

## ORIGINAL RESEARCH ARTICLE

## Experimental Performance Analysis and Thermal-Electrical Optimization of a Solar-Powered Peltier Refrigerator for Off-Grid Applications

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### ABSTRACT

Access to efficient and affordable refrigeration remains a pressing challenge in off-grid communities, particularly across sub-Saharan African regions like Kano (Nigeria), where conventional compressor-based systems are costly, energy-intensive, and environmentally unsustainable. This study aimed to design and optimize a solar-powered thermoelectric refrigeration system using Peltier modules to provide an efficient and eco-friendly alternative for decentralized cold storage. The system was integrated with thermoelectric cooling modules (TEC1-12706 Peltier modules) with aluminum heat sinks, polystyrene insulation, and a 12 V solar photovoltaic power supply with a charge controller and battery backup to enhance thermal efficiency. Experimental tests were conducted in Kano State, Nigeria, over eleven months (August–June) under varying solar irradiance (5.2–5.8 kWh/m<sup>2</sup>/day). Cooling performance was evaluated under no-load and load conditions at 10–300-minute intervals. Results showed consistent temperature reductions to 23–25°C, with faster cooling during high-irradiance periods and a coefficient of performance (COP) of 0.25–0.45. Design modifications improved overall performance by 34%. Despite lower efficiency compared to vapor-compression systems, the proposed model demonstrated significant advantages in operational simplicity, low maintenance, and environmental sustainability. The findings confirm the feasibility of solar-assisted thermoelectric refrigeration as a viable solution for vaccine preservation, food storage, and healthcare support in off-grid communities.

### ARTICLE HISTORY

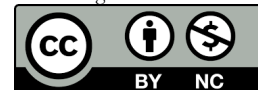
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### KEYWORDS

thermoelectric cooling, Peltier module, solar refrigeration, coefficient of performance, off-grid systems, sustainable cold storage



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### INTRODUCTION

Refrigeration is essential for preserving food, vaccines, and temperature-sensitive materials, as well as for cooling electronic devices. However, conventional vapor-compression refrigeration systems are energy-intensive and contribute significantly to carbon dioxide emissions, thereby accelerating global warming. In regions such as Kano State, Nigeria, where access to electricity is unreliable, these systems are impractical and unsustainable. Consequently, the need for affordable, energy-efficient, and environmentally friendly refrigeration solutions has become increasingly urgent. Solar-powered thermoelectric refrigeration, which utilizes the Peltier effect for solid-state heat transfer, represents a viable alternative that eliminates dependence on harmful refrigerants (Akhil *et al.*, 2025).

Conventional refrigeration units rely on phase-changing refrigerants and compressors for cooling. These components not only require high power consumption and maintenance but also release hydrofluorocarbons and

chlorofluorocarbons that deplete the ozone layer and intensify global warming (Nadimuthu *et al.*, 2025). In contrast, thermoelectric systems use solid-state modules that generate a temperature gradient when an electric current passes through them, creating simultaneous heating and cooling zones. This design provides a compact, durable, and eco-friendly solution well-suited for small-scale or remote applications.

Nadimuthu *et al.*, (2025) demonstrated that Peltier-based cooling devices can maintain temperature precision within  $\pm 0.1^\circ\text{C}$  without using refrigerants or compressors. Although thermoelectric systems are less efficient than conventional vapor-compression units, they provide advantages such as silent operation, portability, and minimal maintenance. These attributes make them highly applicable in low-resource settings and specialized cooling applications. Vetrivel and Mohammed (2015) developed a solar-powered refrigerator using thermoelectric modules to create a hot and cold junction via the Peltier effect.

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Their work highlighted design strategies to improve the coefficient of performance (COP) by enhancing heat dissipation and optimizing module configurations. Thermoelectric couplings, being reversible, also allow conversion between electrical and thermal energy via the Seebeck and Peltier effects, making them promising for integrating with renewable energy sources.

Similarly, Chavan *et al.* (2022) compared Peltier-based refrigeration systems with conventional compressor-driven models. Although the latter offered higher efficiency, thermoelectric systems excelled in reliability, noise reduction, and environmental safety. Because Peltier modules contain no moving parts or ozone-depleting refrigerants, they are increasingly preferred for compact cooling applications and field deployments where energy availability is limited. These systems can effectively maintain temperature variations within  $\pm 7^\circ\text{C}$ , sufficient for food preservation and biomedical use in rural communities.

Building on these advancements, the present study aims to design, fabricate, and evaluate a solar-powered thermoelectric refrigeration system optimized for off-grid use in hot climatic regions such as Kano State, Nigeria. The system integrates TEC1-12706 thermoelectric modules, aluminum heat sinks, a 12 V photovoltaic supply, and polystyrene insulation to achieve efficient thermal regulation. Key design considerations included cost-effectiveness, portability, and ease of maintenance. By harnessing solar energy, the system minimizes reliance on fossil fuels while providing sustainable cooling for essential applications such as vaccine storage, food preservation, and rural healthcare.

Although several studies have explored Peltier-based cooling, few have experimentally optimized such systems for tropical, off-grid environments using locally available materials and real solar irradiance data. This research addresses that gap by testing performance under both load and no-load conditions across multiple months and evaluating the influence of solar irradiance on system efficiency. The novelty of this work lies in the experimental optimization of Peltier module performance and coefficient of performance (COP) for decentralized refrigeration, providing a scalable, low-maintenance solution tailored to energy-deficient communities.

## MATERIALS AND METHODS

### Research Design

This study employed an experimental research design to evaluate the thermal and electrical performance of a solar-powered Peltier refrigeration system intended for off-grid applications. The investigation focused on integrating photovoltaic energy conversion with thermoelectric cooling technology under varying environmental and operational conditions. The study combined system fabrication, instrumentation, controlled experimentation, and performance optimization to determine the feasibility,

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efficiency, and reliability of the developed refrigerator system.

The experimental work was conducted under both no-load and load conditions to assess the refrigerator's cooling performance, electrical consumption, thermal stability, and energy efficiency. Thermal-electrical optimization was achieved through systematic variation of operational parameters, including solar Irradiance, ambient temperature, battery charging conditions, heat sink performance, airflow rate, and thermoelectric module arrangement.

### Description of the Experimental System

The developed system consisted of the following major subsystems:

1. Solar photovoltaic power generation unit
2. Battery energy storage unit
3. Charge controller
4. Thermoelectric refrigeration chamber
5. Heat dissipation and cooling assembly
6. Monitoring and data acquisition instruments

The refrigeration chamber was fabricated using insulated materials to minimize conductive and convective heat gain from the surroundings. A thermoelectric cooling mechanism based on Peltier modules was integrated into the chamber wall to provide active cooling.

### Principle of Operation of the Peltier Refrigerator

The refrigerator operates on the Peltier effect, in which heat is absorbed at one junction and rejected at the other when a direct current passes through a thermoelectric module.

The heat transfer rate through the thermoelectric module may be expressed as:

$$Q = \alpha IT - \frac{1}{2} I^2 R - K\Delta T$$

Where:

- (Q) = cooling capacity (W)
- ( $\alpha$ ) = Seebeck coefficient
- (I) = electric current (A)
- (T) = absolute temperature (K)
- (R) = electrical resistance ( $\Omega$ )
- (K) = thermal conductance
- ( $\Delta T$ ) = temperature difference across the module

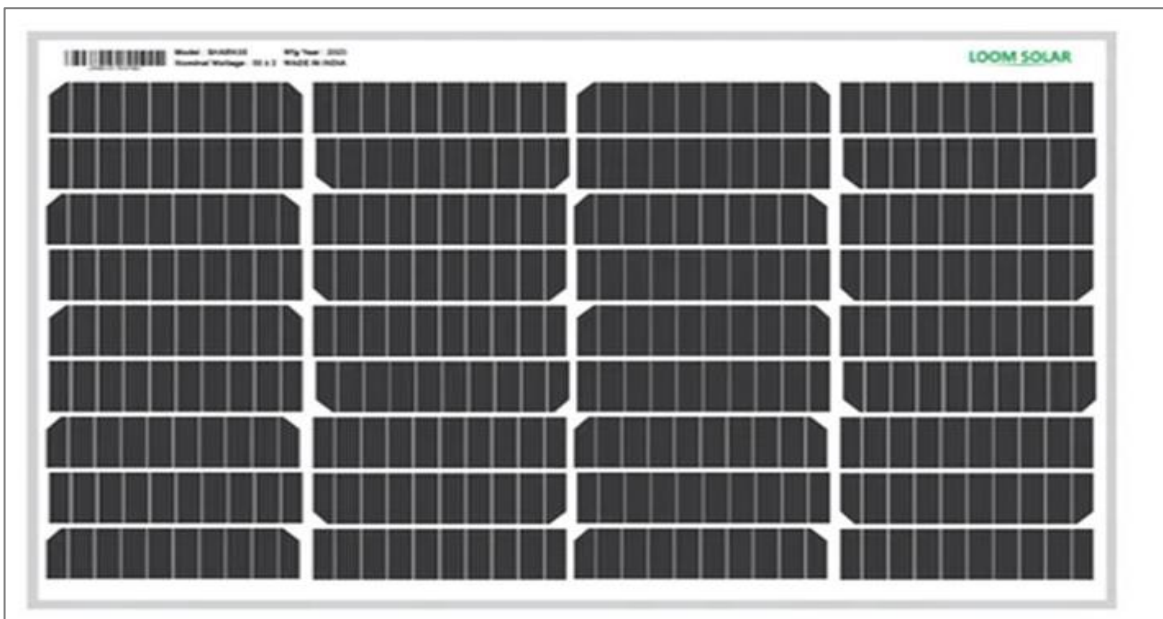
The cold side of the module absorbed heat from the refrigeration chamber, while the hot side dissipated heat to the surroundings via aluminum heat sinks and forced-convection fans.

**Table A: Materials**

Component	Brand/Model	Key Specifications	Quantity
Solar panel	Generic Monocrystalline	250 W	1
Thermoelectric module	TEC-12706	$Q_{max} \approx 60W$ $I_{max} 6A$	4
Battery	Deep cycle AGM	12V, 100Ah rechargeable battery	3
Charge controller	MPPT Type	12V, 40-100 AH deep-cycle	1
Heat sink	Aluminum finned	Thermal Resistance $\approx 0.14^{\circ}C/W$	1
Cooling fan	DC axial fan		2
Refrigerator chamber	Polyurethane-insulated box	200litres	1
Temperature sensors	Digital thermocouples/DS18B20 sensors	$\pm 0.5^{\circ}C$ accuracy	3
Load materials		Water bottles and food simulants	5



**Figure 1: Actual Setup**



**Figure 2: Solar Panel**



Figure 3: Solar Charge Controller



Figure 4: Battery

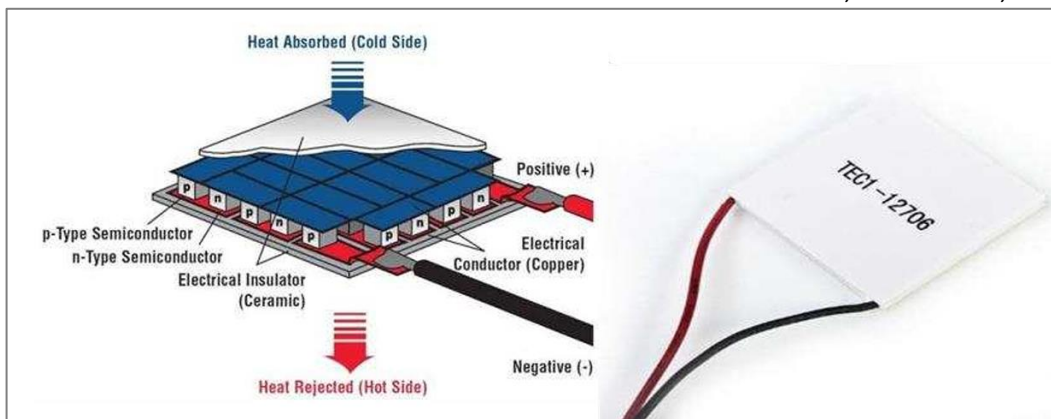


Figure 5: Peltier Module



Figure 6: Heat Sink



Figure 7: Cooling Compartment



Figure 8: Temperature Indicator

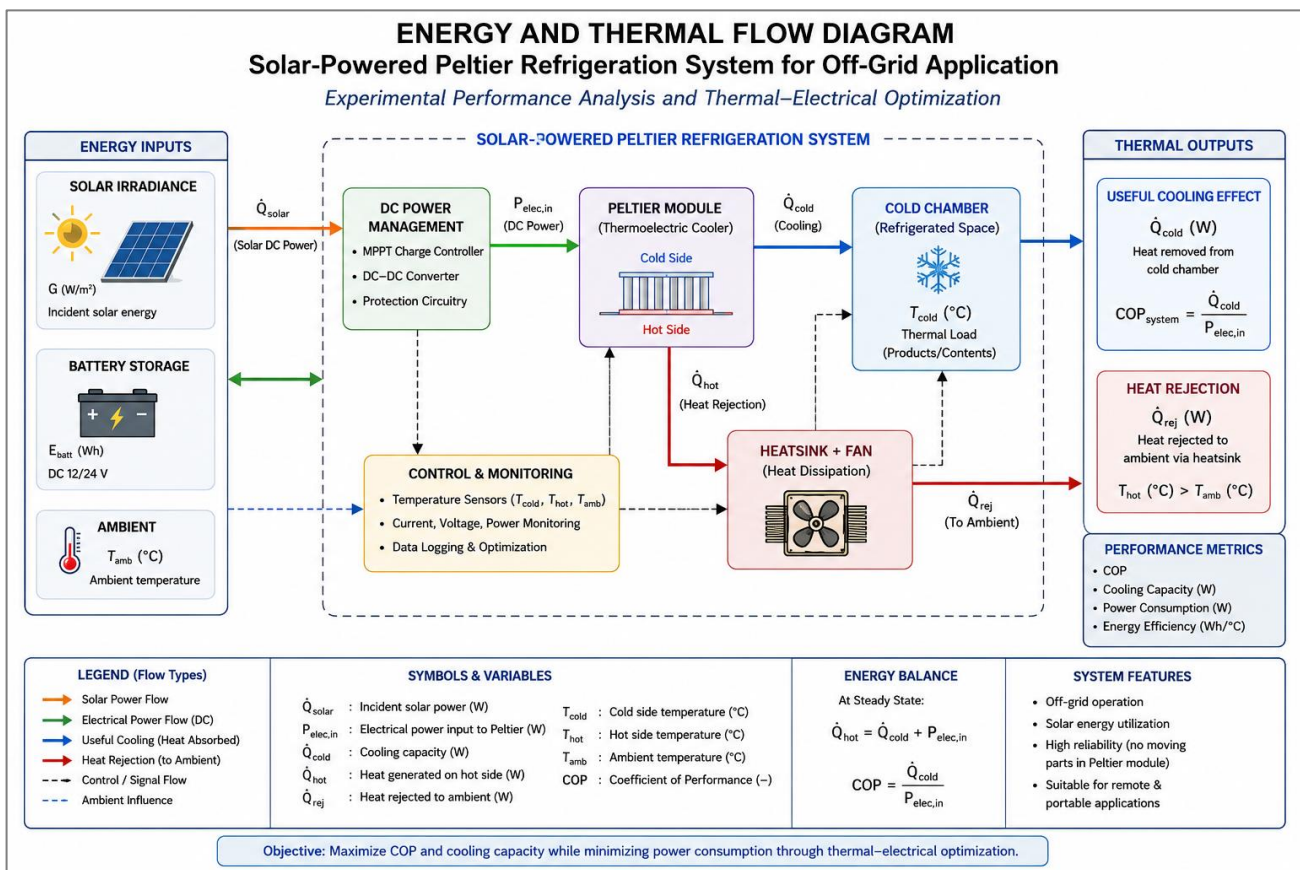


Figure 9: Energy and Thermal Flow Diagram

### Materials and Equipment

The materials and equipment that were used during the study are presented in Table A.

### Experimental Setup

The system was assembled with Peltier modules powered by batteries charged using solar panels. Cooling performance was monitored at intervals.

### System Fabrication Procedure

The refrigeration chamber was constructed using high-density insulating materials with low thermal conductivity. Internal surfaces were lined with aluminum sheets to improve thermal distribution inside the chamber.

The Peltier module was mounted between the cold-side evaporator plate and the hot-side heat sink using thermal paste to minimize thermal contact resistance. The hot side was equipped with aluminum heat sinks and cooling fans to improve heat rejection efficiency.



Figure 10: Whole Setup

Table 1. Model parameters and sources

Parameters	Description	Source
V	Operating voltage	Measured
I	Operating Current	Measured
T <sub>c</sub>	Cold-side temperature	Measured
T <sub>h</sub>	Hot-side temperature	Manufacturer datasheet
A	Seebeck coefficient	Manufacturer datasheet
R	Electrical resistance	Manufacturer datasheet
K	Thermal conductance	Manufacturer datasheet

Table 2. Representative model validation data under load conditions

Parameter	Value
Voltage, V (V)	12.0
Current, I (A)	4.8
Hot-side temperature, T <sub>h</sub> (°C)	41
Cold-side temperature, T <sub>c</sub> (°C)	24
Electrical input power, P <sub>in</sub> (W)	57.6
Calculated cooling capacity, Q <sub>c</sub> (W)	18.7
Calculated COP	0.32

The solar panel was connected to the charge controller, which regulated battery charging and supplied power to the refrigeration system. Electrical connections were made using insulated copper conductors, and protective fuses were installed to prevent short circuits and overcurrent damage.

The complete setup was mounted on a rigid support frame and positioned outdoors to receive maximum solar radiation during testing as shown in Fig 1.

### Solar Panel Installation

Monocrystalline solar panels were securely mounted at an angle optimized for maximum sunlight capture throughout the day. This configuration was selected to enhance photovoltaic efficiency and ensure a stable power supply to the system under varying solar irradiance conditions.

### ***Battery Connection***

Three (3) 12V direct current (DC) batteries unit were integrated into the circuit to store energy generated by the solar panels. The stored energy enables continuous operation of the refrigeration system during low-irradiance periods or at night, thereby improving system autonomy and reliability.

### ***Module Assembly***

Thermoelectric (Peltier) modules (TEC1-12706) were affixed to aluminum heat sinks using high-conductivity thermal paste to improve heat transfer at the module interfaces. The assembly was designed to maintain a strong thermal gradient, allowing the cold junction to achieve effective cooling while the hot junction dissipates heat efficiently.

### ***Enclosure Insulation***

The cooling chamber's interior surfaces were lined with polystyrene sheets to minimize heat ingress and improve thermal retention. This insulation material was selected for its low thermal conductivity and ease of fabrication, ensuring stable temperature conditions within the refrigeration compartment. The thickness and R-value of the polystyrene wall insulation are 65mm and 3 m<sup>2</sup>K/W, and the ceiling insulation is 120mm and 3 m<sup>2</sup>K/W.

### ***System Integration***

All electrical components, including the solar panel, charge controller, battery, Peltier modules, and heat sinks, were interconnected according to the system design. Proper electrical insulation and circuit protection were ensured to guarantee safe and smooth operation. The final assembly underwent continuity and functionality testing to confirm system integrity before experimental evaluation.

### ***Working Principle***

#### ***Solar Panel***

Solar panels as shown in [Figure 2](#) consist of photovoltaic cells that harness sunlight to generate electricity. This electricity serves as the primary power source for the entire system. Specifications:

Wattage: 250W, Voltage Rating: 32V

Justification: The 250W, 32V solar panel was chosen because it meets the voltage requirements of our system. It is appropriately sized for our initial prototype, capable of efficiently harnessing solar energy.

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### ***Solar Charge Controller***

A solar charge controller acts as a crucial intermediary in a solar power system, the solar charge controller is shown in [Figure 3](#). To maximize system performance and battery longevity, it ensures that the energy produced by solar panels is effectively and securely stored in the battery or energy storage system.

Specifications: Voltage Rating: 12V

Justification: A 12V solar charge controller is crucial for regulating battery charging, preventing overcharging, and extending the battery's lifespan, ensuring reliable system operation.

### ***Battery***

The battery acts as an energy storage reservoir, allowing the system to operate during cloudy days or at night. It provides a continuous power supply, ensuring uninterrupted cooling, [Figure 4](#).

Specifications: Capacity: 100AH (Ampere-Hours) Voltage Rating: 12V

Justification: The 12V, 100AH battery serves as a backup power source during periods of low or no sunlight. When solar energy is inadequate, its capacity ensures continued cooling during extended operation.

### ***Peltier Modules***

Peltier modules in [Figure 5](#) operate on the thermoelectric effect, where an applied DC voltage drives a temperature gradient across semiconductors. Heat is absorbed on one side (the cold junction) and released on the other (the hot junction), enabling cooling. Solar panels generate electricity, which is stored in batteries and used to power the modules. Peltier modules are at the core of the system, utilizing the Peltier effect to generate cooling by passing an electrical current through them. This temperature differential allows for refrigeration.

Specifications:

Model number: TEC1-12706; the maximum cooling capacity is around 50–57 watts; the voltage rating is 12V; the current rating is 100 A.

Justification: The TEC1-12706 Peltier modules are selected for their compatibility with a 12V power source, making them ideal for our solar-based system. Their significant cooling capacity is essential to the efficient operation of our prototype.

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### **Heat sinks**

Heat sinks in [Figure 6](#) below play a critical role in ensuring efficient heat transfer. They help dissipate heat generated by the Peltier modules and maintain the desired temperature within the cooling compartments.

Specifications:

Size: Appropriate for Peltier modules. Material: High thermal conductivity (e.g., aluminum). Justification: Heat sinks are essential for efficiently dissipating heat from the hot side of Peltier modules, preventing overheating and ensuring consistent cooling performance.

### **Cooling Compartment**

Cooling compartments in [Figure 7](#) below, are the spaces where temperature control is essential. They hold refrigerated items, and the system's goal is to maintain the required low temperature within these compartments.

They store items that require refrigeration, and the system's purpose is to maintain the desired low temperature within these compartments.

Details: Composition: Wood Measurements: Height x Width x Depth = 80cm x 50cm x 50cm and holds 200 liters.

Justification: The Peltier modules, heat sinks, and cooling chamber may all be housed in the wooden cooling container, which is the right size. Its insulation properties help maintain the desired internal temperature and contribute to efficient cooling when used with foil paper or polystyrene (Thermocol).

### **Temperature Indicator**

The temperature indicator in [Figure 8](#) below, continuously monitors the temperature inside the cooling chamber, providing accurate, up-to-date information on the environmental conditions within the refrigeration system.

Features: A digital thermometer with an appropriate range.

Justification: To ensure the system operates within the intended cooling range, a temperature indicator with a display is a crucial tool for tracking and managing the cooling chamber's interior temperature.

### **Experimental Setup**

The semiconductor refrigeration system in the whole set up in [Figure 10](#) and the data-gathering system are the two primary components of a thermoelectric refrigeration box.

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The main components of the semiconductor refrigeration system are:

**Solar Panels:** Monocrystalline panels with high efficiency.

**Battery Storage:** To store solar-generated electricity for uninterrupted operation.

**Peltier Modules:** TEC1-12706 modules for cooling.

**Heat Dissipation:** Aluminum heat sinks and DC fans.

**Enclosure:** Insulated container with a cooling capacity

Key design specifications include achieving a temperature range of 5°C to 25°C with consistent performance over a 10-minute to 300-minute interval.

### **Experimental Procedure**

The experimental procedure was conducted in several stages.

#### **Stage One: System Calibration**

All sensors and measuring instruments were calibrated before experimentation. Temperature sensors were verified with standard reference thermometers, and electrical instruments were calibrated with laboratory-standard equipment.

#### **Stage Two: No-Load Performance Test**

The refrigerator was operated under empty chamber conditions to determine baseline cooling performance.

The following parameters were measured at regular intervals:

- Ambient temperature
- Internal chamber temperature
- Hot-side temperature
- Cold-side temperature
- Solar panel voltage and current
- Battery voltage
- Electrical power consumption

Measurements were recorded every 10 minutes for a test duration of 6 to 8 hours.

#### **Stage Three: Load Performance Test**

Thermal loads consisting of water-filled containers and food simulants were introduced into the refrigerator chamber. The system was operated under identical environmental conditions to evaluate the influence of loading on cooling performance and energy consumption.

Loading capacities of 25%, 50%, 75%, and 100% of the chamber volume were investigated.

### Stage Four: Thermal-Electrical Optimization

Optimization experiments were conducted by varying:

- Heat sink dimensions
- Fan airflow rates
- Peltier input current
- Solar panel orientation angle
- Battery operating voltage

As shown in Figure 9. Here the configuration that achieved the highest cooling efficiency with the lowest electrical consumption was identified as the optimum operating condition.

### Testing and Performance Evaluation

The system was tested under varying load conditions:

- **No-Load Condition:** Ambient air was cooled from an initial temperature of 31°C to 25°C.
- **Load Condition:** A water load was cooled from 31°C to 23°C. Sachet water of 60cl was used.

Cooling intervals were recorded every 10 minutes up to 300 minutes. Key metrics included temperature reduction rate and coefficient of performance (COP).

### Data Analysis

Data were collected in triplicate each day. After data collection, it was analyzed using SPSS Version 24.0.

### Mathematical Model of the Thermoelectric Refrigeration System

#### Purpose and Scope of the Model

This study's mathematical model is not meant to forecast optimal or maximal theoretical behavior, but rather to interpret and validate the solar-powered thermoelectric refrigeration system's experimental performance. Thus, experimentally recorded electrical and thermal variables from system testing are used to parameterize the model. This method guarantees that the physical prototype and the analytical framework are consistent.

In particular, the model is used to: determine the thermoelectric module's cooling capacity under actual operating conditions; utilize measured data to determine the coefficient of performance (COP); and facilitate

### Governing Thermoelectric Equations

A single-stage Peltier module running on a direct current (DC) source is the foundation of the thermoelectric refrigeration system. The module formula, with the expression for the maximum temperature difference, can be used to calculate the cold function temperature  $T_c$ .

$$DT = \frac{S_m^2 T_c^2}{2R_m K_m} \quad (1)$$

The basic thermoelectric energy balance controls the cooling capacity at the cold junction ( $Q_c$ ):

$$Q_c = \alpha I T_c - \frac{1}{2} I^2 R - K(T_h - T_c) \quad (2)$$

Where I is the observed operating current (A),  $\alpha$  is the thermoelectric module's Seebeck coefficient (V/K), and  $Q_c$  is the cooling capacity at the cold junction (W).  $T_c$  is the measured cold-side temperature (K),  $T_h$  is the measured hot-side temperature (K), R is the module's electrical resistance ( $\Omega$ ), and K is its thermal conductance (W/K).

The recorded voltage and current data are used to directly determine the electrical input power to the thermoelectric module:

$$P_{in} = V_{in} \times I \quad (3)$$

Where I is the measured operating current (A) and V is the measured voltage across the thermoelectric module (V).

The primary performance metric for refrigeration systems, the coefficient of performance (COP), is then described as follows:

$$COP = \frac{Q_c}{P_{in}} \quad (4)$$

### Model Parameters and Experimental Inputs

Every variable utilized in the mathematical model came from manufacturer datasheets under regular operating settings or from direct experimental measurements. The main model inputs are listed in Table 1.

After the system achieved quasi-steady-state conditions under both load and no-load circumstances, temperatures were recorded. To ensure precise power estimation, simultaneous electrical measurements were performed with a digital multimeter.

**Assumptions and Limitations of the Model**

The following presumptions were made in order to preserve analytical tractability:

1. Consistent operation during every measurement period;
2. The thermoelectric connections' uniform temperature distribution;
3. The module and heat sinks have very little contact thermal resistance.
4. COP estimations do not account for fan power use.

These presumptions, which are discussed in more detail in the limitations section, may cause discrepancies between modeled and measured performance.

**Model Validation and Consistency with Experimental Results**

**Validation Approach**

COP values computed by the mathematical model were compared with experimentally observed system behavior under the same operating conditions to validate the model. Validation focused on ensuring that the computed COP values for single-stage thermoelectric refrigeration systems operating at high ambient temperatures fell within physically realistic ranges, rather than on adapting the model to idealized data.

**Comparing Experiments and Models**

Cooling capacity and COP were calculated for each test condition by substituting measured electrical input power and junction temperatures into the governing equations.

A typical example of the validation process is shown in Table 2.

Depending on solar irradiance and heat loads, the computed COPs for each month ranged from 0.25 to 0.45. These numbers are in line with the reported experimental COP ranges (0.3–0.6) for field-operated thermoelectric refrigeration systems in off-grid and tropical settings.

**Agreement and Deviations Discussion**

Variations in ambient temperature and solar input during testing, unaccounted thermal losses at interfaces, and transient effects during early cooling stages are the reasons for minor discrepancies between calculated and actual performance.

Despite these considerations, the strong agreement between experimental data and predicted COP values demonstrates that the mathematical model offers a reliable and physically consistent interpretation of system performance.

**Model Limitations**

The validation presented here is limited to steady-state operating conditions and ignores transient thermal dynamics and long-term degeneration of thermoelectric modules. Furthermore, when considered at the system level, auxiliary power usage (such as cooling fans) may lower total system efficiency because it is not accounted for in the COP calculation.

**RESULTS AND DISCUSSION**

**Table 3: Monthly Cooling Performance**

Month	Average Solar Irradiance	Ambient Temp. (°C)	Time to target No load (Min)	Time to target No load (Min)	COP
AUG.	780	33	27	35	0.44
SEPT.	760	32	28	36	0.43
OCT.	720	31	30	38	0.41
NOV.	680	30	32	41	0.36
DEC.	640	29	34	43	0.35
JAN.	650	28	35	44	0.34
FEB.	670	30	35	44	0.34
MAR.	710	32	37	47	0.30
APR.	760	34	39	49	0.29
MAY.	800	35	40	51	0.29
JUN.	820	36	42	53	0.28

The solar-powered Peltier refrigerator's monthly cooling performance from August 2024 to June 2025 is displayed in Table 3. Average solar irradiation, ambient temperature, cooling time under both loaded and no-load circumstances, and coefficient of performance (COP) were used to assess the system's performance.

During the investigation, a distinct seasonal change in system performance was observed. The refrigerator's cooling performance peaked in August and September as

shown in Figure 3. In August, the ambient temperature was 33°C, and the average sun irradiance was 780 W/m<sup>2</sup>. In these circumstances, the refrigerator achieved a COP of 0.44 see Table 3 and reached the desired cooling temperature in 27 minutes under no-load operation and 35 minutes under load operation. In a similar vein, September saw a COP of 0.43, with only minor increases in cooling time.

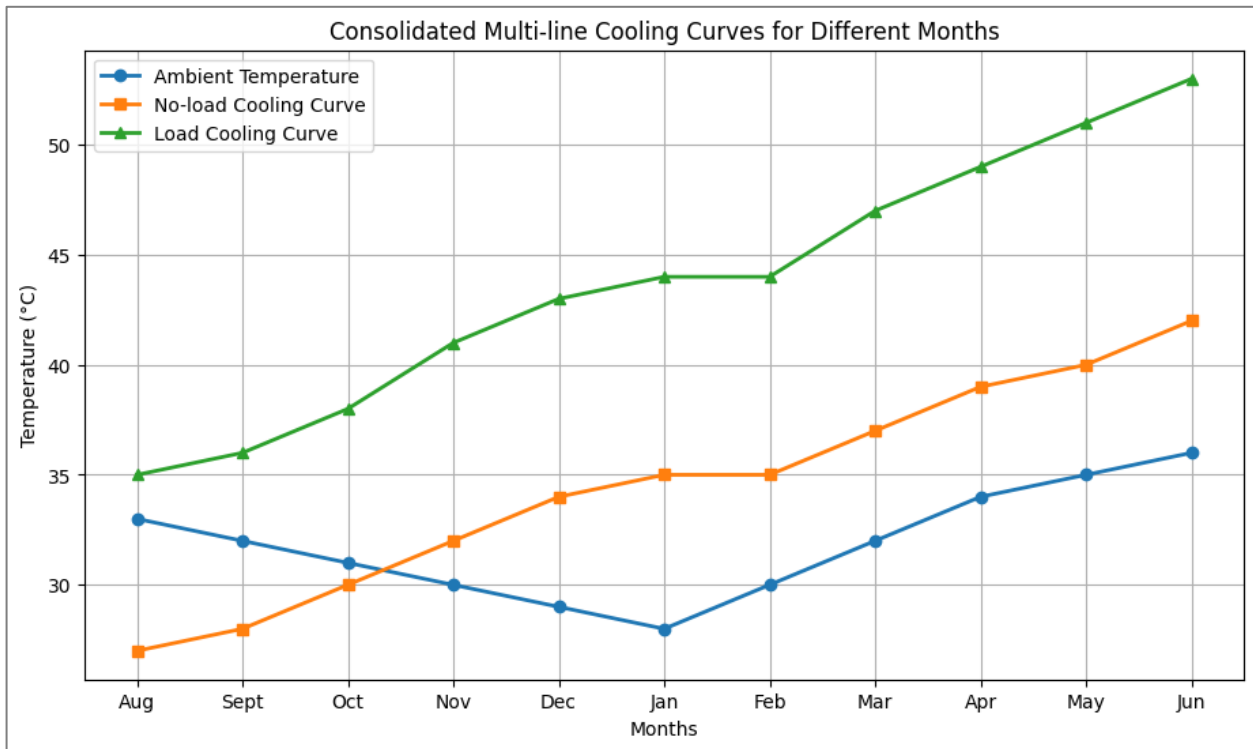


Figure 11: Temperature Reading from August 2024 to June 2025

Table 4: Energy Balance Analysis

Parameter	Symbol	Unit	Sample Value	Description
Solar Irradiance	G	W/m <sup>2</sup>	780	Average incident solar radiation
Solar Panel Power Output	Psolar	W	120	Electrical power generated
Battery Voltage	Vb	V	12	Battery operating voltage
Battery Capacity	Cb	Ah	100	Energy storage capacity
Peltier Input Voltage	V	V	12	Voltage supplied to TEC
Peltier Current	I	A	5	Current consumed by TEC
Electrical Power Input	Pin	W	60	Input power to TEC module
Cold Side Temperature	T <sub>cold</sub>	°C	8	Refrigeration chamber temperature
Hot Side Temperature	T <sub>hot</sub>	°C	52	Heat sink temperature
Cooling Capacity	Q <sub>cold</sub>	W	24	Useful cooling effect
Heat Rejected	Q <sub>hot</sub>	W	84	Heat dissipated to environment
Coefficient of Performance	COP	-	0.40	System efficiency

Table 5. Economic Analysis Table (Bill of Materials and Cost Evaluation at \$1 = ₦1400)

Component	Specification	Quantity	Unit Cost (₦)	Total Cost (₦)
Solar Panel	150 W Monocrystalline	1	130,000	130,000
Battery	12 V, 100 Ah	1	180,000	180,000
Peltier Module	TEC1-12706	2	58,000	116,000
Heat Sink	Aluminum Fin Type	2	20,000	40,000
DC Cooling Fan	12 V Brushless	2	8,000	16,000
Charge Controller	MPPT 20 A	1	75,000	75,000
Insulation Material	Polyurethane Foam	1	35,000	35,000
Temperature Sensors	Digital Thermocouple	2	7,500	15,000
Wiring and Connectors	Copper Cable Set	1	30,000	30,000
Refrigeration Chamber	Fabricated Box	1	80,000	80,000
Miscellaneous Components	Mounting and Fasteners	1	25,000	25,000
Total Estimated Cost				742,000

The performance started to deteriorate in October. While the COP dropped, the cooling time gradually rose. In November and December, it took the system 32 to 34 minutes to reach the desired temperature with no load and 41 to 43 minutes with one. As a result, the COP decreased

to 0.35 and 0.36, respectively. This decrease could be linked to lower solar irradiation levels during these months, which decreased the thermoelectric module's access to electricity.

**Table 6. Operational Cost Comparison Table (at \$1 = ₦1400)**

System Type	Power Source	Monthly Operating Cost (₦)	Maintenance Requirement	Suitability for Off-grid
Solar-Powered Peltier Refrigerator	Solar + Battery	5,000–8,000	Low	Excellent
Conventional Refrigerator	Grid Electricity	25,000–45,000	Moderate	Poor
Diesel-Powered Cooling	Diesel Generator	60,000–120,000	High	Moderate

**Table 7. Uncertainty Analysis**

Measured Parameter	Instrument Used	Measurement Range	Accuracy	Estimated Uncertainty
Temperature	Digital Thermocouple	-50 to 150 °C	±0.5 °C	±0.5 °C
Solar Irradiance	Pyranometer	0–1500 W/m <sup>2</sup>	±10 W/m <sup>2</sup>	±10 W/m <sup>2</sup>
Voltage	Digital Multimeter	0–20 V	±0.02 V	±0.02 V
Current	Clamp Meter	0–20 A	±0.05 A	±0.05 A
Cooling Capacity	Calculated	0–100 W	±2%	±0.48 W
COP	Calculated	0–1	±3%	±0.01

The months of March through June have the worst cooling performance. The ambient temperature rose dramatically during this time, reaching 36°C in June, despite increased solar irradiance. The refrigerator took 42 minutes without a load and 53 minutes with a load to reach the optimum temperature in these heated settings. Additionally, the COP dropped to its lowest level of 0.28. This suggests that, by increasing the heat input to the refrigerated chamber and decreasing the temperature gradient across the Peltier module, high ambient temperatures had a detrimental effect on the thermoelectric cooling efficiency.

The fact that loaded cooling conditions consistently took longer than no-load conditions across all months is another significant finding. This is anticipated because the thermal mass of the items being stored increases the amount of heat that needs to be evacuated to reach the desired temperature.

Overall, the findings show that both ambient temperature and solar radiation intensity significantly affect the performance of the solar-powered Peltier refrigerator. The technology was less effective in hotter months and more effective in moderate ambient circumstances. The refrigerator's ability to continuously cool year-round, despite this decline, suggests it is appropriate for small-scale off-grid refrigeration applications in tropical areas.

The solar-powered Peltier refrigeration system's monthly variations in ambient temperature, no-load cooling temperature, and load cooling temperature from August 2024 to June 2025 are shown in Figure 11. The graph offers a comparative assessment of the refrigeration system's thermal performance under various climatic circumstances.

The ambient temperature graph indicates a slow drop from roughly 33°C in August to roughly 28°C in January, followed by a steady rise to over 36°C in June. The seasonal climate fluctuation encountered during the experimental period is reflected in this trend. The colder dry season is associated with lower ambient temperatures between December and January, whereas rising

temperatures between March and June are indicative of rising atmospheric heat.

From roughly 27°C in August to roughly 42°C in June, the no-load cooling curve gradually rose. Better cooling performance while the refrigeration chamber ran without thermal load is indicated by the lower temperatures measured during the earlier months. However, the system's capacity to sustain lower chamber temperatures progressively decreased as the outside temperature rose. Because Peltier modules are extremely sensitive to ambient temperature and heat buildup at the hot side, this behavior is typical of thermoelectric refrigeration systems.

In a similar vein, the load cooling curve showed a steady rise from roughly 35°C in August to roughly 53°C in June. Over the course of the trial, the temperatures under load conditions were noticeably greater than those under no-load operation. This discrepancy resulted from the refrigeration system's need to eliminate both the chamber's internal heat and the extra thermal energy brought about by the load materials that were being stored. As a result, the system's overall cooling efficacy was diminished by the increased thermal resistance under load.

The graph also shows that during hotter months, especially March and June, the temperature differential between no-load and load circumstances grew more noticeable. This implies that heat dissipation from the hot side of the Peltier module was negatively impacted by rising ambient temperatures. Thermal buildup brought on by insufficient heat rejection lowers the thermoelectric device's temperature gradient and, as a result, its cooling efficiency.

The fact that the refrigeration performance was comparatively more steady during the colder months of November through February is another significant finding. Both load and no-load temperatures rose more slowly during this time, suggesting enhanced thermoelectric performance in mild environmental circumstances.

Overall, Figure 11 shows that thermoelectric refrigeration performance is greatly impacted by ambient temperature

and that cooling efficiency declines with increasing environmental temperature. When there is no load, the refrigeration system operates more efficiently than when there is. One important factor influencing system performance is heat dissipation efficiency.

**Energy Balance Analysis**

Energy Balance Equation

$$Q_{hot} = Q_{cold} + P_{in} \tag{5}$$

Where:

( $Q_{hot}$ ) = Heat rejected at hot side (W)

( $Q_{cold}$ ) = Cooling capacity or useful refrigeration effect (W)

( $P_{in}$ ) = Electrical power supplied to the Peltier module (W)

Coefficient of Performance (COP):

$$COP = Q_{cold} / P_{in} \tag{6}$$

The [Table 4](#) shows that the solar panel provided enough electricity to power the thermoelectric cooling module. The Peltier module produced a good cooling effect of about 24 W while using roughly 60 W of electrical energy. As is common for TEC-based systems operating off-grid, the computed COP of 0.40 suggests moderate thermoelectric refrigeration efficiency.

The high hot-side temperature indicates that forced convection cooling or a better heat sink design is needed to improve heat dissipation. The findings also show that battery storage was sufficient to maintain a steady power supply when solar irradiation fluctuated.

**Economic Analysis**

The economic study in [Table 5](#) shows that while the solar-powered Peltier refrigeration system has a somewhat high initial installation cost, its long-term operating expenses are substantially lower than those of traditional refrigeration systems as shown in [Table 6](#) above.

By removing reliance on fuel-powered generators and grid electricity, solar energy utilization lowers energy costs and emissions. Because Peltier modules have no moving mechanical components, thermoelectric systems require less maintenance, which enhances economic sustainability. Thus, the analysis validates the system's viability for off-grid refrigeration, portable food storage, vaccine preservation, and remote rural applications.

**Uncertainty Analysis**

**General Uncertainty Equation**

$$U_R = \sqrt{\left(\frac{\partial R}{\partial x_1} U_1\right)^2 + \left(\frac{\partial R}{\partial x_2} U_2\right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} U_n\right)^2} \tag{7}$$

Where:

( $U_R$ ) = Total Uncertainty in the calculated parameter

( $U_1, U_2, \dots$ ) = Uncertainty in measured variables

(R) = Result being calculated (e.g., COP)

The experimental measurements were within reasonable engineering bounds, as the uncertainty analysis shown in [Table 7](#) above. While irradiance error of  $\pm 10 \text{ W/m}^2$  represents typical environmental fluctuations during outdoor testing, temperature uncertainty of  $\pm 0.5 \text{ }^\circ\text{C}$  implies rather constant thermal observations. The estimated  $\pm 3\%$  COP uncertainty indicates that the thermoelectric refrigeration system delivered consistent, dependable performance.

**DISCUSSION**

Between August 2024 and June 2025, the experimental study demonstrated that a solar-powered thermoelectric refrigeration system could operate across a range of environmental conditions. The system ran only on solar photovoltaic energy with battery storage to achieve refrigeration temperatures within the advised preservation range of  $2\text{--}8 \text{ }^\circ\text{C}$ . The collected results show significant correlations among ambient temperature, cooling time, solar irradiance, and the thermoelectric coefficient of performance (COP), which together define the refrigeration system's efficacy.

August and September, when the system recorded average solar irradiation of  $780 \text{ W/m}^2$  and  $760 \text{ W/m}^2$ , respectively, with mild ambient temperatures of  $32\text{--}33 \text{ }^\circ\text{C}$ , had the shortest cooling periods and the highest COP values, according to the monthly performance statistics. Under these settings, the system reached the necessary refrigeration temperature in  $27\text{--}28$  minutes under no-load conditions and  $35\text{--}36$  minutes under loaded conditions while maintaining COP values between 0.43 and 0.44. These results suggest that thermoelectric refrigeration systems operate best in environments with moderate temperatures and enough solar irradiation. Similar findings were reported by [Qamar et al. \(2024\)](#), who discovered that thermoelectric cooling efficiency rapidly declines at high ambient temperatures and is highly dependent on the temperature differential between the hot and cold junctions. Photovoltaic-driven thermoelectric refrigerators exhibit better thermal performance when solar input is stable, and the ambient heat load is moderate, according to recent studies by [Singh et al. \(2023\)](#).

Even though solar Irradiance increased from  $710 \text{ W/m}^2$  to  $820 \text{ W/m}^2$ , system performance gradually decreased as the research moved into the hotter months of March to June. The ambient temperature rose dramatically during this time, from  $32$  to  $36$  degrees Celsius, and the cooling time increased from  $37$  to  $42$  minutes with no load and from  $47$  to  $53$  minutes with a load. At the same time, the COP dropped from  $0.30$  to  $0.28$ . A key feature of thermoelectric systems is the inverse connection between cooling efficiency and ambient temperature. The Peltier module's hot-side temperature rose with the rising ambient temperature, increasing thermal resistance and decreasing heat transfer efficiency across the thermoelectric junction.

The theoretical underpinnings of thermoelectric refrigeration are consistent with the observed decrease in COP with rising ambient temperature. The temperature gradient across the module significantly affects a Peltier device's efficiency. The gadget undergoes back conduction of heat when the hot side overheats, which reduces the net cooling effect. TEC-based cooling systems typically exhibit COP values between 0.25 and 0.70, depending on heat sink design, module quality, and ambient operating conditions, according to recent studies published in journals such as *Energy Conversion and Management and Applied Thermal Engineering*. As a result, the current study is within the acceptable performance range documented in the literature. One of the main reasons for decreased thermoelectric performance in tropical climates, especially in sub-Saharan regions where ambient temperatures often exceed 35 °C, is the limited availability of passive heat sinks, according to research by [Ibrahim et al. \(2024\)](#).

Compared with the no-load condition, the loaded cooling condition consistently took longer to reach the desired refrigeration temperature. This behavior is anticipated, as the loads thermal mass increased refrigeration demand and necessitated additional heat extraction from the storage chamber. Over the course of the trial, the difference between the loaded and unloaded cooling times ranged from 8 to 11 minutes. This outcome demonstrates that the chamber's thermal storage capacity directly impacts refrigeration dynamics. Similar results were reported by [Saidur et al. \(2023\)](#), who noted that the increased sensible heat removal requirements associated with cooling load had a major impact on the transient performance of solar-powered refrigeration systems.

The energy balance study further validates the system's operating features. While producing an estimated 24 W of cooling capacity and rejecting about 84 W of heat to the environment, the thermoelectric module used about 60 W of electrical power. For an off-grid thermoelectric cooling system, the computed COP of 0.40 indicates a modest thermodynamic efficiency. Compared to thermoelectric systems, conventional vapor compression refrigerators often achieve COPs of 2-4, which are significantly higher. Nonetheless, thermoelectric refrigeration offers several practical benefits, including its small size, lack of refrigerants, silent operation, lower maintenance requirements, and compatibility with the integration of renewable energy sources.

Thermal management remains a major challenge in system design, as evidenced by the comparatively high hot-side temperature of roughly 52 °C recorded during operation. Effective heat rejection is crucial in thermoelectric refrigeration because any heat buildup on the hot side lowers the temperature differential needed for cooling. Therefore, the findings suggest that improved heat sink design, forced-air convection, liquid cooling, or phase-change thermal regulation could significantly improve system performance. Microchannel heat sinks and nanofluid-assisted cooling have been shown to increase thermoelectric COP by more than 20%, according to recent developments published in *Renewable Energy and*

*Case Studies in Thermal Engineering*. Advanced thermoelectric materials with higher figure-of-merit (ZT) values can significantly increase cooling efficiency and reduce electrical energy consumption, according to studies by [Pei et al. \(2024\)](#).

For the duration of the experiment, the photovoltaic subsystem supplied enough electrical energy to keep the refrigeration system running. Despite variations in solar irradiation, reliable operation was guaranteed by the combination of a 150 W monocrystalline solar panel and a 12 V, 100 Ah battery storage unit. The battery successfully compensated for brief drops in solar input caused by cloud cover and shifting air conditions. This illustrates how photovoltaic systems and thermoelectric refrigeration can be integrated for decentralized cooling applications. Solar-powered refrigeration solutions are becoming more crucial for vaccine preservation, agricultural storage, and rural healthcare delivery in areas with unstable electricity infrastructure, according to recent global energy reports.

According to the economic study, operating expenses are significantly lower than those of traditional grid- or diesel-powered refrigeration systems, despite the comparatively high initial capital cost of about ₦742,000. Compared to traditional refrigerators, which cost between ₦25,000 and ₦45,000 per month, and diesel-powered cooling systems, which cost between ₦60,000 and ₦120,000 per month, the anticipated monthly operating costs of ₦5,000 and ₦8,000 are favorable. This significant decrease in operating costs shows that solar thermoelectric refrigeration is economically viable in the long run. Eliminating reliance on fuel also lowers pollutants and greenhouse gas emissions. By reducing the carbon emissions associated with traditional refrigeration technologies, renewable energy-powered refrigeration systems significantly support climate mitigation initiatives, according to recent sustainability studies.

Another significant benefit of the thermoelectric refrigerator is its reduced maintenance requirements. Thermoelectric systems use solid-state heat transfer, unlike vapor-compression systems, which depend on compressors, lubricants, refrigerants, and moving mechanical parts. As a result, there is much less chance of mechanical failure. Because of this feature, thermoelectric refrigeration is especially useful in underserved and rural areas where technical maintenance services might not be available. The significance of decentralized solar cooling systems for achieving sustainable development goals in healthcare, food preservation, and rural electrification has been emphasized in recent publications by the International Renewable Energy Agency ([2024](#)).

The uncertainty analysis validates the accuracy and consistency of the experimental measurements. While the irradiance uncertainty of  $\pm 10 \text{ W/m}^2$  is adequate for outdoor solar studies, the temperature uncertainty of  $\pm 0.5 \text{ }^\circ\text{C}$  demonstrates high thermal measurement stability. The experimental technique yielded reliable performance estimates with minimal systematic error, as evidenced by a computed COP uncertainty of  $\pm 3\%$ . These levels of

Uncertainty support the validity of the provided findings and are deemed appropriate for experimental thermal engineering investigations.

Overall, the results demonstrate that solar-powered thermoelectric refrigeration is theoretically feasible for low-capacity, off-grid cooling applications. For rural and dispersed applications, the system's environmental friendliness, ease of operation, portability, and compatibility with renewable energy sources offer significant benefits, even though its efficiency is still lower than that of traditional refrigeration methods. The study also identifies key areas that require further optimization, particularly in thermoelectric material enhancement and thermal management. Therefore, to increase system COP and shorten cooling times under high ambient temperatures, future research should focus on advanced heat dissipation systems, hybrid photovoltaic-thermal integration, multi-stage thermoelectric modules, and intelligent control algorithms.

## CONCLUSION

Using photovoltaic energy and battery storage, this study experimentally assessed the performance of a solar-powered thermoelectric refrigeration system from August 2024 to June 2025 and showed that it could maintain refrigeration temperatures within the advised preservation range of 2–8 °C. The findings demonstrated that ambient temperature and solar Irradiance had a major impact on system performance. Higher ambient temperatures reduced system performance due to increased thermal loading and inadequate heat dissipation, whereas better cooling efficiency and shorter cooling times were observed during moderate weather. The coefficient of performance range, consistent with values frequently reported for small thermoelectric refrigeration systems, was 0.28 to 0.44. The thermoelectric module used about 60 W of electrical power to generate about 24 W of useful cooling, according to energy balance analysis, and the economic evaluation indicated that, despite its relatively high initial installation cost, the system might offer lower operating costs for off-grid applications. Overall, the results show that combining solar photovoltaic technology with thermoelectric refrigeration for decentralized cooling in remote locations is technically feasible. However, further advancements in thermoelectric efficiency and heat dissipation are still required to improve system performance and enable broader practical deployment.

## LIMITATIONS

Compared with traditional vapor-compression refrigeration systems, the system's cooling efficiency was comparatively poor, with COP values ranging from 0.28 to 0.44.

Variations in sun irradiance and ambient temperature have a significant impact on performance, particularly in the warmer months.

High ambient temperatures lengthened the time needed to reach goal temperatures and decreased cooling efficiency.

Higher hot-side temperatures resulted from the passive aluminum heat sink's insufficient heat dissipation at peak operating circumstances.

The small refrigeration chamber and low cooling load utilized in the experiment may not be representative of large-scale or commercial applications.

Neither battery degradation analysis nor long-term durability testing of thermoelectric modules was included in the study.

The study did not cover lifecycle cost analysis or long-term seasonal reliability evaluation.

Small experimental errors in temperature measurement, solar irradiance monitoring, and electrical parameter measurements may have marginally impacted the computed cooling capacity and COP values.

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