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Solar Panel Efficiency Booster in Summer Days

P.N Gaurkar, Dhanshree Pote, Aman Dehankar, Yash Bele, Yash Yelgalwar, Sarthak Dongre

Department of Electrical Engineering, Priyadarshini College of Engineering, Nagpur, Maharashtra, India

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ABSTRACT—

Photovoltaic (PV) modules lose a noticeable share of their output as their operating temperature climbs, and the loss is most severe in hot summer conditions. This paper presents the design and construction of a low-cost, temperature-controlled cooling system for a 20 W, 12 V polycrystalline PV panel. A copper pipe arrangement fixed to the rear of the panel carries circulating water, which is chilled by a thermoelectric (Peltier) module whose hot side is relieved by a heatsink and an exhaust fan. An ESP32 microcontroller reads a waterproof DS18B20 temperature sensor and, once the temperature reaches 35 °C, switches the pump and the Peltier module on through relays; they are switched off again when the temperature drops below this value. Panel voltage, current, temperature and cooling status are shown on a 16×2 PC LCD, and a sensor-fault routine shuts the cooling hardware down safely if the temperature probe is lost. The paper explains the architecture and firmware logic and sets out a method for judging net power gain that counts the power drawn by the cooling hardware itself. Published studies suggest that cooling can raise PV output by several percent, but whether a small prototype achieves a net benefit depends on how much power its auxiliary loads consume, and that trade-off is discussed openly.

Index Terms—photovoltaic cooling, solar panel efficiency, Peltier module, thermoelectric cooler, ESP32, DS18B20, water circulation, temperature control.

I. INTRODUCTION

Sunlight costs nothing, but the hardware that turns it into electricity is surprisingly sensitive to heat. A crystalline silicon module converts only a fraction of the light it absorbs, and the rest ends up as heat inside the cells. As the cell temperature rises, the open-circuit voltage falls faster than the short-circuit current grows, so the maximum power of the module drops. Reviews of module behaviour put this loss at roughly 0.4–0.5 % of rated power for every degree Celsius above the 25 °C standard test condition [1], [2]. A panel sitting in direct sun on a summer afternoon runs far above 25 °C, so the shortfall is not a minor correction.

Many ways of keeping modules cooler have been tried. Passive options such as fins and natural ventilation cost nothing to run but have limited capacity, while active options use water or air to carry the heat away. Water flowing over the front surface has been shown to improve electrical yield [3], and the work on cooling PV panels more uniformly, including circulating water behind the module, has been surveyed in [4]. A critical review of cell-cooling methods [5] provides a useful framework for comparing techniques, and one point worth carrying into any design is that pumping and fan power must be counted against the gain.

A recent feasibility study of water cooling for PV systems [6] reported an output increase of about 7.8 % with cooling and about 5.9 % once the losses of the cooling system were deducted. Its test used a 100 Wp monocrystalline panel with a 12 V, 8 W pump delivering 4 L/min. These figures are encouraging, but they come from a different panel and different operating conditions, so they should be read as context rather than as a prediction for our prototype.

This work builds a compact, automatically controlled version of the idea for a 20 W, 12 V polycrystalline panel. Instead of circulating water at ambient temperature, a Peltier module chills the water, and an ESP32 turns the cooling on only when the temperature demands it. The main contributions are: (i) a rear-mounted copper-and-water cooling loop assisted by a thermoelectric cooler; (ii) a simple threshold-based controller with a sensor-fault safeguard and live display of temperature, voltage and current; and (iii) an evaluation method that reports net, not just gross, power improvement.

The remainder of the paper is organised as follows. Section II reviews the underlying physics. Section III describes the hardware, Section IV the control strategy and firmware, and Section V the electrical measurements. Section VI explains how performance is evaluated, Section VII discusses limitations, and Section VIII concludes.

II. BACKGROUND

A. Temperature Dependence of PV Output

Over the normal operating range, the maximum power of a crystalline silicon module can be approximated as a linear function of cell temperature:

$$P(T) = P_{\text{ref}} [1 - \beta (T - T_{\text{ref}})] \quad (1)$$

where P_{ref} is the power at the reference temperature $T_{\text{ref}} = 25^\circ\text{C}$ and β is the temperature coefficient, typically 0.004–0.005 per $^\circ\text{C}$ for crystalline silicon [1], [2]. Under this model, a 10°C reduction in cell temperature would be expected to recover about 4–5 % of the output, which gives a sense of the size of the prize.

B. Thermoelectric (Peltier) Cooling

A Peltier module is a solid-state heat pump. When a direct current flows through its semiconductor junctions, heat is moved from one face (the cold side) to the other (the hot side). The heat absorbed at the cold side can be written as

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

where α is the Seebeck coefficient of the module, I the supply current, T_c the cold-side temperature, R the electrical resistance, K the thermal conductance and ΔT the temperature difference between the two faces [7], [8]. The hot side must reject both the heat pumped from the cold side and the electrical power supplied to the module, so an effective heatsink and fan are essential; without them the hot side warms up and the cooling effect collapses.

C. Water-Based Heat Removal

Copper is chosen for the rear heat-exchange arrangement because of its very high thermal conductivity, which lets heat flow readily from the panel surface into the water [9]. The heat carried away by the water is

$$Q = \dot{m} c_p (T_{\text{out}} - T_{\text{in}}) \quad (3)$$

where $\dot{m}$ is the mass flow rate of the water, c_p its specific heat capacity, and T_{in} and T_{out} the water temperatures entering and leaving the copper arrangement. A cooler inlet temperature, supplied here by the Peltier module, increases the temperature difference available to draw heat out of the panel.

III. SYSTEM DESCRIPTION

A. Overview

The prototype uses a 20 W, 12 V polycrystalline panel with a maximum-power voltage of about 18 V and a maximum-power current of about 1.1 A. Water is circulated by a pump through a copper pipe winding fixed to the back of the panel. The returning warm water is chilled by the cold side of a Peltier module, while the hot side is cooled by a heatsink with an exhaust fan. An ESP32 monitors the temperature and decides when the pump and Peltier module should run. Fig. 1 shows the complete prototype and Fig. 2 the block diagram of the system.

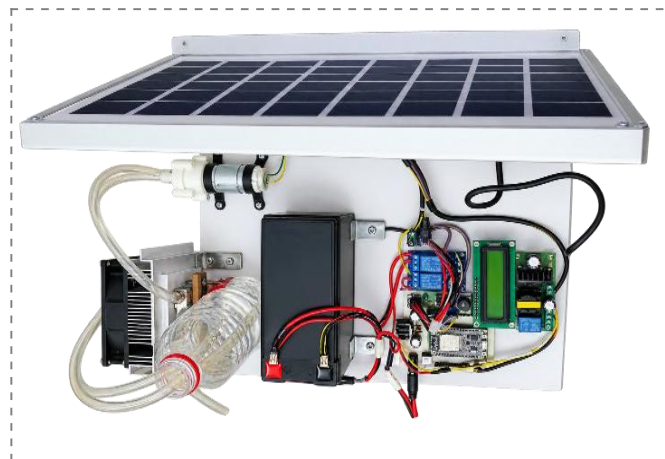


Fig. 1. Complete prototype of the solar panel cooling and efficiency booster.

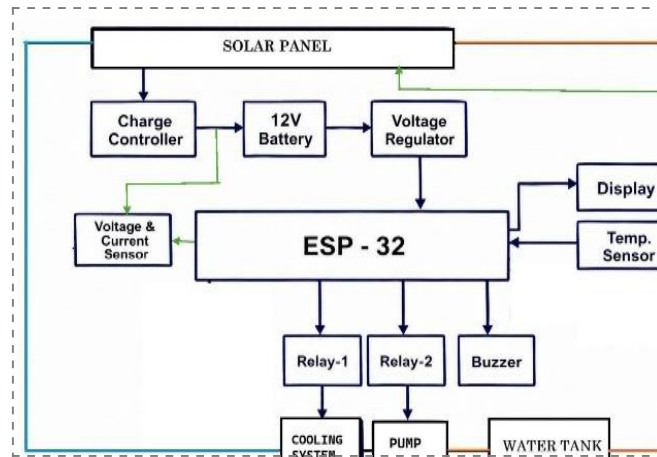


Fig. 2. Block diagram of the proposed cooling system.

B. Hardware Components

The components used and their roles are summarised in Table I.

TABLE I MAIN COMPONENTS AND THEIR ROLES

Component	Specification / Role
Solar panel	20 W, 12 V polycrystalline; $V_{mp} \approx 18$ V, $I_{mp} \approx 1.1$ A
ESP32 DevKit	Main controller: sensing, logic, relay control [10]
DS18B20	Waterproof 1-Wire digital temperature sensor [11]
Peltier module	Thermoelectric cooling of the circulating water
Water pump	Circulates water through the copper winding
Relay module	Switches pump and Peltier loads from ESP32 outputs
16×2 I ² C LCD	Displays temperature, voltage, current, cooling state
Battery	12 V, 7 Ah
Others	5 V piezo buzzer, PCB, 1000 μ F/25 V capacitors, BC547 transistor, 1N4007 diode

C. Cooling Circuit

Copper tubing is wound and fixed against the rear surface of the panel so that as much of the pipe as possible is in contact with the back sheet; good contact matters more than the total pipe length. Water leaving the winding passes the cold side of the Peltier module, where it gives up heat before returning to the panel. The hot side of the module is bonded to a finned heatsink, and an exhaust fan pushes air across the fins. The rear arrangement and the Peltier assembly are shown in Fig. 3 and Fig. 4.



Fig. 3. Copper pipe arrangement fixed to the rear of the solar panel.

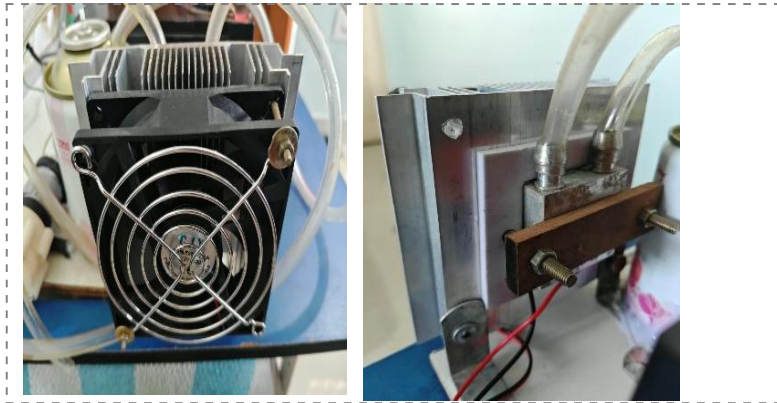


Fig. 4. Peltier module with heatsink and exhaust fan.

D. Electronics and Pin Assignment

The ESP32 [10] reads the DS18B20 [11] over a single data line and measures panel voltage and current through two analogue inputs. The pump and the Peltier module are switched by relays driven from separate output pins, so the low-power controller never carries the load current itself. The pin assignment used in the firmware is given in Table II, and the controller board is shown in Fig. 5.

TABLE II ESP32 PIN ASSIGNMENT

Signal	ESP32 pin
DS18B20 data	GPIO 4
Pump relay	GPIO 26
Peltier relay	GPIO 27
Buzzer	GPIO 25
Voltage sensor (ADC)	GPIO 34
Current sensor (ADC)	GPIO 35
I ² C bus (LCD, 0x27)	SDA: GPIO 21, SCL: GPIO 22

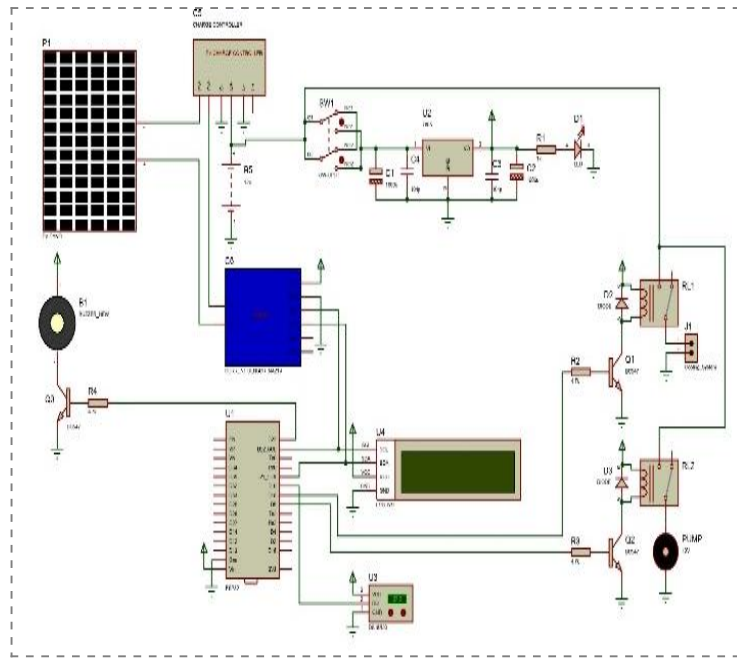


Fig. 5. Controller board with relay module and sensor connections circuit diagram

IV. CONTROL STRATEGY AND FIRMWARE

The firmware runs a simple supervisory loop once per second. The DS18B20 is read first. If the reading is valid, voltage and current are measured and the temperature is compared with the start threshold of 35 °C. When the temperature reaches or exceeds the threshold and cooling is currently off, the pump and Peltier relays are switched on and the buzzer sounds for one second to announce that cooling has started. When the temperature later falls below the threshold while cooling is on, both relays are switched off. A state flag records whether cooling is active, which ensures that the buzzer sounds only once per cooling cycle instead of on every pass through the loop. The logic is summarised in Algorithm 1.

1. Request temperature T from the DS18B20.
2. If the sensor is disconnected: switch pump, Peltier and buzzer OFF, show "TEMP SENSOR ERROR", wait 1 s and return to step 1.
3. Measure panel voltage V and current I .
4. If $T \geq 35$ °C and cooling is OFF: switch pump and Peltier ON, sound buzzer for 1 s, set cooling = ON.
5. Else if $T < 35$ °C and cooling is ON: switch pump and Peltier OFF, set cooling = OFF.
6. Update the LCD and serial monitor (115200 baud), wait 1 s, repeat.

Algorithm 1. Temperature-based control loop of the ESP32.

The sensor-fault branch is a deliberate safety feature. A disconnected probe would otherwise return an invalid value, and a controller that cannot tell how hot the panel is should not leave a Peltier module energised. In that case the outputs are forced off and an error message is displayed. During normal operation the first LCD line shows temperature and voltage and the second shows current and the cooling state (ON or OFF), as in Fig. 6.



Fig. 6. 16x2 LCD output during operation.

V. ELECTRICAL MEASUREMENT

Both electrical quantities are read through the 12-bit ADC of the ESP32, which returns a count N between 0 and 4095 for an input between 0 and about 3.3 V. The voltage at the pin is

$$V_{\text{adc}} = (N / 4095) \times 3.3 \quad (4)$$

The panel voltage is recovered from a resistive divider with a ratio of 5 : 1, so that

$$V_{\text{panel}} = 5 \times V_{\text{adc}} \quad (5)$$

Current is measured with an ACS712-type Hall-effect sensor [12]. For the 5 A variant, the output rests at about 2.5 V at zero current and changes by 0.185 V for each ampere, giving

$$I = (V_{\text{adc}} - 2.50) / 0.185 \quad (6)$$

Negative results, which arise only from noise around the zero point, are clamped to zero in the firmware. The electrical output power is then simply $P = V \times I$.

VI. PERFORMANCE EVALUATION METHOD

To judge whether the cooling is worthwhile, the panel should be tested with and without cooling under the same sunlight and load, ideally alternating between the two conditions within a short time so that irradiance does not drift between runs. The gross improvement is

$$\Delta P_{\text{gross}} (\%) = [(P_c - P_{nc}) / P_{nc}] \times 100 \quad (7)$$

where P_c and P_{nc} are the panel output powers with and without cooling. Because the pump, Peltier module, fan and controller all draw power, the figure that really matters is the net improvement:

$$\Delta P_{\text{net}} (\%) = [(P_c - P_{nc} - P_{\text{aux}}) / P_{nc}] \times 100 \quad (8)$$

where P_{aux} is the total electrical power consumed by the cooling hardware. A system with a positive gross gain but a negative net gain wastes more energy than it saves.

As an arithmetic illustration only, suppose the panel delivers $15.0 \text{ V} \times 0.46 \text{ A} = 6.90 \text{ W}$ without cooling and $15.3 \text{ V} \times 0.50 \text{ A} = 7.65 \text{ W}$ with cooling. Equation (7) then gives $((7.65 - 6.90) / 6.90) \times 100 \approx 10.87 \%$. These numbers show how the formula is applied; they are not measured results. The measured values obtained from the prototype should be entered in Table III and plotted in Fig. 7.

TABLE III MEASURED PERFORMANCE

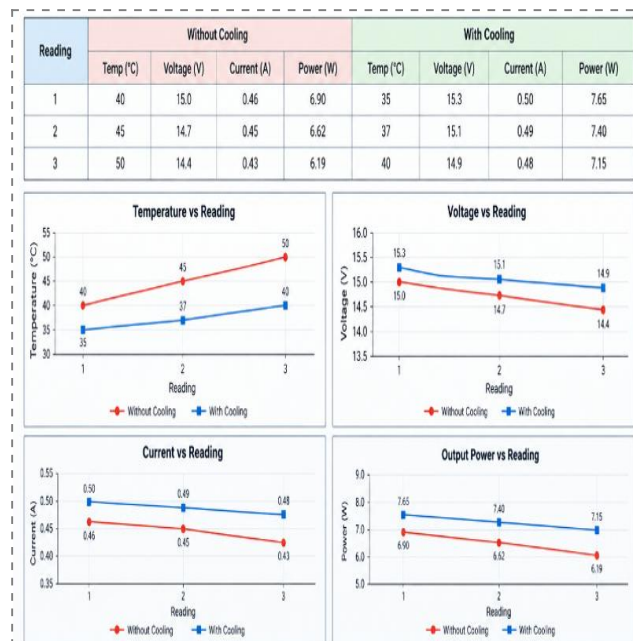


Fig. 7. Panel temperature and output power with and without cooling.

VII. DISCUSSION AND LIMITATIONS

The central challenge for a small prototype is the power budget. A 20 W panel produces little energy to begin with, and a Peltier module, pump and fan can together draw a significant fraction of that output. Whether the net gain in Eq. (8) is positive therefore has to be settled by measurement, not assumed from the gross improvement or from literature values such as those in [6]. Running the cooling only above the threshold, as this controller does, limits the energy spent, and a larger panel would shift the balance in favour of cooling because the auxiliary load does not grow in proportion to the panel size.

Several practical points should be addressed in a final build. First, the current-sensing hardware must match the firmware: the code assumes an ACS712-type analogue sensor on GPIO 35, so any other sensor, such as an I²C power monitor, requires a different read routine. Second, the ADC of the ESP32 accepts only about 3.3 V, so a sensor output that can swing higher must be scaled down, and the readings should be calibrated against a multimeter because the ESP32 ADC is not perfectly linear. Third, the controller uses a single threshold without hysteresis, so a temperature hovering around 35 °C could cause frequent relay switching; a small dead-band or a minimum on-time would protect the relays and the Peltier module. Finally, chilled water and exposed pipes can cause condensation, so electrical connections should be kept clear of the water circuit.

VIII. CONCLUSION

This paper described a temperature-controlled cooling system for a 20 W polycrystalline solar panel that combines a rear copper water loop, a Peltier chiller with a heatsink and fan, and an ESP32 controller. Cooling starts automatically at 35 °C, stops below that value, and is disabled safely if the temperature sensor fails, while the LCD gives a live view of temperature, voltage, current and cooling state. Because crystalline silicon loses roughly 0.4–0.5 % of its power per degree of heating, reducing panel temperature is a sound route to better output, but the real benefit depends on the net result after the cooling hardware is powered. The evaluation procedure given here is intended to measure exactly that.

Future work includes adding hysteresis to the control logic, logging data to a cloud service over the ESP32 Wi-Fi link, optimising the water flow rate and Peltier current, and testing the concept on a larger panel where the auxiliary load is a smaller share of the output.

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