

Design and Experimental Investigation of a Portable Solar Refrigerator

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<https://doi.org/10.18280/ijht.440231>

ABSTRACT

Received: 25 December 2025

Revised: 5 April 2026

Accepted: 19 April 2026

Available online: 30 April 2026

Keywords:

solar photovoltaic, thermoelectric cooler, solar refrigerator

The objective of this study is to design and fabricate a mini solar photovoltaic thermoelectric refrigerator that operates directly on the sun (standalone) without requiring a battery for the transformation of vaccine to benefit Bedouin people living in remote areas where electricity is not yet available. The refrigerator may be used for the transportation of medications, vaccines, and biological items that require storage at low temperatures to prevent expiration. The principle of the solar refrigerator is based on the phenomenon of the Peltier effect to provide cold and hot sides on both sides of the device. The cold side is used to reduce the temperature of the refrigerator's interior, while the hot side is equipped with a heat sink and a fan to dissipate heat into the surroundings. The solar refrigerator was experimentally tested under varying solar radiation from 10:00 AM to 3:00 PM during the day to meet the cooling requirement. The finding indicated that the minimum temperature recorded for the cold side (T_c) was 5.8 °C during the first hour of the experiment, and the cold side temperature was proportional to solar intensity. The coefficient of performance of the solar fridge (COP) was obtained and found equal to 0.25, and the system of solar refrigerator could operate directly on the sun without a battery.

1. INTRODUCTION

A typical refrigerator is a device used to reduce the temperature of pharmaceuticals, food, and other substances by lowering the temperature of its surroundings, thereby preventing them from spoiling or expiring. It has become a crucial device for every family in every household. However, the traditional refrigerator works based on the vapour compression refrigeration cycle, which has side effects, although it introduces a cycle with high efficiency. It was classified as a major contributor to an increase in the greenhouse effect [1]. Solar energy is considered free energy, friendly to the environment, and has recently gained great interest from researchers, in particular photovoltaic solar cells [2-5]. A thermoelectric is a small device made from semiconductors connected electrically in series and thermally in parallel, characterised by a friendly environment, no maintenance needed, and working without moving parts or sounds, working either as a thermoelectric generator (TEG) [6] or thermoelectric cooler (TEC) [7]. TEC work on solar energy offers a good competitive alternative to traditional refrigerators, although it has low performance either in large size [8] or mini size [9]. Nowadays, the transportation of biological items, such as blood, serum, saliva, tissue, and organ samples, to conduct experiments or clinical studies [10, 11] has caught the interest of researchers due to the impact of temperature and other environmental conditions. Swastika

Maity et al. [11] manufactured a small portable fridge to maintain the temperature inside the cabinet between 2–8 °C. The Emvolio was used for the transportation and storage of biologicals, maintained a constant temperature, and enabled efficient preclinical studies. Wang et al. [12] investigated the process of designing a thermoelectric cooling unit based on the humidity, cooling capacity, and thermal effect on the performance of cooling. The theoretical results presented that there was a linear relationship between temperature and cooling performance, while the effect of humidity was nonlinear.

According to the literature, many researchers have investigated a solar PV-powered thermoelectric refrigerator that utilises a battery for charging and discharging via photovoltaics [7-18].

The primary objective of this study is to introduce a non-conventional solar refrigerator that can be used in various locations without requiring a battery and to study the effect of solar radiation on the cold side temperature. Therefore, a portable solar PV-thermoelectric refrigerator was designed and manufactured to explore the impact of solar radiation on the cold side temperature of the solar PV thermoelectric refrigerator, which can operate without a battery during the day. The purpose is to develop a novel, portable device for the storage and transportation of biological samples for short time application. Also, to reduce the cost by getting rid of the dependency on a battery.

2. PELTIER DEVICE

The principle of the Peltier device is basically using the Peltier effect to create a temperature difference across it [19], and it has many applications, one of which is making a small refrigerator. The performance of the device is dependent on the figure of merit which is property related to the material of the Peltier device and define as $ZT = \alpha^2 T / \rho \kappa$ [19], where T is the temperature of the cold side α is the Seebeck coefficient, ρ is the electrical resistivity and κ is the thermal conductivity of the semiconductor of the Peltier device usually bismuth telluride is used.

3. EXPERIMENT

The solar fridge is shown photographically and schematically in Figures 1 and 2, respectively, with dimensions 16 cm × 14 cm × 6 cm and an inside capacity of 0.5 liters. The main components of the solar thermoelectric fridge included: solar cells, a stainless steel box inside a plastic container (which works as an insulator to maintain the temperature inside the solar fridge) called a fridge cabinet, two aluminium heat sinks, a cooling fan, and a TEC known as a Peltier device.

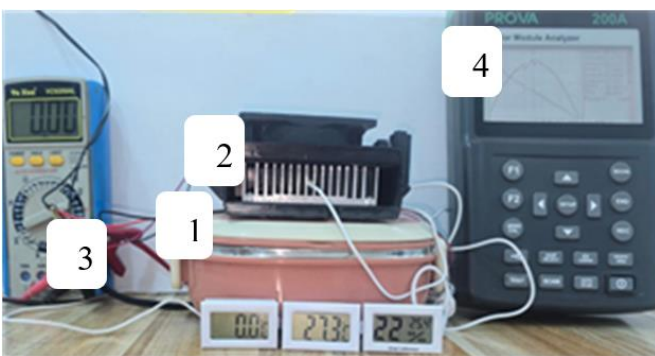
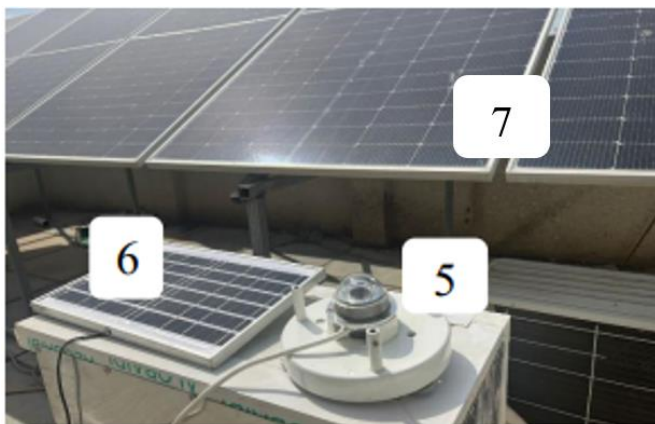


Figure 1. Experimental setup

Notes: 1. Solar refrigerator; 2. Heat sink for cold side; 3. Multimeter; 4. Photovoltaic analyzer; 5. Photovoltaic; 6. Pyranometer; 7. Temperature sensor.

The design procedure included selecting a single TEC, a cooling fan, and matching a proper photovoltaic for them. The maximum voltage for the TEC was 3.8 V, while the electric fan could operate at 2 V. So, the total voltage consumed by the solar refrigerator was less than the voltage produced by the photovoltaic module. The dimensions of the TEC used in the experiment were 4 cm × 4 cm × 0.4 cm. The TEC is operated

directly by the electric power generated from photovoltaic solar cells. The characterisation of the solar cells used in this study is presented in Table 1.

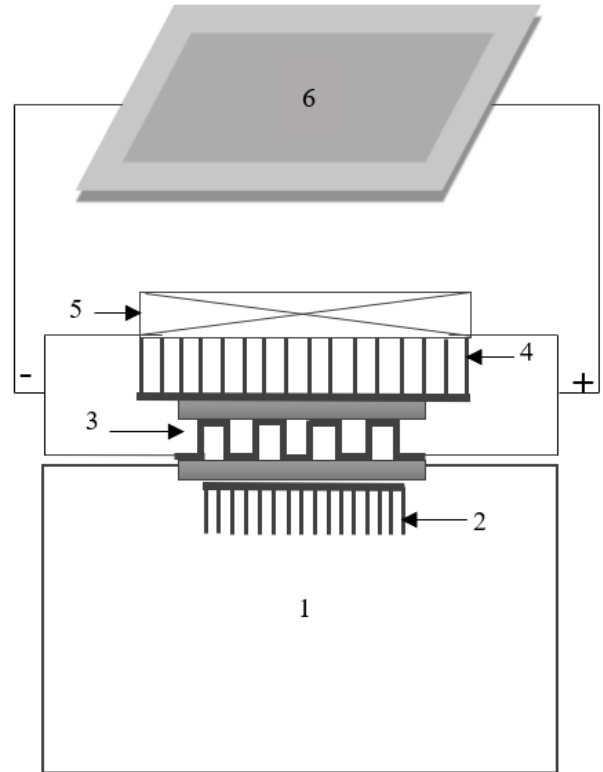


Figure 2. Schematic diagram

Notes: 1. Solar refrigerator; 2. Heat sink for cold side; 3. Peltier device; 4. Heat sink for hot side; 5. Electric fan; 6. Photovoltaic.

Table 1. The characterisation of photovoltaic

No.	Parameter	Value
1	Dimensions	33 cm × 15 cm × 0.3 cm
2	Maximum power	3.3 W
3	Open circuit voltage	7.4 V
4	Closed circuit current	1.4 A
5	Efficiency	8.6%
6	Number of cells	12
7	Area of each cell	15 cm × 34 cm

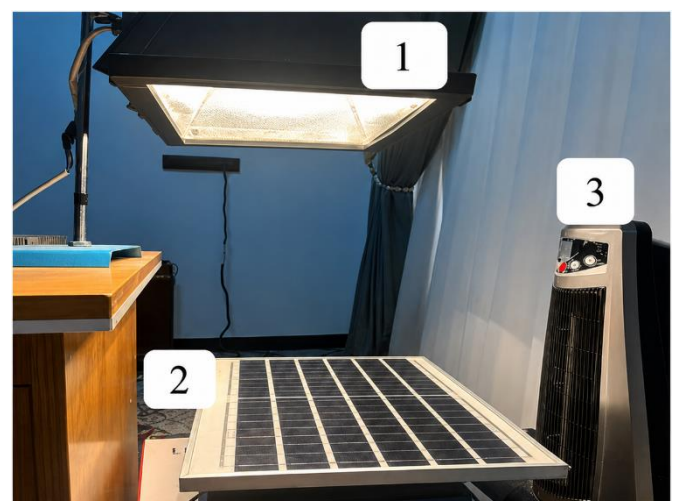


Figure 3. Indoor experiment for characterization of photovoltaic

Notes: 1. Solar simulator; 2. Photovoltaic; 3. Colling fan.

Two heat sinks were used in this study, one for the hot side and the other for the cold side. The one used for the cold side had the following dimensions: 80 mm × 80 mm × 15 mm with 16 fins, while the other used for the cold side had 60 mm × 60 mm × 10 mm dimensions with nine fins. The function of the fins was to increase the heat transfer rate from the cold side and the hot side away from the TEC. The fan attached to the hot side, powered by the solar cells, was used to dissipate heat into the environment, while the inside heat sink was used without an electric fan.

An indoor experiment under fixed solar intensity (1000 W/m²) and environmental conditions was performed to study the effect of increasing temperature on the photovoltaic, as shown in Figure 3. A cooling fan was used to control the temperature of the photovoltaic cells at different levels. The results were presented in Section 5.

4. METHODOLOGY

The experimental work began by connecting the positive wire of the solar cells to the positive wire of the TEC and the electric fan. At the same time, the negative wire of the solar cells was connected with the negative wire of the TEC and the fan. The experimental test began at 10:00 AM and continued for 5 hours on a sunny day.

The open circuit voltage, short-circuit current, maximum power output, and efficiency of photovoltaic solar cells (eff) were measured using a photovoltaic analyser of the Pravo-200A type, calibrated recently, as shown in Figure 1. The dates were recorded every hour. The solar intensity was measured by a Pyranometer solar radiation sensor, as shown in Figure 1. The cold side, hot side, and room temperature were measured using a temperature sensor, as shown in Figure 1. The temperature sensors used in this experiment were K-type with an accuracy of ±0.5 °C.

The room temperature was maintained at a constant level with a variation of ±1 °C by providing the room with an air conditioning (AC) system and setting the temperature to 25 °C. It is worth noting that the cold side of the TEC, which was connected to the heat sink, was positioned inside the solar fridge cabinet to cool the interior. In contrast, the hot side of the TEC was placed on top of the solar refrigerator to extract heat and dissipate it into the environment.

5. RESULTS AND DISCUSSION

The performance of the solar fridge planned to transfer the vaccine to a remote area is dependent basically on the cold side temperature of the TEC, and the cold side temperature is limited by the heat removed from the hot side and the voltage or current supply from the battery or the solar cells. The voltage, current, power, and efficiency of solar cells depend on the intensity of solar radiation and the temperature of the solar cells. So, the hot side of the TEC was almost constant and close to room temperature. Other parameters affecting the cold side temperature were investigated in this work, in case the solar fridge aimed to operate directly from the sun without using a battery. The photovoltaic was characterised firstly by the experiment presented in Figure 3 to study the effect of temperature on the maximum power output, current, and voltage. The results were presented in Figures 4 and 5. It is clear that there was a drop in maximum power output from 3.3

W to 2.3 W and in open circuit voltage from 7.4 V to 6.8 V, respectively, due to an increase in temperature.

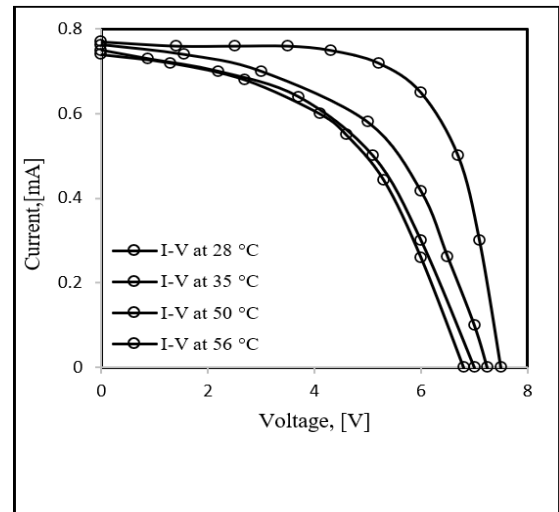


Figure 4. Current - Voltage curve at different temperatures

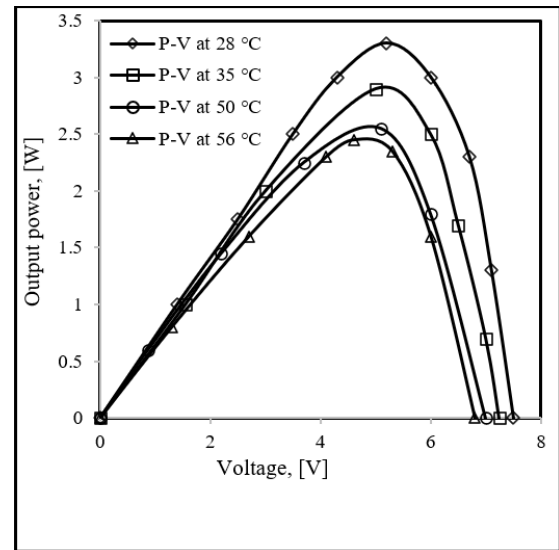


Figure 5. The output power of PV as a function of voltage at different temperatures

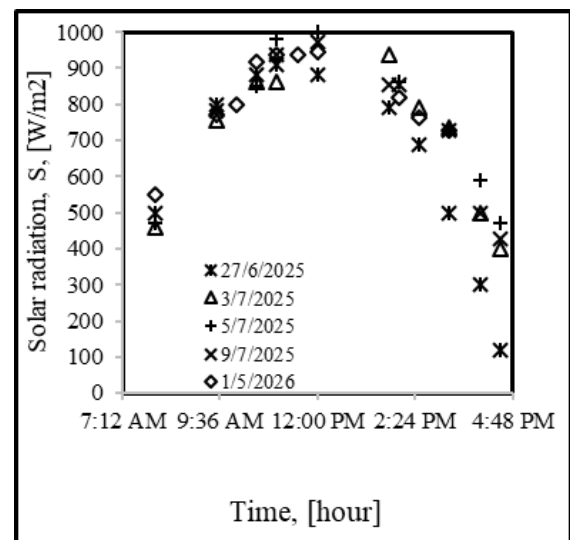


Figure 6. Solar radiation intensity for different sunny days during the year

Figure 6 illustrates the variation of solar radiation with time for different days during the year. It is worth noting that solar radiation fluctuates on different days, resulting from the sky being sunny on some days and cloudy on others. The experimental results demonstrated that the maximum solar radiation occurred between 11:30 AM and 12:30 PM on the days when the measurements were taken, at the location in Karbala city, Iraq, 32°58.962' N and 43°99.684' E.

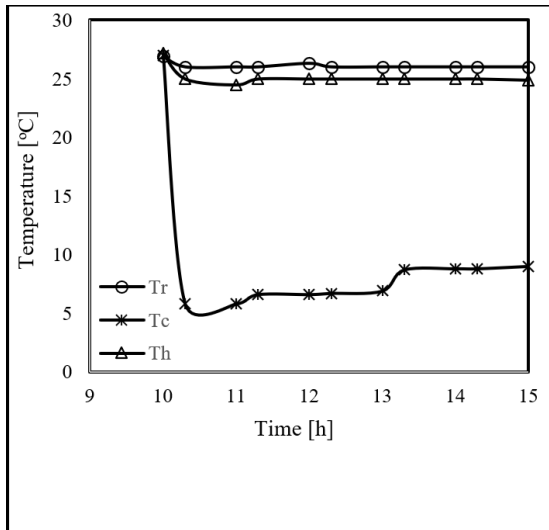


Figure 7. The variation of cold side temperature, hot side temperature, and room temperature with time

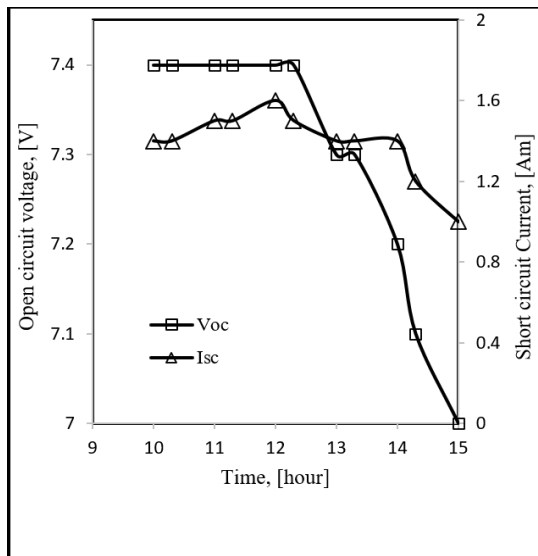


Figure 8. The variation of open circuit voltage and short circuit current with time

Figure 7 illustrates the change of cold side temperature, hot side temperature, and room temperature with time. The experiment began at 10:00 AM and was completed at 3:00 PM, when the sun rose, and the solar radiation was sufficient to operate the TEC. During the first hour of the experiment, the maximum power and open-circuit voltage produced the lowest cold-side temperature, approximately 5.8 °C. Figure 8 shows the open circuit voltage and closed circuit current of the photovoltaic with time, while Figure 9 presents the maximum power output of the photovoltaic with time. At the beginning, the maximum power output was 3.5 W and an open-circuit voltage of 7.4 V, while the short-circuit current was 1.4 A. It

is interesting to note that at the first hour of the experiment, the temperature of the solar cells was low, about 39 °C, and provided sufficient power and voltage to operate the TEC. After that, the temperature of the solar cells started to increase up to 56 °C, causing the maximum power to drop to 2.35 W due to the sensitivity of the maximum power output of photovoltaic cells to temperature, as illustrated in Figure 5. As a result, the cold side temperature rose from 5.8 °C to 9 °C. Figure 9 presents the variation of the maximum power output of the photovoltaic system with time. The percentage drop in maximum power output was 34% due to increasing the temperature over time.

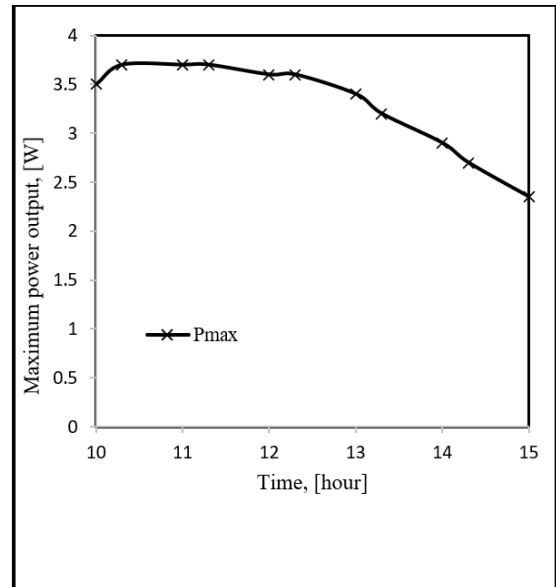


Figure 9. The maximum power output of the photovoltaic with time

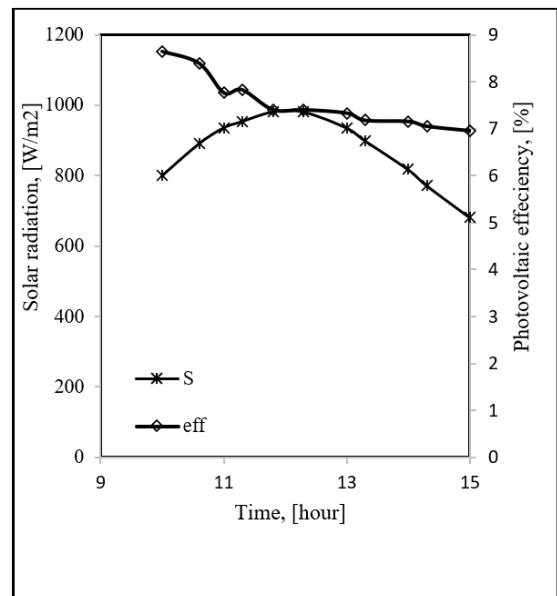


Figure 10. The effect of solar radiation on the photovoltaic efficiency over time

Figure 10 presents the effect of solar radiation on the photovoltaic efficiency. At 10 AM, the efficiency of the photovoltaic was 8.6%, then started to drop during the day because the temperature of the photovoltaic increased with time, and then the maximum power output decreased, as

explained in Figure 9. Figure 11 shows the effect of solar radiation on the cold side temperature during the day (from 10 AM to 3 PM). Increasing solar radiation caused a decrease in the cold side temperature. Also, the performance of the solar refrigerator is limited by the efficiency of the photovoltaic and the TEC. However, the cold side temperature is still in an acceptable range to maintain the inside temperature of the solar fridge box and serve the vaccine inside it.

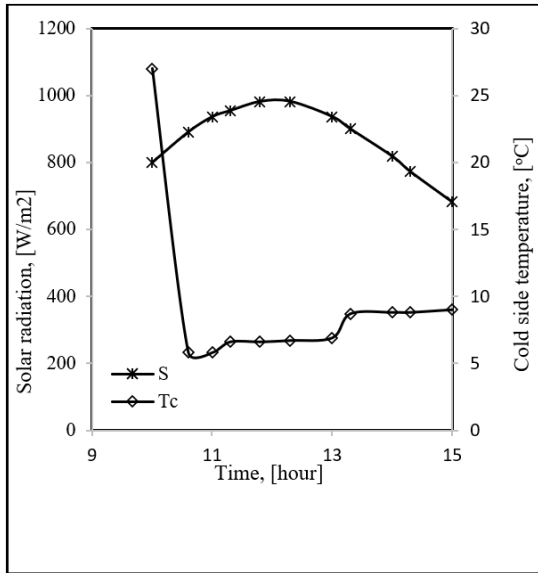


Figure 11. The effect of solar radiation on the code side temperature with time

In summary, the cold side temperature is proportional to solar intensity and the efficiency of solar cells. A coefficient of performance was calculated by dividing the heat transfer of cooling by the total power input, and the results were presented and compared in Table 2.

Table 2. A comparison between experimental results of the cold side temperature of the current work and different works in the literature

References	Period [Minute]	Minimum and Maximum Temperature on Both TEC Sides [°C]	Coefficient of Performance (COP)
Moria et al. [20]	165	10.6 and 65	0.5
Jugsujinda et al. [21]	---	-4.2 and 30	0.65
Ykrelef et al. [22]	60	1.6 and 19.6	0.9
Abdul-Wahab et al. [23]	42	-4.9 and 21.5	0.16
Manikandan et al. [24]	8	12 and 30	0.3
Current work	60	5.8 and 27	0.25

6. UNCERTAINTY ANALYSIS

A calculation has been done to calculate the standard deviation and uncertainty of the experimental results by using the following formulas [25].

$$x_m = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

$$V = \frac{1}{n} \sum_{i=1}^n (x_i^n - x_m^n) \quad (2)$$

$$s = \sqrt{V} \quad (3)$$

$$U = \sqrt{\sum_{i=1}^R a_i^2 x S^2} \quad (4)$$

where,

x_m and x_i are the mean and the specific observations, respectively. The total number of observations is represented by n , while a is the precision. The uncertainty and standard deviation, U and s , respectively.

The procedure of calculating the standard deviation (S) and uncertainty (U) was started by calculating the mean of three different measurements of all variables presented in Table 3. After that, the deviation from the mean was calculated (V), and then the standard deviation and uncertainty were calculated. The results of the calculation were solar radiation (S), open circuit voltage (V_{oc}), short circuit current (I_{sc}), maximum power output (P_{max}), hot side (T_h), and cold side (T_c) temperatures, which were presented in Table 3.

Table 3. The standard deviation and uncertainty calculations

Parameters	V	s	U
G	12.920	3.594	1.607
V_{oc}	0.018	0.134	0.060
I_{sc}	0.061	0.247	0.110
P_{max}	0.388	0.706	0.315
T_h	0.143	0.378	0.169
T_c	0.116	0.341	0.152

7. CONCLUSIONS

The following conclusions were made during the investigation of the experimental work of the solar fridge operating directly on the sun:

- The minimum cold side temperature reached 5.8 °C during the first hour of operation, from 10:00–11:00 AM, and then began to increase as the temperature of the solar cells rose, which affected the voltage, power, and efficiency of photovoltaic solar cells.
- The reduce in cold side temperature of the TEC increases directly with increasing solar radiation and decreases with decreasing solar radiation.
- A solar refrigerator that operates directly by the sun could be used to transport vaccines in remote areas of sunny countries, and could operate for five hours from 10:00 AM to 3:00 PM without a battery, maintaining a temperature between 5.8 °C and 9 °C.
- The coefficient of performance of the solar refrigerator was calculated and compared with other work.
- The challenge facing the solar refrigerator is reducing the cold side temperature, which is influenced by factors such as TEC performance, solar radiation, photovoltaic performance, and environmental

conditions.

A significant development in performance can be achieved by introducing photovoltaic solar cells and a TEC with high performance.

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NOMENCLATURE

I	current, A
I _{sc}	short circuit current, A
L	liter
κ	thermal conductivity
P	power, W
P _{max}	maximum power output, W

PV	photovoltaic
S	solar radiation, W/m ²
s	standard deviation
St	standard deviation
T	temperature, °C
T _C	cold side temperature, °C
TE	thermoelectric
TEG	thermoelectric generator
TEC	thermoelectric cooler
T _H	hot side temperature, °C
T _r	room temperature, °C
T _{amb}	ambient temperature, °C
U	uncertainty
V	voltage
V _{OC}	open circuit voltage, V
eff	photovoltaic efficiency
W	watt
COP	coefficient of performance
ZT	figure of merit

Greek letters

α	Seebeck coefficient, V/K
ρ	electrical resistivity