

Design and Fabrication of a Solar-Powered Thermoelectric Refrigerator

Madhvendra Kumar Dwivedi¹, Khwajuddin Shah^{1*}, Dhiraj Kumar¹, Dilip Kumar¹, Sweta¹

¹Department of Mechanical Engineering, KIPM College of Engineering and Technology, Gorakhpur, India

Abstract: Conventional refrigeration systems heavily rely on environmentally hazardous refrigerants such as chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs), which possess a high global warming potential and contribute significantly to ozone depletion. Additionally, these traditional vapour compression systems are mechanically complex, energy-intensive, and prone to wear, vibration, and noise. To address these challenges, this paper presents the design and fabrication of a solar-powered thermoelectric refrigerator. By leveraging the Peltier effect, the proposed system provides a compact, reliable, and eco-friendly cooling alternative without the need for moving mechanical parts or harmful refrigerants. Powered by a solar photovoltaic (PV) panel and supported by a battery bank, this system is particularly suited for off-grid communities, outdoor activities, and the preservation of temperature-sensitive medical supplies in remote areas.

Keywords: Environmental safety, Mechanical simplicity, Low operational cost, Portability.

1. Introduction

In most developed nations, the shift toward "green" technology is accelerating, with consumers increasingly willing to invest in environmentally friendly and energy-saving appliances. Refrigeration is an essential part of domestic and commercial life, yet the convenience of conventional cooling is often unavailable during outdoor activities, archaeological studies, or in remote rural regions.

Solar refrigeration can be accomplished through vapour compression, vapour absorption, or thermoelectric refrigeration systems. The first two require high and low-pressure sides of a working fluid, making them difficult to develop into lightweight, portable outdoor devices. In contrast, thermoelectric refrigerators (TER) offer several distinct advantages:

- **Environmental Safety:** They do not use CFCs or other polluting refrigerants, eliminating their contribution to ozone depletion.
- **Mechanical Simplicity:** Unlike conventional refrigerators, TERs have no mechanical rotation or moving parts (excluding external fans), meaning there is no vibration, zero noise, and virtually no mechanical wear.
- **Low Operational Cost:** By utilising battery power charged by solar panels rather than grid electricity, the

operational cost is near zero.

- **Portability:** The cooling boxes can be manufactured in a range of sizes and weights, making them highly mobile and flexible.

The primary objective of this project is to design a compact thermoelectric refrigeration system, integrate it with solar PV power, test its performance (cooling rate, power consumption, and Coefficient of Performance), and evaluate its overall feasibility.

2. Literature Review

The foundational theory of thermoelectricity has evolved over nearly two centuries. In 1834, French watchmaker Jean Charles Athanase Peltier discovered that passing a current through a junction of two dissimilar conductors caused a temperature change. The true nature of this phenomenon was clarified by Emil Lenz in 1838, who demonstrated that water could be frozen on a bismuth-antimony junction by passing a current, and melted when the current was reversed. Altenkirch later derived the basic theory in 1909 and 1911, noting that effective thermoelectric cooling requires materials with high Seebeck coefficients, high electrical conductivity to minimise Joule heating, and low thermal conductivity to reduce heat transfer between junctions.

Recent studies have validated the potential of solar-powered TERs. Dai et al. developed a prototype consisting of a thermoelectric module, solar array, controller, battery, and rectifier, demonstrating that the refrigerated space could maintain 5–10°C with a Coefficient of Performance (COP) of about 0.3. Abdullah et al. tested a combined solar thermoelectric-adsorption cooling system, reporting an average thermoelectric COP of ~0.152. While Bansal et al. found that vapour compression refrigerators are currently the most energy-efficient (COP of 2.59) and cost-effective over their lifespan compared to thermoelectric (COP 0.69) and absorption units (COP 0.47), TERs remain indispensable for niche applications due to their high reliability and absence of refrigerants.

3. Theoretical Background: Thermoelectric Effects

The thermoelectric effect is the direct conversion of temperature differences to electric voltage, and vice-versa. At the atomic scale, an applied temperature gradient causes charge

*Corresponding author: shakhwajuddin@gmail.com

carriers to diffuse from the hot side to the cold side. This process encompasses three separately identified, thermodynamically reversible effects:

1. *Seebeck Effect*: Discovered in 1821, this effect generates a voltage (electromotive force) along a conductor subjected to a temperature gradient due to charge carrier diffusion and phonon drag.
2. *Peltier Effect*: When two different materials form a loop, an abrupt change in heat flow occurs at the junctions because the materials carry different Peltier coefficients. A direct current passing through this junction removes heat from one material and transfers it to the other, creating a hot and cold side.
3. *Thomson Effect*: Predicted by Lord Kelvin in 1851, this describes the heating or cooling of a current-carrying homogeneous conductor equipped with a temperature gradient.

A. Semiconductor Physics

Semiconductor devices are crucial to maximising the Peltier effect. Intrinsic (pure) semiconductors are intentionally doped with impurities to modulate their electrical properties.

- *P-Type Semiconductors*: Formed by adding acceptor atoms, which take away weakly bound outer electrons. The resulting vacancy is a "hole." In p-type materials, holes act as the majority charge carriers.
- *N-Type Semiconductors*: Formed by adding donor atoms capable of providing extra conduction electrons, creating an excess of negative charge carriers.
- *P-N Junction*: The boundary between a p-type and n-type semiconductor. In a thermoelectric module, p-type and n-type elements are connected in series by copper strips and sandwiched between two thermally conducting, electrically insulating ceramic plates.

B. Figure of Merit (ZT) and Thermal Conductivity

The efficiency of thermoelectric devices is determined by the Figure-of-Merit (ZT). To maximise ZT, a material must have a large thermopower (Seebeck coefficient), high electrical conductivity, and low thermal conductivity.

$$\text{Figure-of-Merit, } ZT = (S^2 \sigma T) / \kappa$$

Where:

S = Seebeck coefficient (thermoelectric power)

σ = Electrical conductivity

T = Absolute temperature

κ = Thermal conductivity

Metals make poor thermoelectric materials due to high thermal conductivity and low Seebeck coefficients, whereas insulators fail due to poor electrical conductivity. Total thermal conductivity consists of electron and phonon contributions.

Thermal Conductivity, $\kappa = \kappa_{\text{electron}} + \kappa_{\text{phonon}}$

Engineering relies on minimising κ_{phonon} to decouple

thermal and electrical conductivity.

4. Materials for Thermoelectric Devices

Following the development of practical semiconductors in the 1950s, Bismuth Telluride (Bi_2Te_3) emerged as the primary material for thermoelectric cooling. Bi_2Te_3 is a narrow-gap layered semiconductor with a trigonal unit cell that comprises some of the best-performing room-temperature thermoelectric properties.

- *Properties of Bismuth Telluride*: It exhibits a high electrical conductivity of 1.1×10^5 S/m and a very low lattice thermal conductivity of 1.20 W/(m²·K)—comparable to ordinary glass. Because it cleaves easily along the trigonal axis due to Van der Waals bonding, materials used for cooling must be polycrystalline.
- When alloyed with antimony or selenium, n-type bismuth telluride can achieve a Seebeck coefficient of -287 μ V/K at 54° C.
- Other materials of interest include Thallium-doped or Sodium-doped Lead Telluride (PbTe), which can achieve ZT values up to 1.8 at high temperatures (850 K), though Bi_2Te_3 remains superior for refrigeration applications around 300 K.

5. System components

The design and fabrication of the proposed TER require several specialized mechanical and electrical components:

1. *Solar Panel (Photovoltaic Cells)*: A 12V, 20 W solar panel converts sunlight directly into DC electricity through the generation of electron-hole pairs.
2. *Thermoelectric Module (TEC1-12706)*: A 40mm x 40mm x 4mm semiconductor-based heat pump operating from 15.2V DC and 6A. It consists of P-type and N-type Bi_2Te_3 dice.
3. *Battery*: A 12V sealed lead-acid battery (7.2 Ah capacity) stores chemical energy, ensuring the refrigerator can operate continuously at night and on cloudy days.
4. *Charge Controller*: Protects the battery from overcharging and over-discharging while managing the voltage matching within the system.
5. *Heat Sink*: An aluminium alloy (1050A) finned surface used to dissipate heat generated on the hot side of the TEC module into the surrounding air via Fourier's law of heat conduction and convection.
6. *Cooling Fan*: An axial-flow fan forces air to move linearly across the heat sink fins, maintaining the necessary temperature gradient by preventing localised heat buildup.
7. *Thermal Grease*: Used between the imperfectly flat semiconductor components and the heat sink. Since air is approximately 8000 times less efficient at conducting heat than aluminium, thermal grease fills sub-microscopic flaws and air gaps to radically improve thermal conductivity.
8. *Insulated Cooling Chamber*: An aluminium alloy (Al-

Table 1
System components and their specifications

Component	Specification	Function
Solar Panel	20W Polycrystalline	Converts solar energy to DC electricity.
Charge Controller	10A PWM/MPPT	Regulates battery charging and prevents over-discharge.
Battery	12V 7Ah Lead Acid	Stores energy for night or cloudy-day use.
Thermoelectric Module	TEC1-12706	The core cooling element (Peltier Plate).
Heat Sink & Fan	Aluminium finned type	Dissipates heat from the hot side of the TEC.

Si) container is utilised due to its lightweight nature, cost-effectiveness, and corrosion resistance. The cabinet is insulated with materials like polyurethane foam (PUF) or glass wool to slow down convection and conduction, preserving the internal cold environment.

9. *Measurement Devices:* A standard Voltmeter, Ammeter, and Digital Thermometer are integrated to monitor performance.



Fig. 1. 3D model of solar-powered thermoelectric refrigerator

6. Experimental Setup and Fabrication Methodology

The fabrication and assembly process follow a systematic approach designed to maximise the Peltier cooling effect.

A. Assembly Process

1. *Chamber Fabrication:* The refrigeration chamber is constructed and heavily insulated with aluminium sheets to maintain and diffuse the cooling temperature.
2. *Module Mounting:* The TEC1-12706 module is placed with its cold side facing a spacer block attached to the refrigeration cabinet. Thermal grease is applied at all interfaces. The hot side of the module is securely attached to the external heat sink.
3. *Fan Attachment:* A high-speed axial fan is studded directly to the back of the external heat sink to reject accumulated heat out into the atmosphere. Additional internal fans may be added to increase cooling efficiency inside the container.
4. *Wiring and Control:* The red wire (positive) and black wire (negative) of the TEC module are connected through the charge controller to the battery bank, which is simultaneously charged by the 12V solar PV panel.

B. Working Mechanism

During the daytime, sunlight strikes the PV cells, causing electron-hole pair generation that outputs DC current. This current is directed to the battery bank and subsequently to the TEC module. As the current passes through the alternating P-type and N-type semiconductors within the module, heat is absorbed from the internal cooling chamber (acting as the cold

junction) and transferred to the external heat sink (acting as the hot junction). The cooling fan continually dissipates the rejected heat, creating a steady refrigeration effect inside the insulated box.

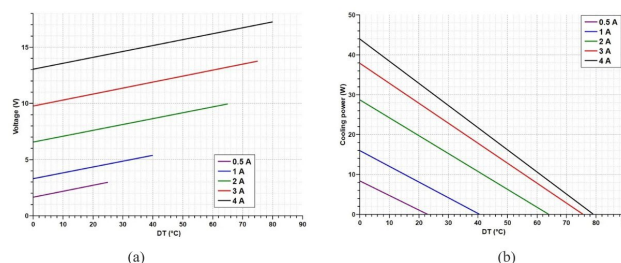


Fig. 2. (a) Voltage – DT curves at different currents for TEC12703 AT 50°C hot side temperature, (b) Cooling power – DT curves at different currents for TEC12703 AT 50°C hot side temperature

Where,

Voltage [V] = The voltage applied on the Peltier cooler.

Current [A] = The current running through the Peltier at a given applied voltage.

The current at a given voltage depends on the temperature of the device.

DT [°C] = Temperature difference between the hot side and the cold side of the Peltier cooler.

Example: $T_h = 50^\circ\text{C}$, $T_c = 2^\circ\text{C}$, $DT = 48^\circ\text{C}$.

Cooling power (Q_c) [W] = The amount of heat that the Peltier cooler can move from the cold side to the hot side at a given current, voltage and DT.

7. System Limitations

While the proposed solar thermoelectric refrigerator offers unique operational benefits, experimental testing reveals certain limitations:

- *Low Coefficient of Performance (COP):* The thermodynamic efficiency is noticeably lower than conventional vapour compression systems. Current systems usually yield a COP ranging from 0.15 to 0.69 depending on the setup.
- *Heat Dissipation Bottleneck:* The Peltier effect generates significant heat on the hot side. Without a highly efficient heat sinking mechanism (and unhindered natural or forced convection), the cooling capacity of the cold side is severely limited.

8. Future Scope and Applications

A. Technological Advancements

To overcome current limitations, the future scope of thermoelectric refrigeration focuses heavily on materials and

hybridization:

- *Improved Materials*: Nanotechnology and advanced material science aim to develop new materials with a Figure of Merit (ZT) of 2 to 3, making TERs competitive with conventional compressors.
- *Phase Change Materials (PCMs)*: Integrating PCMs for thermal energy storage can provide continuous cooling during intermittent sunlight or nighttime operations, reducing load fluctuations.
- *Smart Control and Radiative Cooling*: utilising machine learning to manage power flow in real-time, and integrating radiative sky cooling panels, can drastically decrease the temperature of the module's hot side.
- *Hybrid Systems*: Combining TE systems with vapour compression units allows for highly precise temperature subcooling.

B. Application Potential

Due to its reliability, compact size, and off-grid capabilities, the solar-powered TER has vital applications in:

- *Off-Grid and Remote Areas*: Providing essential cooling without grid electricity.
- *Medical Storage*: The precise, vibration-free temperature control is perfect for storing vaccines, insulin, and sensitive biological equipment in rural and developing regions.
- *Food Preservation & Portability*: Preventing post-harvest losses in rural areas and serving as portable coolers for camping, automotive applications, and cold deliveries.
- *Niche Electronics*: Cooling microprocessors, lasers, and high-power electronic devices.

9. Conclusion

This paper successfully outlines the design and fabrication methodologies for a Solar-Powered Thermoelectric Refrigerator. By converting solar energy into electrical power to drive a Bi_2Te_3 Peltier module, the system creates a sustainable, "green" cooling mechanism that is entirely free of CFCs and mechanical vibration. Although currently limited by a lower Coefficient of Performance compared to traditional systems, advancements in semiconductor materials and heat dissipation integration promise to expand the viability of thermoelectric cooling. For off-grid communities, outdoor applications, and vital medical supply preservation, the solar TER presents an invaluable and highly reliable technological solution.

References

- [1] M. Mirmanto *et al.*, "Experimental performances of a thermoelectric cooler box with thermoelectric position variations," *Engineering Science and Technology, an International Journal*, vol. 22, no. 1, pp. 177–184, 2019.
- [2] S. Palaniappan *et al.*, "Finite element analysis of thermoelectric refrigeration system," in *Proc. International Conference on Design and Manufacturing (IConDM)*, 2013.
- [3] S. Jugsujinda *et al.*, "Analyzing of thermoelectric refrigerator performance," in *Proc. 2nd International Science, Social-Science, Engineering and Energy Conf., Procedia Engineering*, vol. 8, pp. 154–159, 2011.
- [4] H. Moria *et al.*, "Experimental study of solar based refrigerators using thermoelectric effect," in *Proc. 10th International Conference on Applied Energy (ICAE)*, Aug. 2018.
- [5] V. R. Gandhewar, P. G. Bhadake, and M. P. Mangtani, "Fabrication of solar operated heating and cooling system using thermoelectric module," *International Journal of Engineering Trends and Technology*, Apr. 2013.
- [6] R.-R. He *et al.*, "Theoretical and experimental investigations of thermoelectric refrigeration box used for medical service," in *Proc. 10th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC)*, Jinan, China, 2017.