



International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Solar Powered Smart Hybrid Eco-Cooler

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DOI : <https://doi.org/10.55248/gengpi.07.1026.3284>

ABSTRACT :

This paper presents a Solar Powered Smart Hybrid Eco-Cooler that provides an energy-efficient and environmentally friendly cooling solution using Peltier technology with solar and battery power supply. A Peltier thermoelectric module produces the cooling effect without conventional refrigerants or a compressor. A water pump circulates water through the cooling arrangement, while a fan delivers the cooled air into the surrounding environment. DS18B20 temperature sensors continuously monitor the indoor and outdoor temperatures, and an ESP32 microcontroller processes the readings and shows them on an LCD, allowing the user to observe the cooling performance in real time. The system is powered by a solar panel and a rechargeable battery managed through a charge controller; the 12 V battery stores solar energy and directly supplies the Peltier module, water pump and fan, with the control electronics fed from the same battery, when sunlight is insufficient. The cooling capacity of the prototype is fixed, because the battery supplies the loads directly and no manual adjustment is provided. The prototype demonstrates a portable, renewable-energy-based cooling solution with reduced dependence on conventional air-conditioning, suitable for small rooms, outdoor applications, rural areas and locations where grid electricity is limited.

Keywords: Solar Energy, Peltier Module, Thermoelectric Cooling, ESP32 Microcontroller, DS18B20, Battery Storage, Eco-Cooler.

Introduction

Cooling systems play an important role in maintaining comfortable conditions in homes, workplaces, rural areas and outdoor locations. Conventional air-conditioning systems provide effective cooling but generally consume significant electrical energy and depend on refrigerants that may have environmental impacts. There is therefore a growing need for compact, energy-efficient and environmentally friendly cooling systems that can operate with renewable energy sources.

Thermoelectric cooling based on the Peltier effect is a promising alternative. When DC power is supplied to a Peltier module, one side becomes cold while the other side produces heat, so cooling is obtained without refrigerants or compressors. Photovoltaic (PV)-powered thermoelectric coolers are particularly attractive because of their compact size, absence of refrigerants and direct compatibility with the DC output of solar panels [2], [5], [8]. Their performance, however, depends strongly on thermal management, especially the removal of heat from the hot side of the module [15]. Because solar energy is intermittent, the PV supply and the thermoelectric load must be carefully matched to obtain reliable cooling [10], [12].

This paper proposes a Solar Powered Smart Hybrid Eco-Cooler that combines Peltier cooling, water circulation, fan-based air delivery, solar energy and battery storage in a single compact unit. A water pump circulates water through the cooling arrangement to improve heat transfer, and a fan distributes the cooled air. Temperature sensors sense indoor and outdoor measure the temperature variation continuously, and an ESP32 microcontroller displays the values on an LCD for real-time monitoring. During sunlight hours the solar panel supplies the system and charges the battery; the stored 12 V battery energy is fed directly to the cooling loads and operates the cooler when solar power is insufficient.

The proposed eco-cooler is suitable for small rooms, rural areas, outdoor applications, temporary shelters and locations with limited access to grid electricity. By reducing dependence on conventional electrically powered air-conditioning, it demonstrates a compact and portable approach to low-power cooling.

Literature review

Photovoltaic-powered thermoelectric cooling has been studied extensively as a way of providing refrigerant-free cooling. Kaiprath and Kumar [7], [8] reviewed solar PV-powered thermoelectric coolers, their performance enhancements and recent advances. Aboelmaaref et al. [9] presented the design and performance analysis of a thermoelectric air-conditioning system driven by solar PV panels, Seyednezhad and Najafi [12] carried out a parametric study of a solar-powered thermoelectric cooling and heating system for buildings, and Irshad et al. [5] analysed PV thermoelectric air conditioning for personalized cooling in an arid climate.

Several studies have examined how the PV source and the thermoelectric module interact. Liao et al. [10] investigated the coupling properties and parametric optimization of a PV panel-driven thermoelectric refrigerator system, Cai et al. [13] reported bidirectional modelling and performance optimization of a PV-thermoelectric cooling and power generation system, and Chandel et al. [2], [3] analysed PV-powered thermoelectric cooling under different solar loading conditions and for enhanced power generation. Ahmed et al. [1] studied a building cooling system combining PV panels, phase change material and a thermoelectric cooler, including the effect of its orientation.

Hybrid arrangements that improve heat rejection have also been reported. Lv et al. [11], the authors of [4] and the authors of [6] combined radiative sky cooling with PV-driven thermoelectric coolers, Żelazna and Gołębiewska [14] evaluated a PV-powered thermoelectric cooling system with heat recovery, and Atta [15] used closed-loop heat exchangers with macro channels for solar thermoelectric cooling. These works confirm that effective hot-side heat removal is central to the performance of thermoelectric cooling.

Despite this progress, the reviewed works concentrate mainly on modelling, optimization and building-scale or laboratory-scale analysis of PV-driven thermoelectric systems. A compact cooling unit in which a solar panel and a 12 V battery directly supply a Peltier module, a water pump and a fan, with real-time monitoring of indoor and outdoor temperatures, is not commonly addressed. The proposed Solar Powered Smart Hybrid Eco-Cooler addresses this gap using an ESP32 controller, DS18B20 sensors, an LCD, a water pump, fans, a solar panel, a charge controller and a battery.

Background and motivation

1.1. Background

Conventional cooling is commonly based on vapour-compression refrigeration, in which a compressor circulates refrigerant through a condenser, expansion device and evaporator to remove heat from the space. Such systems consume relatively high electrical power, require refrigerants and several mechanical components, and are not always practical for remote or off-grid locations. Evaporative air coolers use less electricity, but their performance depends significantly on ambient humidity and a continuous supply of water.

Solar-powered cooling systems are also available, but many use solar energy mainly to reduce grid consumption and may not operate when sunlight is unavailable unless energy storage is provided. Peltier-based systems are generally restricted to small applications such as portable coolers, electronic equipment cooling and small refrigeration units. These limitations motivate a compact cooler that integrates Peltier cooling, water circulation, solar charging and battery backup.

1.2. Motivation

- To provide cooling without conventional refrigerants or compressor-based mechanisms.
- To use solar energy as the primary power source and reduce dependence on grid electricity.
- To store surplus solar energy in a battery so that the cooler can operate when sunlight is insufficient.
- To monitor the water inlet and outlet temperatures in real time using temperature sensors and an LCD.
- To develop a compact, portable and low-maintenance system for small rooms, outdoor applications and off-grid locations.
- To encourage renewable-energy-based and sustainable cooling technologies.

Proposed methodology

The overall architecture of the proposed system is shown in Fig. 1. A solar panel charges a battery through a charge controller, the 12 V battery directly supplies the system, and an ESP32 microcontroller monitors the temperature sensors, drives the LCD and switches the Peltier module, water pump and DC fan. The operation of each block is described below.

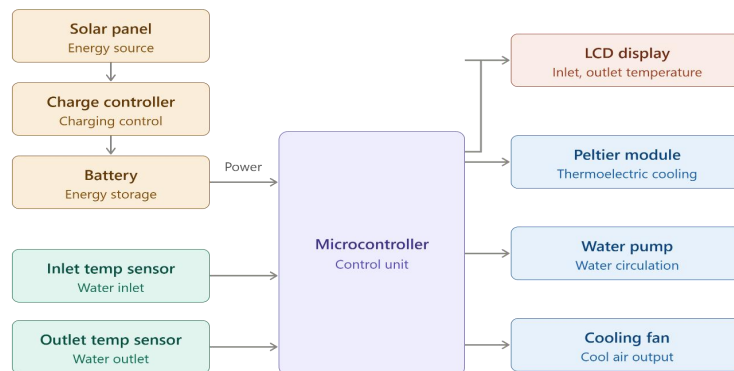


Fig. 1 - Block diagram of the proposed Solar Powered Smart Hybrid Eco-Cooler

1.3. Solar Power Generation and Battery Management

A solar panel is used to generate DC power. The generated power is not supplied directly to the battery; instead, a charge controller is connected between the solar panel and the battery. The charge controller protects the battery by preventing overcharging and over-discharging, thereby increasing its lifespan. Without a charge controller, the battery may become overcharged or deeply discharged, which reduces its lifetime. The stored 12 V battery energy supplies the system when sunlight is insufficient or unavailable.

1.4. Power Distribution

The 12 V battery directly supplies the Peltier module, the water pump and the DC fan; no intermediate DC-DC converter or voltage-control stage is used between the battery and these loads. The ESP32, the DS18B20 temperature sensors and the 16×2 I2C LCD, which need a 5 V logic supply, are fed from the same battery through a small 5 V regulator. Since the loads receive the full battery voltage whenever they are switched on, the cooling capacity of the system is fixed and cannot be increased or decreased by the user.

1.5. Temperature Sensing and Display

Two DS18B20 digital temperature sensors are used: one measures the indoor temperature and the other measures the outdoor temperature. The measured data are sent to the ESP32, which analyses the indoor and outdoor values and shows them on the 16×2 I2C LCD. The firmware, written in Embedded C using the Arduino IDE, reads the sensors every 2 s, displays the values in °C and shows an error message if a sensor is disconnected.

1.6. Control Logic

When the indoor temperature rises to the fixed preset value of 25 °C, the ESP32 switches ON the Peltier module, which in turn starts the water pump and the DC fan, all supplied directly from the 12 V battery. The preset value is set in the firmware and there is no manual adjustment of the cooling level; the system therefore operates at a fixed cooling capacity whenever it is ON.

1.7. Hybrid Evaporative and Thermoelectric Cooling

When the Peltier module is energized (TEC1-12706), one side becomes cold while the other side becomes hot. For the cooled side, the water pump supplies water from the storage unit to the cooling pad, which becomes a wet pad. The DC fan draws outside air through the wet pad, and the cooled air is delivered to the surroundings.

1.8. Heat Dissipation from the Hot Side

The heat generated on the hot side of the Peltier module must be removed to maintain cooling efficiency. A heat sink with a fan is therefore attached to the hot side to reduce the heat; the larger the heat sink, the greater the heat dissipation.

1.9. Operating Sequence

The operation of the prototype follows a fixed sequence. First, during sunlight hours the solar panel charges the 12 V battery through the charge controller. Second, the ESP32 reads the indoor and outdoor DS18B20 sensors every 2 s and shows the values in °C on the LCD. Third, when the indoor temperature reaches the preset value of 25 °C, the ESP32 switches ON the Peltier module, the water pump and the DC fan, which are supplied directly from the 12 V battery.

Fourth, the pump supplies water from the storage unit to the cooling pad and the fan draws air through the wet pad and delivers it to the surroundings, while the heat sink and fan on the hot side of the Peltier module remove the rejected heat. Because the loads are connected directly to the battery and no potentiometer or other control element is used, the cooling capacity stays constant while the system is ON and is limited only by the battery voltage and the available charge.

1.10. Power Supply Considerations

Since the Peltier module, pump and fan are connected directly to the 12 V battery, the load power is set by the ratings of these components. The TEC1-12706 is a 6 A module, so at its maximum rating it can draw up to about 72 W from a 12 V supply, while the water pump draws 130–220 mA according to its rating. The Peltier module therefore dominates the energy demand of the cooler.

The approximate operating time of the cooler on stored energy can be estimated from the usable battery energy divided by the total load power. A larger battery capacity or a higher-rated solar panel therefore extends the operating period, in line with the parametric analyses of PV-driven thermoelectric systems reported in [10] and [12]. The solar panel supplies the loads during daytime and the charge controller keeps the battery within safe limits while it is being charged.

Hardware description

The hardware of the prototype consists of the following units, and their main ratings are summarised in Table 1.

- **ESP32 development board:** The ESP32 is the main controller of the system. It has a dual-core 32-bit Tensilica Xtensa LX6 processor running at up to 240 MHz, 520 KB of SRAM, 4 MB of flash memory and built-in Wi-Fi and Bluetooth. It reads the sensors and controls the display and cooling components.
- **DS18B20 temperature sensors:** The DS18B20 is a digital thermometer with programmable 9- to 12-bit resolution, a range of -55°C to $+125^{\circ}\text{C}$ and $\pm 0.5^{\circ}\text{C}$ accuracy from -10°C to $+85^{\circ}\text{C}$. It uses a single-wire (1-Wire) interface, and each device has a unique 64-bit code. Two sensors measure the indoor and outdoor temperatures.
- **Peltier module (TEC1-12706):** The 6 A TEC1-12706 thermoelectric cooler produces a cold side and a hot side when DC power is applied. It provides the cooling effect of the system and has no moving parts or refrigerant.
- **Heat sink with cooling fan:** The heat sink, together with a cooling fan, absorbs and removes heat from the hot side of the Peltier module and improves its efficiency.
- **Solar panel:** The solar panel, made of silicon photovoltaic cells, converts sunlight into DC electrical energy. It powers the system and charges the battery.
- **Solar charge controller:** The charge controller regulates the charging of the battery from the solar panel and protects the battery.
- **Battery / energy storage:** The rechargeable battery stores solar energy and supplies the system when sunlight is insufficient or unavailable, such as at night.
- **Water pump:** A micro submersible DC pump (3–6 V, 130–220 mA, 80–120 L/h, maximum lift 40–110 mm) circulates water through the cooling arrangement. The water level must stay above the pump because dry running can damage it.
- **16×2 I2C LCD display:** The 16×2 LCD shows 16 characters on each of two lines. Through the I2C interface it displays the measured inlet and outlet temperatures in real time.

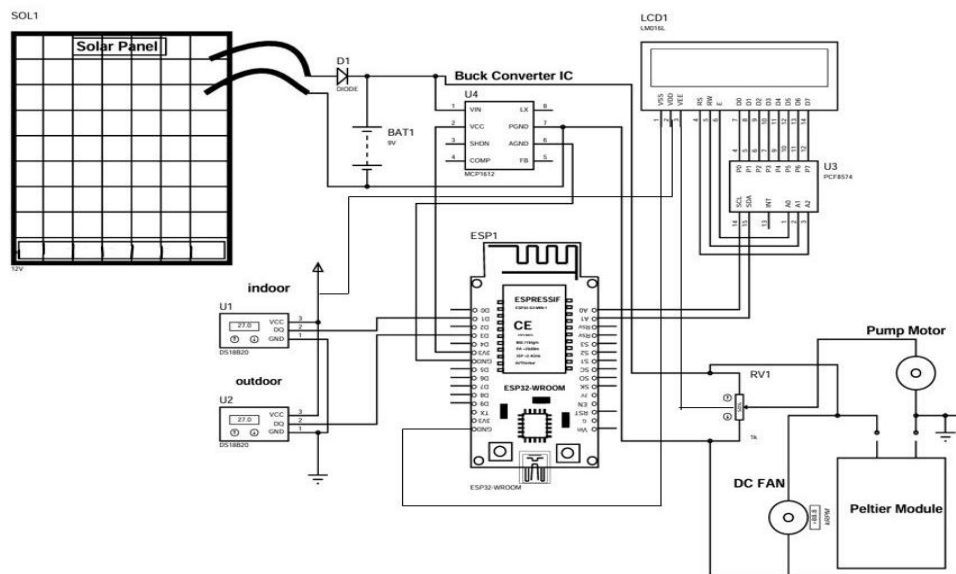
Table 1 - Main components of the eco-cooler

S. No.	Component	Function	Main rating / feature
1	ESP32	Main controller	Dual-core, 240 MHz, 520 KB SRAM
2	DS18B20 (2 nos.)	Indoor and outdoor sensing	-55 to $+125^{\circ}\text{C}$, $\pm 0.5^{\circ}\text{C}$
3	TEC1-12706	Thermoelectric cooling	12 V class, 6 A module
4	Water pump	Water circulation	80–120 L/h, 130–220 mA
5	DC fan and heat sink	Air delivery and hot-side cooling	Fan with heat sink on hot side
6	Solar panel	Energy source	Silicon PV cells, DC output
7	Charge controller	Battery protection	Prevents over-charge / discharge
8	Battery	Energy storage and supply	12 V, supplies loads directly
9	16×2 I2C LCD	Temperature display	Two lines of 16 characters

Circuit diagram and interconnection

The complete circuit diagram of the prototype is shown in Fig. 2. The 12 V solar panel (SOL1) is connected to the battery (BAT1) through the blocking diode D1, which prevents the battery from discharging back into the panel when sunlight is not available. The battery voltage is applied to an MCP1612 buck converter IC (U4), which provides the lower regulated supply needed by the control electronics, while the Peltier module, DC fan and water pump are fed from the battery side as described in Section 4.2.

Fig. 2 - Circuit diagram of the Solar Powered Smart Hybrid Eco-Cooler



The main elements of the circuit are described below.

- **Controller:** The ESP32 module (ESP1) is the central controller. It reads the two temperature sensors, drives the LCD and switches the cooling loads.
- **Temperature sensors:** Two DS18B20 sensors, U1 (indoor) and U2 (outdoor), are powered from the regulated supply and send their readings to digital input pins of the ESP32 over the 1-Wire data line (DQ), with a common ground.
- **Display:** The 16×2 LCD (LCD1) is interfaced through a PCF8574 I2C port expander (U3), so that only the SDA and SCL lines of the ESP32 are needed for the display.
- **Cooling loads:** The Peltier module, the DC fan and the pump motor are switched ON and OFF under the control of the ESP32 and share a common ground with the controller, so that the whole unit works from the single battery supply.

The same circuit diagram is used as the wiring reference for the prototype shown in Fig. 4.

Software flow

The control flow of the firmware, written in Embedded C using the Arduino IDE, is shown in Fig. 3. After power-up the ESP32 reads the indoor and outdoor DS18B20 sensors every 2 s and shows the values in °C on the LCD, with an error message if a sensor is disconnected. The indoor reading is then compared with the fixed preset of 25 °C. When the preset is reached, the ESP32 switches ON the Peltier module, the water pump and the DC fan, all of which are supplied directly by the 12 V battery; otherwise the program returns to reading the sensors.

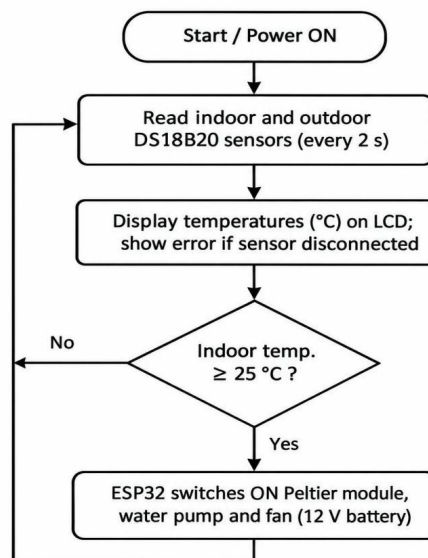


Fig. 3 - Control flow of the ESP32 firmware

Results and discussion

The prototype was developed and tested to evaluate its cooling performance and power operation. The Peltier module produced a cooling effect when supplied with DC power, the water pump circulated water continuously through the cooling arrangement, and the fan distributed the cooled air into the surroundings. The DS18B20 sensors measured the indoor and outdoor temperatures, which were displayed on the LCD in real time; the difference between them indicated that the cooling arrangement reduced the water temperature during operation.

The solar panel supplied electrical energy to the system and charged the battery, and the stored energy could operate the cooler when solar energy was insufficient. The microcontroller monitored the sensors and coordinated the cooling components. Compared with conventional grid-dependent air cooling, which is manually controlled and relies on grid availability, the proposed system uses a hybrid solar–battery supply, operates automatically and continues to work during power interruptions using stored battery energy.

These results demonstrate that the system can provide small-scale cooling using renewable solar energy without a compressor or refrigerant, making it suitable for portable and off-grid applications.

A further observation is that the direct 12 V connection keeps the electrical design simple, because no voltage-control stage is placed between the battery and the cooling loads. The trade-off is that the cooling output cannot be varied during operation: the Peltier module, pump and fan work at the same level whenever they are switched ON, so the user cannot raise or lower the cooling capacity. The 25 °C preset is therefore chosen as the single operating point of the system.

1.11. Final Output

The final output of the proposed system is shown in Fig. 4. The prototype comprises the control unit and Peltier cooling module, the cooling-pad enclosure with air delivery fans, the water pump and the connecting tubes. The proposed Solar Powered Smart Eco-Cooler successfully reduced the indoor air temperature by approximately 1–3 °C under normal operating conditions. The ESP32 automatically controls the Peltier module, water pump and fan based on the temperature sensor reading.

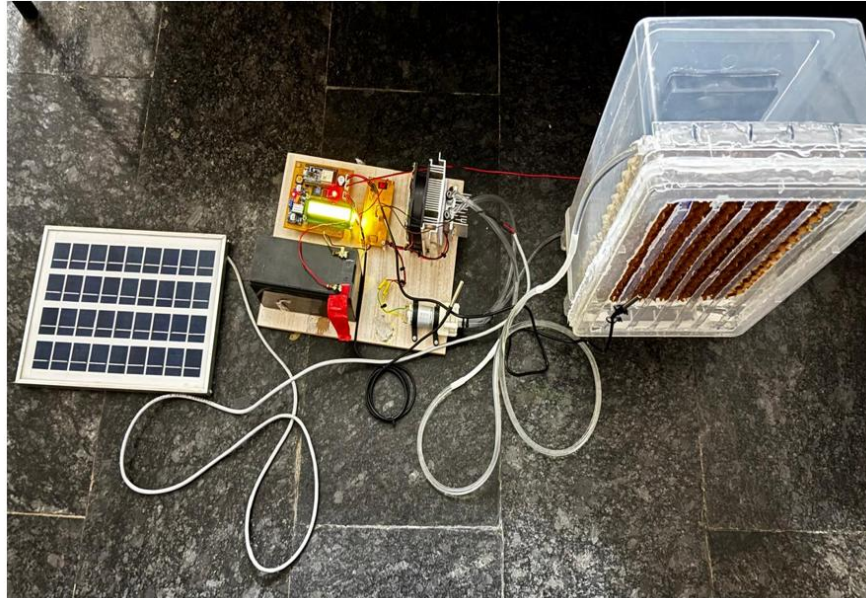


Fig. 4 - Complete hardware prototype of the Solar Powered Smart Hybrid Eco-Cooler

Limitations

The main limitations of the proposed prototype are as follows:

- Solar charging depends on sunlight availability and weather conditions.
- The cooling capacity is fixed because the 12 V battery supplies the loads directly; it cannot be increased or decreased by the user.
- Battery capacity limits the operating duration during low sunlight and at night.
- Cooling performance depends on effective removal of heat from the hot side of the Peltier module; a single-stage module sustains only a limited temperature difference (about 50 K).
- The prototype is intended for small-scale cooling; larger spaces require scaling of the Peltier modules, solar panel and battery.
- The water level in the circulation system must be maintained, since the pump must not run dry.

Advantages

The main advantages of the proposed Solar Powered Smart Hybrid Eco-Cooler are as follows:

- Provides cooling without refrigerants or a compressor, with no moving parts in the thermoelectric module.
- Uses solar energy as the primary source, reducing dependence on grid electricity.
- Operates during low sunlight and at night from the energy stored in the 12 V battery.
- Simple electrical design, since the 12 V battery supplies the loads directly without a voltage-control stage.
- Automatic switching of the cooling loads at the preset temperature, with real-time temperature display.
- Compact, portable and low-maintenance construction suitable for small-scale use.

Applications

The cooler is suitable for the following applications:

- Cooling of small rooms and enclosures.
- Rural and off-grid locations with limited grid access.
- Outdoor use and temporary shelters.
- Backup cooling during power interruptions.
- Educational and renewable-energy demonstration projects.

Conclusion

The proposed Solar Powered Smart Hybrid Eco-Cooler demonstrates an energy-efficient and environmentally friendly approach to small-scale cooling. A Peltier thermoelectric module generates the cooling effect without conventional refrigerants or compressor-based refrigeration, while a water pump and fan improve the cooling process by circulating water and distributing the cooled air. Temperature sensors, the ESP32 microcontroller and an LCD provide real-time information on the cooling performance.

The solar panel and rechargeable battery provide a renewable power source and allow the system to operate where grid electricity is limited or unavailable. The cooler is suitable for small rooms, rural areas, outdoor applications and temporary shelters, and it provides a practical foundation for more efficient and portable renewable-energy-based cooling systems.

REFERENCES

- 1.H. A. Ahmed, S. Nada and H. Hassan, "Performance study of building cooling system composed of photovoltaic panels, phase change material, and thermoelectric cooler: impact of its orientation," *International Journal of Air-Conditioning and Refrigeration*, vol. 33, art. no. 3, 2025.
- 2.R. Chandel, S. S. Chandel, D. Prasad and R. P. Dwivedi, "Experimental analysis and modelling of a photovoltaic powered thermoelectric solid-state cooling system for transition towards net zero energy buildings under different solar loading conditions," *Journal of Cleaner Production*, vol. 442, art. no. 141099, 2024.
- 3.R. Chandel, S. S. Chandel, D. Prasad and R. P. Dwivedi, "A comprehensive analysis of photovoltaic panel integrated thermoelectric cooling system for enhanced power generation," 2024.
- 4.S. Igor and K. Smith, "Investigation on a novel hybrid system based on radiative sky cooling and split thermoelectric cooler driven by photovoltaic cell," *Renewable Energy*, vol. 229, art. no. 120798, 2024.
- 5.K. Irshad, S. Rehman, M. H. Zahir, F. Khan, D. Balakrishnan and B. B. Saha, "Analysis of photovoltaic thermoelectric air conditioning for personalized cooling in arid climate," *Journal of Building Engineering*, vol. 84, art. no. 108533, 2024.
- 6.M. Javier and T. Manvik, "Performance analysis of radiative cooling combined with photovoltaic-driven thermoelectric cooling system in practical application," *Energy*, vol. 294, art. no. 130971, 2024.
- 7.J. Kaiprath and K. K. V. V., "A review on solar photovoltaic-powered thermoelectric coolers," *International Journal of Air-Conditioning and Refrigeration*, vol. 31, art. no. 6, 2023.
- 8.J. Kaiprath and V. V. Kishor Kumar, "A review on solar photovoltaic-powered thermoelectric coolers, performance enhancements, and recent advances," *Society of Refrigeration and Air Conditioning Engineers*, 2023.
- 9.M. Aboelmaaref, M. E. Zayed, A. H. Elsheikh, A. A. Askalany, J. Zhao, W. Li, K. Harby, S. Sadek and M. S. Ahmed, "Design and performance analysis of a thermoelectric air-conditioning system driven by solar photovoltaic panels," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 235, no. 20, pp. 5146–5159, 2021.
- 10.T. Liao, Q. He, Q. Xu, Y. Dai, C. Cheng and M. Ni, "Coupling properties and parametric optimization of a photovoltaic panel driven thermoelectric refrigerators system," *Energy*, vol. 220, p. 119798, 2021.
- 11.S. Lv, Y. Ji, Z. Qian, W. He, Z. Hu and M. Liu, "A novel strategy of enhancing sky radiative cooling by solar photovoltaic-thermoelectric cooler," *Energy*, vol. 219, p. 119625, 2021.
- 12.M. Seyednezhad and H. Najafi, "Solar-powered thermoelectric-based cooling and heating system for building applications: A parametric study," *Energies*, vol. 14, no. 17, p. 5573, 2021.
- 13.Y. Cai, L. Wang, W.-W. Wang, D. Liu and F.-Y. Zhao, "Solar energy harvesting potential of a photovoltaic-thermoelectric cooling and power generation system: Bidirectional modeling and performance optimization," *Journal of Cleaner Production*, vol. 254, p. 120150, 2020.
- 14.A. Żelazna and J. Gołębiewska, "A PV-powered TE cooling system with heat recovery: Energy balance and environmental impact indicators," *Energies*, vol. 13, no. 7, p. 1701, 2020.
- 15.R. M. Atta, "Solar thermoelectric cooling using closed loop heat exchangers with macro channels," *Heat and Mass Transfer/Waerme- und Stoffuebertragung*, vol. 53, no. 7, pp. 2241–2254, Jul. 2017.