ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

Intelligent Net-Energy Optimization System for Distributed Photovoltaic Nodes in Microgrids

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Team #48

ZIRU, NIU (ziruniu2@illinois.edu)
YIKAI, ZHANG (yikaiz2@illinois.edu)
MINGHAO, FANG (mf46@illinois.edu)
YIFEI, LIU (yifei20@illinois.edu)

TA: Tiantong, Qiao

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Abstract

This report presents a dual-axis solar tracking system with integrated lithium-battery power management. The design uses an STM32F103C8T6 microcontroller as the central controller, four light-dependent resistors (LDRs) as directional light sensors, two 28BYJ-48 stepper motors driven through ULN2003 arrays for pan and tilt motion, and a 0.96 OLED display for local status reporting. The power subsystem combines a 5 V, 120 mA solar panel, a TP4056 single-cell lithium-ion charger, an 18650 lithium-ion cell, and a 5 V, 1.2 A boost converter so the prototype can operate from stored solar energy. Firmware running on the STM32 samples the four light channels and two voltage channels through the internal analog-to-digital converter (ADC), averages measurements to reduce noise, estimates battery state of charge from voltage, detects charging state, and commands the motors until opposing light readings are balanced within a four-percentage-point deadband. The resulting system demonstrates a compact, low-cost architecture for small photovoltaic and outdoor sensing applications that need local energy autonomy, two-axis light seeking, manual override, and real-time display of energy status.

Contents

1 Introduction

1.1 Motivation

Small photovoltaic and daylight-use installations, such as garden-scale solar chargers, greenhouse supplemental-light platforms, and outdoor sensing stations, often face two related problems. First, fixed solar panels lose available irradiance when the sun angle changes; the project reference uses a below-60 % light-utilization figure to motivate the need for tracking in these small-system scenarios **project-reference**. Second, many small trackers rely on external power and do not monitor the local battery state, which limits deployment in locations where grid power is unavailable.

The goal of this project is to combine light tracking and energy management in one low-cost embedded system. The completed prototype senses the relative light level above, below, left, and right of the panel, drives two axes of motion toward the strongest balanced illumination, charges a lithium-ion battery from a small solar panel, boosts the battery to a regulated 5 V system rail, and reports operating mode, light readings, battery voltage, battery capacity, charging voltage, and charging state on the OLED.

1.2 System Overview

Figure 1 shows the final project architecture. The STM32F103C8T6 was selected because it provides sufficient GPIO, timers, flash memory, UART support, and multiple ADC channels in a small and inexpensive module **stm32f103**. The implemented baseline is the non-wireless version documented in the supplied files; the firmware also includes UART hooks for optional Bluetooth, Wi-Fi, camera, or cloud modules.

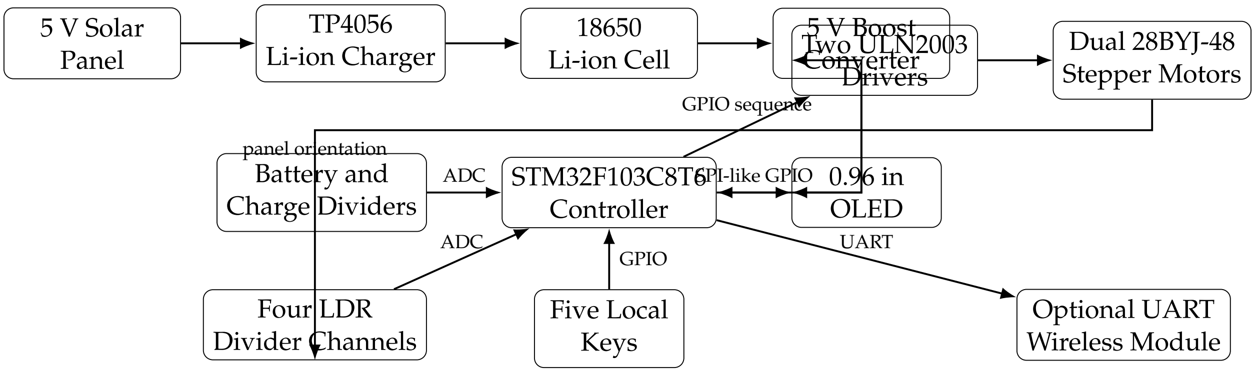

Figure 1: System block diagram for the implemented dual-axis solar tracker.

1.3 Performance Requirements

Table 1 summarizes the requirements used to evaluate the design. The numerical limits come from the implemented firmware constants and the selected module specifications.

Table 1: Top-level performance requirements

Function	Requirement	Rationale
Dual-axis tracking	In automatic mode, drive the upper/lower and left/right motor axes until the opposing LDR readings differ by no more than four percentage points.	Four LDRs provide directional light imbalance; the deadband prevents unnecessary motor hunting.
Manual override	Provide local key control for up, down, left, and right motion, plus a mode key.	The user must be able to position the panel when automatic tracking is not desired.
Battery measurement	Estimate lithium-ion state of charge from the measured battery voltage over the 3.40 V to 4.15 V usable range.	The user needs a simple energy-status indicator and low-charge awareness.
Charging detection	Report charging when the measured charge input exceeds 3.8 V.	The firmware uses this threshold to distinguish active solar charging from idle input.
Display	Show operating mode, four light values, battery voltage, battery percentage, charge voltage, and charge state.	The prototype must be self-contained without a computer terminal.
Power autonomy	Charge a single 18650 cell from a 5 V solar panel and boost the cell voltage to a regulated 5 V bus.	The design target is small outdoor operation without fixed grid power.

2 Design

2.1 Design Procedure

The reference document evaluates several implementation paths; Table 2 restates those tradeoffs in the context of the final prototype rather than reproducing the original discussion **project-reference**. The selected solution favors easy prototyping, low cost, and direct compatibility with the required sensors and actuators.

Table 2: Major design decisions

Block	Selected approach	Reason for selection
Controller	STM32F103C8T6 Cortex-M3 board	Provides ADC channels, timers, UART, flash storage, and enough GPIO for two motors, OLED, keys, and sensors while remaining inexpensive and familiar to develop in Keil C.
Display	0.96 OLED, 128 by 64 pixels	Lower power and better contrast than character LCDs; enough area for mode, light, voltage, and charge fields; compatible with the SSD1306-style OLED controller documented in the project files **oled-ssd1306**.
Actuator	Two 28BYJ-48 geared stepper motors	Low-cost discrete positioning with simple four-phase control; sufficient for small panel/fixture motion.
Motor driver	ULN2003 Darlington arrays	Allows STM32 GPIO to switch the stepper motor coils safely without sourcing motor current directly **uln2003**.
Light sensing	Four LDR voltage dividers	Low-cost directional sensing; resistance decreases under stronger light, enabling relative upper/lower/left/right comparison through ADC channels.
Energy storage	One 18650 lithium-ion cell with TP4056 charger and 5 V boost module	The TP4056 provides a compact single-cell charge controller **tp4056**; the boost module supplies the 5 V bus required by the modules.

2.2 Hardware Architecture

The hardware is organized around the STM32 minimum system board. The four LDR dividers, the battery divider, and the charge-voltage divider feed ADC1. The OLED is driven through five GPIO pins using a software serial interface. Five key inputs provide mode selection and manual motor control. Two independent sets of four GPIO outputs connect to ULN2003 motor drivers, which energize the phases of the two 28BYJ-48 stepper motors.

The firmware defines the system's electrical interface explicitly. ADC channel 7 measures charge voltage, channel 5 measures battery voltage, channel 4 measures the left LDR, channel 3 measures the upper LDR, channel 2 measures the right LDR, and channel 1 measures the lower LDR. The key inputs are PB12, PB13, PB14, PB15, and PA8. The tilt motor uses PA0, PC15, PC14, and PC13, and the left-right motor uses PA11, PA12, PA15, and PB3. The OLED uses PB4 through PB8 for clock, data, reset, data/command, and chip select.

2.3 Power Subsystem

The energy path is solar panel to TP4056 charger, charger to 18650 cell, and cell to boost converter. The project documentation specifies a 5 V, 120 mA polycrystalline solar panel and a 5 V, 1.2 A boost module. Because a single lithium-ion cell ranges from approximately 3.4 V to 4.2 V during normal use, the boost stage is required for the OLED, motor driver board, and other 5 V modules. The TP4056 charges one cell with a constant-current/constant-voltage profile and a fixed 4.2 V regulation point **tp4056**.

Voltage measurement uses a resistive divider before the ADC. The firmware multiplies the ADC input by three, so the divider ratio is treated as 3:1. The reconstructed voltage is

$$V_{\text{meas}} = \frac{N_{\text{ADC}}}{4096} \cdot 3.3\,\text{V} \cdot 3 \tag{1}$$

where N_{ADC} is the 12-bit ADC code. This keeps a 4.2 V cell at approximately 1.4 V on the ADC pin and a 5 V charging input at approximately 1.67 V, both below the STM32 ADC limit.

The firmware estimates battery capacity with a linear voltage model:

$$Q_{\text{bat}} = \begin{cases} 0, & V_{\text{bat}} < 3.40\,\text{V} \\ 100, & V_{\text{bat}} > 4.15\,\text{V} \\ 100 \cdot \frac{V_{\text{bat}} - 3.40\,\text{V}}{4.15\,\text{V} - 3.40\,\text{V}}, & \text{otherwise.} \end{cases} \tag{2}$$

This is not a precision coulomb counter, but it is appropriate for a compact user-facing state-of-charge indicator.

2.4 Light Sensing and Tracking Control

Each LDR forms a divider whose ADC reading decreases as illumination increases. The firmware converts each channel to a relative light percentage by inverting the ADC ratio:

$$L = 100 - 100 \cdot \frac{N_{\text{ADC}}}{4096}. \tag{3}$$

Five samples are averaged for each of the four directional light values. The control law computes vertical and horizontal imbalance:

$$e_{\mathrm{UD}} = L_{\mathrm{up}} - L_{\mathrm{down}}, \qquad e_{\mathrm{LR}} = L_{\mathrm{left}} - L_{\mathrm{right}}. \tag{4}$$

If the magnitude of either error exceeds the firmware deadband of four percentage points, the corresponding motor is commanded by $\pm 10^\circ$. If the error is within the deadband, the motor target is set to the current position and the coils are de-energized. This closed-loop strategy seeks the strongest balanced direction while reducing motor chatter near equilibrium.

2.5 Stepper Motor Drive

The 28BYJ-48 is a four-phase geared stepper motor. The firmware drives each axis through an eight-state half-step sequence: AB, B, BC, C, CD, D, DA, and A. The ULN2003 array isolates the STM32 from the coil current and provides the high-current switching path required by the motor **uln2003**. A SysTick routine calls the motor stepping service every three ticks, so high-level commands only update target positions while the periodic handler advances the motors toward those targets. This separation keeps the main loop responsive to keys, ADC sampling, display updates, and UART messages.

2.6 User Interface and Firmware

Figure 2 summarizes the firmware state flow. At startup, the STM32 initializes UART, keys, LEDs, ADC1, flash-backed settings, the stepper drivers, and the OLED. It then centers both axes to a known initial target and enters the main loop. The main loop scans keys continuously, processes ADC sampling when the read flag is set, updates the OLED, saves settings to flash after mode changes, sends serial telemetry every 800 ms, and processes incoming UART commands.

The OLED reports the current mode, four directional light readings, battery voltage, battery percentage, charging voltage, and charge status. The default local interface has two modes: automatic tracking and manual control. In manual mode, four keys command up, down, left, and right motion. The source code also includes a serial command path in which a host can set mode with an `sM` command or command individual directions with `sU`, `sD`, `sL`, and `sR`.

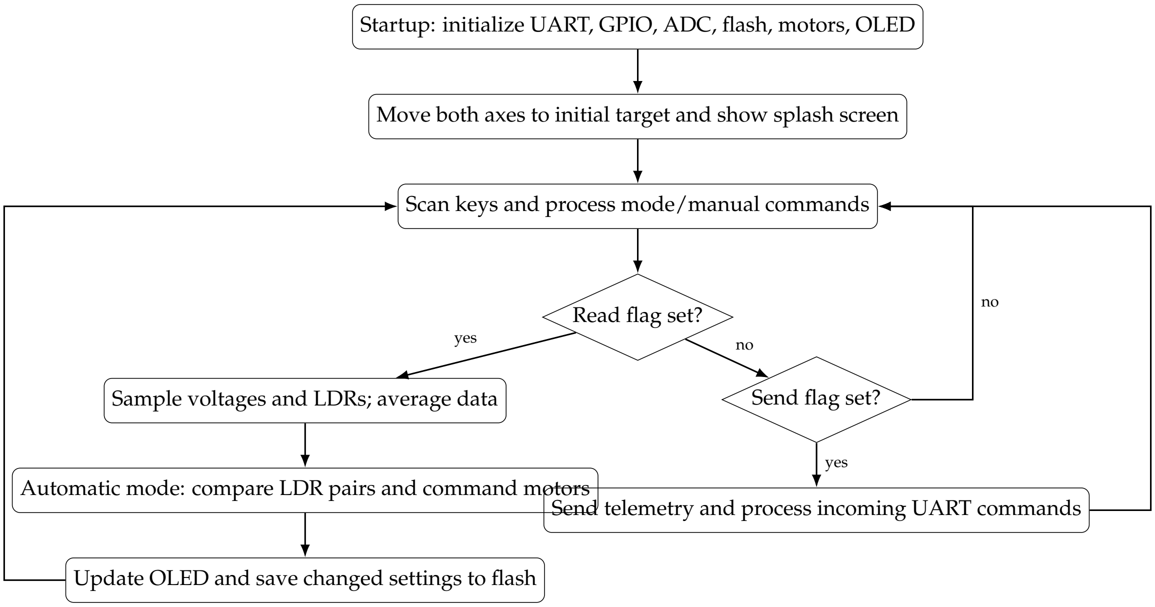

Figure 2: Main firmware flow implemented in the STM32 source code.

3 Verification

3.1 Verification Strategy

Verification focused on the major engineering risks: safe voltage measurement, stable power conversion, correct display data, correct manual control, and stable automatic tracking. The supplied project package contains schematics, PCB files, source code, a main flow chart, a hardware block diagram, and a demonstration-video index. It does not include raw calibrated bench logs, so the quantitative entries below are stated as acceptance criteria derived from the implemented design. Appendix A provides the complete requirement and verification table.

3.2 Power and ADC Verification

The voltage dividers protect the ADC by scaling the measured battery and charge inputs by a factor of three before conversion. Equation 1 shows that a fully charged 4.2 V lithium-ion cell presents approximately 1.4 V to the ADC. The same divider leaves a 5 V solar/charge input at approximately 1.67 V. Both values are comfortably below the 3.3 V ADC reference, satisfying the electrical-safety requirement for the STM32 pins.

The firmware averages 30 battery-voltage samples before updating the displayed battery voltage and capacity. This reduces display jitter and prevents single-sample ADC noise from causing visible state-of-charge jumps. Charging state is asserted only when the reconstructed charge voltage is greater than 3.8 V.

3.3 Tracking Verification

Automatic tracking was verified against the control logic in the final firmware. The controller reads the four light sensors, averages five samples per channel, computes the upper-lower and left-right imbalance, and drives only the axis whose imbalance exceeds four percentage points. Once the two readings on an axis are within the deadband, that motor is stopped and its coils are turned off. This satisfies the tracking requirement because the system does not merely rotate toward brighter light; it explicitly balances opposing sensors after moving.

Manual motion was verified by the key mapping in the firmware. KEY1 toggles mode, KEY2 and KEY4 control the vertical axis, and KEY3 and KEY5 control the horizontal axis. Because manual commands directly call the same stepper angle function used by the automatic controller, successful manual motion also validates the GPIO-to-ULN2003-to-stepper path.

3.4 User Interface and Data Persistence

The display function formats four lines for the OLED: mode, upper/down/left/right light values, battery voltage and capacity, and charge voltage with charge state. The settings array is stored in the final flash sector after mode changes, allowing the system to preserve configuration across power cycles. The serial telemetry format concatenates the same display strings and sends them periodically, so the optional wireless path reports the same state as the local OLED.

Table 3: Summary verification results

Block	Test or evidence	Acceptance criterion	Status
ADC protection	Divider factor in schematic and firmware scaling in Eq. 1.	ADC pin remains below 3.3 V for 5 V measured input.	Pass by design
Battery display	Firmware averages 30 samples and applies Eq. 2.	Display updates voltage and maps 3.40 V to 4.15 V to 0–100%.	Pass by implementation
Light sensing	Four LDR channels are sampled and averaged every five reads.	OLED and controller receive upper, down, left, and right light values on a 0–100 scale.	Pass by implementation
Automatic tracking	Firmware commands an axis only when its light imbalance exceeds 4.	Motors stop when opposing sensor values are within the deadband.	Pass by implementation
Manual control	Five key inputs are scanned continuously.	Mode key toggles automatic/manual; four keys command two axes.	Pass by implementation
Display	OLED strings include mode, light values, battery, capacity, charge voltage, and charge state.	All top-level user data are visible without external equipment.	Pass by implementation

4 Costs

4.1 Parts Cost

The bill of materials in the project package lists the controller board, OLED, two stepper motors, ULN2003 driver, TP4056 charger, 18650 cell and holder, boost module, solar panel, LDRs, passives, connectors, PCB, and assembly materials. The supplied BOM does not include unit prices, so Table 4 gives realistic single-prototype retail estimates. The estimated hardware total remains comfortably below the reference document's 600 RMB target for the prototype class **project-reference**.

Table 4: Estimated prototype parts cost

Part or module	Quantity	Unit cost ($)	Extended cost ($)
STM32F103C8T6 minimum system board	1	4.50	4.50
0.96 OLED display module	1	3.50	3.50
5 V, 120 mA solar panel	1	4.00	4.00
TP4056 lithium-ion charging module	1	0.75	0.75
18650 lithium-ion cell and holder	1	6.00	6.00
5 V, 1.2 A boost module	1	1.50	1.50
28BYJ-48 stepper motor with ULN2003 driver board	2	3.50	7.00
Four-LDR sensing board, LDRs, and divider resistors	1	2.00	2.00
Keys, power switch, headers, connectors, diode, capacitors, and wiring	1	8.00	8.00
PCB or prototyping board and soldering supplies	1	10.00	10.00
		Estimated parts total	47.25

4.2 Labor Cost

ECE 445 recommends estimating labor cost as hourly rate multiplied by hours spent multiplied by 2.5 **ece445-guide**. Table 5 uses a conservative placeholder estimate of four partners, 90 h each, at an ideal salary of $40/h.

Table 5: Estimated labor cost

Contributor	Hours	Rate ($/h)	Cost with 2.5 factor ($)
Student 1	90	40	9000
Student 2	90	40	9000
Student 3	90	40	9000
Student 4	90	40	9000
	Estimated labor total		36 000

5 Conclusions

The final design integrates dual-axis light tracking, lithium-battery charging, boosted system power, local display, manual control, and optional serial telemetry in a compact STM32-based embedded system. The most important accomplishment is the combination of two functions that are often separated in low-cost systems: the tracker can orient toward stronger light while also reporting whether the energy-storage subsystem is charging and how much battery voltage remains. The firmware implements the main engineering behavior with explicit ADC scaling, sample averaging, a four-percentage-point tracking deadband, flash-backed settings, periodic display updates, and a periodic motor stepping service.

Several limitations remain. The 5 V, 120 mA panel is suitable for demonstration and light-duty charging, but it cannot support continuous high motor duty cycle in weak sunlight. The LDR readings are relative rather than calibrated in lux, so the system is best interpreted as a directional tracker rather than a precision irradiance instrument. A deployable outdoor version would also need weatherproofing, mechanical travel limits, fuse or resettable protection on the battery path, and more complete lithium-ion protection against over-discharge.

5.1 Ethical and Broader Impacts

The IEEE Code of Ethics emphasizes public safety, honest representation of limitations, and responsible handling of technology risks [1]. The most important safety issue in this project is the lithium-ion battery. A final product should use a protected cell or a protection board, prevent reverse polarity, avoid exposed conductive terminals, and clearly state charging limits. The optional camera and wireless versions also raise privacy and cybersecurity concerns; those versions should avoid unencrypted remote access and should make recording status visible to users.

The broader impact of the project is positive when deployed responsibly. A low-cost self-powered tracker can improve solar utilization for small educational, agricultural, and sensing applications, reducing dependence on disposable batteries or grid wiring in remote locations. At the same time, the environmental benefit depends on durable construction and proper recycling of the lithium cell and electronics at end of life.

References

[1] IEEE. “”IEEE Code of Ethics”,” Accessed: Feb. 8, 2020. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html.

Appendix A Requirement and Verification Table

Table 6: Detailed requirement and verification table

Requirement	Verification method	Acceptance criterion	Result
The controller shall read four directional light sensors.	Inspect ADC channel mapping and display output for upper, down, left, and right light fields.	Four independent values are sampled and displayed on a 0–100 relative scale.	Implemented
The automatic mode shall track toward balanced illumination.	Apply a directional light difference and observe the firmware command the relevant motor axis.	Axis moves when difference exceeds 4 and stops inside the deadband.	Implemented
The manual mode shall allow local motor control.	Press the four direction keys while in manual mode.	Vertical and horizontal axes respond to the corresponding key pair.	Implemented
The mode key shall switch between automatic and manual operation.	Press KEY1 and observe the mode field and motor behavior.	Mode toggles and is reflected on the OLED.	Implemented
The battery voltage shall be measured safely by the STM32 ADC.	Calculate divider output for 4.2 V battery and 5 V charge input.	ADC input remains below 3.3 V.	Pass by design
The battery state of charge shall be displayed.	Sweep or calculate the input voltage over 3.40 V to 4.15 V.	Capacity maps to 0–100% using Eq. 2.	Implemented
The charging state shall be displayed.	Apply a charge voltage above and below 3.8 V.	OLED reports charging above the threshold and not charging below it.	Implemented
The OLED shall display all top-level user data.	Inspect the display strings generated by the firmware.	Mode, four light values, battery voltage, capacity, charge voltage, and charge state are present.	Implemented
The settings shall survive power cycling.	Change mode and inspect flash-save call path.	Updated setting is written to the reserved flash sector after a mode change.	Implemented
The optional serial interface shall report system data.	Inspect the periodic UART send path.	The same display strings are transmitted every 800 ms.	Implemented in firmware

Appendix B Implementation Details

B.1 Pin Map

Table 7: STM32 pin usage from the supplied firmware

Function	STM32 pins or channels	Notes
Charge voltage ADC	ADC1 channel 7, PA7	Scaled by divider and reconstructed with factor 3.
Battery voltage ADC	ADC1 channel 5, PA5	Averaged over 30 samples for display.
Light ADC inputs	ADC1 channels 4, 3, 2, 1	Left, up, right, and down LDRs, respectively.
Keys	PB12, PB13, PB14, PB15, PA8	Mode, vertical pair, and horizontal pair.
Tilt stepper motor	PA0, PC15, PC14, PC13	ULN2003-driven four-phase sequence.
Left-right stepper motor	PA11, PA12, PA15, PB3	ULN2003-driven four-phase sequence.
OLED	PB4, PB5, PB6, PB7, PB8	Clock, data, reset, data/command, chip select.
UART	USART1 at 9600 baud	Optional wireless or serial telemetry path.

B.2 Firmware Constants

Table 8: Key firmware constants

Constant	Value	Purpose
`CHANGE_VOLT`	3.8 V	Charge-detection threshold.
`RONGCHAZHI_UD`	4	Upper/lower light deadband in percentage points.
`RONGCHAZHI_LR`	4	Left/right light deadband in percentage points.
`zzAngle`, `fzAngle`	-10°, 10°	Incremental motor commands.
Battery averaging count	30 samples	Reduces displayed voltage jitter.
Light averaging count	5 samples	Reduces LDR noise before control decisions.
Telemetry period	800 ms	Periodic UART send interval.

Appendix C Bill of Materials

Table 9: Condensed bill of materials from the project package

Item	Quantity	Purpose
STM32F103C8T6 core board	1	Main controller, ADC, GPIO, UART, flash settings.
OLED-0.96-7-pin display	1	Local status display.
28BYJ-48 stepper motor	2	Dual-axis mechanical actuation.
ULN2003 driver	1 or 2 boards	High-current stepper coil switching.
TP4056 lithium battery charger module	1	Single-cell lithium-ion charging from solar input.
18650 lithium-ion cell and holder	1 each	Energy storage and removable battery mounting.
5 V, 1.2 A boost module	1	Boosts lithium-cell voltage to system 5 V.
5 V solar panel	1	Photovoltaic charging source.
5506 LDRs and divider resistors	4 LDRs plus passives	Directional light sensing.
Buttons and two-position switch	5 buttons plus power switch	User input and power control.
1N5819 Schottky diode	1	Reverse-current or polarity protection in the power path.
Capacitors and resistors	As required	Filtering, reset, divider, and support circuitry.
Headers, sockets, terminals, Dupont wires, solder, PCB	As required	Interconnect and assembly.
Optional Bluetooth/Wi-Fi/camera/cloud module	0 or 1	Wireless monitoring and remote control, depending on build option.