International Journal of Applied Power Engineering (IJAPE)
Vol. 15, No. 2, June 2026, pp. 781~792
ISSN: 2252-8792, DOI: 10.11591/ijape.v15.i2.pp781-792

Smart IoT-based temperature-controlled cooling system for solar panels using Arduino

Mula Sreenivasa Reddy[1], Kondragunta Rama Krishnaiah[2], Anjali Devi Gorla[3], Anantha Sravanthi Peddinti[4], Sanam Nagendram[5], Mohammad Najumunnisa[6], Bodapati Venkata Rajanna[1], Shaik Hasane Ahammad[7], Gongati Pandu Ranga Reddy[8]
[1]Department of Electrical and Electronics Engineering, MLR Institute of Technology, Hyderabad, India
[2]Department of Computer Science and Engineering, R K College of Engineering, Kethanakonda, India
[3]Department of Electrical and Electronics Engineering, VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad, India
[4]Department of Electronics and Communication Engineering, Aditya University, Surampalem, India
[5]Department of Computer Science and Engineering-Artificial Intelligence and Machine Learning, KKR & KSR Institute of Technology and Sciences, Guntur, India
[6]Department of Electronics and Communication Engineering, Dhanekula Institute of Engineering and Technology, Ganguru, India
[7]Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education Foundation, Guntur, India
[8]Department of Electrical and Electronics Engineering, G. Pullaiah College of Engineering and Technology, Kurnool, India

Article Info

Article history:

Received Jun 18, 2025
Revised Feb 15, 2026
Accepted Mar 12, 2026

Keywords:

Arduino UNO
Energy efficiency
Improvement
IoT monitoring
Renewable energy systems
Smart temperature control
Solar PV cooling

ABSTRACT

The efficiency of solar photovoltaic panels declines significantly as their surface temperature increases beyond optimal levels. This paper presents a smart, temperature-controlled cooling system based on an Arduino UNO microcontroller to enhance solar panel performance by mitigating overheating. The system integrates a DS18B20 temperature sensor and a moisture sensor to monitor real-time environmental conditions. When the temperature exceeds a defined threshold, the Arduino activates a CPU fan and water pump to dissipate heat effectively. Experimental testing demonstrated an efficiency improvement of approximately 10% to 12% during peak solar conditions. A hysteresis logic-based system with autonomous control is used to control the amount of energy and water utilized, by only cooling when required. An LCD screen displays real-time information locally on-site, while an ESP8266 WiFi module sends information to a "cloud" so that remote monitoring can occur through the ThingSpeak cloud service. The entire system operates entirely from solar energy and is capable of being operated off-the-grid as well as being environmentally friendly. Due to its low cost, modularity, and energy efficiency, this smart cooling solution provides a viable solution for rural areas or areas with limited resources to enhance the performance of photovoltaic systems.

Corresponding Author:

Bodapati Venkata Rajanna
Department of Electrical and Electronics Engineering, MLR Institute of Technology
Hyderabad, India
Email: rajannabv2012@gmail.com

1. INTRODUCTION

Solar panels become increasingly unproductive as temperatures increase, resulting in decreased electricity generation [1]-[3]. A new smart cooling solution to enhance solar panel output through optimized temperature management [4], [5]. The project uses an Arduino UNO microcontroller to execute all requirements and integrates temperature/moisture sensors to continuously monitor solar panel activity [6], [7]. A water pump and fan are activated when the temperature of the panels exceeds a predetermined threshold [8], [9]. When the temperature has returned to a safe range, the cooling solution will stop operating

to preserve water and energy resources [10]. All sensor information is sent wirelessly through an ESP8266 Wi-Fi module enabling real-time remote access to sensor information/alerts via the ThingSpeak dashboard [11], [12]. The entire system operates with solar panel energy to allow for off-grid living and sustainable practices [13]-[15]. The main objectives of the project are:
- Monitor solar panel temperature and moisture levels in real time [16].
- Transmit live data to ThingSpeak for remote analysis and diagnostics [17].
- Automatically activate cooling components when thermal thresholds are breached [18].
- Minimize energy and water use by intelligently disabling cooling when not needed [19].
- Present operational data locally using an LCD screen [20].
- Ensure complete operation using solar energy for environmental efficiency [21].

An embedded system is a combination of hardware and software tailored for specific tasks. Typical systems like this use microcontrollers for real-time monitoring, decision making, and actuation devices [22]. The proposed solar cooling solution will use an Arduino UNO microcontroller to independently control cooling based on data collected from sensors [23]. The end result is the creation of an eco-friendly, inexpensive, and self-adapting way to manage solar arrays with the addition of IoT technology and automated control [24], [25].

2. SYSTEM ARCHITECTURE AND WORKING PRINCIPLE

An overview of the working of the proposed solar panel cooling system is shown in Figure 1. The system uses an Arduino UNO microcontroller as its Central control unit. It works with sensors to monitor temperature and humidity to determine when to turn ON or OFF the cooling system. The interaction of the various elements in the system is described below:

i) Solar panel and charging circuit: The solar panel uses clean energy to recharge a rechargeable battery via a power module. This allows the solar panel system to operate off of the grid.
ii) Battery power supply and switch: The rechargeable battery holds all the energy that is collected from the solar panel and is connected to a power switch that supplies power to an Arduino board.
iii) Sensors (DS18B20 and moisture sensor):
    - The DS18B20 temperature sensor measures the surface temperature of the solar panel.
    - The moisture sensor indicates the relative humidity of the surrounding environment to help determine the optimal cooling method (for example, when water cooling is not needed in damp conditions).
iv) Arduino UNO microcontroller: The Arduino board takes the input from the sensors and sends out signals to the actuators (fan and water pump) via digital logic. The Arduino board also controls how the Arduino interacts with the Wi-Fi module for IoT connectivity.
v) Cooling and monitoring components:
    - The water pump is controlled through a relay module, which turns on the pump when a temperature threshold is exceeded.
    - A transistor circuit is used to control a CPU fan based on logic-level output from the Arduino microcontroller.
    - The LCD driver and LCD display allow for local viewing of current temperature and moisture levels.
    - An ESP8266 Wi-Fi module sends temperature and moisture level data to ThingSpeak for monitoring and data storage.
vi) IoT platform-ThingSpeak: Sensor readings are sent from the ESP8266 to ThingSpeak, which is an open-source cloud-based system that allows users to see and measure how their system performs from a distance.

2.1. Solar panel specifications and charging circuit description

A polycrystalline solar photovoltaic panel rated at (Vmp = 18 V, Imp = 1.11 A) has an open-circuit voltage of 21.6 V and short-circuit current of 1.2 A, thus making it suitable for low-power embedded and IoT-based applications. This type of solar panel works well when exposed to standard test conditions (STC) of 1000 W/m² irradiance and 25 °C ambient temperature.

A charging circuit has been designed to safely pass energy from the solar panel to a 12 V rechargeable battery so as to allow for continuous operation of the system by providing sufficient power for off-grid systems. In addition to this, the use of a diode protection stage has been incorporated to prevent reverse current from the battery back to the solar panel when the solar panel is experiencing very low irradiance levels and in the evening hours. There are also current limiting and voltage regulation devices in place to protect the battery from overheating or overloading and supply stable DC Power to the Arduino UNO board and other devices connected.

2.2. Working principle

The system runs exclusively off a solar-powered battery that supplies a constant DC voltage to operate continuously. Once the system has received power (from solar charging), it continuously scans both the DS18B20 temperature sensor and the moisture sensor for data readings. If the temperature rises over a set high limit (such as 45 degrees C), the system's CPU fan and watering pump are activated by the Arduino through the use of transistor circuits and relays. The CPU fan and watering pump will remain running until the temperature has fallen to below a defined low limit (such as 40 degrees C). Once the temperature drops below this limit, the entire cooling process will stop to save on both energy and water usage. The current live temperature and moisture values are displayed locally on an LCD screen; in addition, the data is uploaded to ThingSpeak, a cloud-based remote monitoring system via the wireless (Wi-Fi) connection of an ESP8266 Wi-Fi module. Therefore, the system is completely autonomous and powered by renewable solar energy, which allows the system to be deployed in many types of off-grid, sustainable ways across the globe.

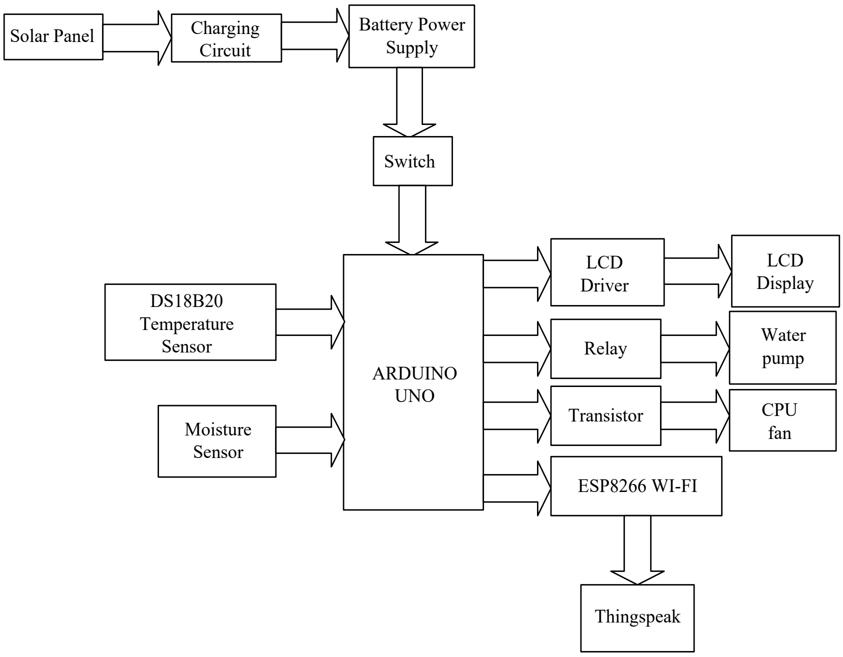


Figure 1. Block diagram of the proposed smart cooling system

3. SCHEMATIC DIAGRAM AND METHODOLOGY

The wiring schematic details the smart cooling system based on temperature, as shown below. This section further elaborates on the circuit-level integration and control methodology employed for the proposed system. It discusses the relationship between the sensing components, the control components, and the actuating components to attain accurate temperature control for the photovoltaic panel. The methodology also discusses the role of programming and IoT communication in achieving autonomous operation. Figure 2 provides additional information on how the key components are connected and integrated. Complementing this, Figure 3 displays the labeled hardware prototype.

3.1. Key components and circuit description

The key components involved in circuit description are:

i) Power supply and charging circuit: The power supply subsystem is made up of a solar panel and rechargeable battery combination that allows for standalone operation. The solar panel's output goes into a charging circuit which provides power to the battery, incorporating: a rectifier diode, a filter capacitor (2200 µF) and a 7805 voltage regulator. The rectifier diode provides reverse polarity protection, whereas the filter capacitor smooths out any fluctuations in voltage. The 7805 voltage regulator steps down the solar panel's output to a regulated voltage of 5 Volts so that it can easily operate the Arduino UNO, sensors, LCD, and ESP8266 modules. The rechargeable battery acts as an energy buffer to allow the smart cooling system to keep operating when solar irradiance is low or when there are very quick fluctuations in load.

ii) Microcontroller (Arduino UNO): The Arduino UNO microcontroller is the control center of the smart cooling system and through the use of its Digital I/O Pins connects all of the peripherals and controls them. The microcontroller will implement the control logic, will read the temperature sensor data, will activate the cooling devices, and will communicate with the smart cooling system and with Wi-Fi.
iii) Temperature sensor (DS18B20): The temperature sensor DS18B20 is an 18B20 digital temperature sensor that will be connected to the Arduino's pin D7. The temperature sensor DS18B20 will measure the temperature of the surface of the solar panel and then provide the temperature information that is used for the control logic.
iv) Moisture sensor: It is connected to analog pin A0. Measures environmental humidity and soil moisture to optimize or override water-based cooling when unnecessary.
v) Cooling system:
   - Water pump: Driven by a relay circuit connected to pin D9 of Arduino. The relay is controlled via a BC547 NPN transistor and protected by a flyback diode.
   - CPU Fan: Driven directly using a transistor switch (BC547), which allows the fan to be toggled based on temperature logic.
vi) LCD display (16x2): It is connected via digital pins D3–D6 to the Arduino and displays real-time temperature and moisture readings, and system status (e.g., “Cooling ON/OFF”).
vii) Wi-Fi communication (ESP8266 module): It is connected to pins D0 and D1 (RX/TX), and it sends sensor data to the cloud-based ThingSpeak IoT platform for remote monitoring.
viii) Reset and control switches: A manual push-button reset is available for system initialization, and a bypass switch can be used to manually disable the system during maintenance.

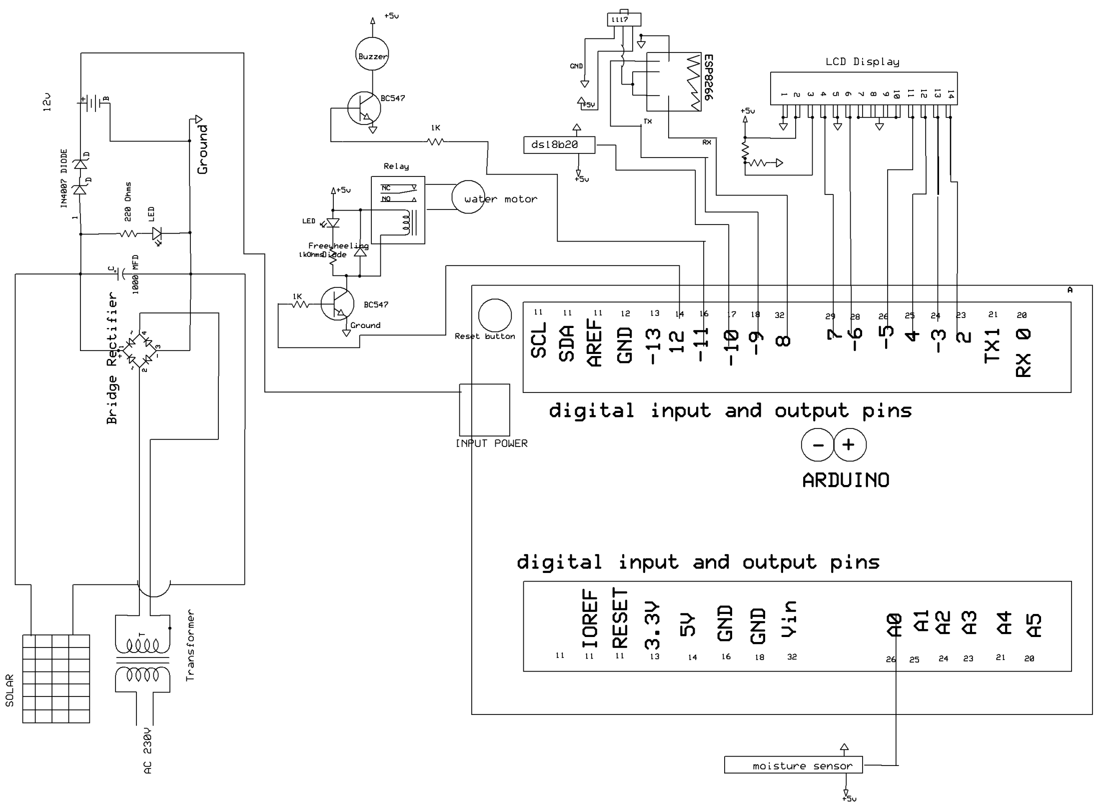
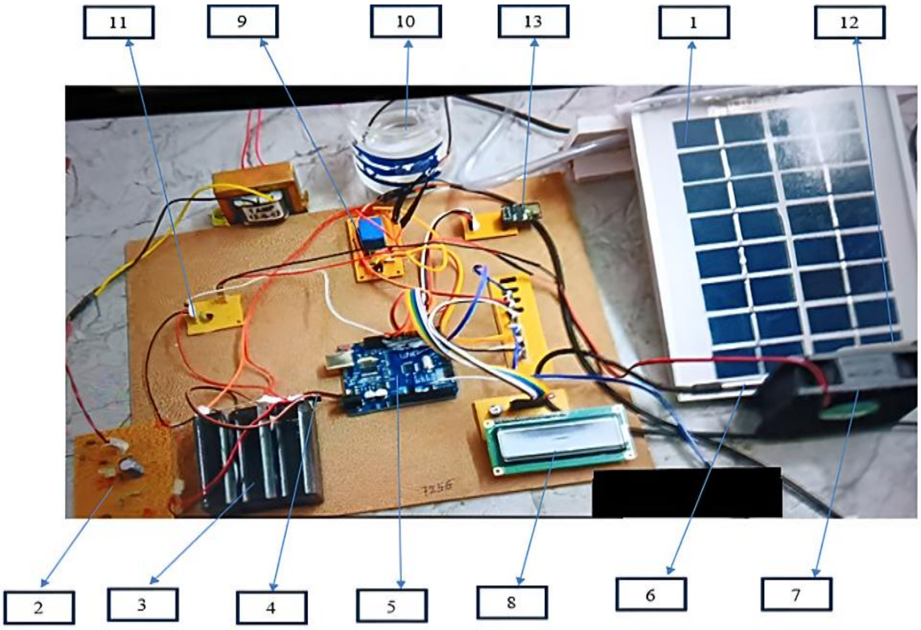


Figure 2. Circuit schematic of the proposed Arduino-based smart cooling system

3.2. Working method

When the Arduino is turned on, it reads all the sensors connected to it. The sensors will be connected to the ThingSpeak application through the ESP8266 Wi-Fi chip. The DS18B20 sensor will be able to read the temperature at the surface of the panel continuously. When the temperature exceeds a certain level that has been predetermined (e.g., 45 °C), the Arduino will turn on the CPU cooling fan through a transistor switch and activate the relay for turning on the water pump. The cooling system will remain in operation until the temperature goes below a certain level determined by hysteresis (e.g., 40 °C). The sensor data are displayed locally on an LCD and sent in real-time to ThingSpeak's cloud for monitoring. If a moisture sensor is used as an option, it will allow for the bypassing of the water down to the panel when the panel is wet after rain. The total setup is inexpensive, self-sufficient, and adequate for utilization in off-grid solar systems for maximum photovoltaic efficiency.



1 Solar Panel, 2 Charging Circuit, 3 Battery, 4 Switch, 5 Arduino UNO, 6 DS18B20 Temperature Sensor,

7 Moisture Sensor, 8 LCD Display, 9 Relay, 10 Water Pump, 11 Transistor, 12 CPU Fan, and

13 ESP8266 Wi-Fi Module. These components correspond directly to those in the schematic and demonstrate the practical realization of the proposed system.

Figure 3. Hardware implementation of the Arduino-based smart cooling system for solar panels

3.2.1. Arduino program for smart cooling logic

The core functionality of the proposed smart cooling system is programmed on an Arduino UNO using embedded C++. The code integrates temperature and moisture sensing, fan/pump control, LCD display, and IoT-based data transmission via ThingSpeak using an ESP8266 module. Algorithm 1 is the source code used in the project.

Algorithm 1. Embedded C++ program for the proposed smart cooling system

```
#include <SoftwareSerial.h>
#include <OneWire.h>
#include <LiquidCrystal.h>
SoftwareSerial mySerial(8,9); //  RX, TX
LiquidCrystal lcd(2,3,4,5,6,7);
OneWire  ds(10);  // on pin 10 (a 4.7K resistor is necessary)
byte i;
byte present = 0;
byte type_s;
byte data[12];
byte addr[8];
float celsius, fahrenheit;
int fan = 11;
int relay = 12;
char ch;
//char data[85];
String data1 = "";
char cnct[10] = ",CONNECT";
int dsize = data1.length();     // previous length of the String
String apiKey = "4OKEMJ4WKL2TMDV9";
int led = 13;
```

```
int tcount = 0;
void setup(void)
{
Serial.begin(9600);
mySerial.begin(115200);
pinMode(led, OUTPUT);
pinMode(fan, OUTPUT);
pinMode(relay, OUTPUT);
lcd.begin(16, 2);
lcd.setCursor(0,0);
lcd.print(" Arduino IOT ");
lcd.setCursor(0,1);
lcd.print("Solar Cooling");
mySerial.print("AT\r\n");
mySerial.println("AT+RST");
delay(300);
digitalWrite(led, HIGH);   // turn the LED on (HIGH is the voltage level)
delay(700);               // wait for a second
digitalWrite(led, LOW);    // turn the LED off by
delay(700);
digitalWrite(led, HIGH);   // turn the LED on (HIGH is the voltage level)
delay(700);               // wait for a second
digitalWrite(led, LOW);    // turn the LED off by
delay(700);
//
Serial.println(" Start... ");
}
void loop(void)
{
int level = analogRead(A0);
level = map(level,0,1023,100,0);
celsius = ds.read();
Serial.print(level);
Serial.print(",");
Serial.println(celsius);
lcd.clear();
lcd.setCursor(0,0);
lcd.print("Temp:");
lcd.print(celsius);
lcd.print(" DegC");
lcd.setCursor(0,1);
lcd.print("Level:");
lcd.print(level);
lcd.print(" %");
delay(1000);     // maybe 750ms is enough, maybe not
if(celsius > 40)
{
lcd.clear();
lcd.setCursor(0,0);
lcd.print("High Temperature");
digitalWrite(fan, HIGH);   // turn the LED on (HIGH is the voltage level)
digitalWrite(relay, HIGH);   // turn the LED on (HIGH is the voltage level)
}
else
{
digitalWrite(fan, LOW);   // turn the LED on (HIGH is the voltage level)
}
if(level > 40)
{
digitalWrite(relay, LOW);   // turn the LED on (HIGH is the voltage level)
}
tcount++;
if(tcount > 12)
{
tcount = 0;
String getStr = "GET /update?api_key=";
getStr += apiKey;
getStr +="&field1=";
getStr += String(celsius);
getStr +="&field2=";
getStr += String(level);
getStr += "\r\n\r\n";
mySerial.print(getStr);
}
}
```

3.2.2. IoT monitoring via ThingSpeak

The ESP8266 Wi-Fi module transmits real-time sensor data, such as the solar panel's surface temperature and moisture levels, to the ThingSpeak cloud platform. ThingSpeak is a web-based service that allows users to save, view, and analyses their data with charts and dashboards in order to monitor the performance of their systems, check the status of the cooling elements, and to troubleshoot any possible problems like failing to cool down enough. The capability to conduct historical trend analyses will help improve the performance of the systems as it will provide the information necessary to establish the optimal operating conditions and predict maintenance needs.

3.3. Component description

Table 1 summarizes the hardware components shown in Figure 3. Each numbered module is essential to the system's operation. It enables sensing, actuation, control, and communication in the smart cooling system.

Table 1. Description of hardware components used in the smart cooling system

Label	Component	Function summary
1	Solar panel	Converts sunlight to electricity to power the entire system.
2	Charging circuit	Manages battery charging safely from solar input.
3	Battery	Stores solar energy to power the system when sunlight is low.
4	Switch	Controls activation of cooling based on sensor feedback.
5	Arduino UNO	Central controller that processes data and manages actions.
6	DS18B20 temperature sensor	Measures solar panel temperature.
7	Moisture sensor	Detects humidity or rain, optimizes cooling decisions.
8	LCD display	Displays real-time temperature, moisture, and system status.
9	Relay	Acts as an electronic switch to control high-power devices like the fan/pump.
10	Water pump	Sprays water for rapid cooling when panel overheats.
11	Transistor	Amplifies Arduino signals to switch higher-current devices.
12	CPU fan	Provides air cooling for the solar panel.
13	ESP8266 Wi-Fi module	Sends data to the internet for IoT-based monitoring.

4. RESULTS AND DISCUSSION

Comparative advantages of the proposed system compared to traditional systems are presented in Table 2 to help illustrate the various benefits. Specifically, the differences in the way the two different types of systems are controlled, how they consume energy, how intelligent the systems are and what their effect is on the environment have been compared between these two types of systems.

The smart cooling system has been successfully deployed and assessed in various environmental settings, and its efficiency is determined based on sensor performance, cooling efficiency, and energy use.

i) Temperature detection: The temperature detector DS18B20 was able to accurately detect surface temperature changes, reporting an accurate surface temperature greater than or equal to 0.5 °C and a 1-second delay in reporting surface temperature changes from the time that it sensed the surface temperature.
ii) Activation of cooling: The activation of the CPU fan and water pump occurred once the surface temperature of the solar panel exceeded 45 °C and continual cooling took place until the temperature of the panels dropped under 40 °C, thereby creating a hysteresis behavior that prevented rapid switching of cooling.
iii) Improvement in performance: Solar panels created a large amount of heat during the heat of the day, but the voltage of the solar panel dropped dramatically once the solar panel surface temperature reached 50 °C with no cooling. The system therefore was able to maintain a range of 38 °C to 44 °C for the panel surface temperature by means of the smart cooling system, which enabled the panel to produce a constant voltage and current. Efficiency increases of approximately 10%-12% were therefore observed at peak load conditions with the smart cooling system.
iv) Electricity consumption: The amount of electricity consumed by the CPU fan and water pump was less than two watts combined, this is a very small addition when considering that the cooled solar panel produced more electricity than the CPU fan and water pump used.
v) Remote surveillance: The ESP8266 module was successful in transmitting all sensor data to the ThingSpeak platform. The platform provided live dashboards for real-time tracking and historical trend analysis. The temperature and moisture data was collected and plotted in real-time using the dashboard (Figure 4), which enabled remote monitoring of system performance and diagnostics.

vi) Scalability and customization: Users can change the temperature thresholds and/or timing via code updates. The ability to modify the firmware allows for the customization of the system for various solar panel sizes, types, and climates.
vii) Limitations: When ambient temperatures exceed 50 °C, air-cooling only does not perform well enough by itself. At those temperatures hybrid systems will use misting or phase-change materials to assist with cooling performance.

The results from this study indicate that the smart cooling system based on Arduino is an efficient way to increase the performance of photovoltaic cells while maintaining a low level of power consumption and a degree of autonomy in operation. The system would be best suited to locations that are remote or have no access to electricity and that rely heavily on solar energy.

Table 2. Comparison of conventional and proposed system

Sl. No.	Parameter	Conventional system	Proposed smart system (Arduino-based)
1	Control method	Manual or passive	Automatic control using Arduino
2	Cooling activation	Always on or fixed schedule	Activates based on real-time temperature sensing
3	Energy consumption	High (continuous operation)	Low (only when required)
4	Temperature monitoring	Absent or manual	Real-time monitoring with sensors (e.g., DS18B20)
5	System intelligence	None	Smart decision-making using Arduino programming
6	Installation cost	Low to moderate	Slightly higher (due to sensors and Arduino board)
7	Maintenance requirement	Higher (due to continuous use)	Lower (optimized usage reduces wear and tear)
8	Cooling method	Fixed cooling (e.g., static fans, water flow)	Dynamic cooling (CPU fan controlled by Arduino)
9	Response time	Slow	Fast (instantaneous response to heat rise)
10	Solar panel efficiency	Lower (due to overheating)	Higher (due to effective cooling)
11	Customization flexibility	Difficult	Easy (can adjust thresholds by changing code)
12	Environmental impact	Higher (more energy wastage)	Lower (energy-efficient smart operation)

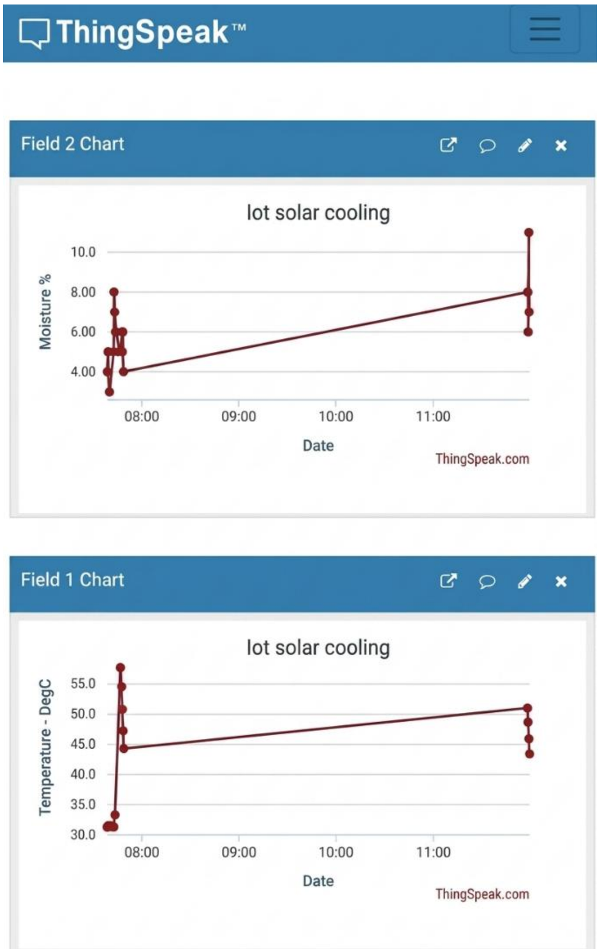


Figure 4. Real-time data visualization of temperature and moisture levels using the ThingSpeak IoT platform

5. CONCLUSION

This project developed a smart cooling system that uses Arduino UNO and is temperature dependent on solar panels. The system measures surface temperature of the solar panel with the DS18B20 temperature sensor and when the temperature goes above a set threshold, the Arduino UNO turns on an electric fan or water pump to cool down the solar panel and return it to its optimal operating state. The smart cooling system is more efficient in its use of energy than traditional cooling systems that either run all the time or according to a pre-programmed schedule, as it only runs when necessary, thereby reducing wasted energy. Additionally, this intelligent use of energy helps to prevent the overheating of solar panels, contributing to increased electrical output and extended life expectancy of solar panels. In addition, the reduced mechanical wear on the cooling system reduces future maintenance needs.

The smart cooling system is an inexpensive alternative for anyone wanting to cool off solar panels and it can be easily modified via program coding to suit any type of small scale, off-grid, and residential application. With the incorporation of the ESP8266 Wi-Fi module and ThingSpeak Cloud Platform, users can monitor their cooling systems through real-time data monitoring and diagnostic capabilities. In conclusion, the smart cooling system is an effective way to cool solar panels in a way that is eco-friendly, sustainable and effective compared to traditional methods for cooling solar panels. Future enhancements may include the integration of predictive algorithms, misting systems, or phase change materials (PCMs) to further improve thermal regulation and system reliability. This work demonstrates the potential of combining embedded automation with renewable energy technologies to create sustainable and efficient energy solutions.

FUNDING INFORMATION

There are no sources of funding agency that have supported the work. So, the authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Mula Sreenivasa Reddy	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Kondragunta Rama Krishnaiah		✓				✓		✓	✓	✓	✓	✓		
Anjali Devi Gorla		✓				✓		✓	✓	✓	✓	✓		
Anantha Sravanthi Peddinti	✓		✓	✓			✓			✓	✓		✓	✓
Sanam Nagendram		✓				✓		✓	✓	✓	✓	✓		
Mohammad Najumunnisa	✓		✓	✓			✓			✓	✓		✓	✓
Bodapati Venkata Rajanna	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Shaik Hasane Ahammad		✓				✓		✓	✓	✓	✓	✓		
Gongati Pandu Ranga Reddy		✓				✓		✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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BIOGRAPHIES OF AUTHORS

Mula Sreenivasa Reddy is currently working as an associate professor at Department of Electrical and Electronics Engineering, MLR Institute of Technology, Dundigal, TS, India. He obtained his B.E. in electrical and electronics engineering and M.Tech. in power system engineering. He published 10 international journals and 10 national and international conferences. His area of interest is renewable energy sources. He can be contacted at email: sreenivasareddy.mula@mlrinstitutions.ac.in.

Kondragunta Rama Krishnaiah is a highly qualified person, an efficient and eminent academician. He is an outstanding administrator; a prolific researcher published 95+ research papers in various national and international journals, and a forward-looking educationist. He has guided several students for their M.Tech. and Ph.D. degrees and also authored 5 textbooks. He worked in prestigious K L (Deemed to be) University for 11.5 years and has contributed his service for NBA accreditation in May 2004, Aug 2007 with 'record rating', ISO 9001:2000 in 2004, Autonomous status in 2006, NAAC accreditation of UGC in 2008, and University status in 2009. Later on, he worked as principal at Nova College of Engineering and Technology, Vijayawada for a period of 3.5 years and NVR College of Engineering & Technology, Tenali, for a period of 1.5 years. He took charge as the Principal, RKCE, Vijayawada in December 2015. Under his able leadership, the college is rising towards a bright future with high academic values and the college got accredited by NAAC with "A" Grade and obtained UGC "AUTONOMOUS STATUS" from the Academic Year 2024-25. He has received the "Appreciation Award" for the senior principals from JNTUK, Kakinada, in the year 2024. He can be contacted at email: kondraguntark@gmail.com.

Anjali Devi Gorla received the B.Tech. degree in electrical and electronics engineering from V.K.R. and V.N.B Engineering College, Gudivada, AP, India in 2014, the M.Tech. advanced electrical power systems from JNT University Kakinada, AP, India in 2019, and pursuing Ph.D. in NIT Warangal. She has 5 years of teaching experience. She has been working as an assistant professor in EEE Department of VNR VJIET since 2020. Her research interests are in power system protection and AC microgrid operation, and energy technologies. She can be contacted at email: anjalidevi_g@vnrvjiet.in.

Anantha Sravanthi Peddinti received M.E. from University College of Engineering, OU. Currently working as an associate professor in ECE Department at Aditya College of Engineering & Technology, Surampalem, AP, India. Her research interest area is image processing. She can be contacted at email: sravanthi.angara@acet.ac.in.

Sanam Nagendram received her B.Tech. degree in electronics and computer engineering from Koneru Lakshmaiah College of Engineering and Technology, Vaddeswaram, India, in 2006, followed by an M.Tech. degree in computer science and engineering from Jawaharlal Nehru Technological University, Kakinada (JNTUK), India, in 2010. She earned her Ph.D. degree specializing in Computer Science and Engineering from Acharya Nagarjuna University, Guntur, India. Currently, Dr. Nagendram serves as an associate professor at KKR & KSR Institute of Technology and Sciences, Vinjanampadu, Guntur, Andhra Pradesh, India. Her research interests primarily focus on computer networks, mobile Ad Hoc networks (MANETs), artificial intelligence, and machine learning. Dr. Nagendram is committed to advancing knowledge in these fields through innovative research and active collaboration with academic and industry professionals. She can be contacted at email: reena1286@gmail.com.

Mohammad Najumunnisa is currently serving as an assistant professor in the Department of Electronics and Communication Engineering at Dhanekula Institute of Engineering and Technology, Ganguru, A.P. – 521131. She earned her Ph.D. (microwave imaging) and M.Tech. in radar and communication systems from Koneru Lakshmaiah Education Foundation, Vijayawada. She completed her B.Tech. in electronics and communication engineering from Nimra Institute of Science and Technology, Ibrahimpatnam. Her academic journey reflects strong expertise in communication and electronic systems. She has published six journal papers in reputed journals like sensors, food analytical methods, and scalable computing. Her research spans MIMO antennas, RFID, and microwave imaging. She holds four national-level patents focused on antenna design, medical monitoring, and industrial heating applications, reflecting her innovation in electronics and communication. She can be contacted at email: mohammednazia440@gmail.com.

Bodapati Venkata Rajanna is currently working as an associate professor in Department of Electrical and Electronics Engineering at MLR Institute of Technology, Hyderabad, India. He received B.Tech. degree in electrical and electronics engineering from Chirala Engineering College, JNTU, Kakinada, India, in 2010, M.Tech. degree in power electronics and drives from Koneru Lakshmaiah Education Foundation, Guntur, India, in 2015, and Ph.D. in electrical and electronics engineering at Koneru Lakshmaiah Education Foundation, Guntur, India, in 2021. His current research includes, dynamic modeling of batteries for renewable energy storage, battery management systems (BMS) for electric vehicles and portable electronics applications, renewable energy sources integration with battery energy storage systems (BESS), smart metering and smart grids, micro-grids, automatic meter reading (AMR) devices, GSM/GPRS, and power line carrier (PLC) communication, and various modulation techniques such as QPSK, BPSK, ASK, FSK, OOK, and GMSK. He can be contacted at email: rajannabv2012@gmail.com.

Shaik Hasane Ahammad (student member, IEEE) received his B.Tech. and M.Tech. degrees in electronics and communication engineering from Jawaharlal Nehru Technological University, Kakinada, in 2011 and 2014, respectively. He earned his Ph.D. in ECE from Koneru Lakshmaiah Education Foundation (KLEF) Deemed to be University, Vaddeswaram, Guntur, Andhra Pradesh. Currently, he is serving as an assistant professor in the Department of ECE at KLEF, where he also holds the position of associate dean for research and development, and has published over 246 research papers in reputed international journals. He is a passionate researcher with deep interests in machine learning, computer vision, and biomedical image analysis. He can be contacted at email: ahammadklu@gmail.com.

Gongati Pandu Ranga Reddy received his B.Tech. in EEE from JNTU Hyderabad, M.Tech. in control systems, and Ph.D. in electrical engineering (renewable energy sources) from JNTUA, Anantapur. He is currently professor and HOD at Department of EEE, G. Pullaiah College of Engineering and Technology, Kurnool, with 20 years of teaching and research experience. His research interests include matrix converters, power quality, renewable/conventional energy sources, intelligent and optimization techniques. He has published 55 research papers in SCI/Scopus-indexed journals and reputed conferences, received the Best Researcher National Award (2019), serves as a reviewer for international journals, and holds four patent publications. He can be contacted at email: gprreee@gmail.com.