Design And Performance Evaluation of a Solar PV-Based Peltier Air-Cooling System for Localized Cooling Applications

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***Abstract*—This paper presents the design and experimental performance analysis of a solar photovoltaic (PV)-powered thermoelectric air-conditioning system using Peltier modules. The system integrates a PV panel, DC-DC power converter, Peltier cooling module, heat sink, fan, temperature and humidity sensor, and Arduino-based control. The Peltier module provides refrigerant-free cooling, while the heat sink and fan dissipate heat from the hot side. The system performance is evaluated in terms of PV power, Thermoelectric Cooling (TEC) power, temperature reduction, and relative humidity under varying solar irradiance. The proposed system offers a compact, environmentally friendly, and renewable-energy-based solution for localised cooling applications.**

***Index Terms*—Arduino, Peltier module, solar PV, thermoelectric cooler.**

I. INTRODUCTION

The increasing demand for air conditioning has become a major contributor to electrical energy consumption, particularly in regions experiencing high ambient temperatures and increasing cooling loads. Conventional vapour-compression air-conditioning systems generally require compressors, refrigerants, condensers, and evaporators, resulting in relatively high electrical consumption and increased mechanical complexity.

The integration of renewable-energy sources with alternative cooling technologies is therefore receiving increasing attention for reducing the environmental and energy impacts of conventional cooling systems [1], [2].

Thermoelectric cooling (TEC) is a solid-state cooling technology based on the Peltier effect, in which heat is absorbed at one surface of a thermoelectric module and rejected at the opposite surface when direct current is applied. Since a thermoelectric module has no compressor, refrigerant circulation, or major mechanical moving components, it provides a compact and controllable alternative for localized cooling applications [5], [10]. Recent reviews have highlighted the potential of thermoelectric cooling for applications requiring compact size, precise temperature control, low maintenance, and refrigerant-free operation [10].

The combination of solar photovoltaic (PV) generation and thermoelectric cooling is particularly attractive because both systems operate using electrical DC power. A PV panel can therefore supply a thermoelectric module through an appropriate DC-DC power-conditioning circuit, reducing the need for DC-AC conversion stages [10]. However, the variable nature of solar irradiation introduces challenges in maintaining a constant TEC operating condition. Consequently, appropriate PV-TEC power matching, maximum power point tracking (MPPT), thermal management, and control strategies are important for achieving satisfactory system performance [1], [10].

Recent experimental studies have demonstrated the feasibility of PV-powered thermoelectric cooling for buildings and localized cooling applications. Chandel *et al.* experimentally investigated a photovoltaic-powered thermoelectric solid-state cooling system and reported temperature reductions of approximately 5–16 °C under different solar loading conditions,

demonstrating the potential of PV-TEC systems for low-energy building applications [7]. Irshad *et al.* investigated photovoltaic thermoelectric air conditioning for personalized cooling in an arid climate and reported a maximum cooling capacity of 54.8 W with a COP of approximately 0.498 at a particular operating condition [6]. These results indicate that TEC systems can provide useful cooling but that their performance is strongly dependent on operating current, ambient conditions, and thermal management.

The thermal management of the hot side is one of the most important factors affecting thermoelectric cooling performance. Since the heat rejected by the hot side consists of both the heat absorbed from the cooled space and the electrical power supplied to the TEC, the heat rejection requirement can be expressed as

$$Q_h = Q_c + P_{TEC} \quad \ldots\ldots\ldots (1)$$

Where Q_h is the hot-side heat rejection, Q_c is the cooling capacity, and P_{TEC} is the electrical power consumed by the thermoelectric module. Therefore, an inadequate heat sink can increase the hot-side temperature and consequently reduce the cooling capacity and COP of the TEC. Recent studies have demonstrated that optimization of heat exchangers, thermal resistance, TEC structure, and operating conditions can significantly improve thermoelectric cooling performance [5], [8].

Zhang *et al.* developed an advanced sandwich-structured thermoelectric cooling and heating system and reported a cooling capacity of 588.82 W and a COP of 1.18 at a 500-W input condition, demonstrating the importance of thermal and structural optimization of TEC systems [5]. Similarly, Lv *et al.* investigated a system combining radiative cooling, photovoltaic generation, and thermoelectric cooling and reported a cooling power density of 93.48 W/m² with a COP of 0.64 under their reported operating conditions [8].

These studies demonstrate that combining thermoelectric cooling with renewable-energy and advanced thermal-management technologies can improve overall system performance.

Thermal energy storage can also improve the operation of solar-powered thermoelectric systems because photovoltaic power is strongly dependent on solar irradiation. Fenton *et al.* investigated solar-powered thermoelectric refrigeration integrated with phase-change material (PCM) and demonstrated the potential of thermal storage to extend cooling operation and reduce the effect of solar-power fluctuations [9]. Similarly, Ahmed *et al.* investigated a building cooling system incorporating photovoltaic panels, phase-change material, and thermoelectric coolers, demonstrating the potential benefits of integrating thermal storage with solar-powered thermoelectric cooling [4].

Recent developments have also investigated enhanced heat-transfer techniques. Bakthavatchalam *et al.* studied a photovoltaic thermoelectric air-conditioning system assisted by Nano fluid cooling and reported a cooling capacity of 571 W with a COP of 1.27 under their experimental conditions [3]. Such developments indicate that improvements in hot-side heat rejection can significantly influence the overall performance of TEC-based cooling systems.

Despite these developments, low coefficient of performance, solar-power intermittency, hot-side heat rejection, and limited cooling capacity remain important challenges for practical PV-TEC air-conditioning applications [1], [6], [10]. Advanced control techniques, MPPT-based power conditioning, thermal energy storage, improved heat exchangers, and intelligent energy-management strategies are therefore required for further performance enhancement. Recent research also emphasizes the importance of integrated optimization of thermoelectric materials, module configuration, thermal management, power electronics, and control systems [1].

In this work, a solar-powered air-conditioning system using Peltier thermoelectric modules is designed and developed for compact/localized cooling applications. The proposed system integrates a solar PV panel, DC power-conditioning circuit, Peltier thermoelectric cooling module, hot-side heat sink, forced-air fan, temperature and humidity sensor, Arduino Nano controller, 16×2 LCD, and switching/control circuitry. The Arduino-based controller continuously monitors temperature and humidity and controls the cooling system according to the predefined temperature threshold. The developed prototype is experimentally investigated to assess its temperature-control capability and provide a basis for further evaluation of PV power utilization, cooling capacity, and coefficient of performance.

The major contribution of this work is the development of a low-cost, compact, solar-powered thermoelectric cooling prototype with integrated temperature/humidity monitoring and automatic control, intended particularly for small-space and localized cooling applications.

The proposed architecture provides a practical platform for future implementation of MPPT, PWM-based TEC control, battery storage, IoT monitoring, and intelligent thermal-energy management.

II. RESEARCH METHODOLOGY

The proposed system consists of five principal subsystems:
Solar PV energy generation.
DC power conditioning.
Thermoelectric cooling.
Heat rejection and air circulation.
Monitoring and automatic control.

The complete system is shown conceptually in Fig. 1 below.

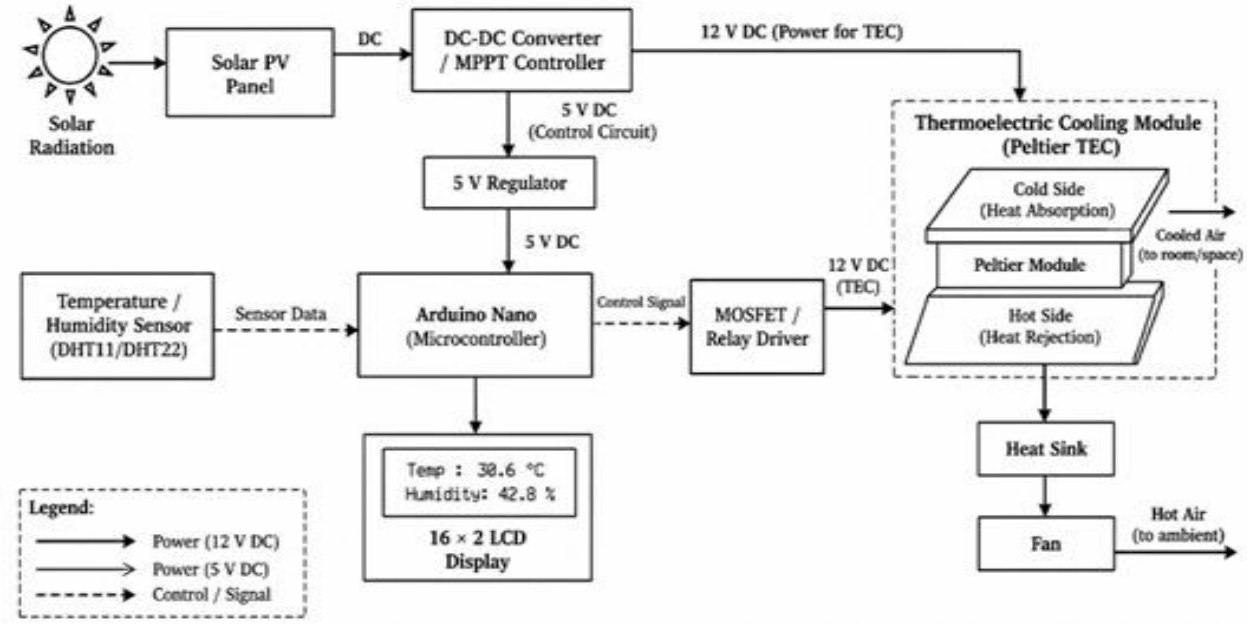


Fig. 1 Block Diagram

Working of the Solar PV-Powered Peltier Air-Conditioning System
Solar Energy Conversion: Solar radiation falls on the PV panel, which converts solar energy into DC electrical power.

DC-DC Conversion and MPPT: The DC-DC converter/MPPT controller regulates the PV output and provides suitable DC voltage levels. Approximately 12 V DC is supplied to the Peltier TEC and fan, while 5 V DC is supplied to the Arduino control circuit.
Temperature and Humidity Sensing: The DHT11/DHT22 sensor continuously measures the ambient temperature and relative humidity and sends the data to the Arduino Nano.

Control Action: The Arduino processes the sensor data and compares the measured temperature with a predefined temperature set point. It generates a control signal to operate the MOSFET/relay driver.

TEC and Fan Operation: The MOSFET/relay driver controls the power supplied to the thermoelectric cooler (TEC) and the DC fan. When cooling is required, the TEC is energized. Cooling and Heat Rejection: The cold side of the TEC absorbs heat from the air, producing cooled air that is directed toward the room or localized space. The heat generated at the hot side is transferred to the heat sink and removed by the fan to the surrounding atmosphere.
Display and Monitoring: The Arduino displays the measured temperature and humidity on the 16×2 LCD.

The system continuously monitors conditions and switches the TEC/fan ON or OFF according to the programmed temperature-control strategy.

III. HARDWARE COMPONENTS

TABLE I Major Hardware Components

Component	Proposed specification	Function
Solar PV panel	12-V nominal, 100 W	Solar energy generation
Peltier module	TEC1-12706 class, 12 V, up to ~6 A	Cooling
Arduino Nano	ATmega328P, 5 V, 16 MHz	Controller
LCD	16×2, 5 V	Display
Temperature sensor	DHT11/DHT22	Temperature measurement
Humidity sensor	DHT11/DHT22	Relative-humidity measurement
DC-DC converter	Input according to PV, regulated 12 V output	TEC power conditioning
5-V regulator	5 V, ≥1 A	Controller supply
MOSFET	Logic-level, low $R_{DS(ON)}$,≥15 A design margin	TEC switching
Fan	12 V DC	Hot-side heat rejection
Heat sink	High-performance aluminium	Hot-side thermal management
Relay	5-V coil, load rating selected for actual application	Auxiliary load switching
Buzzer	5 V	Alarm
LEDs	3/5 mm	Status indication
Battery, optional	12 V, selected according to backup requirement	Energy storage
Component	Proposed specification	Function
Solar PV panel	12-V nominal, 100 W design value	Solar energy generation
Peltier module	TEC1-12706 class, 12 V, up to ~6 A	Cooling
Arduino Nano	ATmega328P, 5 V, 16 MHz	Controller

IV. WORKING PRINCIPLE

The PV panel converts solar radiation into DC electricity:

$P_{PV} = V_{PV}\, I_{PV}$ ……. (2)

The generated power is conditioned by the DC-DC converter and supplied to the TEC and control circuit. The thermoelectric module absorbs heat at the cold side and rejects heat at the hot side.

A simplified thermoelectric heat-transfer model is:

$Q_c = \alpha I T_c - \frac{1}{2} I^2 R - K(T_h - T_c)$….. (3)

Where:

Q_c= cooling capacity,

α= effective Seebeck coefficient,

I= TEC current,

T_c= cold-side absolute temperature,

T_h= hot-side absolute temperature,

R= electrical resistance,

K = thermal conductance.

Electrical input power is approximately:

$P = VI$ ... (4)

The heat rejected at the hot side

$Q_h = Q_c + P_{TEC}$ ….. (5)

The co-efficient of performance is

$$COP_{system} = \frac{Q_c}{P_{TEC}} \text{ ... ... (6)}$$

For the complete system

$$COP_{system} = \frac{Q_c}{P_{TEC} + P_{fan} + P_{control}} \text{ ... ... (7)}$$

This system COP is more representative for evaluating the actual prototype than the TEC-module COP alone.

V. SOLAR PV SYSTEM DESIGN

For a representative 100W PV panel

$P_{PV} = 100W$

$V_{mp} = 18V$

$$I_{mp} = \frac{P_{PV}}{V_{mp}}$$

$I_{mp} = \frac{100}{18}$ =5.56A

Thus, a 100-W panel can theoretically provide approximately 5.56 A at 18 V under rated test conditions.

Actual PV output will vary with:
Solar irradiance
Cell temperature
Panel orientation
Shading
Dust
Cable losses
Converter efficiency
The literature confirms that solar irradiance strongly influences PV-TEC performance.

VI. PELTIER MODULE DESIGN

For a TEC1-12706-class module:
V_{TEC}=12V

$I_{TEC,max} = 6A$
Therefore
$P_{TEC,max} = V_{TEC}\ I_{TEC}$
$P_{TEC,max}$ = 12x6=72W

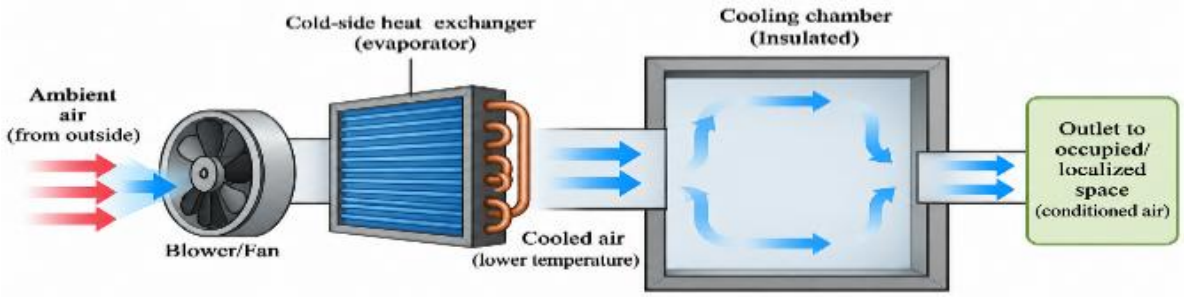
This is an electrical-input design estimate.
The hot-side heat rejection can be considerably greater than the cold-side cooling load because the electrical input power is also converted into heat.
$Q_c = 40W$
$P_{TEC} = 60W$
$Q_h = Q_c + P_{TEC}$
= 40W+60W=100W
Consequently, the hot-side heat sink should be capable of rejecting approximately 100 W under that operating condition.

VII. THERMAL MANAGEMENT

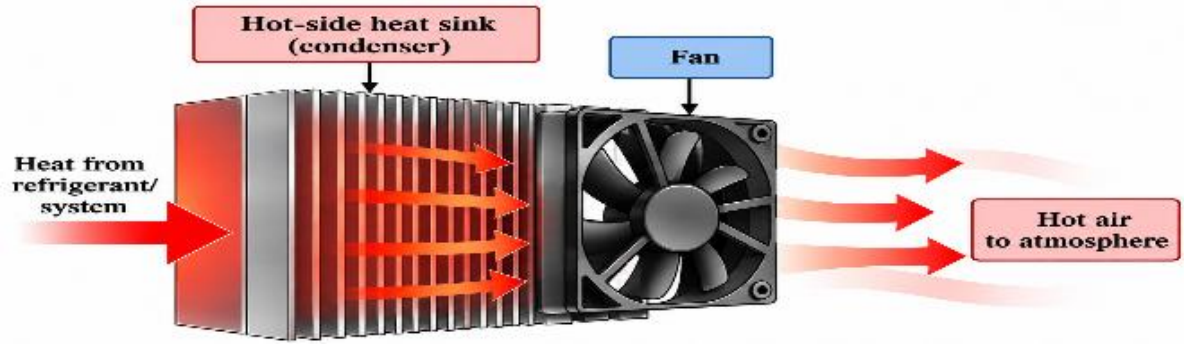
Thermal management is the most important part of the proposed system.
The hot-side thermal resistance can be represented approximately by:
$R_{\theta,HA} = \frac{T_h - T_a}{Q_h}$….. (8)
Where:
$R_{\theta,HA}$= heat-sink-to-ambient thermal resistance,
T_h = TEC hot-side temperature,
T_a= ambient temperature,
Q_h = heat rejected.
Lower thermal resistance results in lower hot-side temperature.
Since decreases Q_h when T_h increases, effective heat rejection directly improves cooling performance.

VIII. AIRFLOW SEQUENCE

The proposed prototype uses forced air.
The cold-side air path is:



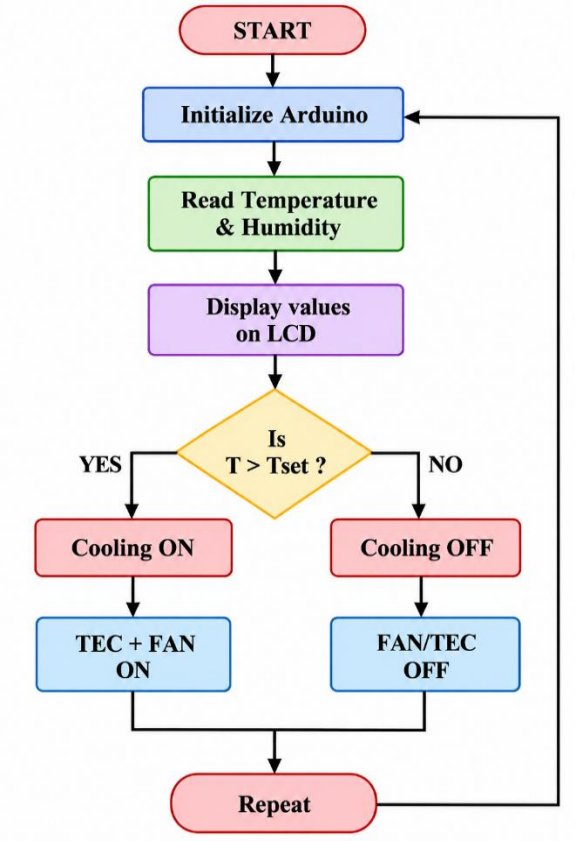
The hot-side airflow is:



The two airflow paths must be thermally isolated.
If hot air from the hot-side heat sink mixes with the cold-side air, the effective cooling performance decreases significantly.

IX. ARDUINO-BASED CONTROL

The Arduino receives temperature and humidity information from the sensor.
The control logic can be expressed as:



A hysteresis-based control Algorithm is preferable to simple ON/OFF control
$T_{ON} = 28℃$
$T_{OFF} = 26℃$

TEC turn ON when $T > 28℃$ and
turns OFF when $T \leq 26℃$

X. EXPERIMENTAL PROTOTYPE

The developed prototype shown in the Fig. 2 contains:
Solar PV panel
Cooling enclosure
Peltier-based cooling assembly
Aluminium heat sink
Cooling fan
Arduino Nano
16×2 LCD
Temperature/humidity sensing
Relay/power-control circuitry
DC power-conditioning circuitry
Indicator LEDs
Buzzer/control interface.

XI. EXPERIMENTAL PROCEDURE

The following experimental procedure is recommended for performance data.

Step 1
Place the prototype in a controlled test environment.

Step 2
Measure:
Ambient temperature
Relative humidity
Solar irradiance
PV voltage
PV current
TEC voltage
TEC current
Hot-side temperature
Cold-side temperature
Outlet-air temperature.

Step 3
Record measurements at regular intervals, e.g., every 10 min.

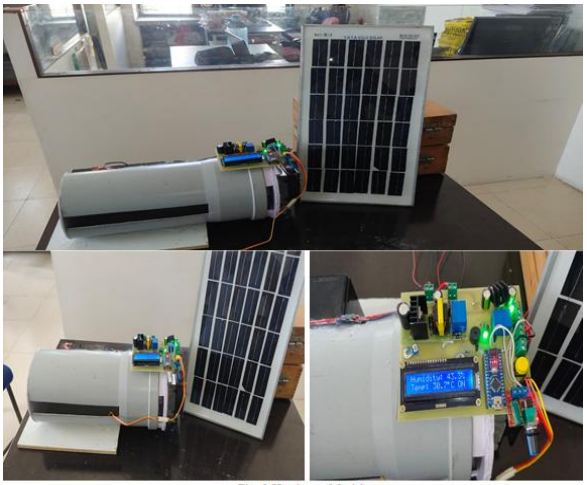


Fig. 2 Hardware Model

Step 4
Perform experiments under different TEC currents:

$$I_{TEC} = 2,\ 3,\ 4,\ 5,\ 6A$$

Step 5
Measure cold-side and hot-side temperatures.

Step 6
Calculate TEC electrical power:

$$P_{TEC} = V_{TEC} I_{TEC}$$

Step 7
Calculate cooling capacity using an air-side energy balance:

$$Q_c = \dot{m}_a C_p (T_{in} - T_{out})$$

where

- $\dot{m}_a$ = mass flow rate of air,
- C_p = specific heat of air,
- T_{in} = inlet air temperature,
- T_{out} = outlet air temperature.

Step 8
Calculate: COP

XII. EXPERIMENTAL RESULT

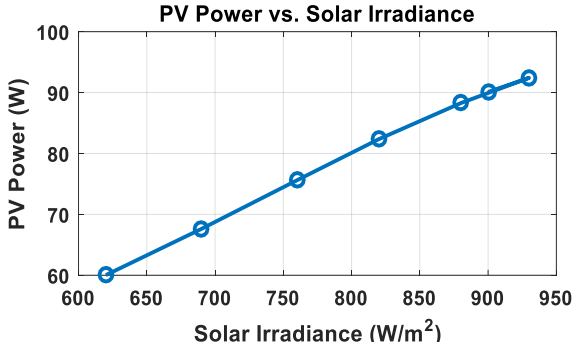
The illustrative experimental data for the prototype is present in TABLE-2

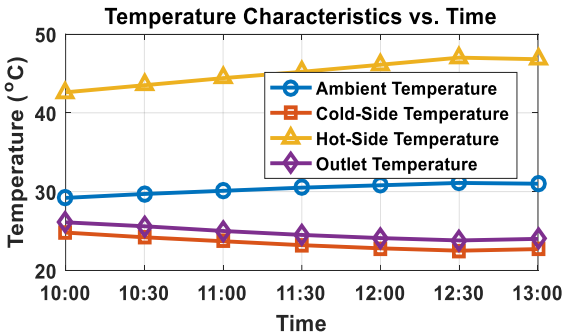
Time	Solar Irradiance (W/m²)	PV Voltage (V)	PV Current (A)	TEC Voltage (V)	TEC Current (A)	T_a(°C)	T_h(°C)	T_c(°C)	Outlet Temp. (°C)	RH (%)
10:00	620	17.4	3.45	11.8	4.20	29.2	24.8	42.6	26.1	55.2
10:30	690	17.7	3.82	11.9	4.35	29.7	24.2	43.5	25.6	53.8
11:00	760	18.0	4.20	12.0	4.50	30.1	23.7	44.4	25.0	51.9
11:30	820	18.1	4.55	12.0	4.65	30.5	23.2	45.2	24.5	50.4
12:00	880	18.2	4.85	12.1	4.80	30.8	22.8	46.1	24.1	48.9
12:30	930	18.3	5.05	12.1	4.95	31.1	22.5	47.0	23.8	47.2
13:00	900	18.2	4.95	12.0	4.90	31.0	22.7	46.8	24.0	47.8

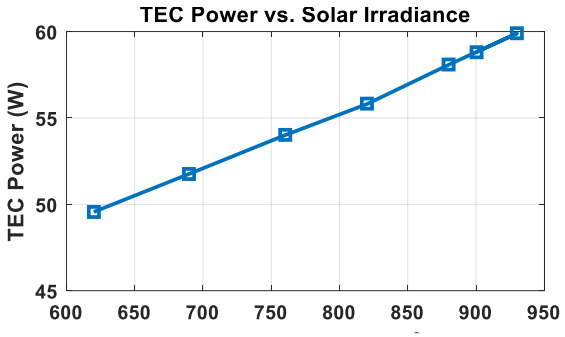
The representative results indicate that increasing solar irradiance from 620 W/m² at 10:00 to approximately 930 W/m² at 12:30 increases the available PV power from approximately 60 W to 92 W. The TEC operating power increases from approximately 49.6 W to 59.9 W.

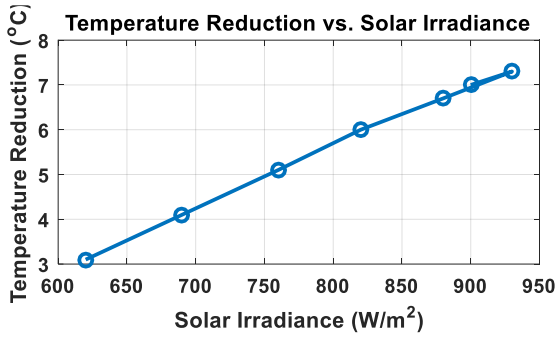
Consequently, the cold-side temperature decreases from approximately 24.8 °C to 22.5 °C, while the outlet air temperature decreases from 26.1 °C to 23.8 °C.
The corresponding temperature reduction between ambient air and outlet air increases from approximately 3.1 °C to 7.3 °C.

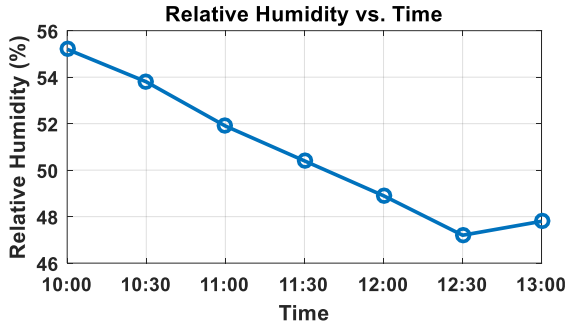
The hot-side temperature increases as the TEC power increases, reaching approximately 47 °C. This demonstrates the importance of the heat sink and forced-air cooling system for rejecting the heat generated by the Peltier module.

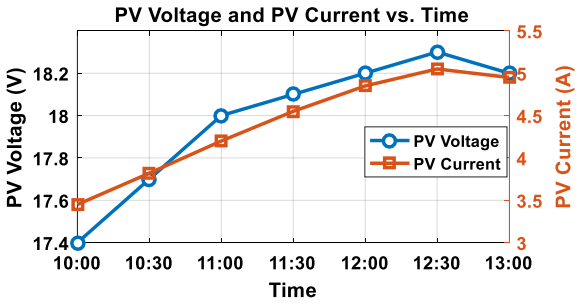


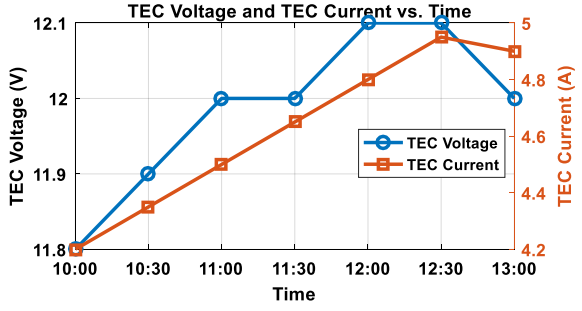


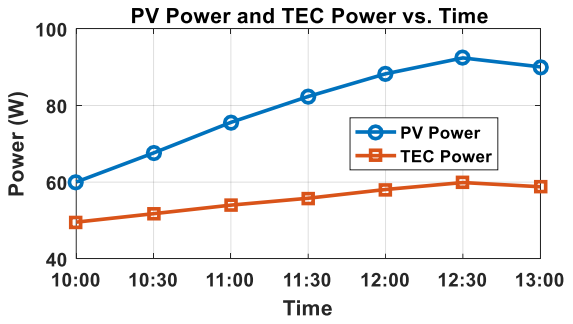


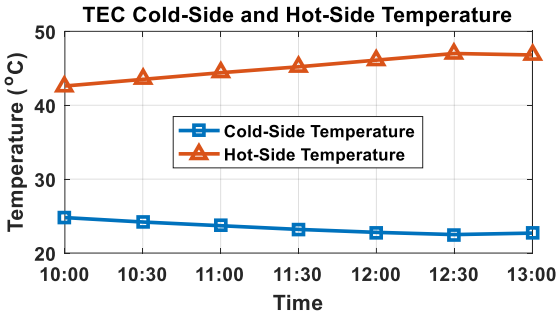












XIII. CONCLUSION AND RESULT

A compact solar-powered thermoelectric air-conditioning system using Peltier modules has been designed and experimentally prototyped. The system integrates a photovoltaic energy source, DC power-conditioning circuit, thermoelectric cooling module, heat sink, forced-air fan, Arduino Nano, temperature/humidity sensor and LCD display.

The prototype demonstrates the feasibility of using solar-generated DC electricity for direct thermoelectric cooling. The observed prototype display indicated an ambient temperature of approximately 30.6 °C and relative humidity of 42.8%, with the cooling system operating. The system architecture provides automatic monitoring and can be extended to closed-loop temperature control.

Theoretical analysis demonstrates that the principal design constraint is the heat rejected from the hot side. The proposed system should therefore be regarded as a localized/compact solar cooling system, rather than a direct one-to-one replacement for a conventional room air conditioner. Its strongest applications are small enclosures, personal cooling, laboratories, remote/off-grid locations, electronics cooling and educational renewable-energy demonstrations.

The systematic measurements of solar irradiance, PV voltage/current, TEC voltage/current, hot-side temperature, cold-side temperature, airflow rate and

cooling capacity, followed by COP and economic analysis. Such measurements will allow the prototype to be converted from a demonstration model into a quantitatively validated research system.

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