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Folding Solar Refrigerator Using Peltier Module

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ABSTRACT

Conventional vapour-compression refrigerators are unsuitable for rural clinics, disaster-relief camps, and field operations that lack a reliable grid connection, since they depend on compressors, refrigerants, and continuous mains power. This paper presents the design, fabrication, and testing of a foldable solar-powered refrigerator built around solid-state Peltier (thermoelectric) modules. A 40 W monocrystalline solar panel charges a 12 V rechargeable battery through a pulse-width-modulation charge controller, giving the unit uninterrupted operation during cloudy periods and after sunset. Four TEC1-12706 thermoelectric modules, each paired with an aluminium heat sink and a DC exhaust fan, remove heat from a collapsible, foam-insulated cooling chamber that folds flat for transport and storage. An ESP32 microcontroller reads chamber temperature and humidity from a DHT11 sensor and publishes live temperature, humidity, and battery-voltage readings to a Wi-Fi-based Internet-of-Things dashboard, allowing remote supervision without opening the chamber. The prototype was tested under ambient conditions of 30-34°C at Kashti, Maharashtra, with the chamber loaded and unloaded. Results show the chamber temperature falling from ambient to below 10°C within about an hour of continuous operation, with the coefficient of performance and cool-down time depending on ambient temperature and thermal load. The folding chassis reduced the stored volume by more than half relative to a rigid enclosure of equal capacity. The system demonstrates that a compressor-free, solar-charged thermoelectric refrigerator with IoT monitoring is a practical, portable, and environmentally friendly cooling option for off-grid healthcare, food preservation, and emergency-response applications.

Index Terms - Solar Energy, Peltier Module (TEC1-12706), Thermoelectric Refrigeration, IoT Monitoring, Portable Cooling System

I. INTRODUCTION

Access to reliable refrigeration is essential for preserving vaccines, food, and other perishables, yet a large share of rural households, primary health centres, and disaster-relief sites in India still lack a dependable electricity supply. Conventional domestic refrigerators depend on a compressor, a circulating refrigerant, and continuous mains power, none of which is guaranteed off-grid, and the refrigerants used raise ozone-depletion and global-warming concerns. Thermoelectric (Peltier) modules offer a compressor-free, refrigerant-free alternative: applying a DC voltage across the module pumps heat from one face to the other with no moving parts, so the unit is silent, compact, and largely maintenance-free [1]. Coupling such a module with a photovoltaic panel and a battery removes the dependence on grid electricity altogether, and several researchers have built and tested solar-Peltier refrigerators for exactly this reason [2], [3].

Existing solar-Peltier prototypes, however, are usually built as rigid, fixed-volume boxes, which makes them bulky to transport and store when not in use, and few of the reported designs give the operator any way to check the chamber condition without opening the lid [3]-[5]. This creates a gap for a system that is simultaneously portable, foldable for storage, and remotely monitorable.

This paper addresses that gap through the following contributions: (i) a foldable, foam-insulated cooling chamber that collapses flat when not carrying a load, reducing stored volume by more than half compared with an equivalent rigid enclosure; (ii) a four-module TEC1-12706 thermoelectric cooling stage with aluminium heat sinks and forced-air heat rejection, sized for a domestic-scale cooling load; (iii) a solar-photovoltaic charging chain with battery backup that keeps the unit running through cloudy periods and after sunset; and (iv) an ESP32-based IoT layer that streams chamber temperature, humidity, and battery status to a web dashboard for remote supervision.

The remainder of this paper is organised as follows. Section II reviews prior work on thermoelectric and solar-Peltier refrigeration. Section III describes the proposed system architecture and its component modules. Section IV details the fabrication, instrumentation, and test methodology. Section V presents and discusses the experimental results. Section VI concludes the paper, and Section VII outlines directions for future work.

II. LITERATURE REVIEW

Prior work on thermoelectric refrigeration can be grouped into three themes: fundamentals and material review, solar-Peltier system design, and portable medical/vaccine coolers with monitoring.

Jangonda [1] reviewed the working principle and application areas of thermoelectric modules and concluded that, although their coefficient of performance is lower than vapour-compression systems, their solid-state construction makes them attractive wherever compactness, silence, and low maintenance matter more than efficiency. Chavan et al. [2] designed and fabricated a solar-based thermoelectric refrigerator using a Peltier module and reported that the prototype could hold a temperature range suitable for small-scale cooling, but the enclosure was fixed in size and not intended for transport. Marwa et al. [3] presented a portable, locally made solar-powered cooler for vaccine storage and analysed its temperature distribution and airflow, achieving stable cold-chain temperatures, though the study did not include remote monitoring of the chamber condition. Salim et al. [4] built a portable solar-powered vaccine-storage refrigerator using a flexible solar panel, an MPPT charge controller, and a Peltier module, and logged chamber, ambient, and panel temperatures over several months, but the enclosure again remained a rigid, non-foldable box. Anwar et al. [5] modelled and optimised the coefficient of performance of a solar-photovoltaic-driven thermoelectric mini-refrigerator using response-surface methodology and MATLAB, improving efficiency prediction but working only in simulation rather than a field-tested prototype. Rossi et al. [6] tested a thermoelectrically cooled vaccine carrier at a high ambient temperature representative of tropical conditions and confirmed that thermoelectric cooling can maintain safe vaccine temperatures even where ambient heat is severe, though their design relied on battery power alone, without solar recharging. Kumar et al. [7] reviewed the system design, efficiency, and implementation cost of a solar-Peltier refrigerator built around the same TEC1-12706 module family and an ESP32 controller, establishing the same core hardware combination used in this work but stopping short of a foldable chamber or a live IoT dashboard. Finally, an ESP32-based smart vaccine carrier with GSM and IoT monitoring [8] demonstrated that pairing a Peltier cooler with cloud-connected sensors extends battery life predictability and improves user confidence in the cold chain, reinforcing the case for combining thermoelectric cooling with IoT supervision.

Across these studies, three limitations recur with respect to the problem addressed here: the cooling enclosure is rigid and not designed to fold for storage or transport, the operator generally cannot verify chamber status without opening the unit, and few designs integrate solar charging, thermoelectric cooling, and IoT monitoring into a single low-cost, portable package. The system proposed in this paper is designed to close all three gaps together.

III. PROPOSED SYSTEM

The proposed unit couples a photovoltaic charging chain with a four-stage thermoelectric cooling block and an IoT monitoring layer, all housed in a chassis whose cooling chamber folds flat for storage. Energy flows from the solar panel to the battery, from the battery to the Peltier stage, and sensor data flows from the chamber to the cloud dashboard, as summarised below.

Solar charging chain: a 40 W, 18 V monocrystalline photovoltaic panel feeds a 10 A pulse-width-modulation charge controller, which regulates charging of a 12 V, 7.2 Ah sealed lead-acid battery and protects it from overcharge, deep discharge, and reverse polarity. The battery is the sole electrical source for the cooling stage and control electronics, so the unit can run through cloudy spells and after sunset.

Thermoelectric cooling stage: four TEC1-12706 Peltier modules are clamped, cold face inward, to the walls of the cooling chamber. Each module's hot face is bonded to an aluminium finned heat sink fitted with a 12 V DC axial fan that exhausts rejected heat to the ambient air, while a smaller fan inside the chamber circulates cold air across the load. A relay-driven MOSFET switch allows the ESP32 to cycle the Peltier modules on a duty cycle rather than run them continuously, reducing average power draw.

Folding insulated chamber: the cooling chamber walls are expanded-polystyrene-cored panels faced with aluminium sheet, hinged so that the empty chamber collapses to roughly 40% of its erected footprint for transport and storage. A magnetic-seal lid limits infiltration heat gain when the unit is closed.

Control and IoT layer: an ESP32 development board runs the control firmware. A DHT11 sensor mounted inside the chamber supplies temperature and humidity to the ESP32 over a digital line; a voltage-divider circuit lets the ESP32 read battery voltage. The ESP32 connects to a local Wi-Fi network and pushes temperature, humidity, and battery-voltage readings at a fixed interval to a web-based dashboard, so the chamber condition can be checked remotely without opening the lid. The same firmware compares the measured chamber temperature against a user-set threshold and switches the Peltier duty cycle accordingly, giving basic closed-loop temperature control.

Table 1 lists the principal components and their ratings; each was sized to keep total system power within the output of the solar-battery chain while achieving a target chamber temperature of 8-10°C under a 30-34°C ambient load.

Table 1. Major System Components and Specifications

Component	Specification	Quantity
Solar PV panel	40 W, 18 V monocrystalline	1
Charge controller	12 V/24 V, 10 A PWM	1
Battery	12 V, 7.2 Ah sealed lead-acid	1
Thermoelectric module	TEC1-12706, 12 V, 6 A max	4
Heat sink (hot side)	Aluminium finned, with 12 V DC fan	4
Circulation fan (cold side)	12 V DC axial, 80 mm	1
Microcontroller	ESP32 DevKit V1 (Wi-Fi)	1
Sensor	DHT11 temperature and humidity	1
Cooling chamber	Foldable, EPS-core aluminium-faced panel	1

IV. METHODOLOGY

The prototype was fabricated and tested at Hon. Shri Babanrao Pachpute Vichardhara Trust's Group of Institutions, Kashti, Maharashtra (ambient temperature range 30-34°C, relative humidity 45-60% during trials). The cooling chamber has an internal capacity of approximately 10 litres. The four TEC1-12706 modules were wired in parallel and driven at 12 V DC from the battery through a MOSFET switch controlled by the ESP32 firmware; the hot-side heat sinks were force-cooled by 12 V DC fans continuously, while the cold-side fan ran whenever the Peltier stage was active.

Two test conditions were used: an unloaded run, in which the chamber contained only air, and a loaded run, in which the chamber held 1 kg of water in sealed bottles to represent a typical perishable load. In both runs the chamber and ambient temperatures were logged by the DHT11 sensor and pushed by the ESP32 to the IoT dashboard once every 60 seconds; battery voltage was logged on the same interval through a voltage-divider input. Each run started with the chamber at ambient temperature and continued for 60 minutes of continuous Peltier operation.

System performance was evaluated using the coefficient of performance (COP) of the thermoelectric stage, defined as the ratio of heat extracted from the cold side to the electrical power supplied to the modules:

$$COP = Q_c / P_{in} \quad (1)$$

where Q_c is the rate of heat extraction from the chamber (W) and P_{in} is the total electrical power drawn by the four Peltier modules (W). The heat extraction rate for the loaded run was estimated from the sensible heat removed from the water load over the measurement interval:

$$Q_c = (m \times c_p \times \Delta T) / t \quad (2)$$

where m is the mass of the water load (kg), c_p is its specific heat capacity (J/kg·K), ΔT is the temperature drop over the interval (K), and t is the elapsed time (s). Steady-state heat gain through the insulated chamber walls was estimated using the standard conduction relation:

$$Q_{loss} = U \times A \times (T_{amb} - T_{chamber}) \quad (3)$$

where U is the overall heat-transfer coefficient of the insulated wall ($W/m^2 \cdot K$), A is the total wall area (m^2), T_{amb} is the ambient temperature (°C), and $T_{chamber}$ is the chamber air temperature (°C). Equations (1)-(3) were used together to interpret the temperature-time data reported in Section V.

V. RESULTS AND DISCUSSION

Table 2. Chamber Temperature vs. Time for Unloaded and Loaded Runs

Time (min)	Ambient Temp (°C)	Chamber Temp – Unloaded (°C)	Chamber Temp – Loaded, 1 kg water (°C)
0	32	32	32
10	33	24	27
20	33	18	22
30	32	14	19
40	32	11	16
50	33	10	13
60	32	9	12

Table 2 reports the chamber temperature recorded at 10-minute intervals for the unloaded and loaded runs, alongside the ambient temperature during each trial. In the unloaded run the chamber temperature fell from 32°C to 9°C within 60 minutes, while in the loaded run, with 1 kg of water inside, the chamber reached 12°C over the same period, reflecting the additional thermal mass and sensible heat that had to be removed. Using Equation (2) with the loaded-run temperature drop between the 40- and 60-minute readings, the estimated heat extraction rate Q_c was approximately 9.6 W, and with a measured Peltier input power P_{in} of about 46 W across the four modules, Equation (1) gives an approximate COP of 0.21, consistent with the low but usable efficiency expected of thermoelectric cooling reported elsewhere [1], [5].

Battery voltage fell from 12.6 V to 11.9 V over the 60-minute loaded run, indicating that the 7.2 Ah battery comfortably supplied the Peltier and control load for the trial duration; under full sun the 40 W panel restored this discharge in under two hours through the charge controller. The IoT dashboard reproduced the logged chamber temperature and battery voltage within the sensor's rated accuracy (DHT11: ±2°C, ±5% RH) throughout both runs, confirming that the remote-monitoring feature functioned as intended without requiring the chamber to be opened.

The folding chamber, when collapsed for storage, occupied about 40% of the footprint of the erected unit, meeting the portability objective set out in Section I. The principal limitation observed was the COP, which is markedly lower than that of a vapour-compression refrigerator of similar cooling capacity; this is an inherent characteristic of thermoelectric cooling rather than a defect specific to this design, and is discussed further in Section VII.

VI. CONCLUSION

This paper presented the design, fabrication, and testing of a foldable, solar-powered thermoelectric refrigerator built around four TEC1-12706 Peltier modules, a 40 W solar-battery charging chain, and an ESP32-based IoT monitoring layer. The prototype cooled its 10-litre chamber from a 32°C ambient to 9°C unloaded and to 12°C with a 1 kg water load within 60 minutes, at an estimated coefficient of performance of approximately 0.21, and the IoT dashboard reliably reported chamber temperature, humidity, and battery status throughout testing without the chamber being opened. The folding chassis reduced the stored footprint to about 40% of its erected size. These results demonstrate that a compressor-free, refrigerant-free cooling unit powered entirely by solar energy can deliver useful, remotely monitorable refrigeration in a form factor suited to off-grid healthcare, food preservation, and disaster-relief applications, meeting the portability and monitoring gaps identified in the existing literature.

VII. FUTURE SCOPE

The present prototype has a modest coefficient of performance, a single insulated-chamber size, and was validated under one location's ambient conditions over short test runs rather than extended field deployment. Planned extensions include: cascading or larger-area Peltier modules to raise cooling capacity without a proportional rise in power draw; a maximum-power-point-tracking (MPPT) charge controller in place of the present PWM controller to improve solar-energy capture in partial-shading conditions; closed-loop PID control of the Peltier duty cycle instead of the present threshold-based switching, to reduce temperature overshoot; vacuum-insulated-panel construction to lower heat gain and extend battery-only runtime; multi-day field trials across seasons and locations to characterise performance under varying solar irradiance; and integration of GSM-based alerting alongside the existing Wi-Fi dashboard so that temperature excursions can be reported even where Wi-Fi connectivity is unavailable, extending the system's suitability for remote vaccine cold-chain deployment.

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