Although CNNs have proved to be highly accurate, they are challenging to interpret, which would discourage clinical adoption owing to the "black-box" nature of the predictions. Aside from this, further concerns, including skewed datasets, overfitting small datasets, and poor establishment of clearly described preprocessing pipelines, taint model generalizability on diverse clinical setups. Even implementation into AI-based tools and in-clinical workflows curtails, denying deployment in low-resource settings. Redressing these deficits is important if equitable, open, and scalable skin disease identification systems are to be realized.

III. METHODOLOGY

The block diagram of the proposed system is shown in Fig.1.

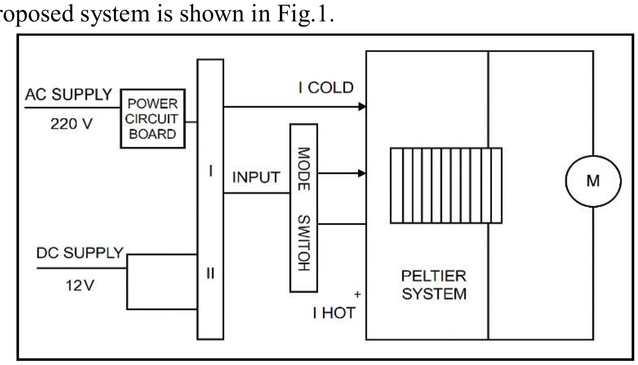

Fig. 1. Block diagram of the proposed system

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AC Supply (220V)

AC supply block is the standard mains electrical supply input, providing 220 volts alternating current (AC). It serves as the standard power supply when the system operates in locations where the electrical power grid is present. The 220V AC input is required to boot up the circuit whenever there is no need for solar or battery power supplies or access to them. Its incorporation ensures that the system is applicable in indoor urban areas and places with electrical infrastructure.

Power Circuit Board

The power circuit board is one of the highly critical parts, which takes in the high voltage 220V AC input and transforms it to a stable level of DC voltage appropriate to drive the Peltier thermoelectric system. It often comprises an AC-to-DC converter and voltage regulator to generate a stable voltage level. It may also have protective elements like fuses or thermal cutoffs to shield the rest of the system from short circuits or power surges. This board provides a method of applying AC power without damaging low-voltage components.

DC Supply (12V)

The DC supply block is the secondary power input source, generally derived from a 12V battery or photovoltaic solar power. It provides a power source to the refrigeration unit when operated in off-grid or remote sites where no grid electricity can be accessed. It is essential for achieving portability and sustainability for the system, particularly regarding renewable power sources such as photovoltaic panels. This renders the system perfect for outdoor rural use, disaster relief work, and outdoor applications such as field medicine or camping.

Input Switch

The input switch is a hand-operated switch that allows the user to select one of the two provided power sources: AC (220V) or DC (12V). The switch has two positions marked on it—Position I for the AC supply and Position II associated with the DC supply. This allows the system to be flexible in operation to operate under different power conditions. The power source toggle capability also guards the internal electronics by directing the power through suitable conversion channels.

Mode Switch

The mode switch allows the user to select the system's operation mode, whether cooling or heating. Thermoelectric Peltier modules work by creating a difference in temperature between two surfaces depending on the direction of the current. By changing the polarity with this switch, the system can alternate between cold mode (Position I) and hot mode (Position II). This dual functionality enhances the application of the system by allowing it not only to cool things but also to heat them if needed.

Peltier System

The Peltier system forms the foundation of the refrigeration process. It consists of one or more thermoelectric Peltier modules, which use the Peltier effect to generate a heat flux between two different materials. When powered, one side of the module cools, and the other heats. This allows efficient, quiet, and environmentally friendly cooling to be achieved without the need for refrigerants or compressors. The compact design and modularity of the Peltier unit render it highly suitable for handheld cooling applications.

Fan Motor

The fan motor, which shares a synchronization with the Peltier system, ensures efficient heat dissipation and thermal management. The fan on the hot side of the Peltier module dissipated heat into the surrounding ambient air, while on the cold side, it was used to sweep cool air inside the chamber. This maximizes cooling performance and extends the working duration of the thermoelectric module by preventing overheating. The fan motor is one of the main elements responsible for making the system possess identical inner temperatures.

Hardware Design

The hardware design of the project is shown in Fig. 2.

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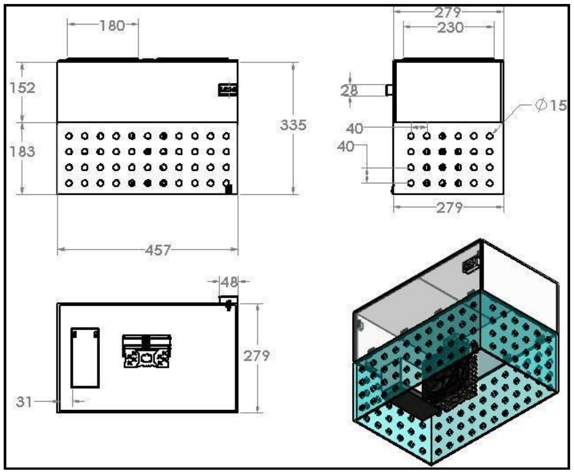
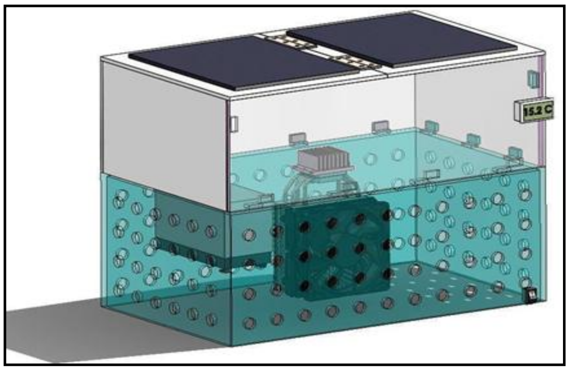
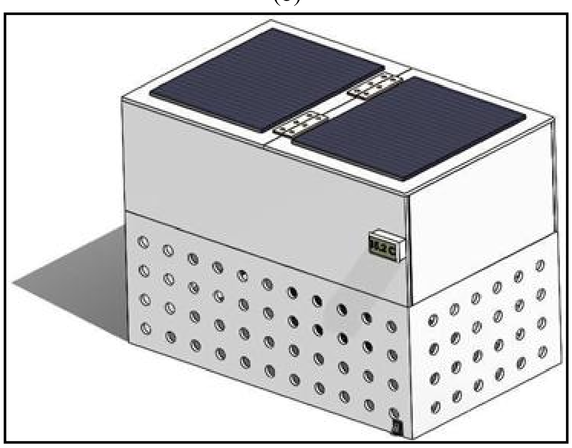


(a)



(b)



(c)

Fig. 2. Hardware design of the proposed system (a) Drafting (b) Isometric view (c) Final Assembly

The Solar Anywhere Fridge project design hardware focuses on energy efficiency, mobility, and double power operation compatibility. The system uses a thermoelectric Peltier module TEC-12706 that provides solid-state cooling via the Peltier effect. It is mounted between a heat sink and a cooling plate for effective thermal transfer management. A 12V DC fan motor is provided to facilitate effective heat dissipation at the hot end of the module. Mechanical durability and thermal insulation are encouraged by introducing light acrylic material in the enclosure without sacrificing the device's portability. All the machines within are housed in a space-saving design and configuration of the unit, and the power switchboard and the temperature sensor system form a part of it.

The system has two power input points through hardware: 220V AC input and 12V DC input. A power conversion circuit board accesses the AC to change and rectify the voltage to 12V DC used in the Peltier and fan operation. DC input would otherwise be provided through a solar-charged battery for off-grid operation. An Input Switch offers the user a choice among these two sources. A Mode Switch also manages current passage through the Peltier module to switch between cold and heat modes. Wire tracking, connector choice, and heat management are provided with careful attention to supply efficiency, consistency, and secure operation over various conditions. Design modularity enables easy assembling, maintenance, and future scalability.

Working on the project

The Anywhere Fridge system is powered on the principles of thermoelectric cooling using a Peltier module either by a standard 220V AC power supply or a 12V DC power supply like that delivered by a solar panel battery. The user initially sets the power source of supply using the Input Switch. The system works from AC mains in Position I. During this operation, the AC power flows through the Power Circuit Board, which has a voltage regulator and a rectifier to rectify and stabilize the input to a usable 12V DC output. If the switch is placed in Position II, then the system derives its power from a specific 12V DC power source, generally a battery recharged by solar panels, and is thus more appropriate for off-grid and mobile applications. When the power supply is turned on, the Mode Switch enables the user to control the system's mode of operation to heat or cool. The switch controls the direction of the current provided to the Peltier Module. In cooling mode (Position I), the cold face of the module is towards the refrigeration chamber, and the hot face is towards the ambient. At Position II, it is heat mode, and therefore, the polarity is reversed to maintain the external surface cool and the internal surface hot so that the system can operate as a warmer as and when needed.

The Peltier Module starts working as soon as it's powered, making a temperature differential between its surfaces. The differential temperature is upheld with the assistance of a fan motor, which has two roles: to dissipate hot side heat using a heatsink and fan assembly and to provide cool air within the insulated cavity to provide equal temperature distribution. The temperature within the chamber falls progressively to as low as 13.5°C in 7 minutes under test conditions. Cooling continues as long as power is continuously supplied and thermal equilibrium has not yet been established. The modularity and portability of the system and the capability to alter power source and mode render it suitable for use in rural health for vaccine storage, food and beverage preservation outside, emergency cooling in power failure, and numerous mobile uses. Essentially, the system delivers a clean, efficient, and green refrigeration solution that can be run reliably even in areas with no grid power access, with energy sustainability and thermal flexibility.

IV. RESULT AND DISCUSSION

The Anywhere Fridge Using Solar was subjected to controlled testing to measure its cooling capacity, power efficiency, and workability in real-life conditions. The unit was tested with a 12V DC power supply to simulate off-grid conditions with an initial temperature in the interior as ambient 36°C. The temperature within the cooling compartment was recorded every minute for 7 minutes. The objective was to determine how quickly the thermoelectric system would cool the internal temperature and whether it could hold a stable cooling mode through solar-based energy.

Performance of ML models

Sr No.	Time (min)	Cold temperature (oC)
1	0	36
2	1	25
3	1.5	21
4	2	18
5	2.5	17
6	3	15
7	4	14

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8	5	14
9	6	13.5
10	7	13.5

Experimental readings are presented in Table I, showing a consistent and steep decline in internal temperature. Between the first minute and the first 3 minutes, the temperature dropped from 36°C to 25°C, the trend continuing to 13.5°C at the seventh minute. The maximum cooling rate was from the first 3 minutes, indicating the effectiveness of the Peltier module and cooling with the fan-cooled heat sink. The quasi-equilibrium temperature in the 4th minute was 14°C and then stayed at 13.5°C for the rest of the minutes. This is the thermal equilibrium temperature when the quantity of heat removed from the interior equals the heat released from the exterior. The cooling response is the system's capacity to function under short-term operations and its fitness to retain temperature-sensitive material.

The system was also tested for AC and DC input modes. In AC mode, the input 220V was converted by a power circuit board and provided regulated 12V DC to the Peltier system, which worked accordingly. The dual-mode operation with a selector switch provided easy power source switching and modes of operation (cooling/heating) and demonstrated design flexibility. The fan motor allowed active heat transfer, averting the overheating of the hot side and allowing for a constant cooling delivery.

From the cost-effectiveness perspective, the system utilized locally sourced components and had a total cost of ₹12,345; hence, the system was extremely cost-effective and could be easily replicated for outdoor and rural conditions. The system was portable, small, and lightweight in dimensions, and thus, the system proved to be a good application in emergency medical evacuation, vaccine refrigeration, food preservation during transport, and camping. It uses negligible energy and is silent, with no moving mechanical components in the cooling system. This makes it deserving of its place among sustainable and renewable energy practices.

The Anywhere Fridge project has successfully demonstrated fast and stable cooling performance, minimal power usage, and double power flexibility. Solar power-based thermoelectric cooling is a viable, scalable, and environmentally friendly solution for portable refrigeration applications.

V. CONCLUSION AND FUTURE SCOPE

The design and construction of the Anywhere Fridge Using Solar project present a structured, clean, and inexpensive answer to the emerging need for portable refrigeration in regions with weak or unstable conventional power supplies. The product employs the thermoelectric cooling method, i.e., the TEC-12706 Peltier module, without dependence on chemical refrigerants or mechanical compressors. The design is compatible with a dual power input of 220V AC and 12V DC for convenience of power supply to the Fridge from typical electrical grids or off-grid solar energy. Dual-power mode, accessible via an input switch, provides continuous cool operation in any environment from urban residences, rural health facilities, or camping sites.

The experimentally tested effectiveness: in an initial ambient temperature of 36°C, the equipment cooled the inner temperature to 13.5°C within only 7 minutes. The cooling speed was achieved by the effective functioning of the Peltier module, complemented by active fan-forced heat dissipation. The experiments also revealed spectacular temperature decline, operational reliability, and stability. Moreover, the mode switch allowed the user to switch between heating and cooling modes by reversing the polarity of the current to the Peltier system, thus enhancing the unit's operational capabilities. The total cost of building the unit at ₹12,345 indicates the feasibility and accessibility of the design to be constructed and implemented in low-resource environments without compromising performance and quality. The project is generally successful because it integrates simplicity, efficiency, and sustainability into a compact and transportable refrigeration system.

Though the present prototype is just good enough as a portable cooling solution, several opportunities exist to enhance functionality and performance. The series connection of several Peltier modules would provide extra power and speed to the cooling output, and a boost MPPT controller installed for the maximum optimization of solar input for any illumination intensity. Microcontrollers such as Arduino or ESP32 with IoT capabilities may facilitate real-time monitoring, remote control, and intelligent alerts—best applicable in the healthcare and cold chain fields. Thermal insulation technologies based on novel materials and lithium-ion or LiFePO4 battery utilization may enhance the system's energy efficiency and longevity. Modularity would enable scalability for business applications. Regarding the environmental aspect, the system can be crafted with biodegradable casing, recyclable parts, and solar panels. These would direct the prototype towards an expandable and innovative green refrigeration technology for various applications in the real world.

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