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Article

Eco-Smart Integration: Harnessing ESP32 Microcontroller for Solar-Powered Home Efficiency

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Abstract: As smart home technology advances, the quest for sustainable energy management solutions grows. This study examines the interaction between solar energy systems and smart home activities, focusing on using an ESP32 microcontroller to regulate lighting and temperature. The proposed system combines sophisticated software algorithms with authentic hardware components to allow for real-time monitoring and control of light and temperature conditions, as well as online tracking of solar system data. Communication protocols and the ESP32 microcontroller create an integrated smart home system that allows homeowners to control their environment remotely using smart mobile devices. Solar panel installation enhances energy efficiency and decreases dependence on traditional grid-based electricity, promoting an environmentally friendly household setting. This study demonstrates how smart home systems may significantly change household energy usage patterns by evaluating hardware design and software execution to ensure comfort, safety, and sustainability. This research showed considerable advancements in energy conservation and improved home environmental control. We integrated smart controllers and light sensors to reduce daily lighting energy consumption from 0.17 kWh to 0.12 kWh, and our smart system reduced the initial air conditioning energy needs from 15.6 kWh/day to 14.48 kWh/day. These results indicate improvements in energy management and home environmental control.

Keywords: smart home; ESP32; solar energy; light control; temperature control; renewable energy; energy efficiency

1. Introduction

In the modern era, where environmental concerns and energy efficiency are prioritized, integrating renewable energy sources into daily life has emerged as a critical endeavor [1]. Particularly in the residential sector, the emergence of smart home technology has paved new ways to optimize energy consumption and bolster sustainability [2]. This paper introduces a novel system that synergizes solar energy with smart home technology, centering on a solution based on the ESP32 microcontroller for home lighting and temperature control [3]. Additionally, the paper delves into an analysis of electricity consumption in a home of 88.1 m^2 in Lumberton, Texas, providing an estimation of the potential impact of our system on this specific setting. After setting the controller and light and temperature sensors in the laboratory and confirming the result, in the next stage of this research in the future, the focus is on the installation and operation of the system in a greenhouse in Texas.

The idea of smart homes, previously considered futuristic, has quickly become achievable due to advancements in technology and improved connectivity [4]. Modern smart homes are equipped with devices and systems that provide control over household settings, leading to increased comfort, convenience, and better

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energy management [5]. Central to this transformation is the development of microcontrollers like the ESP32, which serve as the brains of these systems [6]. Parallel to the growth of smart home technology is the increasing emphasis on sustainable energy solutions [7]. Solar energy, a clean and renewable resource, has emerged as a front-runner in the quest to reduce reliance on fossil fuels and mitigate environmental impact [8].

By harnessing the power of the sun, solar energy systems provide a viable alternative to conventional grid-based electricity, reducing carbon footprints and fostering a more sustainable lifestyle [9]. The ESP32 microcontroller represents a leap forward in integrating technology and sustainability [10]. As a compact yet powerful device, it can perform various tasks simultaneously, from processing sensor data to executing complex algorithms [11].

In the context of a solar-powered smart home system, the ESP32 acts as a control center, managing the interactions between the solar energy system and the home's environmental controls. This includes real-time monitoring of solar panel output, management of energy storage in battery banks, and intelligent control of home temperature and air conditioning to optimize energy consumption [12].

The system includes several key components: the design of the solar energy, including photovoltaic panels and a battery bank for energy storage, along with an ESP32 microcontroller and interface, and the home's lighting, heating, and cooling systems. Initially, the ESP32 microcontroller, sensors, and other core elements were prepared and tested in a laboratory environment to ensure proper integration and functionality [13]. Testing and setting up the controller and sensors in the laboratory environment are the practical aspects of the initial phase of this system [14]. The photovoltaic panels convert solar energy into electricity, and the inverter plays a crucial role in managing the interchange of power between the solar system, and battery storage [15]. The ESP32 microcontroller, equipped with sophisticated software algorithms, performs real-time analysis of energy usage and environmental conditions [16]. It enables autonomous adjustment of home lighting and temperature, tailoring the environment to user preferences while maximizing energy efficiency [17]. The system controller is programmed to dynamically respond to changes in solar energy availability and user needs [18]. Despite the potential of solar-powered smart homes, several challenges persist [19]. These include managing the initial cost and ensuring the longevity of the system components, balancing energy production and consumption, maintaining grid stability, and dealing with variable weather conditions that affect solar energy generation [20].

This study addresses these challenges by optimizing component selection for durability and cost-effectiveness, applying advanced algorithms for energy management, and in the next phase integrating a battery bank to provide a constant power supply. Additionally, this system is not just about technological innovation; it is about making a positive environmental impact [21]. By reducing dependence on grid power and increasing the use of renewable energy, the system contributes to a reduction in greenhouse gas emissions and fosters a more sustainable living environment [22].

2. Implementation

The implementation of an integrated smart home system powered by solar energy, controlled via an ESP32 microcontroller, involves several critical stages: system design, hardware selection and setup, software development, integration, and testing.

2.1. System Design and Planning

The first stage in the implementation process involves a detailed system design and planning phase. This encompasses defining the system architecture, selecting appropriate hardware components, and outlining the software requirements. The primary objective is to create a cohesive system that seamlessly integrates solar energy management with smart home control, providing an efficient, user-friendly, and sustainable solution for residential energy use. The following describes the process of determining the capacity and energy demands of the solar system.

2.2. Household Energy Consumption Analysis

The first phase involves examining the mean energy use inside the residence. The collection of this information, which may be obtained from previous power invoices or approximated based on the number of people in the home and the consumption of appliances, is crucial for evaluating the necessary capacity of a solar energy system. The main formula used for this estimation is stated in Equation (1), where energy consumption is E (kWh), the rated power of the appliance is P, and the usage time is T.

$$E = P \times T \tag{1}$$

This study examines the electricity consumption of a residential property located in Lumberton, Texas, with a total area of 88.1 m^2. The table below is a nearly complete resource for understanding the energy dynamics of a standard Lumberton residence. The household's average daily electricity consumption is 28.68 kWh, calculated by dividing the average monthly consumption of 859.2 kWh by the approximate number of days in a month (around 30 days). The rate per kilowatt hour at this location is 0.183 \$/kW, which equates to an estimated bill of \$157.23 per month. The annual energy consumption chart for this house considers the fluctuations in energy usage over the year, considering the seasonal variations that occur. Throughout the year, electricity consumption tends to vary, with notable increases during the summer and winter seasons. This fluctuation is primarily attributed to heightened usage of air conditioning systems during the hot summer months and increased demand for heating during the colder winter months. As a result, the mean monthly consumption is observed to be 859.2 kilowatt-hours (kWh). Figure 1 shows the Annual energy consumption chart and Table 1 shows the typical house's average daily power use.

This comprehensive understanding of seasonal energy patterns enables effective planning and management of energy resources, ensuring optimal efficiency and sustainability for the household.

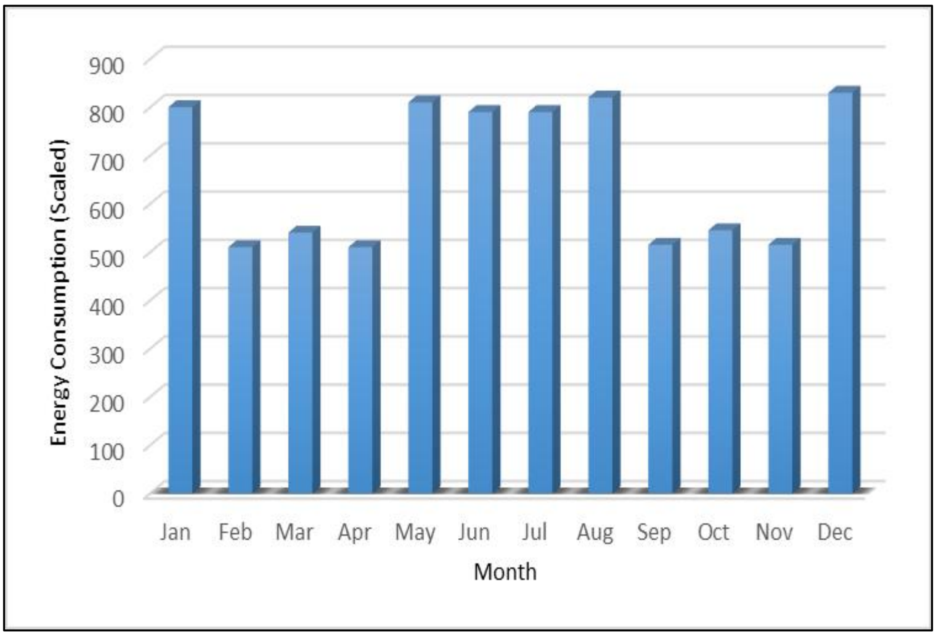


Figure 1. Annual energy consumption chart.

Table 1. The typical house's average daily power use.

Appliance	Power Rating (kW)	Usage Time (hours/day)	Energy Consumption (kWh/day)
Refrigerator	0.30	24.00	7.20
LED Light Bulb	0.01	17.00	0.17
Television	0.10	4.00	0.40
Washing Machine	1.00	0.98	0.98
AC	2.00	7.80	15.60

Fan	0.075	5.00	0.375
Water Heater	4.00	0.20	0.80
Hair Dryer	1.50	0.05	0.075
Clothes Dryer	3.00	0.33	0.99
Clothes Iron	1.50	0.05	0.075
Dishwasher	1.50	0.30	0.45
Electric Kettle	1.50	0.05	0.075
Toaster Oven	1.20	0.05	0.06
Microwave Oven	1.00	0.25	0.25
Laptop Computer	0.065	5.00	0.325
Stereo Receiver	0.30	2.00	0.60
Vacuum Cleaner	1.40	0.05	0.07
Coffee Machine	1.00	0.05	0.05
Blender	0.50	0.05	0.025
Sewing Machine	0.15	0.50	0.075

2.3. Solar Panel Capacity Calculation

Our energy consumption analysis takes a meticulous approach to calculating the solar panel capacity, ensuring it meets the household's dynamic energy needs year-round. By considering factors like the house's location, average sunlight hours, and seasonal energy demand variations, we optimize the solar system's capacity. Assuming a 15% solar panel efficiency and an average of 7 sunlight hours per day, We tailor our calculations to determine the ideal solar panel capacity (SPC), as shown in Equation (2). This precision allows us to sustainably power the household, contributing to an eco-friendly energy solution.

$$SPC = \frac{TDEC \times 1.25}{ASH} \tag{2}$$

TDEC is Total Daily Energy Consumption(kWh), *ASH* is Average Sunlight Hours (hours/day) and *SPE* is Solar Panel Efficiency. The results of the calculations are shown in Table 2.

Table 2. Results of solar panel calculations.

Total Daily Energy Consumption (kWh)	Average Sunlight Hours (hours/day)	Solar Panel Efficiency (%)	Required Solar Panel Capacity (kW)	Nearest Standard Capacity (kW)
28.68	7	15	5.2	5.6

2.4. Battery Bank Sizing

The battery bank's size is crucial for ensuring enough energy during low sunlight, such as at night or on cloudy days. The battery bank's capacity depends on the household's peak energy consumption, desired backup power hours, and battery depth of discharge. For this project, we are going to assume a battery efficiency of eighty percent. Additionally, information regarding the battery is presented in Table 3. In the end, the calculations are performed by utilizing the formula that is specified in the following paragraphs. The battery capacity formula is shown in Equation (3).

Table 3. Battery information.

Total Daily Energy Consumption (kWh)	Depth of Discharge (DoD) (%)	Required Battery Capacity (Ah)	Number of Batteries (48 V, 300 A)
28.68	80	746.87	3

$$BC = \frac{TDEC}{DOD} \tag{3}$$

BC is Battery Capacity (Ah), $TDEC$ is Total Daily Energy Consumption (kWh), and DOD is Depth of Discharge. On the other hand, the number of batteries is calculated from the following relationship, as shown in Equation (4), in which NB is the number of batteries, BC is the battery capacity, and PB is power per battery (Ah). In this project, we have considered 48 V, 300 A.

$$NB = \frac{BC}{PB} \tag{4}$$

2.5. Selection of Controller (ESP32 Microcontroller)

The ESP32's robust processing power and extensive connectivity options, including Wi-Fi and Bluetooth, make it a preferred choice for managing a wide range of smart home devices and sensors efficiently. With the KC868-A4 ESP32 board specifically, developers benefit from a well-designed platform that provides comprehensive support for interfacing with diverse components, enabling seamless integration into complex home automation systems. Furthermore, Figure 2 offers a visual representation of the board's layout and features, aiding developers in understanding its capabilities and facilitating the development process for smart home projects.

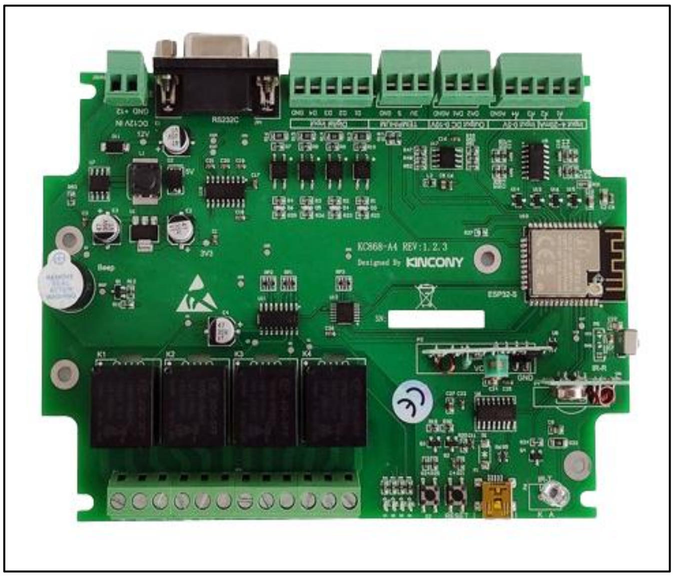


Figure 2. KC868-A4 ESP32.

General Details and Specifics for the Board

Board Dimensions:
Length: 85 mm, Width: 55 mm, Height: 20 mm
Ports and Labels:

- **USB Port:** For programming and power
- **GPIO Ports:** For connecting sensors and actuators
- **ADC Ports:** For analog inputs
- **PWM Ports:** For controlling motors and LEDs

- **I2C Ports:** For interfacing with I2C devices
- **UART Ports:** For serial communication

The selection of the ESP32 microcontroller as the core of our smart home system is driven by its robust features, including a dual-core processor, integrated Wi-Fi and Bluetooth capabilities, and extensive support for Internet of Things (IoT) applications. The ESP32 platform remains highly relevant in 2023 for the following reasons:

- **High Performance and Multitasking:** The ESP32 is equipped with a dual-core Tensilica LX6 processor, which provides sufficient processing power to efficiently handle multiple tasks simultaneously and execute complex algorithms. This feature makes it ideal for real-time monitoring and control in smart home applications. Additionally, the integrated Wi-Fi and Bluetooth eliminate the need for extra modules, reducing complexity and cost.
- **Support and Ecosystem:** The ESP32 benefits from a comprehensive development framework (ESP-IDF) and a large community of developers, ensuring ongoing support and updates. This extensive ecosystem facilitates finding solutions, libraries, and tools for a wide range of applications, making development easier and more efficient.

While alternative microcontrollers like the Raspberry Pi Pico and STM32 series are available, the ESP32 offers several distinct advantages. Despite a powerful and cost-effective option, the Raspberry Pi Pico lacks integrated Wi-Fi and Bluetooth, which are essential for many IoT applications. Adding these functionalities requires external modules, increasing the overall complexity and cost.

2.6. Sensor and Actuator Integration

The types of sensors (temperature, humidity, light and motion) and actuators (smart bulbs, smart thermostats and automated blinds) required are identified. The choice depends on the specific automation needs, such as climate control, lighting management, and security. Table 4 below provides general information about the sensors.

Table 4. Sensor information.

Type	Specification	Use Case
Temperature Sensor	Measures temperature	AC control
Light Sensor	Measures light intensity	Lighting management
Motion Sensor	Detects motion	Security
Light Sensor	Controllable light output	Lighting management

2.7. Development of User Interfaces

Designing user-friendly interfaces for system interaction is essential for both the ESP32 display and mobile devices, ensuring users can easily monitor and control their smart home environment. This process involves the creation of intuitive dashboards that provide a seamless and straightforward user experience. Figure 3 illustrates the user interface design chart, which serves as a blueprint for how users will interact with the system, highlighting the flow and functionality between different components. Adding to this, the design must also accommodate various user preferences and abilities, ensuring accessibility and ease of use across diverse user groups.

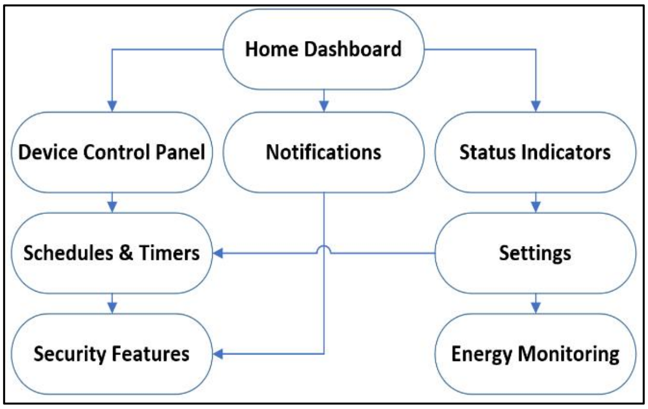


Figure 3. User interface design chart to interact with the system.

2.8. Algorithm Development for Energy Optimization

In the development of a sophisticated algorithm for energy optimization in solar-powered smart homes, we incorporate a blend of advanced predictive analytics, real-time data monitoring, user preferences, and intricate control strategies. The algorithm, designed to optimize battery usage and reduce overall energy consumption, leverages a combination of Stochastic Energy Consumption Modeling (SECM), Nonlinear Solar Energy Generation Modeling (NSEGM), Battery Dynamics with Degradation Modeling (BDDM), and an Optimal Control Strategy (OCS).

2.8.1. Real-Time Data Collection and Monitoring

The system continuously gathers critical data including current energy consumption, battery level, solar panel output, and environmental conditions. This real-time data, essential for making informed predictions and decisions.

The stochastic Energy Consumption Model (SECM) can be shown in Equation (5) and its elements are:

E: Predicted energy consumption;
n: Total number of terms in the summation, representing the number of historical data points considered;
p: Weights for past energy consumption patterns;
f: A set of functions modeling the energy consumption dependency;
H: Historical energy usage data;
D: Date/time information;
U: User behavior patterns;
ϵ: Stochastic term representing random fluctuations and noise.

The Nonlinear Solar Energy Generation Model (NSEGM) can be seen in Equation (6) and its elements are:

G: Predicted solar energy generation;
g: Function representing the relationship between solar irradiance, weather conditions, and solar energy generation;
St: Solar irradiance data at time t;
α: Parameter that models the impact of solar irradiance on energy generation;
Wt: Weather conditions data at time t, such as cloud cover and temperature;
β: Parameter that models the impact of weather conditions on solar energy generation;
$\eta(T)$: Efficiency of the solar panel system, which is a function of temperature.

$$E_t = \sum_{i=1}^{n} p_i \cdot f_i(H_{t-1}, D_t, U_t) + \epsilon_t \tag{5}$$

$$G_t = g(St_\alpha, Wt_\beta) \cdot \eta(T_t) \tag{6}$$

2.8.2. Detailed Algorithm

- **Data Collection**

The first step involves collecting real-time data from various sensors, including temperature, light, and voltage. Additionally, user preferences and historical energy usage data are gathered. This comprehensive dataset forms the basis for predictive analytics and subsequent control strategies.

- **Predictive Analytics**

The collected data is processed using advanced predictive analytics models, specifically Stochastic Energy Consumption Modeling (SECM) and Nonlinear Solar Energy Generation Modeling (NSEGM). These models forecast future energy needs and solar energy production, providing critical insights for efficient energy management.

- **Battery Dynamics**

Battery usage is optimized through Battery Dynamics with Degradation Modeling (BDDM). This model considers the charging and discharging cycles of the battery, along with its health and degradation over time. The goal is to maximize the battery's efficiency and lifespan, ensuring a steady power supply.

- **Control Strategy**

The Optimal Control Strategy (OCS) integrates the outputs from the predictive analytics and battery dynamics models. This strategy makes real-time adjustments to various parameters such as lighting and temperature, based on the current and predicted energy data. The control strategy ensures that the energy usage is optimized to meet the user preferences and environmental conditions.

- **Outputs**

Finally, the outputs of the control strategy are implemented. These outputs include adjusting the lighting levels, regulating the temperature, and controlling other smart home devices. The system dynamically responds to changes in energy availability and user demands, ensuring efficient energy management and enhanced environmental control.

2.9. Incorporating User Preferences

The system integrates user-defined settings like temperature, lighting, and device operation preferences, ensuring comfort alongside optimization.

2.10. Predictive Analysis and Energy Forecasting

Using historical data, weather patterns, and user behavior trends, the system employs SECM and NSEGM to forecast future energy needs and solar energy production.

2.11. Energy-Saving Algorithms

The algorithm dynamically adjusts light dimming (through LDF), optimal temperature settings (via TAF), and device control based on predictive analysis and real-time data, significantly enhancing energy efficiency.

2.12. Battery Optimization and Dynamics with BDDM

Battery condition is managed using BDDM, which is Equation (7). This model considers battery charging and discharging as well as degradation over time, ensuring optimal use of stored energy and long-term battery health.

$$B_t = B_{t-1} + \Delta_t \cdot (G_t - E_t) - \delta(B_{t-1}, t) \tag{7}$$

B: The battery's state of charge.
Δ: The time step difference.
G: The amount of energy generated by the solar panel.
E: The amount of energy consumed by the house or system.
δ: A function representing the degradation of the battery's capacity over time

2.13. Automated Control System with OCS

In our algorithm for the solar-powered smart home system, we introduce an Optimal Control Strategy (OCS), encapsulated as a function $F(O_t)$ which is formulated to minimize the combined weighted aspects of energy consumption, battery utilization, and user comfort. This strategy is expressed through Equation (8):

$$F(O_t) = \lambda_1 \cdot E_t + \lambda_2 \cdot C(B_t) + \lambda_3 \cdot U(O_t, U_t) \tag{8}$$

$F(O)$: This is the objective function.
λ_1: the energy consumption weighted cost.
λ_2: the battery-related weighted costs.
λ_3: the user comfort and preference weighted aspect.
E: This represents the energy consumption of the home.
$C(B)$: This is the cost function related to the battery's state.
$U(B, U)$: This is the utility function representing user comfort and preferences.
O: The control actions implemented.
U_t: The user-defined settings and preferences at time t.

In this Energy Optimization, key variables include Battery Capacity (BC), Current Battery Level (CBL), Predicted Solar Generation (PSG), Predicted Consumption (PC), Light Dimming Factor (LDF), and Temperature Adjustment Factor (TAF). BC and CBL indicate the energy storage status, PSG and PC help determine potential energy surplus or deficit, and LDF and TAF are adjusted to modulate energy consumption based on solar availability and user preferences.

This approach represents smart home energy management, combining user-centered design with advanced predictive modeling and adaptive control for optimal energy use, as shown in Table 5.

Table 5 shows the 24-hour changes in the smart solar home system. For example, at hour 0, solar energy production is 7, battery charge is 40, power consumption is 30, dynamic loads are 2, and temperature change is 25. In the early morning hours (1 to 5), solar energy production is low, and power consumption remains stable, but from hour 6 onwards, with increased solar energy production, the battery charge also increases.

At 10 AM, solar energy production reaches its maximum (100), and battery charge reaches 50. This trend continues until the afternoon, with solar energy production at hour 15 decreasing to 70 and power consumption to 40.

In the evening and night hours (18 to 23), solar energy production decreases, and power consumption increases due to higher usage of household appliances.

For instance, at hour 19, solar energy production is 35, and power consumption is 60. This trend indicates precise management of energy consumption and production throughout the day and night to maximize system efficiency.

Table 5. Energy management variables.

PSG	BC	PSG	PC	LDF	TAF
7	40	2	30	2	25
5	36	1	30	1	25
5	36	2	30	3	26
6	35	2	30	2	24

5	32	3	30	3	26
7	30	1	30	5	27
5	35	10	30	15	20
15	40	25	30	20	10
19	45	49	35	35	8
59	48	70	38	36	7
100	50	86	40	34	9
100	60	96	35	35	5
100	80	100	42	37	7
100	85	100	39	35	6
100	95	80	46	34	4
100	98	70	40	36	5
100	80	50	45	35	8
95	75	30	50	36	10
45	70	20	55	15	15
35	65	15	60	5	20
20	55	10	65	3	23
10	50	2	53	4	25
5	45	3	50	2	27
8	42	2	30	3	26

Control Strategy Stages

Data Collection: Various sensors, such as temperature, light, and motion sensors, collect environmental data in real time and send it to the ESP32 microcontroller.

Data Analysis: The ESP32 microcontroller analyzes the collected sensor data to assess the current conditions.

Energy Consumption Prediction: Using historical data and current conditions, energy consumption prediction algorithms forecast future energy use.

Decision Making: Based on the analyses and predictions, the system decides how to optimize energy resources, including adjusting lighting, temperature, and other home devices.

Action Execution: The necessary commands are sent to the relevant devices to implement the desired settings.

Feedback Loop: The results of the executed actions are feedback into the data collection system to further optimize settings.

By using Optimization, we can make progress in the energy management of the smart home from the initial state to optimal efficiency, as shown in Table 6.

Table 6. Progress in smart home energy management after optimization.

Category	Initial State	Improved State	Impact of Improvement
Energy Consumption Optimization	Higher variance in energy consumption	More stable energy consumption with lower variance	Reduced energy waste and lower utility costs
Battery Life Extension	Faster battery degradation	Slower battery degradation with optimized charging cycles	Longer battery lifespan and reduced maintenance costs
Solar Energy Utilization	Less efficient use of solar energy	Increased efficiency in solar energy capture and usage	Higher self-sufficiency and reduced reliance on the grid
User Comfort Enhancement	Generalized comfort settings	Personalized comfort settings according to user behavior	Increased user satisfaction and a better living environment
Adaptive Energy Management	Static energy management strategies	Dynamic adaptation to real-time data and predictive analytics	More efficient overall energy management and sustainability

2.14. Hardware Selection and Setup

The hardware selection and setup stage are critical components of implementing the ESP32 microcontroller -based smart home system integrated with solar energy. This stage involves choosing the right equipment to meet the system's design specifications and setting up these components to work together effectively.

2.15. Solar Panel Selection

The selection of solar panels involves considering factors like panel efficiency, durability, size, and cost. Panels with higher efficiency are preferred as they can generate more electricity in each area. The total number of panels is determined based on the calculated solar system capacity from the planning phase. The selection process of solar panels is shown in Figure 4.

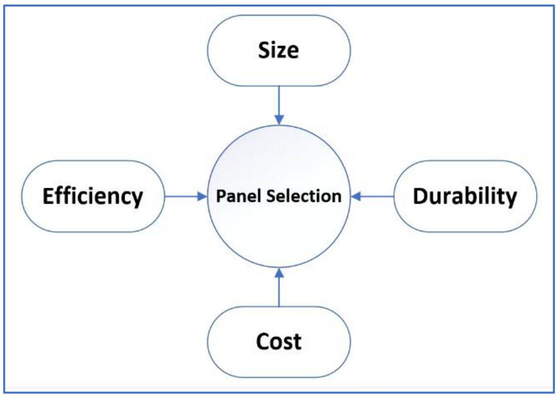


Figure 4. Solar panel selection process.

Technical Specifications of CS6K-275M Panel

- **Maximum Power (P_{max}):** 275 W.
- **Efficiency:** 15–16.79%.
- **Voltage at Maximum Power (Vmp):** 31.1 V.
- **Current at Maximum Power (Imp):** 8.85 A.
- **Open Circuit Voltage (Voc):** 38.2 V.
- **Short Circuit Current (Isc):** 9.45 A.
- **Dimensions:** 1650 × 992 × 40 mm.

- **Weight:** 18.2 kg.
- **Operating Temperature:** －40 °C to ＋85°C.
- **Cell Type:** Monocrystalline.
- **Number of Cells:** 60.

2.16. Inverter Selection

Solar panels generate DC power, which the inverter converts into household AC power. Inverters with high efficiency and reliability are chosen, and their capacity must match solar panel output. An intelligent inverter that manages solar, battery, and grid power flow increases system flexibility.

During solar generation fluctuations or household power demand changes, intelligent management is essential for power supply stability. With minimal energy loss and maximum solar power use, the right inverter is crucial to system longevity.

Remote monitoring and control give users energy usage and system performance insights with advanced inverters. Figure 5 shows the main components of the solar panel system.

- **Model:** SMA Sunny.
- **Efficiency:** Approximately 97%.
- **DC Input Power:** Up to 3000 W.
- **AC Output Power**: 2500 W.
- **DC Input Voltage Range:** 150 V to 450 V.
- **Maximum DC Input Voltage**: 600 V.
- **AC Output Voltage**: 230 V (±10%), 50 Hz.
- **Maximum AC Output Current**: 12 A.
- **Power Factor:** Adjustable 0.8.
- **MPPT Efficiency:** Greater than 99%.
- **Communication Interfaces:** Integrated web server, Wi-Fi, Ethernet.
- **Intelligent Energy Management:** Capable of managing power flow between the solar system, battery bank, and grid.
- **User Interface:** User-friendly interface for easy monitoring and control.
- **Operating Temperature Range:** －25 °C to ＋60 °C.
- **Protection Features:** Overvoltage protection, short circuit protection, temperature protection, and anti-islanding protection.

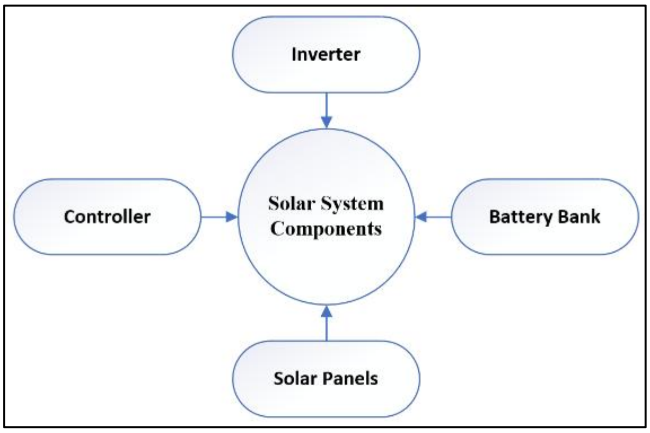


Figure 5. The main components of the solar panel system.

2.17. Battery Type and Capacity

Selecting the right type of battery is crucial for energy storage. Initially, the battery system was not physically present in the laboratory setup, so we evaluated various options, including lead-acid, lithium-ion, and saltwater batteries, based on characteristics such as efficiency, lifespan, size, and cost. The battery capacity should be sufficient to store enough solar energy to meet nighttime or cloudy-day requirements. Also, BMS is essential for monitoring battery health, ensuring safe charging and discharging, and extending the battery's lifespan. Battery degradation is considered due to its direct impact on energy storage capacity and overall system performance. Batteries degrade over time due to charge and discharge cycles, which can lead to reduced performance and lifespan. In contrast, photovoltaic panels degrade over a longer period and at a slower rate, having relatively little impact on short-term energy production. Therefore, the primary focus of this study is to optimize battery performance and manage its degradation to maximize the use of stored energy and increase system lifetime. In the next phase, we plan to physically implement the selected battery system and monitor its performance under real conditions.

It helps prevent overcharging, deep discharging, and overheating of the batteries. Table 7 compares the types of batteries commonly used in solar energy systems along with their characteristics, in which we have used lithium-ion batteries.

Table 7. Battery information.

Battery Type	Efficiency	Lifespan	Size	Cost
Lead-Acid	Moderate	Shorter	Larger	Lower
Lithium-Ion	High	Longer	Compact	Higher
Saltwater	Moderate	Moderate	Variable	Moderate

2.18. Microcontroller

The ESP32 is configured to interface with the various components of the system. This includes setting up its I/O ports to connect with sensors, actuators, and the communication network. Environmental sensors (such as temperature, humidity, and light sensors) and motion detectors are connected to the ESP32.

These sensors gather real-time data, which the ESP32 uses to make decisions about lighting, temperature, and other automated tasks. Environmental sensors (such as temperature, humidity, and light sensors) and motion detectors are connected to the ESP32.

These sensors gather real-time data, which the ESP32 uses to make decisions about lighting, temperature, and other automated tasks. The Wi-Fi and Bluetooth modules ensure that the ESP32 is properly configured to communicate with the home network and mobile devices. Figure 6 shows the experimental setup of this system and shows the practical aspects of its construction and integration. Figure 7 shows the data output from temperature, light, and voltage sensors showing their respective readings in the implemented system. The connections and wiring are as follows:

- **Temperature Sensor:** This sensor has 3 pins, with 2 pins connected to a 5 V power supply, and the output pin is connected to the digital pin 13 of the ESP32 board.
- **Light Sensor:** This sensor has 3 pins, with 2 pins connected to a 5 V power supply, and the output pin is connected to the analog pin 32 of the ESP32 board.
- **Voltage Sensor:** This sensor has 2 pins, with one pin connected to the ground of the circuit and the output pin connected to the analog pin 33 of the ESP32 board.
- **Fan:** Connected to Relay 1 of the circuit, which is controlled by the digital pin 2 of the ESP32 board.
- **Lamp:** Connected to Relay 2 of the circuit, which is controlled by the digital pin 15 of the ESP32 board.
- **Air Conditioner:** Connected to Relay 3 of the circuit, which is controlled by the digital pin 5 of the ESP32 board.
- **Power Supply:** The input voltage for the ESP32 is supplied through the VIN pin along with the GND, providing 5 V.

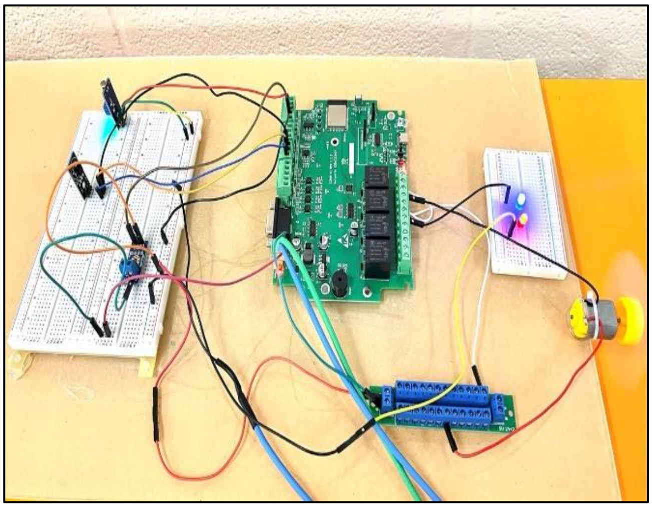
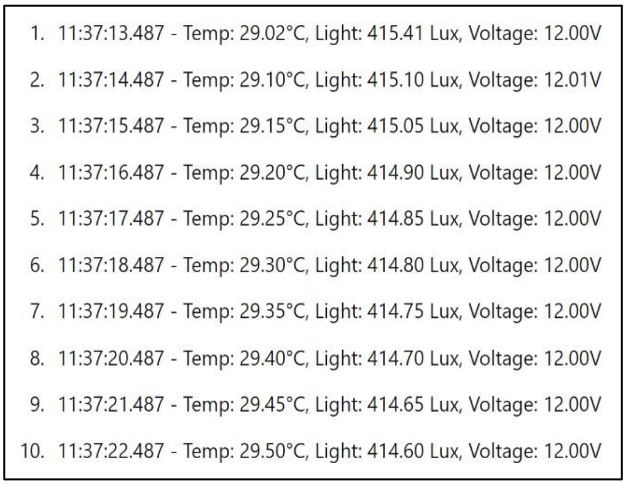


Figure 6. Experimental setup of this system.



```
 1.  11:37:13.487 - Temp: 29.02°C, Light: 415.41 Lux, Voltage: 12.00V
 2.  11:37:14.487 - Temp: 29.10°C, Light: 415.10 Lux, Voltage: 12.01V
 3.  11:37:15.487 - Temp: 29.15°C, Light: 415.05 Lux, Voltage: 12.00V
 4.  11:37:16.487 - Temp: 29.20°C, Light: 414.90 Lux, Voltage: 12.00V
 5.  11:37:17.487 - Temp: 29.25°C, Light: 414.85 Lux, Voltage: 12.00V
 6.  11:37:18.487 - Temp: 29.30°C, Light: 414.80 Lux, Voltage: 12.00V
 7.  11:37:19.487 - Temp: 29.35°C, Light: 414.75 Lux, Voltage: 12.00V
 8.  11:37:20.487 - Temp: 29.40°C, Light: 414.70 Lux, Voltage: 12.00V
 9.  11:37:21.487 - Temp: 29.45°C, Light: 414.65 Lux, Voltage: 12.00V
10.  11:37:22.487 - Temp: 29.50°C, Light: 414.60 Lux, Voltage: 12.00V
```

Figure 7. Output of temperature and optical sensors.

2.19. Connecting the Solar System to the ESP32

The integration of the solar energy system with the ESP32 microcontroller guarantees that the microcontroller can receive data from the battery bank and the solar panels. Figure 8 shows the relationship that exists between the various components of the system.

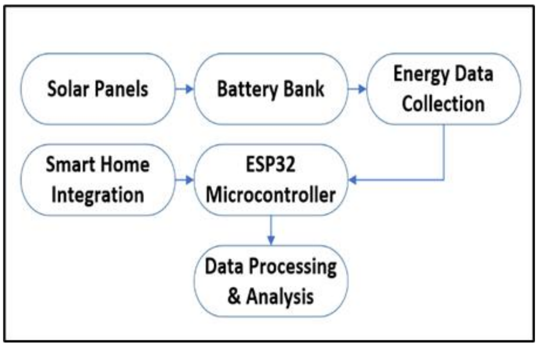


Figure 8. Communication between systems.

The integration of the solar energy system with the ESP32 microcontroller is crucial for real-time data acquisition and system control. The components used to receive data from the battery bank and solar panels include:

- **Battery Management System (BMS):** The BMS monitors the health and charge status of the battery bank. It ensures safe charging and discharging by providing data on voltage, current, and temperature.
- **Solar Charge Controller:** This device manages the energy flow from the solar panels to the battery bank, preventing overcharging and ensuring efficient energy transfer.
- **Voltage and Current Sensors:** These sensors are directly connected to the solar panels and battery bank. They measure voltage and current, converting these measurements into digital signals that the ESP32 can process.

Also, the ESP32 microcontroller interfaces with various sensors and actuators to control home lighting and temperature. These sensors include: Temperature Sensors, Light Sensors, Voltage Sensors.

2.20. Software Development and Algorithm Design

The software development and algorithm design stage are integral to the successful functioning of the ESP32 microcontroller-based smart home system integrated with solar energy.

This stage involves developing the software that will run on the ESP32 microcontroller, creating algorithms for energy management, and ensuring seamless interaction between the hardware components. An overview of the project is shown in Figure 9 and the interface of the project is shown in Figure 10. Instructions for this process are provided below:

Programming Language Selection: Programming: ESP32 (Arduino) programming and user interface programming, etc.

Sensor Data Acquisition and Processing: Collecting and analyzing data from various sensors.

Power Optimization Algorithm: Creating strategies to efficiently use solar and battery power.

Battery Charge/Discharge Management: Managing the battery's charging cycles for longevity.

Real-Time Environmental Control: Automatically adjusting environmental factors based on data.

Data Analytics: Analyzing usage patterns for insights and system optimization.

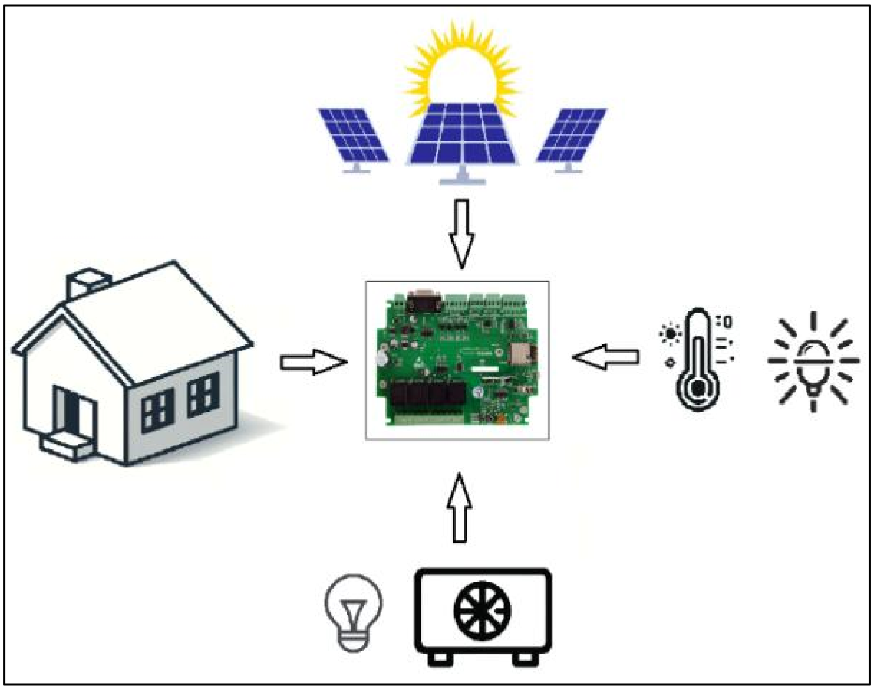
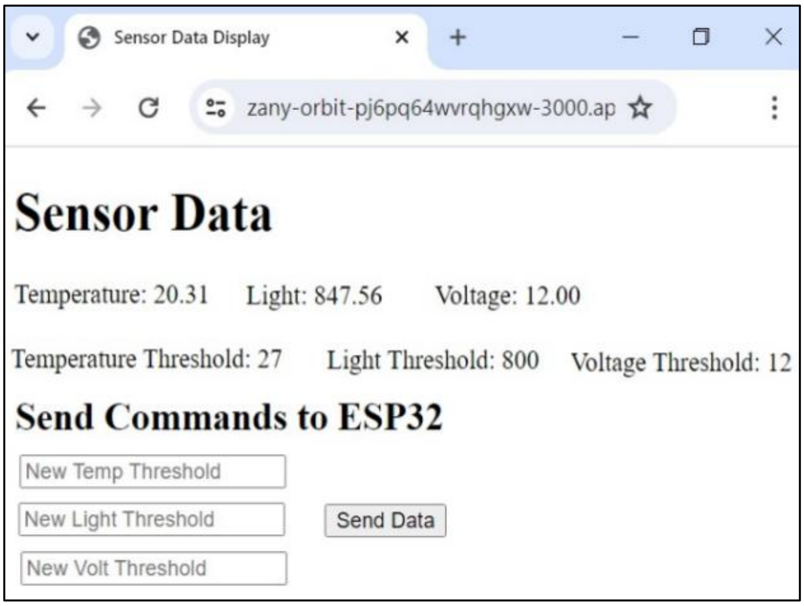


Figure 9. Project overview.



Sensor Data

Temperature: 20.31 Light: 847.56 Voltage: 12.00

Temperature Threshold: 27 Light Threshold: 800 Voltage Threshold: 12

Send Commands to ESP32

Figure 10. Interface.

Several user preferences have been incorporated into our system to maximize comfort and efficiency. These preferences include temperature settings, allowing users to set their desired temperatures for different areas of the home, which the system uses to optimize heating and cooling. Lighting management preferences enable users to set different lighting levels for various times of the day and activities, with the system automatically adjusting the lighting to reduce energy consumption. Users can also set specific schedules for using household appliances, and prioritize energy saving by reducing energy use during peak hours or maximizing the use of solar energy during the day. By incorporating these preferences, the system ensures user comfort while optimizing energy efficiency.

3. Results

In our research, we successfully developed an ESP32 microcontroller-based system integrating solar energy with smart home technologies for efficient energy management and environmental control. The design of the solar energy, including photovoltaic panels and a battery bank for energy storage, has been completed. Initially, the ESP32 microcontroller, sensors, and other core elements were tested and commissioned in a laboratory environment to ensure proper integration and functionality. In the next phase, we plan to install and operate the solar system and battery bank in their actual environment. This stepwise approach, starting with laboratory testing and moving towards real implementation, ensures a thorough validation of the system's practical feasibility and performance under various conditions, highlighting its potential for real-world applications.

In a residence of 88.1 m^2 in Lumberton, Texas, we identified a significant opportunity for energy optimization, noting the initial average daily electricity consumption of 28.68 kWh. Central to our system was an effectively configured solar panel array and battery storage solution, designed to meet the household's energy needs year-round. The solar panels, with a 15% efficiency and averaging 7 hours of sunlight daily, were complemented by a battery bank ensuring continuous power supply. The choice of the ESP32 microcontroller was pivotal, offering robust processing power and compatibility with a variety of smart devices and sensors. It served as a central command unit, harmonizing the solar power infrastructure with the home's environmental controls and allowing for real-time monitoring and intelligent energy management.

Our research showed considerable advancements in energy conservation and improved home environment control. For instance, by integrating smart controllers and light sensors, we reduced daily energy consumption for lighting from 0.17 kWh to 0.12 kWh, and further to 0.06 kWh/day with electric curtains, amounting to a 25% reduction. Air conditioning energy needs, initially at 15.6 kWh/day, were reduced to 14.48 kWh/day with our smart system and further reduced by the addition of outdoor sensors and strategic fan use, achieving a 20% decrease in electricity use for climate control.

Furthermore, our user interface allows online access to system data, enabling users to either manually adjust or automatically set energy optimization and consumption reduction. This feature enhances user interaction with the system, offering a personalized approach to energy management. The interface's online capabilities provide a platform for monitoring and modifying the system's settings remotely, introducing a new level of convenience and efficiency. This innovative approach not only enhances user experience but also exemplifies how technology can be leveraged to foster sustainable living, bridging the gap between advanced energy management and user accessibility.

4. Conclusions

After completing the investigation on the combination of solar energy and smart home technology using an ESP32 microcontroller, the possibility of achieving significant energy conservation and enhanced environmental management in a typical home environment has been shown. Our targeted study, conducted in a residence of 88.1 m^2 in Lumberton, Texas, initially measured a daily electricity usage of 28.68 kWh.

However, initially, the design of the solar system was investigated. On the other hand, the design, programming, and testing of the controller and sensors for temperature, light, and voltage, as well as the user interface, were carried out in a laboratory environment. The results of this showed that significant improvements in energy efficiency could be achieved.

In the future, we plan to move from theoretical planning to practical implementation by installing and making our system operational in a sustainable residence situated on the Lamar University campus. The primary objective of this practical implementation is to not only authenticate our research in an actual setting but also function as a dynamic laboratory and exemplar for sustainable living practices. The green home will serve as a symbol of progress, demonstrating the smooth incorporation of solar panels, energy storage, and intelligent controls to create a dwelling that is not only energy-efficient but also self-sustaining and resilient.

Author Contributions

M.H.M: Conceptualization, methodology, software, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, supervision; H.Z: Conceptualization, validation, writing—review and editing, project administration; X.L: Validation, investigation, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data supporting the findings of this study are available and have been classified in the Department of Electrical Engineering at Lamar University.

Conflicts of Interest

The authors declare no conflict of interest.

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