PROBLEM STATEMENT

To develop an IoT-based off-grid solar home automation system that enables accurate monitoring of voltage, current, power, energy usage, and battery percentage, while providing reliable remote control of home appliances through cloud connectivity, ensuring efficient energy management and improved convenience for off-grid users.

DESIGN AND IMPLEMENTATION OF PROTOTYPE

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ABSTRACT

The Solar Home Automation – Off-Grid Prototype is a sustainable smart energy system designed to automate essential household appliances using solar power as the primary energy source. This project integrates renewable energy technology with Internet of Things (IoT) capabilities to create a reliable and efficient automation model suitable for homes located in remote or non-electrified regions.

The system operates entirely on an off-grid solar setup, where energy generated from a solar panel is stored in a battery and used to power connected loads such as fans, lights, and a motor pump. An ESP32 microcontroller serves as the central control unit, enabling real-time monitoring and remote operation of appliances through Firebase Realtime Database and a smartphone interface.

A high-accuracy INA219 voltage and current sensor is used for continuous measurement of voltage, current, power, and energy consumption, allowing users to track battery percentage and daily power usage. The system employs four low-level triggered relays for safe switching of DC loads, while time-based software routines ensure non-blocking sensor acquisition and cloud communication.

Additional reliability features such as automatic Wi-Fi scanning, stored fallback sensor values, and reconnection handling help maintain uninterrupted operation in real-world off-grid environments. Sensor data and relay statuses are updated to Firebase at regular intervals, enabling users to monitor and control their home appliances from anywhere with internet access.

This prototype demonstrates the practical integration of renewable energy and automation in a compact, low-cost, and energy-efficient model. It highlights how solar-powered IoT systems can improve convenience, safety, and power management in off-grid households. The project serves as a foundation for scalable smart solar homes and future development in green energy-based automation technologies.

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INTRODUCTION

The rapid rise in global energy demand and the growing concern over environmental degradation have intensified the need for sustainable and renewable energy solutions. Among all renewable sources, solar energy stands out as the most abundant, clean, and accessible resource. Solar power systems are increasingly adopted in both urban and rural areas to reduce dependence on conventional fossil-fuel based electricity. However, despite the availability of solar technology, integrating it effectively with modern home automation systems still remains a challenge—especially in off-grid locations where households rely entirely on battery storage and solar panels.

The purpose of this prototype is to demonstrate how renewable energy can be combined with Internet of Things (IoT) technology to automate essential household appliances such as fans, lighting systems, and water pumps. Using an ESP32 microcontroller as the brain of the system, the project establishes a smart home environment capable of real-time sensing, decision-making, and remote control.

The ESP32's built-in Wi-Fi capability enables cloud connectivity through Firebase Realtime Database**,** allowing users to monitor solar power generation, battery health, and energy usage directly from a mobile application. This introduces a modern, user-friendly interface for controlling devices even when the user is physically away from home. The system is specifically designed as an off-grid model, meaning it functions independently without any support from the electricity grid, making it suitable for rural homes, disaster-prone regions, farmhouses, and portable emergency shelters.

A critical aspect of an off-grid solar system is the accurate measurement of real-time electrical parameters to ensure efficient energy utilization and battery longevity. For this purpose, the system integrates the INA219 precision current and voltage sensor, which continuously monitors bus voltage, solar charging current, load consumption, instantaneous power, and total energy usage in watt-hours. The data collected by the INA219 enables the system to calculate battery percentage, detect overloads, and track how much energy the connected appliances are consuming throughout the day.

This information is particularly important in off-grid setups where energy availability is limited and must be managed efficiently. The project also includes four individual relay channels for appliance control, using low-level triggering to ensure safe switching of DC loads such as fans, LED lights, and the motor pump. These relays are controlled automatically through Firebase commands, giving the user full remote access to the system.

To ensure uninterrupted operation, the software is designed with multiple reliability mechanisms. The Wi-Fi connection system performs automatic scanning of all nearby networks and connects to any known SSID stored in the program, eliminating the need for manual configuration. If a sensor becomes temporarily unavailable, the system uses previously recorded valid values to maintain stable data transmission to the cloud.

Time-based functions handle Firebase relay updates and sensor readings separately, preventing delays and ensuring smooth IoT communication. Energy consumption is calculated continuously by comparing time intervals and power readings, allowing users to understand the long-term performance of their solar setup. The entire code is modular, optimized, and designed for long-term continuous operation without rebooting.

The hardware prototype effectively represents a small-scale model of a solar home. A solar panel charges a lithium-ion or lead-acid battery which acts as the primary energy reservoir. The ESP32, relays, and sensors operate on this stored solar power, demonstrating how a complete household can function sustainably without any grid connection.

The integration of IoT technology transforms the system from a basic solar circuit into a smart energy-aware automation model capable of adapting to user needs, energy availability, and environmental conditions. This makes the design suitable not only for academic study but also for real-world deployment in rural electrification programs, green homes, and low-cost smart housing solutions.

CHAPTER 2

LITERATURE REVIEW / BACKGROUND STUDY

The adoption of renewable energy systems and smart automation technologies has grown significantly in the past decade due to rising global awareness about sustainability, energy conservation, and environmental protection. Among all renewable sources, solar energy has emerged as the most practical and widely used alternative, especially in regions that experience unreliable grid supply or no electricity access. Solar photovoltaic (PV) systems offer clean, noise-free, and maintenance-friendly power generation, making them suitable for rural homes, small industries, agricultural fields, and portable off-grid applications.

However, one of the major limitations of conventional solar systems is the lack of intelligent monitoring, energy management, and automation capabilities. This limitation has led researchers and developers to explore the integration of IoT and microcontroller technologies into solar installations to create smarter and more efficient systems.

Early research on solar-based automation focused primarily on standalone charge controllers and manual switching systems**,** where users monitored battery voltage using simple LED indicators or analog meters. While these systems served basic energy regulation needs, they lacked real-time data visibility and remote accessibility. With advancements in sensing technology, precision sensors such as the INA219 enabled accurate measurement of voltage, current, and power, allowing researchers to build more data-driven solar monitoring systems. Studies have shown that accurate measurement of electrical parameters significantly improves battery life and overall system efficiency by preventing over-discharge, overload, and poor load management.

The evolution of Internet of Things (IoT) technologies further transformed the approach to smart energy systems. Research contributions highlight the use of microcontrollers like ESP8266, ESP32, Arduino, and Raspberry Pi to transmit solar data to cloud platforms. Firebase, MQTT, Blynk, and Thingspeak became popular cloud services for storing and visualizing real-time energy data.

IoT-enabled solar systems enabled users to monitor panel performance, battery state-of-charge, load consumption, and environmental conditions directly from smartphones or web dashboards. These innovations bridged the gap between renewable energy generation and modern smart home requirements.

Home automation technologies also evolved simultaneously. Earlier automation systems used basic RF modules or IR-based remote switches, which required proximity and lacked two-way feedback. Later, Wi-Fi-based automation using ESP32 and relay drivers gained popularity, enabling remote control of fans, lights, pumps, and other appliances. Researchers emphasized the importance of low-power microcontrollers**,** reliable relay switching, and cloud-based command handling to maintain automation stability. Several studies recommended low-level triggered relays for safe DC switching, which is crucial in solar-powered home setups.

A significant area of research has focused on off-grid systems, which operate independently without any grid electricity support. Off-grid systems are widely deployed in remote villages, farms, and temporary shelters where grid supply is either unreliable or absent. Literature indicates that off-grid solar systems face challenges such as limited battery capacity, variable sunlight, and inconsistent energy availability. Therefore, integrating intelligent monitoring and automation helps users manage loads more efficiently. Background studies show that smart energy systems reduce unnecessary power usage, increase the lifespan of batteries, and ensure efficient utilization of limited solar energy.

The work conducted in this project builds upon these previous research findings. By combining off-grid solar power**,** IoT monitoring**,** real-time sensing, and remote automation, the proposed system contributes to the existing literature by offering a compact, low-cost, and user-friendly prototype.

Unlike conventional systems, it integrates accurate INA219-based measurement, cloud synchronization, multi-network Wi-Fi scanning, and Firebase-based control into a single optimized model. The literature review clearly highlights the relevance and growing importance of smart solar automation, positioning this project as a modern, practical, and future-ready solution for sustainable energy management.

CHAPTER 3

SYSTEM ANALYSIS & PROBLEM STATEMENT

3.1 System Analysis

Off-grid solar systems commonly used in rural homes work without grid support and depend entirely on battery power. However, most existing systems lack smart monitoring and automation. Users cannot check real-time voltage, current, power, or battery percentage, and appliances like lights, fans, and pumps must be operated manually. These limitations often cause unnecessary power usage, battery over-discharge, and inconvenience. Conventional systems also lack remote access, cloud monitoring, and accurate sensors, making them unsuitable for modern energy management.

There is a clear need for an intelligent, IoT-based system that monitors energy parameters accurately and automates load control according to battery conditions.

3.2 Problem Statement

To develop an IoT-based off-grid solar home automation system that enables accurate monitoring of voltage, current, power, energy usage, and battery percentage, while providing reliable remote control of home appliances through cloud connectivity, ensuring efficient energy management and improved convenience for off-grid users.

3.3 Need for the Proposed System

- Off-grid homes require smarter load management to avoid battery drain.
- Users need remote control of appliances for better convenience and safety.
- Accurate sensing improves efficiency and prolongs battery lifespan.
- Cloud connectivity provides real-time monitoring from anywhere.

3.4 Objectives

- Monitor off-grid solar energy parameters using the INA219 sensor.
- Control fan, lights, and pump through ESP32 and relays.
- Send all readings to Firebase for real-time access.
- Implement Wi-Fi auto-connection for uninterrupted operation.
- Build a compact and cost-effective prototype suitable for rural/remote homes.

CHAPTER 4

HARDWARE COMPONENT DESCRIPTION

4.1 ESP32 Microcontroller

- Dual-core processor with built-in Wi-Fi and Bluetooth.
- Reads sensor data (voltage, current, battery level).
- Controls 4-channel relay module for loads (lights, fan, motor pump).
- Sends data to Firebase Cloud and receives commands from the mobile app.
- Low power consumption, ideal for solar-powered systems.

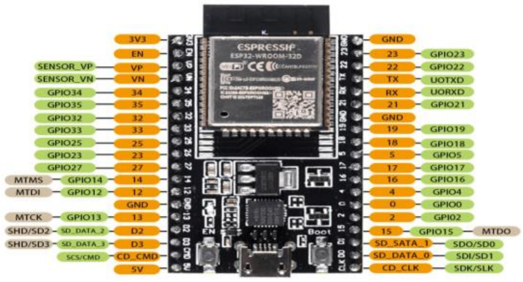

Fig 4.1 ESP32 Microcontroller

4.2 INA219 Current & Voltage Sensor

- Solar panel voltage
- Load current
- Battery charging/discharging current
- Power consumption

  It uses I2C communication and provides accurate measurements for safe charging and load monitoring.

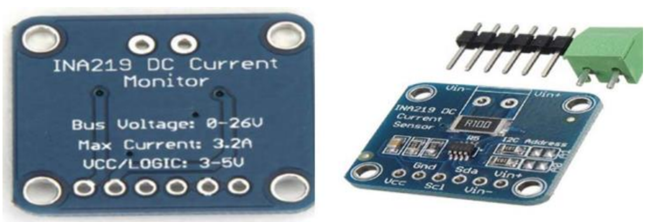

Fig 4.2 INA219 current sensor

4.3 4-Channel Relay Module

A 5V/12V 4-channel relay module is used to switch:

- Light 1 (12V)
- Light 2 (12V)
- 12V Fan
- 12V Water Pump

Features:

- Optocoupler isolation for protection
- Can switch up to 250V AC or 30V DC
- Controlled through ESP32 GPIO pins

Fig 4.3 4-Channel Relay Module

4.4 12V Solar Panel

The 12V solar panel is the primary energy source.

- Converts sunlight into electrical energy
- Charges the 3S Li-ion battery via charge controller
- Supplies power to loads during the daytime
- Typical rating: 10W–30W depending on system design

Fig 4.4 Solar Panel

4.5 12V 3S Li-Ion Battery Pack

The energy storage battery is a 3-cell lithium-ion pack (3S) with:

- Nominal voltage: 11.1V to 12.6V
- Capacity: 7500mAh
- Has a 3S BMS for overcharge, over-discharge, and short-circuit protection
  It powers lights, fan, motor pump, and ESP32 when solar energy is low.

Fig 4.5 Li-ion Battery

4.6 Wiring & Power Distribution

- Solar panel → Charge controller → 3S battery
- Battery → Step-down regulator (to 5V) → ESP32 & sensors
- Battery → Relays → 12V loads
- INA219 placed in series to measure charging/discharging current
- All grounds (GND) connected commonly
  Proper wiring ensures stable operation and prevents voltage drops.

4.7 ESP8266 as Wi-Fi Extender

The ESP8266 Wi-Fi module is configured as a Wi-Fi repeater to increase network coverage.

- Receives weak Wi-Fi signal
- Extends and rebroadcasts it as a new hotspot
- Helps ESP32 and ESP32-CAM stay connected even in long-distance setups

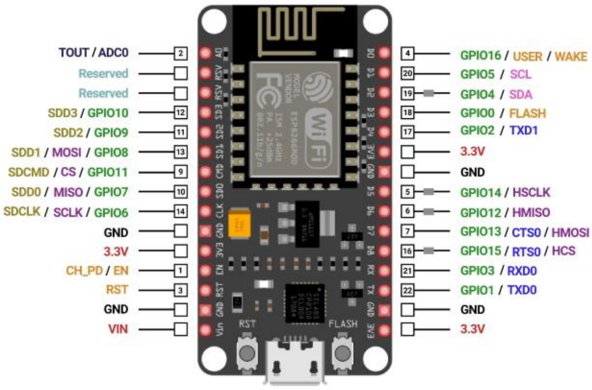

Fig 4.6 ESP8266 Wi-Fi module

4.8 ESP32-CAM for Camera Monitoring

The ESP32-CAM provides real-time video streaming.

- Built-in OV2640 camera
- Streams live footage to smartphone over Wi-Fi
- Useful for remote field monitoring, security, or observing pump activity
- Low power and compact size

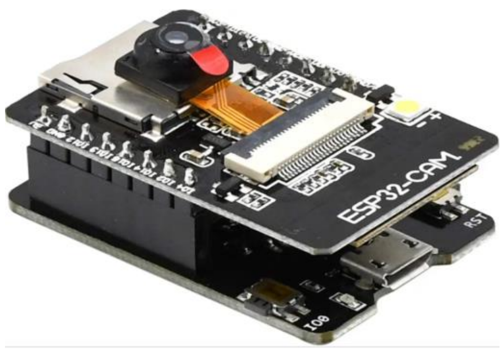

Fig 4.7 ESP32 CAM

4.9 12V LED Lights

Two 12V LED lights are used as controllable loads.

- Low power consumption
- Controlled through relays
- Can be switched ON/OFF remotely using the mobile app

Fig 4.8 12v Light

4.10 12V DC Fan

A small 12V DC fan is included.

- Used for ventilation or cooling of the battery/system
- Controlled via relay
- Low energy consumption

Fig 4.9 12v Fan

4.11 12V Water Pump

A 12V mini motor pump supplies water when required.

- Controlled through relay module
- Used for irrigation purpose
- Protected by the battery BMS and relay isolation

Fig 4.10 12v mini motor pump

4.12 3S 10A BMS (Battery Management System)

The 3S 10A BMS is used to protect and manage the 3-cell (3S) lithium-ion battery pack used in the system. It ensures the battery operates safely charging and discharging, efficiently, and with long life.

- Over-Charge Protection
- Over-Discharge Protection
- Over-Current / Short-Circuit Protection
- Cell Balancing

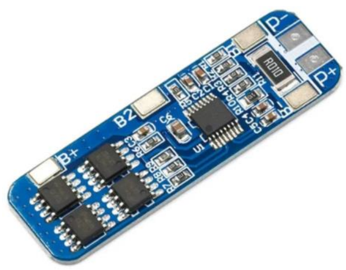

Fig 4.11 3s 10A bms

CHAPTER 5

SOFTWARE DESCRIPTION

5.1 Arduino IDE

Arduino IDE is used as the primary software platform for writing and uploading the program to the ESP32 microcontroller. It provides a simple interface, necessary libraries, and debugging tools that allow the ESP32 to read sensor data, control relays, and communicate with the internet. The IDE supports serial monitoring, which helps in testing and verifying the hardware connections and data flow during development.

5.2 Firebase Cloud

Firebase Realtime Database is used as the cloud backend to enable communication between the hardware and the mobile application. All sensor readings such as voltage, current, and power are uploaded to Firebase, and the relay control commands from the app are stored there as well. Firebase ensures real-time updates, allowing the system to function reliably even over long distances, making it suitable for remote monitoring and automation.

5.3 MIT App Inventor

MIT App Inventor is used to design the mobile application that allows users to monitor and control the solar home automation system. The app reads data directly from Firebase and displays live sensor values, while also sending commands to turn ON/OFF appliances like the fan, lights, and water pump. Its drag-and-drop interface simplifies app development and provides an easy-to-use control panel for the entire system.

CHAPTER 6

RESULTS

The prototype of the solar home automation system successfully demonstrated the ability to monitor and control household loads using an off-grid power source. The ESP32 reliably measured voltage, current, power, and battery status using the INA219 sensor and updated the values to Firebase in real time. The MIT App remained synchronized with the cloud and displayed accurate live readings on the mobile device. All four relays—including the fan, two lights, and the 12V water pump—responded immediately to control commands sent from the app. The Wi-Fi scanning logic ensured stable connectivity by automatically selecting an available network. Overall, the system performed efficiently, showing stable power usage data, smooth cloud communication, and accurate load switching, proving the feasibility of a complete off-grid solar automation solution.

Fig 6.1 control and monitor app interface

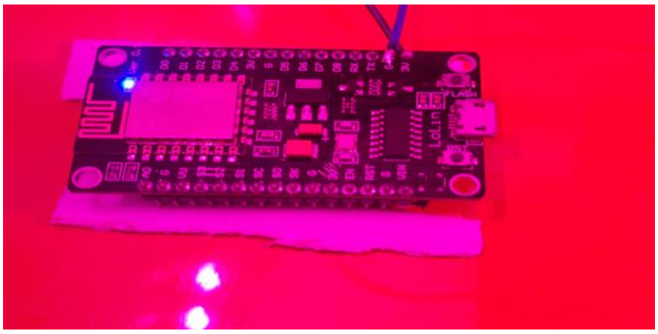

Fig 6.2 ESP8266 as wifi extender

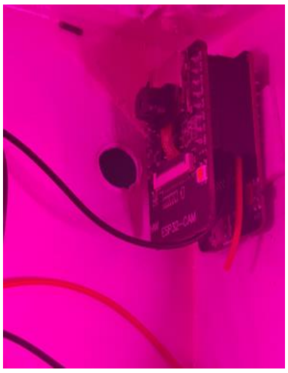

Fig 6.3 ESP32 CAM as camera

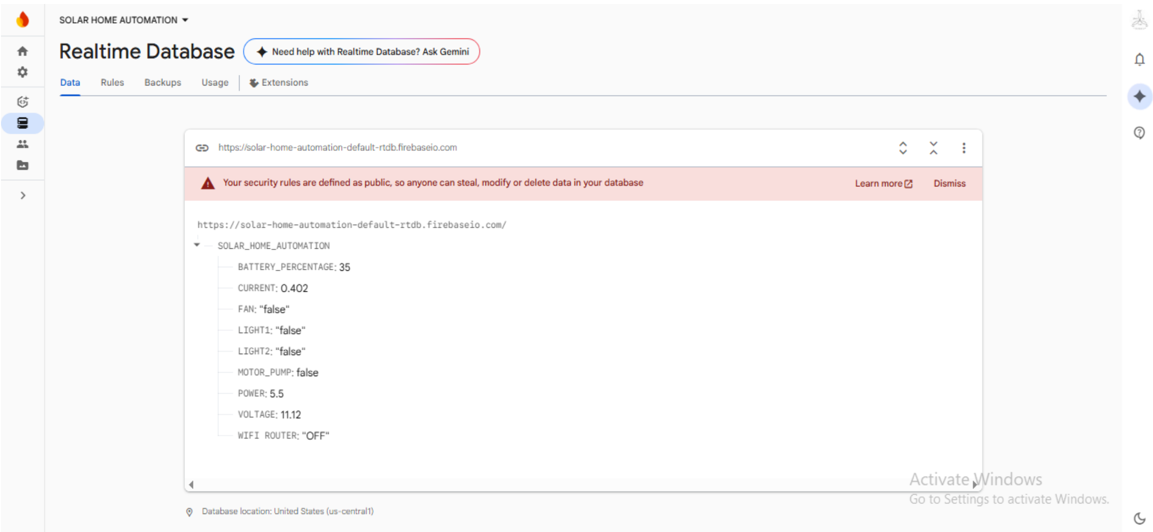

Fig 6.4 firebase cloud

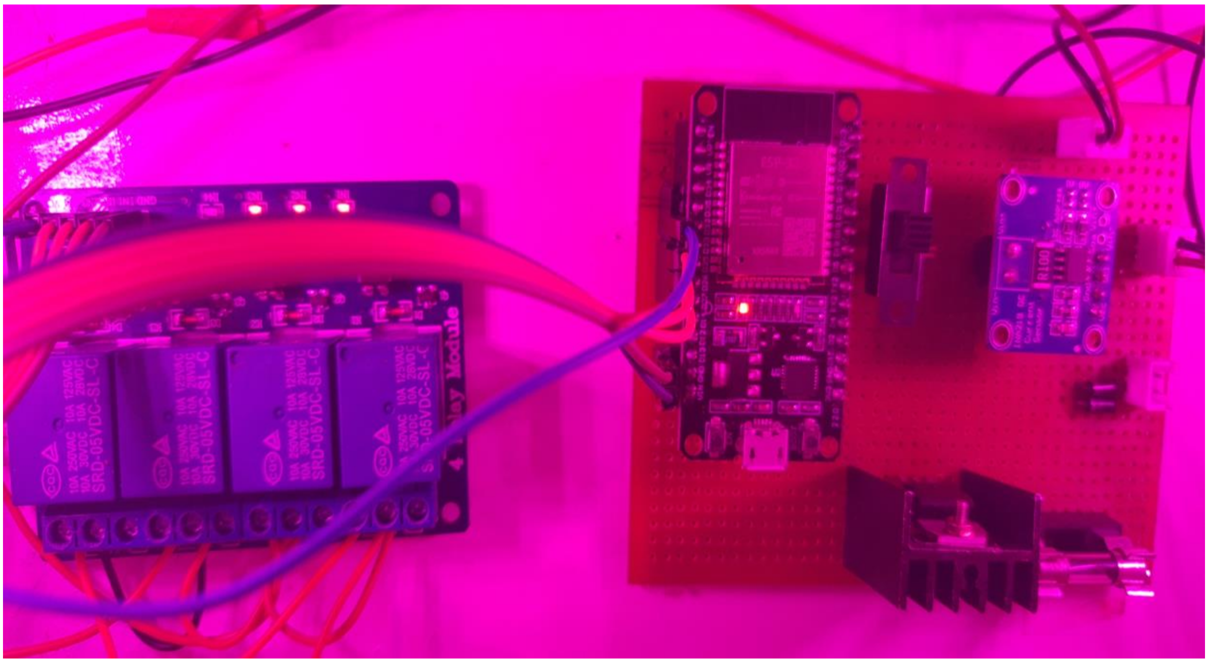

Fig 6.5 controller circuit and relay module

Fig 6.6 solar panel

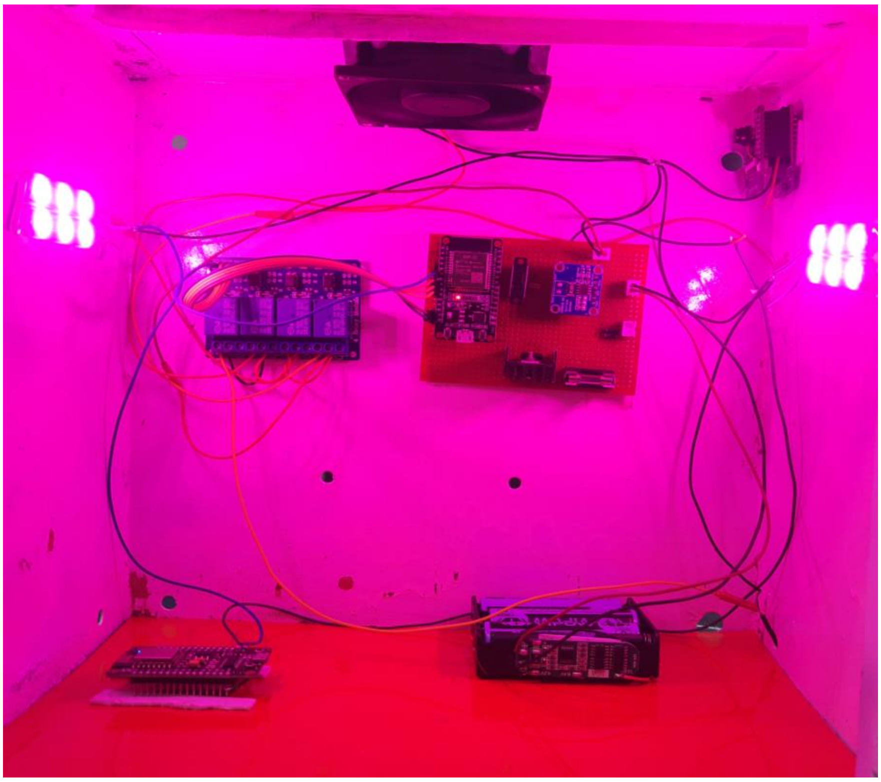

Fig 6.7 full setup

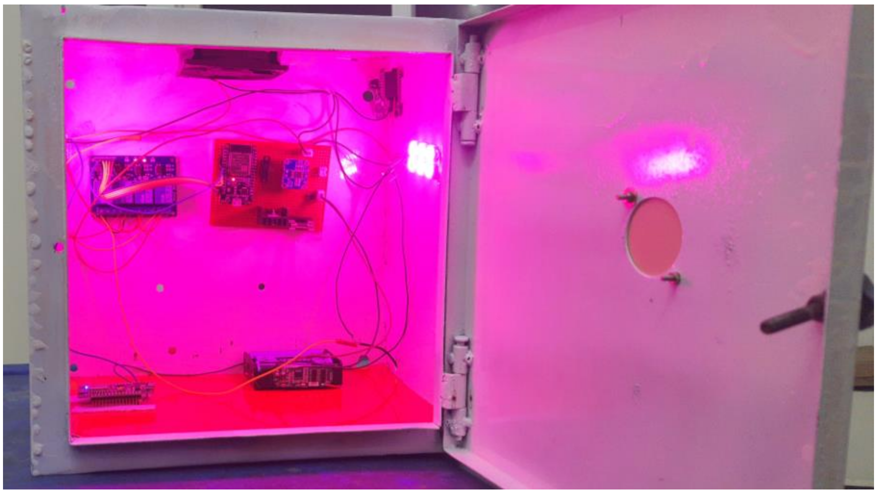

Fig 6.8 Solar Home Automation in Offgird

CHAPTER 7

CONCLUSION

This project successfully developed a functional off-grid solar home automation system that integrates hardware, cloud services, and a mobile application to provide real-time monitoring and control. The ESP32 acted as the central controller, managing both sensor data and relay operations, while Firebase enabled seamless communication between the hardware and the mobile app.

The system demonstrated reliable performance in monitoring battery health, energy usage, and the status of various 12V appliances. The prototype confirms that low-cost microcontrollers combined with cloud technology can create an efficient, scalable, and user-friendly solution for rural homes, farms, and remote locations where traditional power sources are limited. This project serves as a strong foundation for future enhancements such as automation algorithms, weather prediction, or full-scale smart home integration.