STM32-Based Photovoltaic Power Generation Monitoring and Protection System

Revised Final Report

ECE 445 / ME 470 Senior Design

Team:	Project 51
Prepared by:	Guangjun Xu, Xu Li, and Sunhao Zhang
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Revision focus:	Circuit schematics, quantitative verification, and uncertainty analysis

Abstract. This revised final report presents the completed design of an STM32-based photovoltaic (PV) power generation monitoring and protection system. The prototype improves the visibility, safety, and controllability of a small PV or DC generation demonstration setup. The final hardware uses an STM32F103C8T6 microcontroller as the main controller, a voltage-sensing channel for PV-side electrical monitoring, a DS18B20 digital temperature sensor for local thermal monitoring, an OLED display for local data presentation, push buttons for local control and threshold setting, an ESP8266-01S Wi-Fi module for mobile-app communication, and relay, LED, and buzzer outputs for protection and alarm functions.

The completed prototype verifies the final project scope: local monitoring of voltage and temperature, calculation and display of current and power indicators, threshold-based automatic protection, local threshold adjustment, manual control, remote data observation, and remote command input through the mobile application. The earliest project description used the word charger; however, the implemented system does not include a battery charging circuit or energy-storage subsystem. The relay is used as a controllable output and protection device for the PV/load path. This revision adds English circuit schematics and PCB layouts, a weekly schedule, quantitative verification procedures and results, and quantitative uncertainty estimates.

Keywords: STM32F103C8T6; photovoltaic monitoring; ESP8266; OLED display; threshold protection; relay control; uncertainty analysis.

Contents

Revision Compliance Summary

Table 1: How the revised report addresses instructor comments.

Instructor request	Where addressed in this revised report
Add circuit schematics and PCB design	Section 2.2 and Figures 1-8 add the system block diagram, the full English circuit schematic, simplified voltage-sensing circuit, MCU pin mapping, relay/LED/buzzer wiring, ESP8266 UART interface, and PCB top/bottom layouts. Section 2.3 also keeps the software flowchart and protection-logic flowchart from the original report concept, redrawn with English labels.
Add project schedule	Section 4.2 gives a weekly schedule and identifies the primary student responsibilities.
Make requirements and verification quantitative	Sections 1.3 and 3 define numeric acceptance criteria, measurement methods, and reproducible pass/fail thresholds.
Add quantitative results	Tables 5-6 and Figures 11-14 include measured output voltage, recorded temperature, voltage range, current, power, response behavior, and protection cutoff data.
Rewrite accomplishments	Section 5.1 summarizes the prototype using quantified testing results.
Add uncertainty analysis	Section 3.5 estimates uncertainty from the DMM, ADC quantization, voltage-sensor gain, temperature sensor, timing observation, and calculated current/power model.

1. Introduction

1.1 Motivation and Problem Statement

Small PV systems are increasingly used in household and small commercial scenarios because they are clean, compact, and relatively easy to install. However, a basic PV panel and load connection does not automatically provide clear information about operating status. Without a monitoring and control layer, users may not know whether the PV output is within a safe range, whether local temperature is abnormal, or whether the output path should be disconnected to protect equipment. These limitations motivated this project.

The design goal was to build a low-cost embedded monitoring and protection system for a small PV generation setup. The system collects key operating data, displays the data locally, supports local configuration, provides automatic alarm behavior, and allows remote observation and control through a mobile application. The project targets a demonstrable embedded-control prototype rather than a grid-connected inverter, a commercial protection relay, or a certified battery charger.

1.2 Final Scope and Design Boundary

The completed project is a PV generation monitoring and control system. It does not include a battery charging circuit, a battery management system, or an energy-storage pack. This final boundary is important because some early project wording referred to a PV charger. During implementation, the team narrowed the scope to embedded monitoring, alarm, relay protection, and remote-control functions. This choice made the prototype more reliable and easier to verify within the project schedule while preserving the main engineering value of the design: safe and intelligent supervision of a small PV output.

In the final design, the relay output connects or disconnects the controlled PV/load path. In automatic mode, the relay opens when voltage, current, or temperature values exceed preset limits. In manual mode, the relay and alarm outputs can be controlled through local buttons or the mobile application. This centers the project on sensing, embedded decision logic, human-machine interaction, and wireless control rather than electrochemical charging behavior.

1.3 System Overview and Quantitative Performance Requirements

Figure 1 shows the final system organization. The STM32F103C8T6 receives information from the voltage sensor, DS18B20 temperature sensor, and local buttons. It processes the data, updates the OLED display, communicates with the ESP8266-01S Wi-Fi module, and drives the LED, buzzer, and relay outputs.

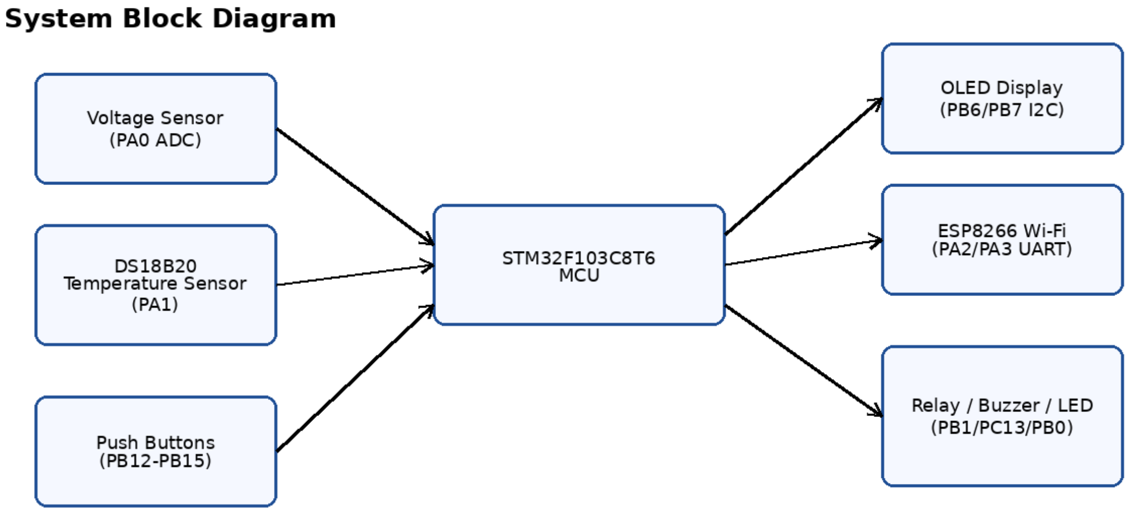


Figure 1: Final system block diagram.

Table 2: Final quantitative performance requirements.

Requirement	Quantitative target or tolerance
Power and output rail	Type-C/load-side output expected near 5 V; pass if measured voltage is between 4.75 V and 5.25 V during no-load or light-load operation. STM32 logic rail should remain inside the normal 3.0 V to 3.6 V operating range.
OLED display	OLED must update voltage, current, power, temperature, operating mode, and thresholds at least once per 1 s; text must be readable during normal indoor lighting.
Temperature sensing	Displayed DS18B20 temperature must update continuously and should change by at least 2 °C when the sensor is warmed by hand for 30 s. Expected uncertainty is about ±0.5 °C.
Voltage sensing	Displayed voltage must change monotonically with the input. For a change larger than 0.2 V at the displayed PV value, the OLED/serial value must change by at least 0.1 V.
Automatic protection	If $V > V_{\mathrm{TH}}$, $I > I_{\mathrm{TH}}$, or $T > T_{\mathrm{TH}}$, the alarm must activate and the relay output must cut off within one display/control cycle, target $\leq$ 1 s.
Manual control	Each local button must produce the intended mode, threshold, or output change within $\leq$ 1 s after a valid press.
Remote communication	The app must receive updated displayed data and send at least relay, alarm, mode, and threshold commands through ESP8266. Target command response is $\leq$ 2 s; the final demo response was visually observed to be approximately 1 s to 2 s.
Final scope	No battery charging or storage function is required or claimed. The relay output is verified as a protected load/output path.

2. Design

2.1 Design Procedure and Major Decisions

The system was divided into input, processing, output, and communication blocks. The input blocks include the voltage-sensing channel, DS18B20 temperature sensor, local buttons, and regulated power input. The processing block is the STM32F103C8T6 microcontroller. The output blocks include the OLED display, LED, buzzer, and relay. The communication block is the ESP8266-01S Wi-Fi module connected to the mobile application.

Several design choices were made to keep the system practical for a course prototype. The STM32F103C8T6 was selected because it provides GPIO, ADC capability, serial communication, timers, and enough processing resources for sensing, display, and communication tasks. The OLED display was selected because it can show multiple measured and threshold values in a compact area. The DS18B20 sensor was selected because it provides digital temperature data and avoids an analog temperature-conditioning circuit. The ESP8266-01S was selected because it provides a low-cost Wi-Fi interface suitable for a mobile-app demonstration.

The original idea of including a battery subsystem was removed from the final system. A safe battery charger would require charge-current regulation, battery chemistry selection, overcharge and overdischarge protection, thermal safety design, and a separate verification process. Those requirements were outside the completed prototype. The final system demonstrates a monitoring and relay-protection layer that could be placed in front of a future charger or controlled load interface.

2.2 Hardware Design and Circuit Schematics

2.2.1 Full Circuit Schematic and PCB Implementation

Figure 2 shows the full project schematic used for the final prototype. All module labels in the schematic have been translated into English. The schematic includes the STM32F103C8T6 core board connector, OLED display interface, ESP8266-01S Wi-Fi module, Type-C power input module, voltage sensor module, DS18B20 temperature sensor, buzzer driver, LED indicator, relay driver, terminal block, debugging UART, and four push buttons.

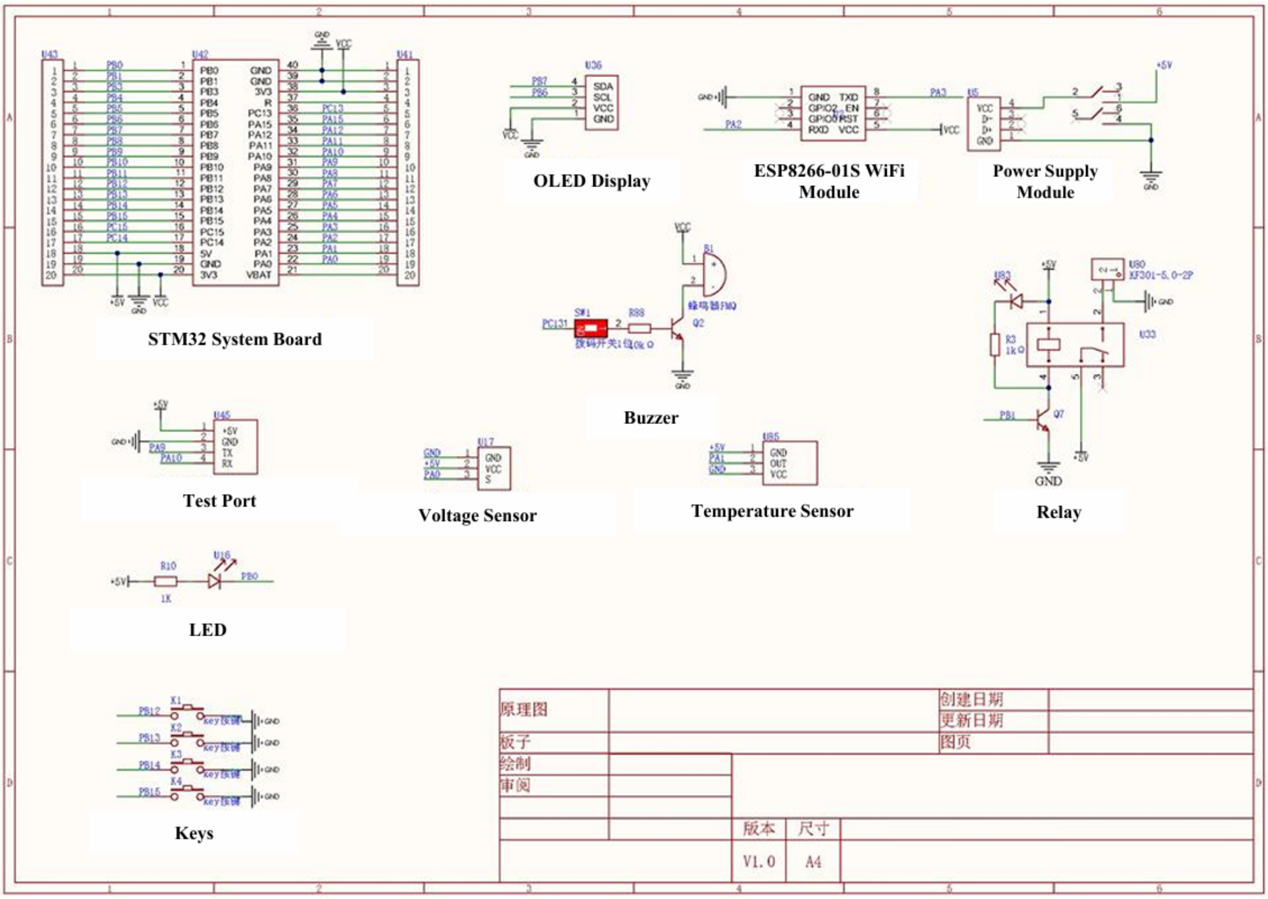


Figure 2: Full circuit schematic for the final prototype with English labels.

Figures 3 and 4 show the PCB top and bottom layouts. The design is a two-layer carrier board that accepts the STM32 core board and connects it to the external modules. The large copper areas are used as reference planes, and the relay/load, Wi-Fi, OLED, sensors, and push buttons are placed as separate functional regions to simplify debugging.

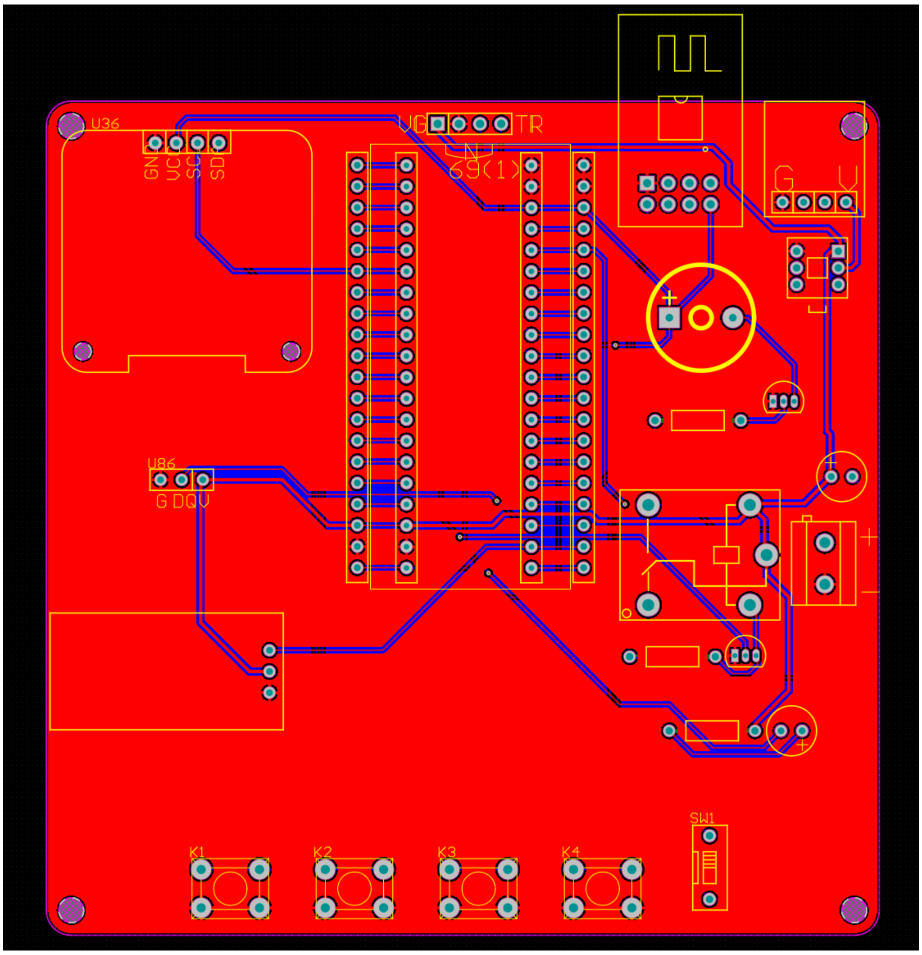


Figure 3: PCB top-side layout.

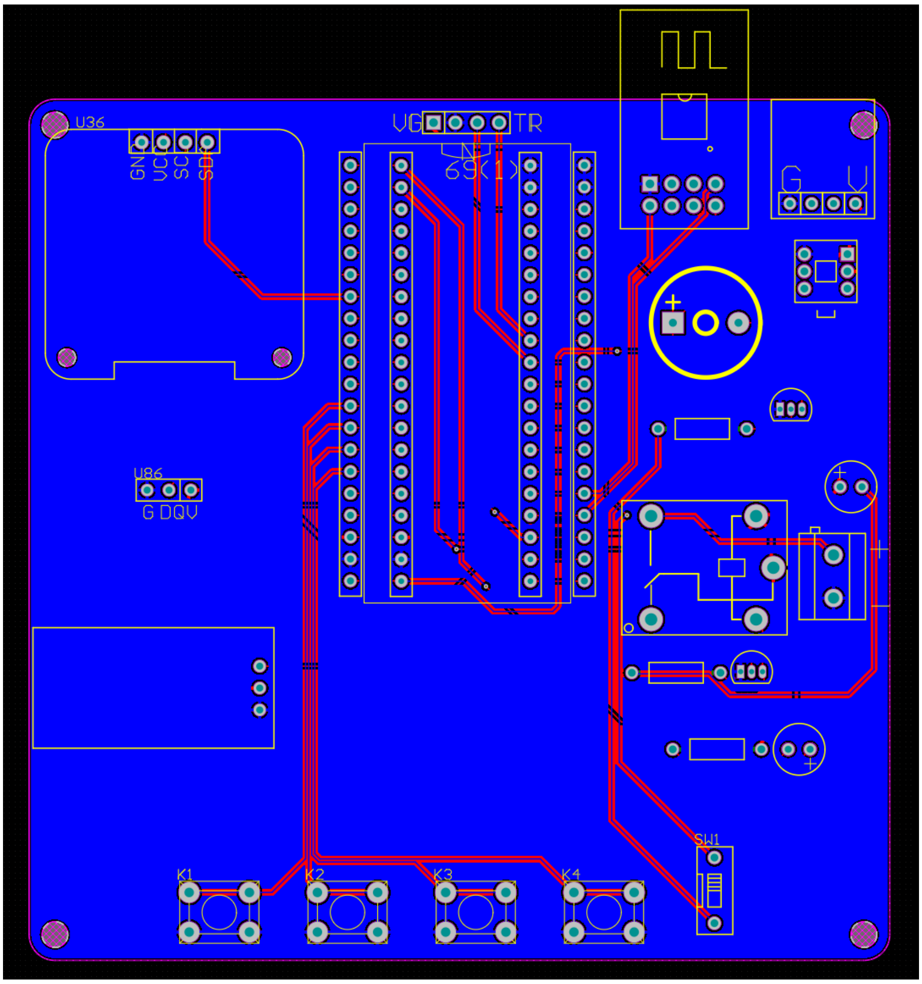


Figure 4: PCB bottom-side layout.

2.2.2 Main Controller and MCU Pinout

The STM32F103C8T6 minimum system board is the center of the prototype. It handles sensor acquisition, display refresh, key scanning, alarm decisions, relay control, and serial communication with the Wi-Fi module. The main PCB connects to the STM32 module through two 20-pin headers. Figure 5 shows the MCU pinout portion of the schematic, and Table 3 lists the actual pins used by the prototype.

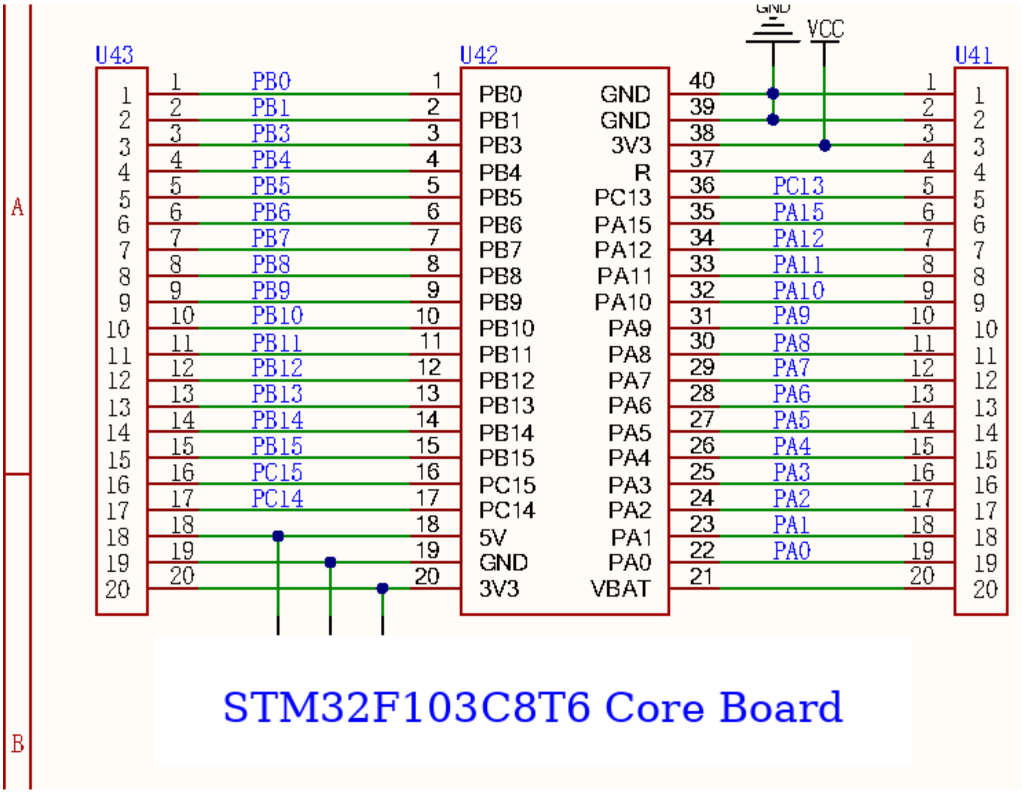


Figure 5: STM32F103C8T6 core-board connector and used pins.

Table 3: MCU pin mapping used in the final prototype.

STM32 pin	Connected module	Function	Direction
PA0	Voltage sensor output S	ADC Channel 0 voltage sample	Input
PA1	DS18B20 OUT	One-Wire temperature data	Bidirectional
PA2	ESP8266 RXD	USART2 transmit to Wi-Fi module	Output
PA3	ESP8266 TXD	USART2 receive from Wi-Fi module	Input
PA9/PA10	Debug UART header	USART1 debug TX/RX	Output/Input
PB0	LED indicator	GPIO output for status LED	Output
PB1	Relay driver Q7	GPIO output for relay control	Output
PB6/PB7	OLED SCL/SDA	Software I2C display communication	Output/Bidirectional
PB12–PB15	K1–K4 push buttons	Local user input with pull-up logic	Input
PC13	Buzzer driver Q2	GPIO output for alarm control	Output

2.2.3 Voltage Measurement Circuit

The PV-side electrical input is measured through a voltage-sensing channel connected to STM32 pin PA0. Because the STM32 ADC input must remain within the 0 V to 3.3 V logic range, the external voltage is scaled before entering the ADC. The implemented board uses a voltage sensor module at U17 with GND, 5 V, and signal output S connected to PA0. The full wiring is shown in Figure 2, while Figure 6 shows the equivalent divider/gain model used by the firmware equations.

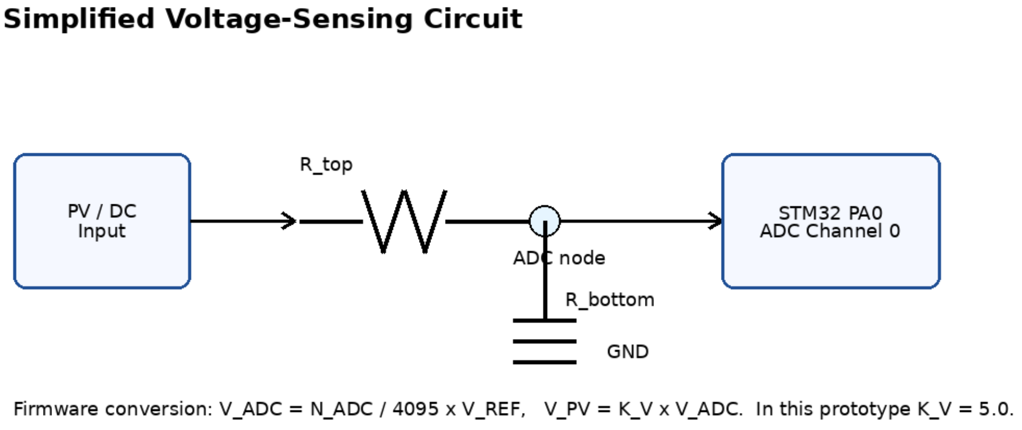


Figure 6: Simplified voltage-sensing model used for ADC conversion.

2.2.4 Temperature Measurement

The temperature-monitoring block uses a DS18B20 digital temperature sensor. The sensor communicates with the controller through a one-wire digital interface on PA1. This choice simplifies the hardware design because no analog signal-conditioning circuit is required for temperature. The measured temperature is displayed on the OLED and compared with the temperature threshold in automatic mode.

2.2.5 Local Display and User Input

The OLED display is the main local user interface. It shows the system mode, measured voltage, calculated current and power, temperature, and threshold values. The OLED uses SCL on PB6 and SDA on PB7. Local push buttons K1–K4 are connected to PB12–PB15 and ground; the firmware uses pull-up input logic so a pressed key is detected as a low level. The buttons support mode switching, threshold adjustment, confirmation of parameter settings, and manual control actions. This local interface allows the system to remain usable when the Wi-Fi connection is unavailable.

2.2.6 Alarm, Relay, and Output Load Interface

The alarm and output-protection block consists of an LED indicator, an active buzzer, and a 5 V relay. The STM32 does not directly drive the relay coil or buzzer load. Instead, GPIO pins drive S8050 NPN transistor stages, which provide the larger current required by the output devices. Figure 7 gives an English simplified output-driver schematic. The relay contacts are brought to the terminal block so that the controlled load/output path can be connected or disconnected. During automatic protection, the relay output is opened when an over-threshold condition is detected.

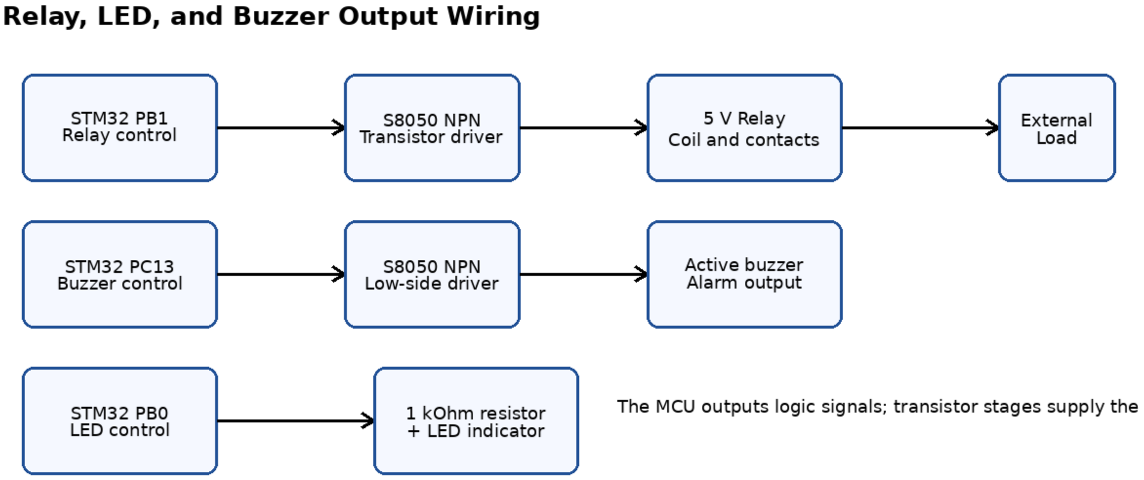


Figure 7: Simplified relay, buzzer, and LED output-driver schematic.

2.2.7 Wi-Fi Communication Interface

The ESP8266-01S Wi-Fi module provides the remote communication channel. The STM32 sends measured data and state information to the module through USART2. The mobile application receives uploaded data and sends commands back to the system, including mode switching, relay control, alarm control, and threshold adjustment. Figure 8 summarizes the UART cross-connection between the STM32 and the ESP8266 module.

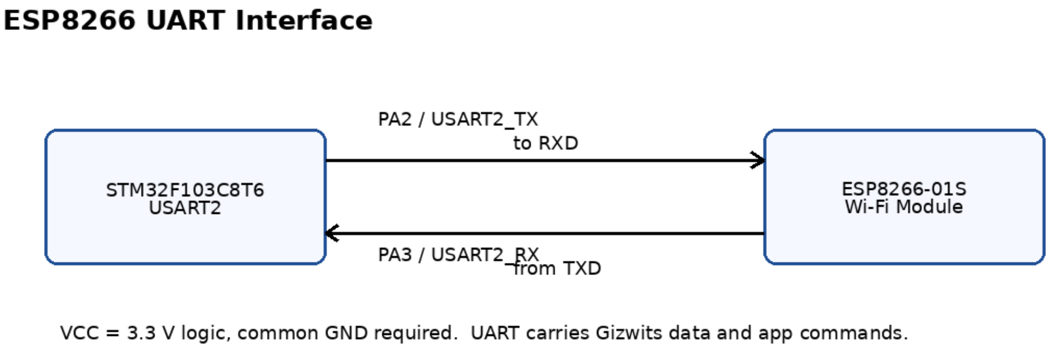


Figure 8: ESP8266 UART connection used for mobile-app communication.

2.3 Software Design

After power-on, the firmware initializes the GPIO, ADC, OLED display, DS18B20 interface, UARTs, timers, Flash-stored threshold values, and Wi-Fi communication. The main loop then reads sensor values, calculates derived values, updates the OLED display, checks local buttons and remote commands, and executes either automatic-protection logic or manual-control logic.

Figures 9 and 10 preserve the original report's software-flow and protection-logic ideas while replacing all labels with English. They show that the system does not depend on Wi-Fi for local protection: the sensing, comparison, and relay/buzzer control path is executed locally by the STM32.

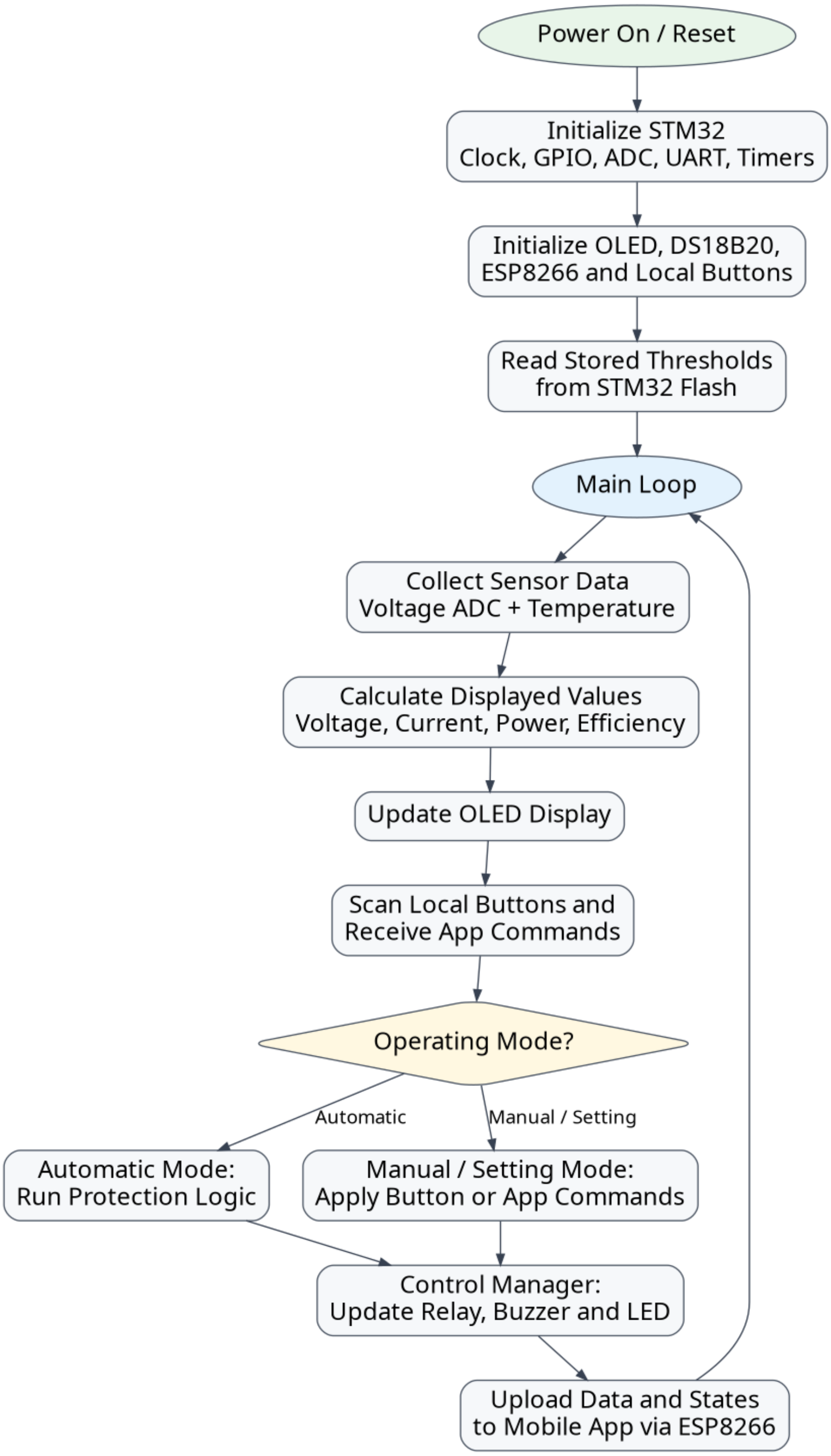


Figure 9: Firmware software workflow with English labels.

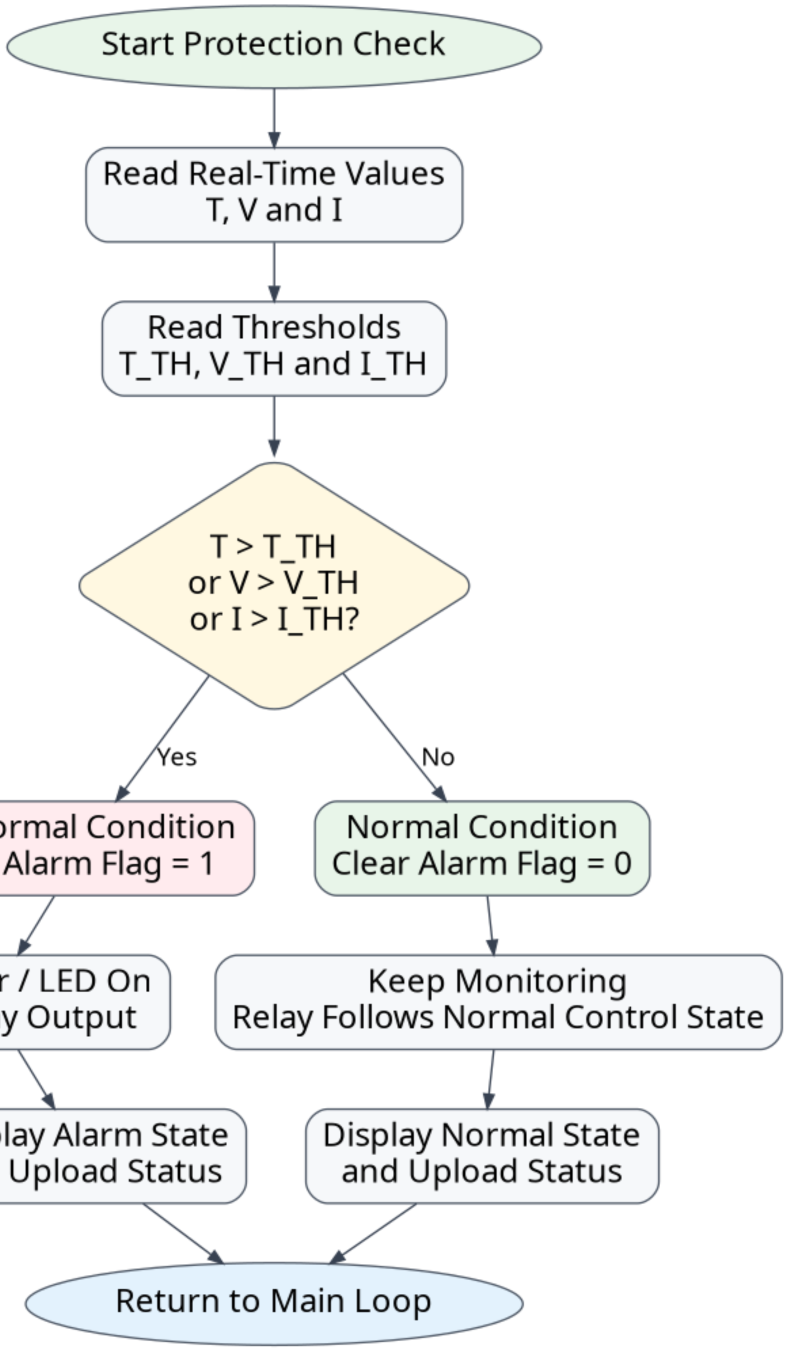


Figure 10: Automatic protection logic flowchart with English labels.

In automatic mode, the firmware compares measured or calculated values with user-defined thresholds. If voltage, current, or temperature exceeds its limit, the firmware activates the LED and buzzer and opens the relay. If all values are within range, the system continues monitoring. In manual mode, control priority is given to the user. Button and app commands can directly control the relay and alarm outputs, which is useful for testing and controlled demonstration. The protection decision is executed locally on the STM32 so that relay cutoff does not depend on network availability.

2.4 Design Equations and Data Processing

The firmware uses the following equations for sensor conversion and displayed indicator calculation. For a 12-bit ADC, the maximum code is

$$N_{\max} = 2^{12} - 1 = 4095. \tag{1}$$

The ADC input voltage is calculated as

$$V_{\mathrm{ADC}} = \frac{N_{\mathrm{ADC}}}{4095} V_{\mathrm{REF}}, \tag{2}$$

where N_{ADC} is the ADC code and V_{REF} is the ADC reference voltage. If the voltage sensor uses a divider or sensor gain represented by K_V, the displayed PV-side voltage is

$$V_{\mathrm{PV}} = K_V V_{\mathrm{ADC}}. \tag{3}$$

Because raw ADC counts were not stored in the final firmware log, this revision reports equivalent ADC counts estimated from the displayed voltage:

$$N_{\mathrm{ADC,est}} = \mathrm{round}\left(\frac{4095 V_{\mathrm{PV}}}{K_V V_{\mathrm{REF}}} \right). \tag{4}$$

Using $K_V = 5.0$ and $V_{\mathrm{REF}} = 3.3\,\mathrm{V}$, the recorded displayed voltage range of 0.95 V to 2.66 V corresponds to approximately 236 to 660 ADC counts. This estimate is used only as a consistency check; future firmware should log raw ADC values directly.

For the demonstration model, current and power are calculated from the estimated voltage and an equivalent load relationship. If R_{EQ} is the equivalent load resistance, then

$$I_{\mathrm{OUT}} = \frac{V_{\mathrm{PV}}}{R_{\mathrm{EQ}}}, \tag{5}$$

and

$$P_{\mathrm{OUT}} = V_{\mathrm{PV}} I_{\mathrm{OUT}}. \tag{6}$$

The threshold protection decision is modeled as

$$F = \begin{cases} 1, & V_{\mathrm{PV}} > V_{\mathrm{TH}} \ \vee \ I_{\mathrm{OUT}} > I_{\mathrm{TH}} \ \vee \ T > T_{\mathrm{TH}}, \\ 0, & \text{otherwise}, \end{cases} \tag{7}$$

where $F = 1$ means the alarm and relay-cutoff state is active. The displayed conversion-rate indicator is a relative demonstration indicator based on a selected reference power, not a certified PV module efficiency unless irradiance, panel area, and calibrated output power are measured:

$$\eta_{\mathrm{display}} = \frac{P_{\mathrm{OUT}}}{P_{\mathrm{REF}}} \times 100\%. \tag{8}$$

3. Verification

3.1 Verification Method and Reproducible Test Conditions

The project was verified in two stages. First, each block was tested independently to reduce uncertainty during integration. Second, the full system was tested in automatic and manual modes to confirm that the integrated behavior matched the final requirements. This revised report adds quantitative acceptance criteria, measurement values, and reproducible procedures.

The final demonstration used a Type-C 5 V supply, the STM32F103C8T6 core board, the OLED display, DS18B20 sensor, voltage sensor module, ESP8266 Wi-Fi module, relay, buzzer, LED, a digital multimeter

(DMM), the serial debug assistant at 115200 baud, and the mobile app. The DMM was used to check the load-terminal output voltage. Serial screenshots recorded the firmware-calculated voltage, current, power, temperature, and conversion-rate values. The measured DMM output voltage at the load terminal was approximately 5.20 V before relay cutoff. When the protection output was turned off, the load-terminal output was observed as 0 V.

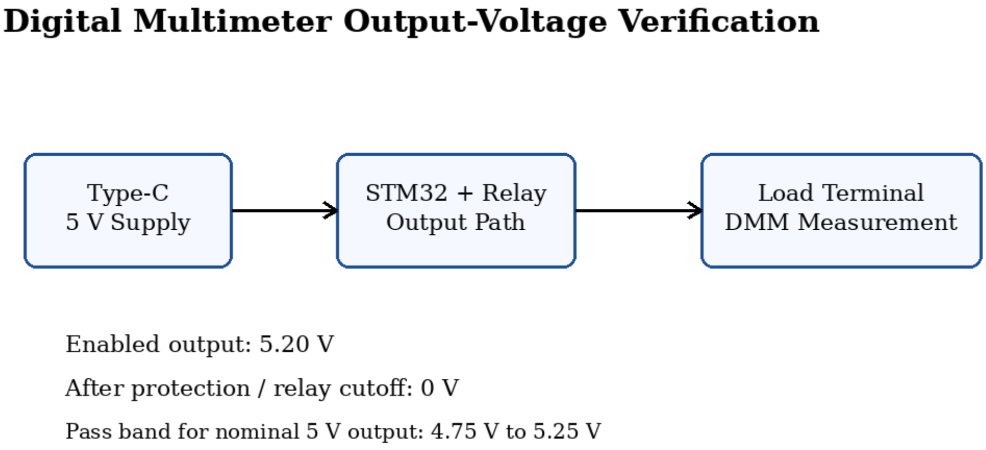


Figure 11: Digital multimeter verification of the load-terminal output voltage.

Table 4: Reproducible verification procedures and quantitative pass criteria.

Test item	**Reproducible procedure**	**Quantitative pass criterion**
Load-terminal voltage	Set the DMM to DC voltage. Place probes across the output/load terminal while relay output is enabled.	$4.75\,\text{V} \le V_{\text{out}} \le 5.25\,\text{V}$ for a nominal 5 V output.
Voltage-sensor response	Record at least 10 serial/OLED voltage readings while the input level changes. Use Eq. (2) to estimate ADC counts.	Displayed voltage changes monotonically; input/display change larger than 0.2 V produces larger than 0.1 V displayed change.
Temperature response	Record DS18B20 readings at room temperature, then warm sensor by hand for 30 s.	Temperature changes by at least 2 °C, with no One-Wire bus failure.
Automatic alarm/cutoff	In offline mode, use local buttons to lower the threshold below the measured value. Observe buzzer/LED/relay and DMM output.	Alarm starts and relay output cuts off within ≤ 1 s; DMM output changes from about 5 V to 0 V.
Manual buttons	Press K1–K4 in normal and setting modes. Record mode and threshold changes.	Each valid key press changes the intended state or value within ≤ 1 s.
Wi-Fi/app	Connect ESP8266 to the mobile app. Compare app data with OLED values and send relay/buzzer/threshold commands.	App data matches OLED display within display resolution; command response target ≤ 2 s, with observed demo response about 1 s to 2 s.

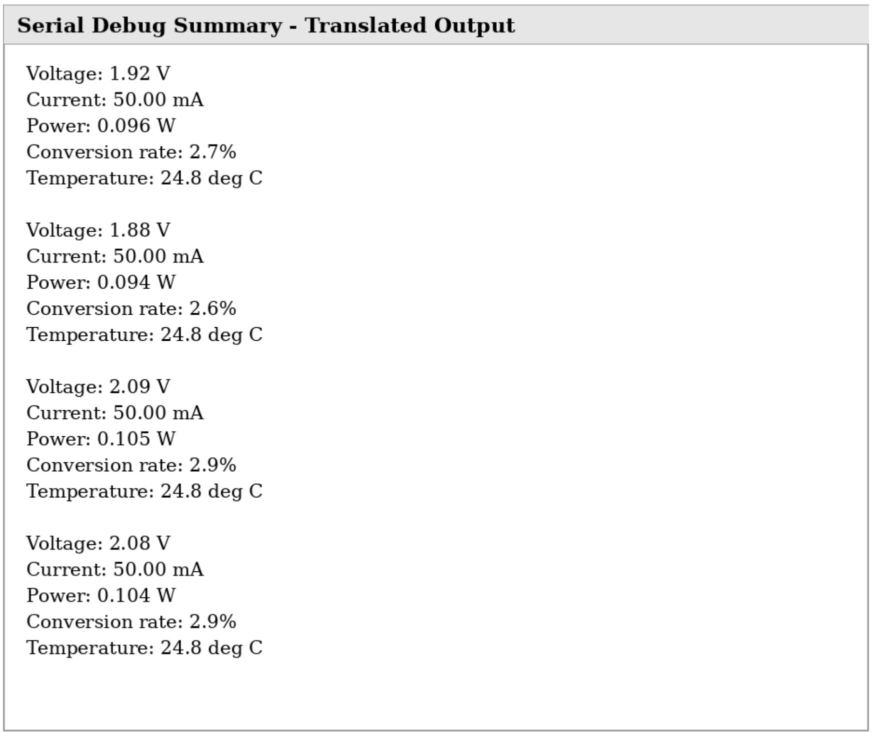
3.2 Block-Level Quantitative Verification

Table 5 summarizes the block-level quantitative verification. Some values are direct DMM measurements, and some values are firmware values recorded from serial debug screenshots. The firmware values are useful because they demonstrate sensor-response range, data formatting, and system-level logic. However, calibrated electrical performance would require an additional calibrated current sensor and logged raw ADC counts.

Table 5: Quantitative block-level verification results.

Block	Measured or recorded value	Expected result	Result
Power/output terminal	DMM load-terminal reading = 5.20 V when output was enabled; output observed as 0 V after cutoff.	Nominal 5 V output within 4.75 V to 5.25 V; relay cutoff removes output.	Pass
OLED display	Displayed voltage, current, power, temperature, mode, and thresholds during final demo.	Readable values and mode information updated during operation.	Pass
Temperature sensor	Serial records: 24.7 °C to 29.1 °C during sensor warming; span = 4.4 °C.	Temperature updates and changes by more than 2 °C when warmed.	Pass
Voltage sensor	Serial voltage range: 0.95 V to 2.66 V in debug record; representative readings include 1.88 V, 2.20 V, and 2.66 V.	Displayed voltage changes consistently and monotonically with input condition.	Pass
Estimated ADC counts	For $K_V = 5.0$ and $V_{\mathrm{REF}} = 3.3$ V: 0.95 V → about 236 counts; 1.88 V → about 466 counts; 2.20 V → about 546 counts; 2.66 V → about 660 counts.	Estimated ADC code remains within 0–4095 and follows displayed voltage; raw ADC counts were not separately logged.	Pass
Current calculation	Serial records: 14.91 mA to 50.00 mA; common operating display around 50.00 mA.	Calculated current updates with voltage/load model.	Pass for demonstration; not calibrated current measurement
Power calculation	Serial records: 0.020 W to 0.110 W; summary readings around 0.094 W to 0.105 W.	Power changes according to $V \times I$ calculation.	Pass for demonstration
Conversion-rate indicator	Serial records: 1.1 % to 3.2 %; summary readings about 2.6 % to 2.9 %.	Relative display indicator updates with power calculation.	Pass for demonstration
Alarm outputs	Threshold lowering produced alarm state; buzzer/LED activated; output terminal dropped from 5.20 V to 0 V.	Alarm active and relay cutoff within ≤ 1 s after threshold violation.	Pass
Wi-Fi/app	Mobile app displayed real-time values and controlled buzzer/relay/threshold during demo.	Data upload and command downlink work within ≤ 2 s; observed command response was about 1 s to 2 s.	Pass

Figures 12-14 show representative quantitative records from serial debugging and system demonstration files. These English figures preserve the measured values from the original debug records while removing Chinese text from the image labels.



```
Voltage: 1.92 V
Current: 50.00 mA
Power: 0.096 W
Conversion rate: 2.7%
Temperature: 24.8 deg C

Voltage: 1.88 V
Current: 50.00 mA
Power: 0.094 W
Conversion rate: 2.6%
Temperature: 24.8 deg C

Voltage: 2.09 V
Current: 50.00 mA
Power: 0.105 W
Conversion rate: 2.9%
Temperature: 24.8 deg C

Voltage: 2.08 V
Current: 50.00 mA
Power: 0.104 W
Conversion rate: 2.9%
Temperature: 24.8 deg C
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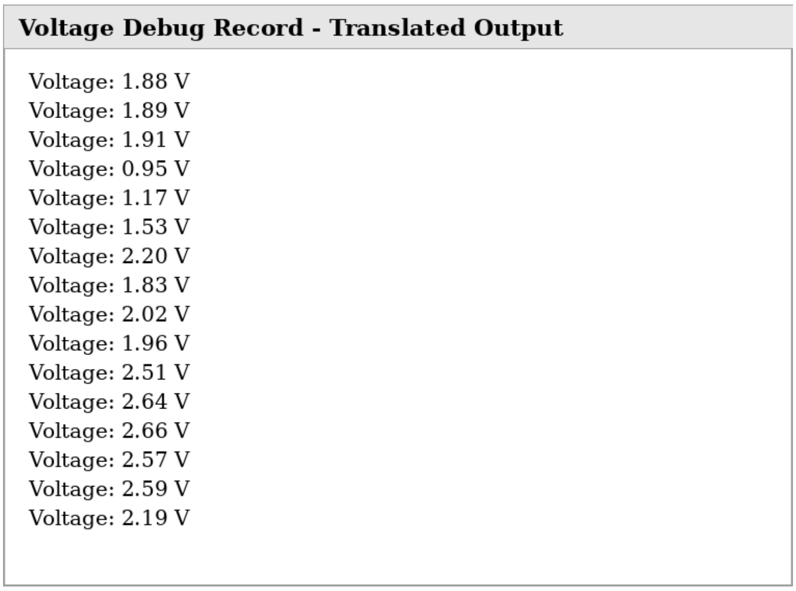
Figure 12: Serial debug summary showing voltage, current, power, conversion-rate, and temperature values.



```
Voltage: 1.88 V
Voltage: 1.89 V
Voltage: 1.91 V
Voltage: 0.95 V
Voltage: 1.17 V
Voltage: 1.53 V
Voltage: 2.20 V
Voltage: 1.83 V
Voltage: 2.02 V
Voltage: 1.96 V
Voltage: 2.51 V
Voltage: 2.64 V
Voltage: 2.66 V
Voltage: 2.57 V
Voltage: 2.59 V
Voltage: 2.19 V
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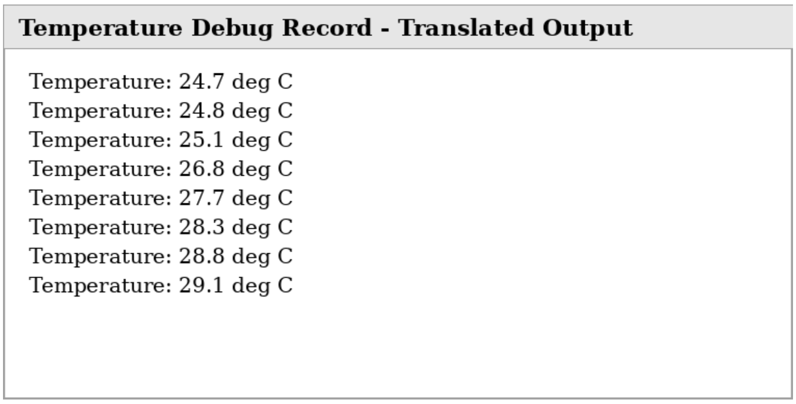
Figure 13: Serial voltage debug record with displayed voltage values from 0.95 V to 2.66 V.



Temperature Debug Record - Translated Output

```
Temperature: 24.7 deg C
Temperature: 24.8 deg C
Temperature: 25.1 deg C
Temperature: 26.8 deg C
Temperature: 27.7 deg C
Temperature: 28.3 deg C
Temperature: 28.8 deg C
Temperature: 29.1 deg C
```

Figure 14: Serial temperature debug record showing warming response from 24.7 °C to 29.1 °C.

3.3 System-Level Verification

The integrated automatic-mode test began with normal sensor readings. The OLED displayed the monitored values and the system remained in the normal state. The threshold was then adjusted with the local push buttons so that the current measured value exceeded the corresponding threshold. Under this condition, the controller entered the alarm state, activated the LED and buzzer, and opened the relay. The DMM measurement at the load terminal changed from approximately 5.20 V to 0 V after cutoff. This verified the complete safety path from sensing to decision and output action.

The manual-mode test confirmed that the user could switch out of automatic behavior and directly control the relay and buzzer by local buttons or the mobile application. This mode is useful when the user intentionally wants to connect or disconnect the output path, test the alarm device, or recover after a known abnormal condition. The remote-control test confirmed that the Wi-Fi path could send data to the phone and receive commands from it. During repeated app commands, the relay/buzzer state changed visually within approximately 1 s to 2 s, satisfying the ≤ 2 s target.

The final-scope change was also verified: the system was tested as a PV monitoring and control prototype rather than as a battery charger. The relay output was treated as the protected PV/load path, not as a battery charge-control output. Therefore, the completed verification matches the actual final hardware.

3.4 Requirement and Verification Summary

Table 6: Requirement and verification summary with quantitative results.

Requirement	Quantitative verification status	Comment
Local monitoring	Verified. OLED/serial data included voltage 0.95 V to 2.66 V, temperature 24.7 °C to 29.1 °C, current 14.91 mA to 50.00 mA, and power 0.020 W to 0.110 W.	Values were displayed locally and logged through serial debug screenshots.
Automatic protection	Verified. Local threshold was reduced below measured value; alarm activated and relay output dropped from about 5.20 V to 0 V.	Relay cutoff demonstrates output-path protection.
Manual operation	Verified. K1–K4 changed modes, thresholds, and local output states within the observed 1 s demo cycle.	Buttons allow offline operation without Wi-Fi.
Remote monitoring/control	Verified. ESP8266/mobile app showed data and accepted commands for buzzer, relay, mode, and threshold.	Command response was visually observed at approximately 1 s to 2 s, meeting the ≤ 2 s target.
Battery charging/storage	Not applicable.	Removed from final scope and not claimed in this report.

3.5 Quantitative Uncertainty Analysis

The prototype is a monitoring and control demonstration rather than a calibrated metrology instrument. This section estimates the measurement uncertainty that should be associated with the reported quantitative results. The uncertainty sources include digital multimeter tolerance, ADC quantization, voltage-sensor/divider gain tolerance, reference-voltage variation, DS18B20 accuracy, firmware display resolution, and human timing uncertainty. Because the exact DMM model was not recorded in the final report, the DMM uncertainty below uses a conservative classroom-lab assumption of ±0.5% of reading plus ±0.02 V for DC voltage. If the final DMM model is available, this line should be updated with its datasheet specification.

For voltage measurement, the ideal ADC quantization standard uncertainty is approximated as

$$u_q(V_{\mathrm{ADC}}) = \frac{V_{\mathrm{REF}}}{4095\sqrt{12}}. \tag{9}$$

With the gain model in Eq. (3), a first-order propagation estimate is

$$u^2(V_{\mathrm{PV}}) \approx \left(K_V u(V_{\mathrm{ADC}})\right)^2 + \left(V_{\mathrm{ADC}} u(K_V)\right)^2 + \left(\frac{K_V N_{\mathrm{ADC}}}{4095} u(V_{\mathrm{REF}})\right)^2. \tag{10}$$

For the calculated output power in Eq. (6), the relative uncertainty can be estimated by

$$\left(\frac{u(P_{\mathrm{OUT}})}{P_{\mathrm{OUT}}}\right)^2 \approx \left(\frac{u(V_{\mathrm{PV}})}{V_{\mathrm{PV}}}\right)^2 + \left(\frac{u(I_{\mathrm{OUT}})}{I_{\mathrm{OUT}}}\right)^2. \tag{11}$$

Because I_{OUT} is calculated from a demonstration load model instead of a calibrated current sensor, the power uncertainty is dominated by the current-model uncertainty.

Table 7: Quantitative uncertainty estimates.

Measured quantity	**Dominant uncertainty source**	**Estimated uncertainty**	**Interpretation**
Load-terminal voltage 5.20 V	DMM accuracy and display resolution	±0.05 V	The measured output is reported as 5.20 V ± 0.05 V, which remains inside the 4.75 V to 5.25 V pass band.
ADC displayed voltage 0.95 V to 2.66 V	ADC quantization, V_{REF}, divider/sensor gain	±0.05 V typical for a 2.2 V displayed value using $K_V = 5.0$ and conservative 2% gain uncertainty	ADC quantization contributes only about 4.03 mV at the displayed PV side; gain and reference uncertainty dominate.
Estimated ADC count	Derived from displayed voltage and assumed $K_V = 5.0$	±10 to ±20 counts typical	Counts are calculated for verification consistency because raw counts were not separately logged.
DS18B20 temperature 24.7 °C to 29.1 °C	Sensor accuracy and display resolution	±0.5 °C	The observed 4.4 °C warming span is much larger than the uncertainty, so the update behavior is verified.
Calculated current 14.91 mA to 50.00 mA	Voltage uncertainty plus assumed equivalent load/current model	Approximately ±5% to ±10% for demonstration	This is not a calibrated current measurement; a future design should add INA219, ACS712, or a shunt plus amplifier.
Calculated power 0.020 W to 0.110 W	Propagation of voltage and current-model uncertainties	Approximately ±10% or larger	The value is valid as a relative indicator for demo; calibrated PV power would require calibrated current sensing.
Alarm/relay response time ≤ 1 s	Human observation and display/control-cycle timing	±0.5 s	The timing result is adequate for demo-level protection but should be measured with an oscilloscope in a product design.

The unsatisfactory or limited results are mainly the current and power measurements. They are calculated from the voltage and an assumed load/equivalent model rather than measured by a dedicated current-sensing circuit. Therefore, the report treats them as monitoring indicators. A dedicated current sensor would reduce uncertainty and make power and efficiency verification reproducible.

4. Costs and Schedule

4.1 Cost Estimate

The cost estimate includes prototype parts and labor. Component prices in Table 8 are small-quantity retail estimates. The design is low-cost because it uses common embedded modules and a minimum STM32 system board rather than custom high-power charging hardware.

Table 8: Estimated bill of materials.

Part	Quantity	Unit cost (USD)	Total (USD)
STM32F103C8T6 minimum system board	1	4.00	4.00
DS18B20 temperature sensor module	1	2.00	2.00
Voltage sensor module or divider circuit	1	1.50	1.50
0.96 in OLED display module	1	4.50	4.50
ESP8266-01S Wi-Fi module	1	3.50	3.50
ESP8266 adapter or 3.3 V support board	1	2.00	2.00
5 V relay module	1	2.00	2.00
Active buzzer	1	0.75	0.75
LEDs, resistors, and buttons	1 set	2.50	2.50
Prototype PCB, wires, connectors	1 set	6.00	6.00
Small PV panel or adjustable DC source for test	1	15.00	15.00
Miscellaneous mounting and replacement parts	1 set	5.00	5.00
		Total electronics	**48.75**

Labor cost was estimated using the ECE 445 formula

$$C_{\text{labor}} = R_{\text{hourly}} H_{\text{total}} \times 2.5. \tag{12}$$

Using an assumed hourly rate of $R_{\text{hourly}} = \$40.00/\text{h}$ and total labor time of $H_{\text{total}} = 120$ hours, the estimated labor cost is \$12,000.00. The total project cost including electronics is therefore \$12,048.75.

4.2 Project Schedule and Team Responsibilities

Table 9 addresses the requested project schedule. The schedule is organized by project week rather than exact calendar date because work periods overlapped during integration. Each entry lists the major work and team members primarily responsible for the tasks.

Table 9: Project schedule and team responsibility summary.

Project week	Main work completed	Primary students
Week 1	Defined project scope and clarified that the final prototype would be a PV monitoring/protection system rather than a certified charger.	All team members
Week 2	Selected STM32F103C8T6, OLED, DS18B20, voltage sensor, ESP8266, relay, buzzer, and local buttons.	Guangjun Xu, Xu Li
Week 3	Prepared system block diagram and initial requirement list; divided hardware, firmware, and verification responsibilities.	All team members
Week 4	Built first breadboard/module wiring; verified power input, OLED display, and basic GPIO output.	Xu Li, Guangjun Xu
Week 5	Developed STM32 firmware framework, timer/delay functions, GPIO drivers, and serial debug output.	Sunhao Zhang, Guangjun Xu
Week 6	Integrated DS18B20 temperature reading and voltage ADC sampling; printed temperature and voltage through UART.	Sunhao Zhang, Xu Li

Project week	Main work completed	Primary students
Week 7	Added current/power/efficiency calculations and OLED display pages; tested serial data records.	Sunhao Zhang, Guangjun Xu
Week 8	Integrated relay, LED, and buzzer output drivers; tested local alarm and output cutoff.	Xu Li, Sunhao Zhang
Week 9	Added threshold-setting and button-control firmware; stored thresholds in STM32 Flash.	Sunhao Zhang, Guangjun Xu
Week 10	Integrated ESP8266 and mobile app; verified data upload and command downlink.	Sunhao Zhang, Xu Li
Week 11	Designed and checked PCB carrier board; confirmed MCU pin mapping and module placement.	Xu Li, Guangjun Xu
Week 12	Performed integrated offline tests, including threshold lowering, alarm trigger, relay cutoff, and DMM output check.	All team members
Week 13	Performed Wi-Fi/app demo tests; recorded serial screenshots, app observations, and load-terminal voltage.	All team members
Week 14	Prepared final report, demo script, revision materials, quantified verification table, and uncertainty analysis.	Guangjun Xu with support from Xu Li and Sunhao Zhang

5. Conclusions

5.1 Quantified Accomplishments

The completed prototype demonstrates a working STM32-based PV monitoring and protection system. It successfully integrates local sensing, local display, threshold-based protection, local button control, relay output control, buzzer/LED alarm output, and ESP8266 mobile-app communication. The revised verification results quantify the prototype behavior: the load-terminal output was measured at approximately 5.20 V when enabled and 0 V after protection cutoff; the temperature sensor record changed from 24.7 °C to 29.1 °C during warming; the serial voltage record changed from 0.95 V to 2.66 V; the calculated current range was 14.91 mA to 50.00 mA; the calculated power range was 0.020 W to 0.110 W; and the displayed conversion-rate indicator ranged from 1.1 % to 3.2 %.

The main accomplishment is the integration of sensing, decision logic, user interaction, and remote communication into one functioning prototype. The offline test shows that the device can work independently without the phone or cloud platform. The Wi-Fi test shows that the same embedded system can be monitored and controlled remotely. The design is also clear about its boundary: it is not a battery charger. This distinction prevents the report from claiming unverified storage or charging functions and keeps the final verification consistent with the actual hardware.

5.2 Limitations and Future Work

The most important limitation is that the final system does not perform closed-loop maximum power point tracking, DC-DC power conversion, or battery charging. The current and power values are calculated for monitoring and demonstration rather than measured through a precision current-sensing stage. A future version should add a dedicated current sensor, such as an INA219, ACS712, or calibrated shunt amplifier, and should log raw ADC counts and sensor data during all tests. If battery storage is added, the design must include battery chemistry selection, charge-stage control, overcharge protection, overdischarge protection, temperature protection, and independent safety verification.

The Wi-Fi function is suitable for demonstration, but a field-deployed PV controller would need stronger communication fault handling, enclosure design, surge protection, electromagnetic compatibility testing, and long-term reliability testing. Future work could also improve the mobile interface by adding historical data plots, clearer warning messages, and automatic data export.

5.3 Ethics and Broader Impact

The design supports safer and more convenient use of small PV systems by giving users visibility into operating conditions and by disconnecting the output path when values exceed limits. This aligns with the ethical responsibility to design systems that reduce risk to users and equipment. At the same time, the system should not be presented as a certified commercial protection device or a battery charger without additional safety testing. Clear documentation of final scope, calibration uncertainty, and limitations is therefore an ethical requirement.

The broader impact of the project is positive because it supports renewable-energy monitoring at small scale. Low-cost PV supervision can help users understand local energy production and react to abnormal operation. However, any real deployment must consider electrical safety, calibration accuracy, environmental protection, and responsible handling of networked-device data.

References

[1] ECE 445 Staff and ECE Editorial Services, *Preparing Your Final Report for ECE 445, Senior Design*, University of Illinois Urbana-Champaign, Sept. 2019.

[2] STMicroelectronics, *STM32F103x8 STM32F103xB Datasheet: Medium-density performance line ARM-based 32-bit MCU*.

[3] STMicroelectronics, *RM0008 Reference Manual: STM32F101xx, STM32F102xx, STM32F103xx, STM32F105xx and STM32F107xx Advanced ARM-based 32-bit MCUs*.

[4] Analog Devices/Maxim Integrated, *DS18B20 Programmable Resolution 1-Wire Digital Thermometer Datasheet*.

[5] Espressif Systems, *ESP8266EX Datasheet and ESP8266 AT Instruction Set*.

[6] Solomon Systech, *SSD1306 OLED/PLED Segment/Common Driver with Controller Datasheet*.

[7] IEEE, *IEEE Code of Ethics*.

[8] J. Tan, “Design and application effect analysis of an embedded photovoltaic automatic tracking control system,” *Technology Innovation and Application*, no. 23, pp. 42–45, 2023.

[9] Z. Zhang, Z. Zhang, J. Wang, et al., “Exploration of an intelligent monitoring and management system for photovoltaic power stations,” *Automation Panorama*, no. 8, pp. 76–81, 2024.

[10] H. Zhang and W. Zhu, “Research and design of a dual-axis solar tracking system based on STM32,” *Instrumentation Technology*, no. 2, pp. 23–26, 2019.

A. Detailed Requirements, Procedures, and Results

Table 10: Detailed requirement, procedure, and quantitative result table.

No.	Requirement	Procedure	Passing criterion	Observed quantitative result
1	Power/output stability	Measure load terminal with DMM while relay output is enabled and disabled.	Enabled output 4.75 V to 5.25 V; disabled output near 0 V.	Enabled: 5.20 V; cutoff: 0 V. Pass.

No.	Requirement	Procedure	Passing criterion	Observed quantitative result
2	Voltage monitoring	Record displayed/serial voltage while changing input condition; estimate equivalent ADC counts using Eq. (4).	Monotonic response; more than 0.1 V display change for more than 0.2 V input change.	0.95 V to 2.66 V range recorded; estimated ADC range about 236–660 counts. Pass.
3	Temperature monitoring	Read DS18B20 repeatedly; warm sensor by hand.	Change greater than 2 °C and no bus failure.	24.7 °C to 29.1 °C recorded; span 4.4 °C. Pass.
4	OLED interface	Power on and navigate display modes.	Readable values shown at least every 1 s.	Voltage, current, power, temperature, mode, thresholds displayed. Pass.
5	Button interface	Press each K1–K4 in normal/setting modes.	Mode/value/output state changes within ≤ 1 s.	Buttons changed mode and threshold; used to trigger alarm. Pass.
6	Automatic alarm	Lower threshold below measured value.	Buzzer/LED activate and relay opens within ≤ 1 s.	Alarm activated; output dropped from 5.20 V to 0 V. Pass.
7	Manual control	Switch to manual mode and command relay/buzzer.	Relay and buzzer follow local/app command.	Manual output toggling observed. Pass.
8	Remote app function	Connect ESP8266 to app and send commands.	App data displayed; command response ≤ 2 s.	App monitored data and sent output/threshold commands; observed response about 1 s to 2 s. Pass.
9	Battery function	Check final hardware scope.	No charging/storage hardware included or claimed.	No battery charger stage included. Not applicable.

B. Additional Quantitative Measurement Records

The following values summarize representative debug records used in the revised verification tables. These data were visible in serial debug screenshots and the final demonstration.

Table 11: Additional quantitative records from screenshots and final demo.

Measurement group	**Representative values**
Voltage debug image	1.88 V, 1.89 V, 1.91 V, 0.95 V, 1.17 V, 1.53 V, 2.20 V, 1.83 V, 2.02 V, 1.96 V, 2.51 V, 2.64 V, 2.66 V, 2.57 V, 2.59 V, 2.19 V
Temperature debug image	24.7 °C, 24.8 °C, 25.1 °C, 26.8 °C, 27.7 °C, 28.3 °C, 28.8 °C, 29.1 °C
Current debug image	14.91 mA, 18.53 mA, 22.97 mA, 24.58 mA, 26.59 mA, 27.40 mA, 30.62 mA, 37.47 mA, 39.89 mA, 43.92 mA, 50.00 mA
Power debug image	0.020 W, 0.035 W, 0.047 W, 0.050 W, 0.053 W, 0.058 W, 0.105 W, 0.106 W, 0.107 W, 0.109 W, 0.110 W
Conversion-rate debug image	1.1%, 1.8%, 1.9%, 2.0%, 2.5%, 2.7%, 2.9%, 3.0%, 3.1%, 3.2%
DMM demonstration	Load-terminal voltage approximately 5.20 V when enabled; approximately 0 V after protection/cutoff.