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Experimental Assessment of Cooling Performance of a Portable Solar-Powered Thermoelectric Cooler

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A B S T R A C T

Portable cooling systems powered by renewable energy are of interest for outdoor applications where conventional refrigeration is inconvenient. This study experimentally assesses the practical cooling performance of a portable solar-powered thermoelectric cooler based on cooling time and sustained cooling duration. The prototype has external dimensions of 400 mm × 400 mm × 350 mm and was designed for a nominal temperature range of 10–20 °C using a 100 W solar energy source. Cooling performance was evaluated using food and beverage loads and compared with a common cooler box. Three recorded trials were used for each load category. The portable solar cooler required an average of 85 min to cool the food samples and 34 min for drinks, whereas the common cooler required 60 min and 25 min, respectively. Although the prototype exhibited a slower pull-down time, its cooling duration was approximately 8 h compared with 3 h for the common cooler box. The results, therefore, indicate a trade-off between initial cooling rate and sustained temperature holding. The study contributes an experimentally based performance assessment of a low-cost solar-assisted thermoelectric cooling configuration and identifies thermal insulation, heat rejection and enclosure sealing as key areas for further improvement.

K E Y W O R D S : Solar Cooling; Thermoelectric Cooler; Peltier Module; Portable Cooler; Photovoltaic Energy

1. INTRODUCTION

Portable refrigeration is increasingly relevant to outdoor activities, mobile food handling and applications in locations where conventional electrical refrigeration is inconvenient and unavailable. The main traditional solution for these scenarios is the insulated cooler, whose cooling performance relies entirely on stored ice and fluctuates sharply due to multiple factors, including initial thermal conditions, ice storage volume, ambient temperature, frequency of box openings, and the insulation quality of the cooler body. The cited literature notes that cold chain scenarios must strictly adhere to compliant time-temperature profiles; any temperature deviation will accelerate product spoilage and irreversibly damage commodity quality.

To address the shortcomings of traditional solutions, thermoelectric cooling technology has emerged as a viable alternative. Solar-powered thermoelectric cooling combines photovoltaic energy conversion with solid-state heat pumping and can operate without the refrigerant circuit and compressor used in conventional vapour-compression systems. The technology is attractive for portable applications because thermoelectric modules are compact, refrigerant-free, and electrically controllable [1]-[5].

The operating principle is based on the Peltier effect: electrical current through a thermoelectric module transfers heat from the cold side to the hot side. Consequently, the cooling performance is strongly affected by the hot-side heat rejection, the temperature difference across the module, the thermal contact resistance, the insulation, and the electrical operating conditions [1], [2]. Recent reviews show that the performance of solar photovoltaic thermoelectric coolers depends substantially on solar irradiance and the hot- and cold-side temperature difference, and that improvements in heat sinks and thermal interfaces can increase performance [1].

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Experimental studies have demonstrated the feasibility of portable solar thermoelectric refrigeration. Rahman et al. reported a portable solar thermoelectric refrigerator capable of cooling the cold chamber to approximately 10 °C [3]. Biswas and Kandasamy developed and experimentally evaluated a portable, solar-powered thermoelectric cooler for perishable foods using a thermoelectric module, heat sinks, fans, a photovoltaic panel, a battery, and a charge controller [4]. More recent work has investigated direct solar operation, temperature control and system-level performance, including a 2023 solar thermoelectric refrigerator study in which two Peltier modules and internal fans reduced the cabin temperature to 4.1 °C in 44 min under the reported test conditions [5]. A 2024 study further showed that solar tracking can substantially influence the coefficient of performance by increasing the available solar input [6].

In addition, more recent work has investigated direct solar operation, temperature control and system-level performance. Hee and Jumaat [7] developed a solar-powered portable cooler/warmer, while Nohay et al. [8] further demonstrated the application of portable solar thermoelectric refrigeration for insulin storage, highlighting the potential of this technology for applications requiring controlled temperature conditions. Yusof et al. [9] also investigated the design and analysis of a portable solar-powered refrigerator unit. These studies demonstrate the continued development of compact solar-assisted refrigeration systems for portable applications.

Despite these developments, performance results are highly dependent on enclosure size, thermal insulation, product load, heat-rejection configuration, and operating conditions. Consequently, results from one prototype cannot be transferred directly to another. The present study provides a useful case study of a compact cooler developed with a 100 W solar source, a single TEC1-12703 module, forced heat rejection and a 400 mm × 400 mm × 350 mm enclosure. The research gap addressed here is therefore the systematic interpretation of the reported experimental cooling times and holding duration in relation to the cooling-system configuration and known thermoelectric performance limitations.

The objective of this study is to evaluate the cooling performance of the fabricated portable solar cooler by: (i) quantifying the cooling time for food and beverage loads; (ii) comparing the measured cooling times with those of a common cooler box; and (iii) evaluating the time duration to maintain a low temperature. The contribution is an experimentally grounded assessment of the performance trade-off between pull-down time and sustained cooling in a low-cost portable solar thermoelectric configuration.

2. METHODOLOGY

2.1 System design and configuration

The prototype was designed in Autodesk Inventor and fabricated as a portable enclosure measuring 400 mm × 400 mm × 350 mm. It specifies a target operating temperature range of 10–20 °C and a 100 W solar energy source. Table 1 summarises the specifications for the developed prototype. The enclosure was constructed primarily from PVC board. Internal insulation comprised a polystyrene layer and an aluminium layer. The cooling system consisted of a TEC1-12703 thermoelectric module rated at 12 V and 3 A, a heat sink and fan for hot-side heat rejection, a temperature controller, a solar charge controller, a DC–DC step-down module and a 12 V lithium battery. The system was designed so that photovoltaic energy could supply the cooling system and charge the battery.

2.2 Fabrication

Figure 1 shows the final design chosen for this prototype. The overall dimensions for the final concept were 400 mm × 400 mm × 350 mm. Meanwhile, Figure 2 shows a developed portable solar cooler box. The steps included in the fabrication process were cutting, drilling, soldering, and hot-glue bonding. The PVC board was cut and assembled according to the CAD dimensions to fabricate the device's outer shell. After that, the installation of the internal insulation layer, the setup of cooling components, and the series wiring of all electrical components were subsequently completed. The electrical components consisted of the solar panel, charge controller, battery, temperature controller, thermoelectric module and fan. The temperature controller was included to regulate operation around the selected
temperature set point. Finally, the prototype was assembled and inspected before testing.

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Table 1. Main prototype specifications.

Parameter	Specification
Enclosure dimensions	400 mm × 400 mm × 350 mm
Nominal temperature range	10–20 °C
Solar energy source	100 W
Thermoelectric module	TEC1-12703, 12 V, 3 A
Battery	12 V lithium battery
Main enclosure material	PVC board
Insulation	Polystyrene and aluminium layers
Cooling components	Peltier module, heat sink and fan
Control components	Temperature controller, solar charge controller and DC–DC step-down module
Listed material cost	RM292.59

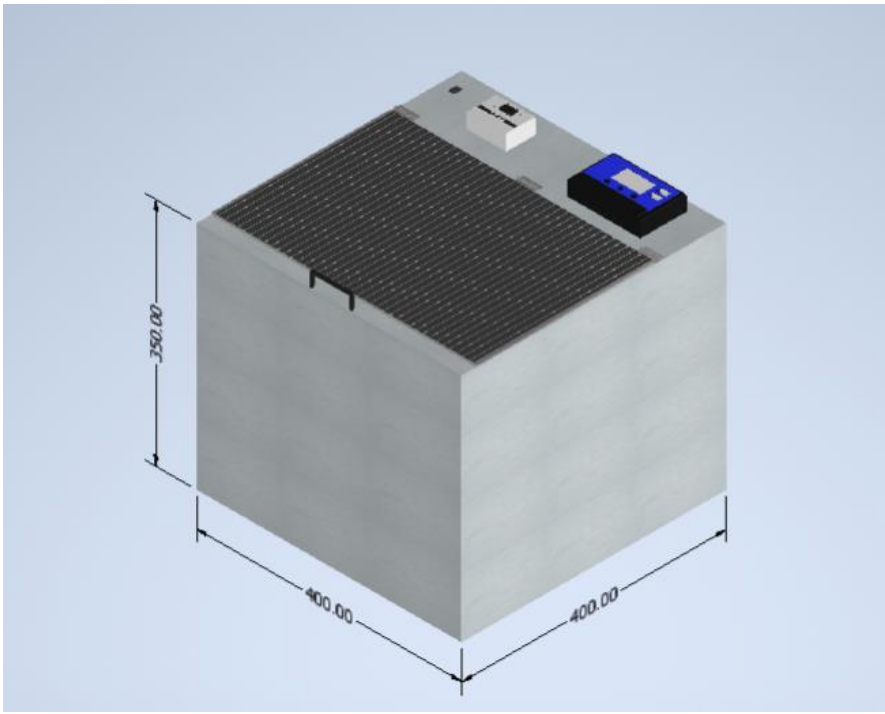


Figure 1. CAD model of the solar cooler box with overall dimensions.

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Figure 2. Fabricated portable solar cooler prototype.

2.3 Experimental evaluation

The experimental evaluation was designed to assess the practical cooling performance of the developed portable solar-powered thermoelectric cooler. The assessment focused on cooling time and sustained cooling duration rather than a complete thermodynamic characterisation of the refrigeration system. Cooling performance was evaluated by comparing the developed portable solar cooler with a common cooler box (Mr DIY brand). Two types of samples, food and beverages, were used to test the cooling duration for both coolers. The food and beverage samples used in this experiment were fruits and canned drinks. Three trial values for food and three trial values for beverages were recorded for each cooler type. The averages were calculated from these three recorded trials. A second comparison assessed the reported duration of cooling. The recorded average cooling time was 3 h for the common cooler box using ice and 8 h for the portable solar cooler.

2.4 Data analysis

Cooling-time performance was compared using the arithmetic means of the three recorded trials. Relative differences were calculated as the difference between the prototype and the common cooler average divided by the common cooler average. The reported cooling-duration improvement was calculated as (8 − 3)/3 × 100%, giving a 166.7% longer reported duration, or approximately 2.67 times the duration of the common cooler.

3. RESULTS AND DISCUSSION

3.1 Cooling-time performance

Table 2. Cooling time comparison between the portable solar cooler and a standard cooler box.

Cooler type	Load	Trial 1 (min)	Trial 2 (min)	Trial 3 (min)	Average (min)
Portable solar cooler	Food	90	80	85	85
Portable solar cooler	Drinks	30	35	38	34
Common cooler box	Food	60	55	65	60
Common cooler box	Drinks	25	23	28	25

Table 2 shows a cooling-time comparison between the portable solar cooler and a common cooler box. The cooling temperature set in this experiment was below 20 ^{0}C. For the portable solar cooler, food cooling times were 90, 80, and 85 min, yielding an average of 85 min; drink cooling times were 30, 35, and 38 min, yielding an average of

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approximately 34 min. Meanwhile, for the common cooler box, food cooling times were 60, 55, and 65 min, yielding an average of 60 min; drink cooling times were 25, 23, and 28 min, yielding an average of approximately 25 min.

The portable solar cooler required an average of 85 min to cool the food load, compared with 60 min for the common cooler, representing a 41.7% longer pull-down time. For drinks, the portable system required approximately 34 min compared with 25 min for the common cooler, representing a 36.0% longer cooling time. The prototype, therefore, did not provide a faster initial cooling rate under the reported test conditions.

The slower pull-down performance is consistent with the thermal behaviour expected from a thermoelectric system in a relatively large enclosure. A single 12 V, 3 A TEC module has limited heat-pumping capacity, while the enclosure's dimensions provide comparatively large thermal mass and internal volume. In addition, the thermoelectric module must reject both the heat removed from the cooled compartment and the electrical input power as heat at the hot side. Literature identifies hot-side heat rejection and the temperature difference across the thermoelectric module as major determinants of performance [1], [5]. The present result is therefore not evidence that the Peltier system is ineffective; rather, it indicates that the selected configuration prioritised portability and sustained cooling over rapid pull-down.

The results are also, in principle, comparable to previous experimental studies that report substantial cooling times for solar thermoelectric prototypes. Abdul-Wahab et al. reduced the temperature of a prototype refrigerator from 27 °C to 5 °C in approximately 44 min using multiple thermoelectric modules and heat sinks [10], while Alam et al. reported a cabin temperature of 4.1 °C after 44 min for a two-module solar thermoelectric refrigerator with internal fans [5]. However, direct numerical comparison should be treated with caution because the present study used a different enclosure, module count, load, temperature criterion, and test protocol. The important observation is that cooling time is highly configuration-dependent.

3.2 Sustained cooling duration

Table 3. Cooling duration comparison.

System	Cooling method	Reported duration (h)
Common cooler box	Ice	3
Portable solar cooler	Solar / AC current	8

Table 3 presents the comparison of cooling duration between the portable solar cooler and the common cooler box. Although the portable cooler cooled the test loads more slowly, it can maintain the low-temperature range (≈ 10- 20 °C) for 8 h, compared with 3 h for the common cooler box. This corresponds to an additional 5 h and a 166.7% increase relative to the reported duration of the common cooler. Expressed as a ratio, the prototype duration was approximately 2.67 times longer.

This distinction is important when evaluating the system. A cooler should not be judged only by the time required to reduce the initial product temperature. For outdoor applications, the ability to maintain a lower temperature over an extended period can be equally important. The prototype's combination of active thermoelectric cooling, temperature control, battery storage, and photovoltaic input provides continuous active cooling rather than relying exclusively on melting stored ice. Similar solar thermoelectric systems have demonstrated the feasibility of maintaining low temperatures over extended operating periods when electrical storage and control are incorporated [3], [4], [11].

However, the 8 h value should be interpreted as a prototype-level holding-duration result rather than a universal operating-time specification. Solar availability, battery state of charge, ambient temperature, enclosure heat leakage, and the frequency of lid opening can substantially affect the operating duration. The previous study by R. Saidur and colleagues identifies frequent openings and inadequate enclosure sealing as causes of rapid temperature disturbances and recommends a rubber seal and thicker insulation [12].

3.3 Engineering interpretation and improvement priorities

The experimental evidence points to three principal performance limitations. First, the heat rejection assembly requires improvement. The hot-side heat sink and fan must remove heat efficiently; otherwise, the hot-side temperature increases, reducing the effective temperature lift available from the thermoelectric module. Second, the

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thermal resistance of the enclosure should be reduced through thicker or better-designed insulation and improved sealing. Third, the cooling capacity should be matched to the enclosure volume and product load.

Recent research supports this design direction. Kaiprath and Kumar identify thermal interfaces, heat sinks and the hot-side thermal management system as important routes for improving solar thermoelectric cooler performance [1]. Qamar et al. further demonstrate that the coefficient of performance of a solar thermoelectric refrigerator is sensitive to solar irradiance, input power and solar collection strategy [6]. A recent review also emphasises efficiency improvement and operational optimisation as important considerations for solar PV-powered refrigeration [13]. Thus, future testing of the present prototype should measure solar irradiance, photovoltaic voltage and current, thermoelectric voltage and current, hot- and cold-side temperatures, internal air temperature, ambient temperature and battery state of charge simultaneously.

3.4 Comparison with existing research

Table 4 summarises the comparison of the developed solar cooler box with several previous studies. Overall, previous research demonstrates that solar-powered thermoelectric refrigeration is feasible, with reported cooling temperatures ranging from approximately 4.1°C to 10°C depending on the system configuration, the number of thermoelectric modules, and the solar PV arrangement.

Meanwhile, the present study uses a simpler and lower-cost configuration consisting of a single TEC1-12703 module, a 100 W solar panel, a battery, and a controlled enclosure. Although its initial cooling time is longer (85 min for food and 34 min for drinks) than some previous systems, its main advantage is the ability to provide sustained cooling for up to 8 hours. Therefore, the present prototype is particularly relevant for portable outdoor food and beverage storage, where longer cooling duration and energy independence are more important than rapid pull-down cooling.

Table 4. Comparison with existing research.

Study	Configuration	Reported performance	Relevance to the present study
Dai et al. [11]	Solar-cell-driven thermoelectric refrigerator with battery support	Maintained 5–10 °C	Demonstrates the feasibility of solar/battery thermoelectric refrigeration.
Abdul-Wahab et al. [10]	Portable solar refrigerator with multiple TEMs, heat sinks and fans	27 °C to 5 °C in ≈44 min	Shows the importance of module count and heat rejection.
Rahman et al. [3]	Portable solar thermoelectric refrigerator	Cold chamber designed for ≈10 °C	Supports portable solar thermoelectric application.
Biswas & Kandasamy [4]	Portable solar thermoelectric cooler for perishables	Experimental evaluation with and without product load	Closely related to food-storage application.
Alam et al. [5]	Two-module solar thermoelectric refrigerator with internal fans	4.1 °C in 44 min	Shows effect of multiple modules and internal air circulation.
Qamar et al. [6]	Solar-powered thermoelectric refrigerator with fixed/tracking PV	Performance varied with solar collection configuration	Shows strong dependence on solar input and PV configuration.
The present study	Single TEC1-12703, 100 W solar source, battery and	Food: 85 min; drinks: 34 min;	Demonstrates a low-cost prototype with slower pull-down but longer

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	controlled enclosure	Sustained cooling duration: 8 h	holding duration.

4. CONCLUSION

This study evaluated the cooling performance of a portable solar-powered thermoelectric cooler fabricated using a TEC1-12703 module, photovoltaic power, battery storage, forced heat rejection and temperature control. The first performance objective was addressed by quantifying cooling times: the portable solar cooler required average times of 85 min for food and 34 min for drinks, compared with 60 and 25 min for the common cooler box. The prototype, therefore, exhibited approximately 41.7% slower initial cooling for food and 36.0% for drinks. The second major finding concerns sustained cooling. This study records an average cooling duration of 8 h for the portable solar cooler compared with 3 h for the common cooler box. The recorded duration is therefore 5 h longer, equivalent to a 166.7% increase or approximately 2.67 times the duration of the common cooler. The central performance finding is consequently a trade-off: the active solar thermoelectric system did not cool the test loads as rapidly as the common ice-based cooler, but it provided a substantially longer reported cooling duration.

The findings indicate that the developed prototype is capable of providing active cooling for portable outdoor applications. However, the present study should not be interpreted as a complete thermodynamic or energy-performance evaluation of the thermoelectric refrigeration system. Cooling capacity, TEC electrical power, hot- and cold-side temperatures, temperature lift, heat rejection, coefficient of performance (COP), solar irradiance, photovoltaic output and battery energy balance were not measured simultaneously during the original experimental programme. Consequently, these parameters are not calculated or estimated in the present study. Future development should therefore focus on improving the hot-side heat-rejection system, enclosure insulation and sealing, and matching the thermoelectric cooling capacity to the enclosure volume and intended load. Future experimental work should incorporate simultaneous thermal, electrical and solar measurements to enable a more comprehensive assessment of cooling capacity, energy consumption, COP and overall system efficiency. Overall, the study demonstrates the practical cooling behaviour of a low-cost portable solar-powered thermoelectric cooler and provides experimental evidence of the trade-off between initial pull-down cooling time and sustained cooling duration.

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AUTHORS' CONTRIBUTIONS

H.P.L. and **L.C.** contributed to the conceptualization of the study, methodology development, supervision, formal analysis, data validation, as well as writing the original draft and reviewing the manuscript. **L.C.** and **I.R.B.A.** were responsible for investigation, data curation, formal analysis, data visualization, and preparation of the original draft. Meanwhile, **H.P.L**. and **I.R.B.A.** contributed to conceptualization, methodology development, project supervision, project administration, and manuscript review and editing.

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