Empowering Smart Grid for the Future of Urban Centers

Submitted

By:

1. **AHMED ABDULRAHMAN ABDULLAH BIN ALFAQEEH**
   BU21EECE0200026
2. **SEEPALA SIVA KUMAR**
   BU21EECE0200038
3. **YASHWANTH M**
   BU21EECE0200033

Under the Guidance of:

Dr. P.SUNDARARAMAN

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Department of Electrical, Electronics and Communication Engineering

GITAM School of Technology

GITAM

(DEEMED TO BE UNIVERSITY)

(Estd. u/s 3 of the UGC Act 1956)

NH 207, Nagadenehalli, Doddaballapur taluk, Bengaluru-561203 Karnataka, INDIA.

DECLARATION

We declare that the project work contained in this report is original and has been done by us under the guidance of our project guide.

Names:
AHMED ABDULRAHMAN ABDULLAH BIN ALFAQEEH (BU21EECE0200026)
SEEPALA SIVA KUMAR (BU21EECE0200038)
YASHWANTH M (BU21EECE0200033)

Date: **Signature of the Student**

Department of Electrical, Electronics, and Communication Engineering
GITAM School of Technology, Bengaluru-561203

CERTIFICATE

This is to certify that

1. **AHMED ABDULRAHMAN ABDULLAH BIN ALFAQEEH (BU21EECE0200026)**
2. **SEEPALA SIVA KUMAR (BU21EECE0200038)**
3. **YASHWANTH M (BU21EECE0200033)**

have satisfactorily completed Capstone Project Entitled in partial fulfillment of the requirements as prescribed by University for VIIIth semester, Bachelor of Technology in "Electrical, and Electronics Engineering" and submitted this report during the academic year 2024-2025.

Signature of the Guide **Signature of HOD**

Abstract

As urban centers grow, the demand for reliable and sustainable energy sources becomes critical. Our project, **"Empowering Smart Grid for the Future of Urban Centers,"** progresses from simulation to hardware implementation. It focuses on integrating renewable energy sources, wind turbines, and solar panels as primary generation units, supported by batteries for energy storage.

On the consumption side, we implement distributed energy systems with solar panels and battery storage to enhance localized energy generation and management, ensuring flexibility and resilience.

To enable real-time monitoring and control, we employ IoT devices such as ESP32 microcontrollers, Arduino boards, and sensors, creating a two-way communication network for seamless data exchange and optimized energy production, storage, and consumption.

The project also features fault detection and automated responses to ensure grid reliability. By integrating renewable energy, IoT-enabled control, and robust energy distribution, this project establishes a smarter, more adaptive energy system for urban environments.

Expected outcomes include improved energy efficiency, increased clean energy usage, enhanced grid stability, and valuable insights for future urban energy planning, supporting sustainable development and energy security.

Acknowledgement

We express our gratitude to the **Almighty**, whose blessings have given us the strength and determination to successfully complete this project.

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Chapter 1: Introduction:

With the increasing global demand for energy and the urgent need to transition towards renewable energy sources, this project focuses on real-world integration of solar and wind energy, energy storage, and automated power management.

This smart grid system is designed to efficiently generate, store, and distribute power using Arduino Mega and ESP32 for automation. It incorporates sensors, relays, and power converters to dynamically manage power flow between renewable sources, battery storage, and different loads. The system also features fault detection mechanisms to enhance reliability and security.

A key aspect of this project is the two-way communication system, which enables real-time monitoring and control of power flow. This allows the system to send and receive data between energy sources, loads, and the grid, ensuring efficient decision-making and automated power management. The two-way communication feature helps in demand-side management, grid stability, and remote control of distributed energy resources.

By implementing this smart grid in hardware, we aim to demonstrate real-time energy management, improve system efficiency, and explore practical challenges in renewable energy integration. This hands-on approach provides deeper insights into the practical feasibility and operational control of smart grid technology.

1.1 Overview of the problem statement:

The increasing energy demands of urban centers are putting immense pressure on traditional power grids, which face challenges in integrating renewable energy sources, managing real-time energy consumption, and ensuring a stable and reliable power supply**.** These conventional grids suffer from inefficiencies, frequent outages, and a lack of flexibility**,** making them unsustainable for future energy needs. To overcome these challenges, there is an urgent need for smart grid systems that can enhance energy management, improve reliability, enable two-way power flow, and seamlessly integrate renewable energy sources to support the future of urban infrastructure.

1.2 Objectives and goals

1. Implementing a scalable and flexible smart grid to support expanding urban centers.
2. Integrating different energy sources like solar and wind turbines, along with battery storage, to reduce dependency on fuel and lower carbon footprints in urban areas.
3. Integrating IoT technologies for better reliability, accelerating fault detection, enabling two-way communication, and improving overall system efficiency.
4. Enabling real-time monitoring and control, allowing data-driven decision-making for enhanced energy management and optimized power distribution.

Main Goals

1. Enhance Grid Scalability and Flexibility
2. Improve Grid Reliability and Efficiency

3. Empower Real-Time Monitoring and Control

Additional Goals

1. Gain proficiency in multiple software platforms used for smart grid design, simulation, and analysis.
2. Learn how to effectively integrate and manage IoT devices within the smart grid to enhance monitoring.

Chapter 2 : Literature Review:

S.No	Article	Authors	Published on	Description
1	Investigating the use of MATLAB/SIMULIK and LabVIEW in Microgrid Modelling and Simulation	Mahmoud Laban	25 Aug 2017	He has modeled and simulated a microgrid using MATLAB/and Simulink, but he did not integrate the IoT devices that enable 2-way communications.
	Recent advancement in smart grid technology: Future prospects	Osama Majeed Butt a,⇑ , Muhammad Zulqarnain a , Tallal Majeed Butt	7 July 2020	Future research in smart grids focuses on improving forecasting, optimizing power flow, enhancing communication, integrating microgrids, managing energy demand, ensuring standards, scalability, cost-effectiveness, data security, and automating generation, transmission, and distribution.
3	Solar power integration in Urban areas: A review of design innovations and efficiency enhancements	Emmanuel Augustine Etukudoh 1, *, Zamathula Queen Sikhakhane Nwokediegwu 2, Aniekan Akpan Umoh 3, Kenneth Ifeanyi Ibekwe 4, Valentine Ikenna Ilojianya 5 and Adedayo Adefemi	16 Jan 2024	Integrating IoT devices into the smart grid is the future trend in the structure of power systems, including the use of smart city technologies to optimize solar energy capture and grid reliability in urban environments.
4	Modeling and Control for Smart Grid Integration of Solar/Wind Energy Conversion System	Emad Natsheh, Alhussein Albarbar, Javad Yazdani	_____	Novel model of a smart grid-connected PV/WT hybrid system, incorporating photovoltaic arrays, wind turbines, and control components, developed using MATLAB/SIMULINK. By utilizing real-time data and the Perturb and Observe (P&O) algorithm for maximum power point tracking (MPPT), the model demonstrates effective performance optimization and system reliability under various operating conditions

Table1: Literature Review

Chapter 3 : Strategic Analysis and Problem Definition

3.1 SWOT Analysis

Strengths

S1. High Efficiency

S2. Fast Fault Detection

S3. Energy saving

Weaknesses

W1. High Capital Cost

W2. Dependency On Weather Conditions

W3. Complex Implementation

W4. Data Storage

Opportunities

O1. Integration Of Renewable Sources

O2. Reduction Of Carbon Emission

O3. Support For Electric Vehicles

O4. Latest research areas

Threats

T1. Cybersecurity Risks

T2. scarcity of components

3.2 Project Plan - GANTT Chart

ID	Title	Start Time	End Time
1	Wind turbine type selection	11/25/2024	11/29/2024
2	Abstract	12/02/2024	12/06/2024
3	Permission and wind speed	12/03/2024	12/06/2024
4	Making the circuit diagram	12/09/2024	12/16/2024
5	Theoretical calculation and	12/11/2024	12/17/2024
6	designing the wind turbine	12/16/2024	12/25/2024
7	Purchasing components and	12/24/2024	01/06/2025
8	Component procurement an	12/16/2024	12/26/2024
9	Circuits design	12/23/2024	01/05/2025
10	Components purchases and	01/06/2025	01/19/2025
11	Wind turbine testing and re	01/20/2025	02/03/2025
12	Circuit assembling	02/11/2025	02/28/2025
13	Coding	02/15/2025	03/09/2025
14	Testing	03/03/2025	03/09/2025

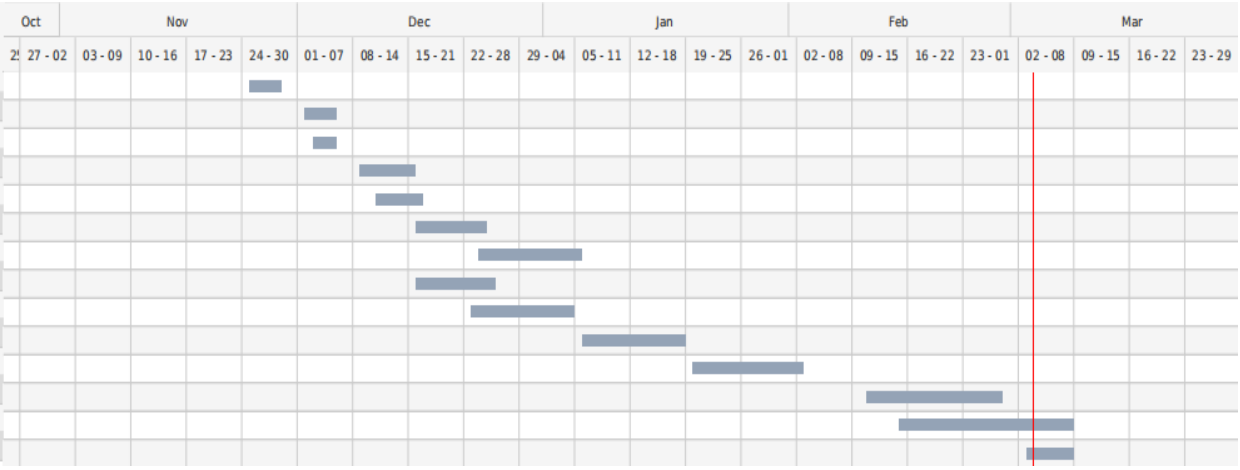


Fig 1: Gantt chart

3.3 Refinement of problem statement

Urban centers are rapidly expanding, leading to a surge in energy demand that traditional power grids are incapable of managing efficiently. These conventional grids are designed for one-way energy flow from centralized power plants to consumers, limiting their ability to integrate decentralized renewable energy sources like solar and wind. As a result, they suffer from inefficiencies, high operational costs, and frequent power outages, especially during peak loads or unexpected disruptions.

Additionally, traditional grids lack real-time monitoring and automated control, making energy distribution inefficient and prone to significant losses. The absence of intelligent fault detection and dynamic energy optimization further reduces the grid's reliability and flexibility.

To overcome these challenges, a smart grid system is essential. By integrating renewable energy sources, enabling two-way communication between energy producers and consumers, and utilizing IoT-based real-time monitoring and control, a smart grid can enhance energy efficiency, improve grid reliability, and support the sustainable development of urban centers

Chapter 4: Methodology

4.1 Description of the approach

- The proposed smart grid hardware system integrates renewable energy sources(Solar-Wind), battery storage, and automated control to ensure efficient energy management. The system operates automatically, with relays controlling the power flow based on preset voltage, current, and power sensor values while allowing manual intervention when necessary. Monitoring and control are achieved using Blynk, providing real-time data visualization and remote operation.
- The total capacity of the system is 170W, comprising various renewable energy sources and power management components. The primary energy sources include a 50W solar panel and a 50W wind turbine, which either charge the battery or supply power directly to the grid. In the case of over generation, excess energy is sent to the grid through a 200W inverter. If additional energy is required, the system can draw power from the grid using a 60W rectifier. The battery(12.8V\12Ah) functions as an energy storage unit, capable of charging from multiple sources, including the main solar panel, wind turbine, rectifier, or on-grid load. It discharges energy as needed to ensure uninterrupted power supply to the loads.

The system includes four distinct loads:

1. **On-grid load – Powered by a 10W solar panel**: which also contributes to charging the battery. This load operates as part of the grid-connected system.
2. **Overvoltage load and short circuit load – Powered by 10.5W micro solar panels**: these loads are dedicated to fault detection. They do not send power to the grid but can receive energy when required. Each has a small battery for backup power.
3. **Industrial load – Powered by a 10W solar panel**: this load functions independently, receiving energy but not sending it to the grid. It also includes a small battery for energy backup.

- Automation and control are implemented using Arduino Mega and ESP32 microcontrollers. These devices process real-time data from voltage, current, and power sensors, ensuring efficient energy distribution and fault management. The system enables two-way communication, allowing data exchange between energy sources, loads, and control units. Automated switching mechanisms, controlled by relays, adjust energy flow based on sensor readings, ensuring stable operation and intelligent fault detection.
- By integrating renewable energy, two-way communication, and automated control, the smart grid system enhances energy efficiency, improves grid reliability, and supports the sustainable development of urban centers

4.2 Tools and techniques utilized

Hardware Usage

Microcontrollers

Microcontrollers are the core processing units of the system, responsible for handling sensor data, controlling relays, and enabling communication.

- **Arduino Mega:**
  - Acts as the brain of the system, processing inputs from multiple sensors and executing programmed logic to control relays and other components.
  - All IoT components, including sensors, relays, buzzers, and actuators, are connected to it.
  - Based on the real-time sensor readings, the Mega sends signals to the relays to trip or activate loads, ensuring proper power flow and protection.
- **ESP32:**
  - Primarily used for Wi-Fi and Bluetooth communication, enabling remote monitoring and control.
  - Sends real-time data to the Blynk application, allowing users to monitor system parameters like voltage, current, power, and load status.
  - Facilitates two-way communication, enabling users to control relays remotely through Blynk.

Sensors

Various sensors are deployed in different parts of the system to monitor parameters crucial for smart grid operations.

- **Voltage, Current, and Power Sensors:**
  - Installed in multiple sections to measure real-time voltage, current, and power consumption.
  - These readings are sent to the Arduino Mega, which analyzes the data and triggers relays if any abnormal conditions occur.
  - Helps ensure a fast response to faults, preventing overvoltage, overcurrent, and short circuits.
- **Light Sensor:**
  - Used to measure solar irradiance, which helps optimize solar panel performance based on available sunlight.
  - The data is logged in the system for better energy management.
- **Temperature Sensor:**
  - Collects data on ambient temperature to monitor how environmental conditions affect system performance.
  - Helps in ensuring safe operating conditions for batteries and power components.
- **Anemometer (Wind Speed Sensor):**
  - Measures wind speed to determine the efficiency of the wind turbine.
  - Ensures that the turbine operates within safe wind speed limits to prevent damage.

Power Converters

Power converters are used to regulate voltage levels to match the requirements of different system components.

- **Buck Converter:**
  - Steps down the voltage for loads that require lower operating voltages.
  - Used in industrial and grid sections to supply 5V or 12V, ensuring compatibility with connected devices.
- **Boost Converter:**
  - Increases the voltage where required, ensuring that the connected loads receive sufficient power.
  - Used on the wind turbine side to regulate voltage output to 12V.
  - Also used at the battery charging input, ensuring the battery is charged at 13.6V.
- **Buck-Boost Converter:**
  - Maintains a stable voltage at the output even when the input fluctuates.
  - Connected to the main solar panel to ensure a constant 12V output regardless of variations in solar power.

Relays & Switching

Relays play a crucial role in automating power flow and ensuring circuit protection.

- Relays function as automated switches that control the flow of power based on sensor data.
- The Arduino Mega processes sensor readings and sends signals to the relays to turn on/off various components.
- Relays are connected to buzzers, providing an audible alert whenever a status change occurs.
- The system ensures smooth power distribution and automatically isolates faulty sections to prevent damage.

Energy Storage

Energy storage systems ensure power availability and provide backup in case of grid failure.

- **Main Battery:**
  - Stores energy from multiple sources (solar, wind, and grid).
  - Supplies power to the system when renewable sources are insufficient.
  - Ensures stable energy availability for critical loads.
- **Load-Side Batteries:**
  - Installed at individual loads to store excess power generated by solar panels.
  - Supplies power as per requirement, reducing dependency on the main grid.
  - Helps in maintaining a continuous power supply for off-grid operations.

Software & Communication

The project integrates multiple software tools for designing, programming, monitoring, and control.

- **Arduino IDE:**
  - Used for writing and uploading code to the Arduino Mega and ESP32.
  - The code includes logic for sensor data processing, relay control, and fault protection.

- **Blynk:**
  - Provides a real-time monitoring dashboard that displays sensor readings in categorized sections:
    - Battery Status
    - Load Monitoring
    - Solar Power Generation
    - Wind Power Output
    - Grid Power Flow
  - Enables remote relay control, allowing users to switch loads and relays on/off via the Blynk app.
- **Lucid-chart:**
  - Used for designing the electrical and control circuit diagrams of the system.
- **Fusion 360:**
  - Used for 3D modeling of the wind turbine, ensuring proper structural design before implementation.
- **Gantt Chart:**
  - Helps in tracking project progress, ensuring each phase is completed on time.

Communication Protocols

To enable seamless interaction between different system components, multiple communication **protocols are used:**

- **Wi-Fi:**
  - Used by ESP32 to transmit data to Blynk for remote monitoring and control.
- UART (Universal Asynchronous Receiver-Transmitter):
  - Used for serial communication between the Arduino Mega and ESP32, allowing them to exchange data.
- **I2C (Inter-Integrated Circuit):**
  - Used for connecting multiple sensors with the Arduino Mega efficiently.

Protection & Control

Ensuring system safety is a crucial aspect of the project. The following measures are implemented for fault detection and protection:

- **Overvoltage, Short Circuit, and Fault Detection:**
  - Pre-set voltage, current, and power limits are programmed into the Arduino Mega.
  - If any sensor detects a value exceeding these limits, the relays trip immediately, isolating the faulty section.
  - Helps prevent damage to components and ensures system stability.
- **LEDs, Buzzers, and Push Buttons:**
  - LEDs and buzzers provide visual and audible alerts for relay switching and fault detection.
  - Push buttons allow for manual control, ensuring operational flexibility when needed.

4.3 Design considerations

1. Circuit Diagrams & System Architecture

The system is designed with multiple interconnected components to ensure efficient power distribution, automation, and protection. The circuit diagrams illustrate the layout of microcontrollers, sensors, relays, converters, and communication modules. Each part of the system is designed to function in coordination, with the Arduino Mega serving as the central controller.

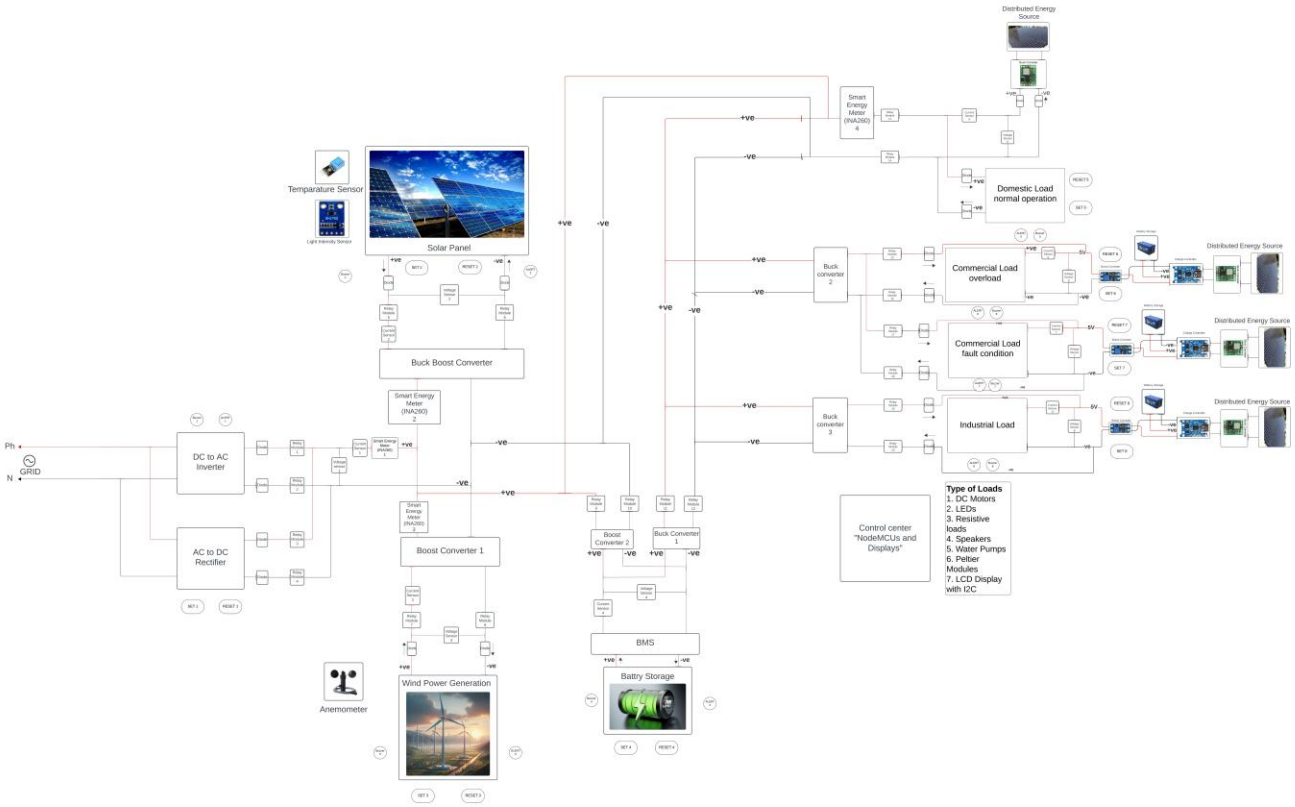


Fig 2: Electrical Circuit Diagram

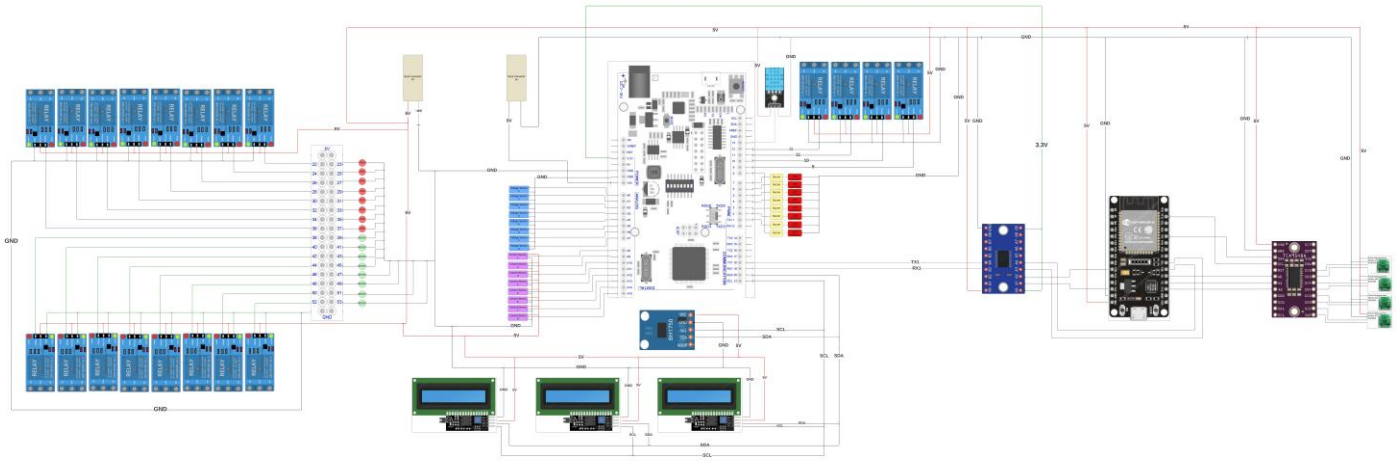


Fig 3: Electrical Circuit Diagram

2. Theoretical Calculations for the Wind Turbine

The wind turbine design is based on real-time wind speed data collection and theoretical calculations. Key considerations include:

Given:

1. Type of Wind Turbine: Vertical Axis Wind Turbine (VAWT) H Rotor Type
2. Main supporting Column:
   a. Diameter: 60 mm
   b. Length: 1.2 m
3. Rotor Shaft:
   a. Diameter: 25 mm
   b. Length: 30 cm
4. Rotor Diameter: 80 cm
5. Blades:
   a. NO. 6
   b. Height: 60 cm
   c. Semi-circle of area A≈91.1cm^2
6. Wind Speed: 3.9 m/s

1) **<u>Tip Speed Ratio (TSR):</u>**

3.5 (Chosen for typical efficiency in VAWT systems, considering blade characteristics and rotor design.)

2) <u>Calculate RPM:</u>

The formula to calculate RPM (Revolutions Per Minute) is:

RPM = (v_rotor * 60) / (π * D_rotor)

- Where:

- v_rotor = Rotor speed in m/s (calculated earlier as 9.74 m/s)
- D_rotor = Rotor diameter in meters (80 cm)

Substituting the values:

RPM = (9.74 * 60) / (π * 1.03)

RPM = 232.52

Calculated RPM: 232.52

3) **Calculate Angular Velocity:**

The formula to calculate angular velocity (ω) is:

ω = (2 * π * RPM) / 60

- Where:
- RPM = Rotational speed in revolutions per minute (calculated as 180.7)

Substituting the values:

ω = (2 * π * 232.52) / 60

ω ≈ 24.35 rad/s

Calculated Angular Velocity: 24.35 rad/s

4) **Calculate Power:**

The formula to calculate power (P) is:

P = 0.5 * ρ * A * v_wind^3 * Cp

- Where:
- ρ = Air density (1.225 kg/m³ at sea level)
- A = Swept area of the turbine (π * (D_rotor / 2)^2)
- v_wind = Wind speed (3.9 m/s)
- Cp = Power coefficient (typically 0.35 for VAWTs)

Substituting the values:

A = π * (0.8 / 2)^2 ≈ 0.5 m²

P = 0.5 * 1.225 * 0.5 * (3.9)^3 * 0.35

P ≈ 10.33 W

Calculated Power: 6.51 W

5) **Calculate Torque:**

The formula to calculate torque (T) is:

T = P / ω

- Where:
- P = Power in watts (calculated as 6.51 W)
- ω = Angular velocity in rad/s (calculated as 24.35 rad/s)

Substituting the values:

T = 10.33 / 24.35

T ≈ 0.547 N·m

Calculated Torque: 0.424 N·m

- **Wind turbine Block Diagram:**

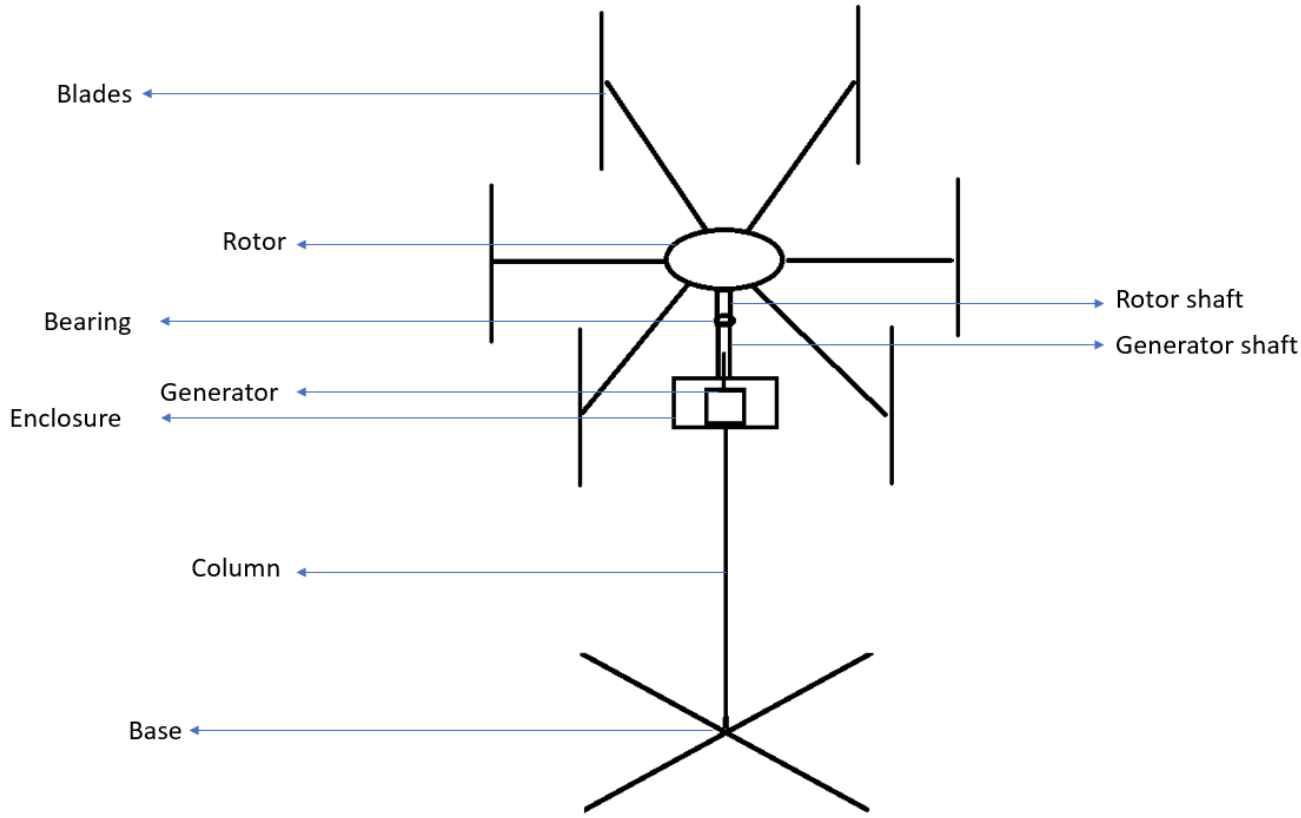


Fig 4: Wind turbine Block Diagram:

- **Fusion 360 Design**

Fig 5: Wind turbine Fusion 360 Design

4. **Power Conversion & Stability Considerations**

To ensure consistent power delivery, various power converters were used:

- **Buck Converters:** Used in different system sections to step down voltage for stable operation of microcontrollers and sensors.
- **Boost Converters:** Integrated with the wind turbine and solar panels to regulate voltage for battery charging.
- **Buck-Boost Converters:** Used to maintain a stable voltage output despite input fluctuations from renewable sources.

5. Safety, Protection, and Fault Handling

To safeguard the system, automated protection mechanisms were implemented:

- **Overvoltage and Overcurrent Protection:** Sensor thresholds are pre-set in the Arduino Mega's code, triggering relays to disconnect faulty components in case of abnormal readings.
- **Short Circuit Protection:** Dedicated relays and fuses are placed at critical points to prevent circuit damage.
- **Visual & Audio Indicators:** LEDs and buzzers are connected to the relays to provide real-time status updates on system operation.

Chapter 5 : Implementation

5.1 Description of how the project was executed

- **The simple block diagram of the smart Grid:**

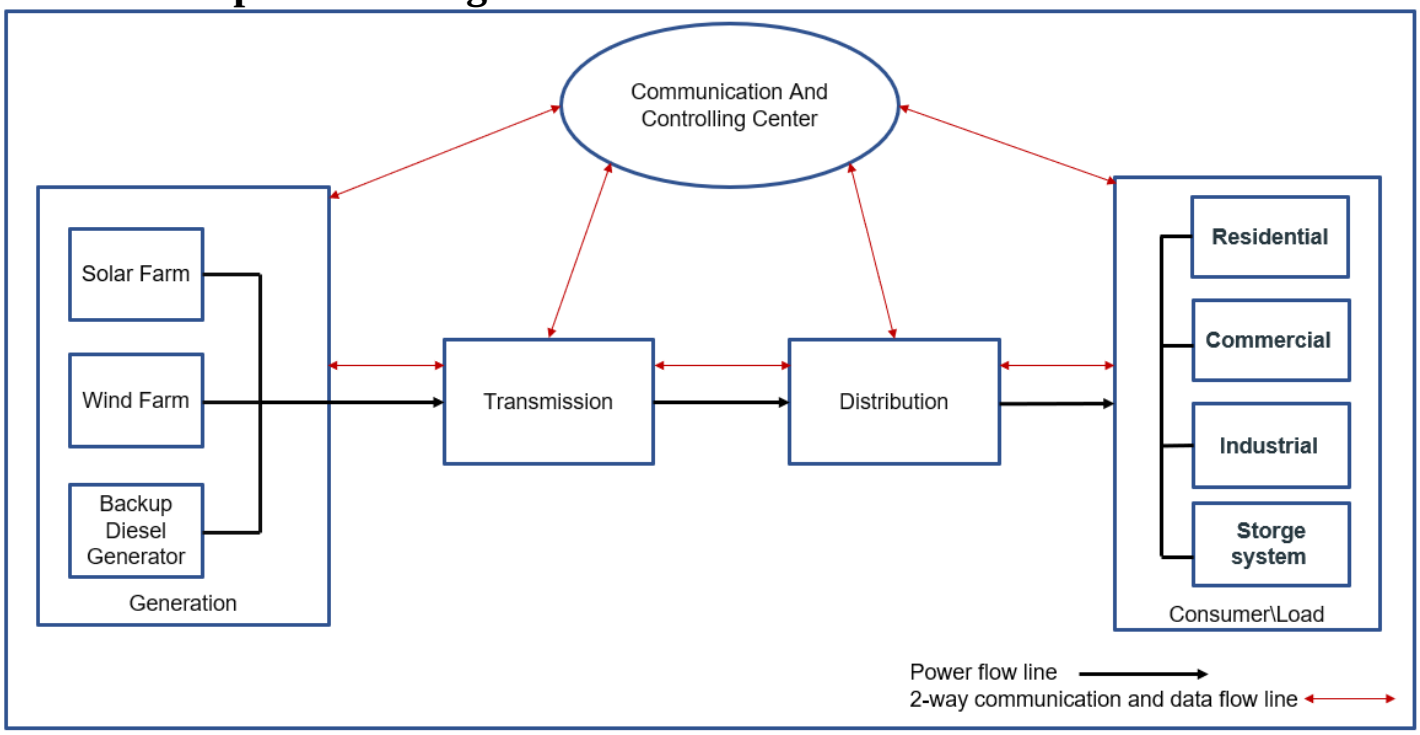


Fig 6: Simple Block Diagram of the Smart

Implementation of the wind turbine:

- **Wind Turbine Specifications**:
  - **Type of Wind Turbine:** Vertical Axis Wind Turbine (VAWT) – H Rotor Type
  - **Main Supporting Column:**
    a) Diameter: **60 mm**
    b) Length: **1.2 m**
  - **Rotor Shaft:**
    a) Diameter: **25 mm**
    b) Length: **30 cm**
  - **Rotor Dimensions:**
    a) Rotor Diameter: **80 cm**
  - **Blades:**
    b) Number of Blades: **6**
    c) Height: 60 **cm**
    d) Semi-circle Area (per blade): **≈91.1 cm²**

- **The used components:**
  - **Mechanical Components**
    a) **Base:** Metal (for stability and support)
    b) **Rotor Shaft:** Seamless pipe (**25mm diameter, 30cm length**
    c) **Rotor Bars:** Aluminum (for structural support)
    d) **Rotor Blades:** PVC (**6 blades, 60cm height, 6-inch width**)
    e) **Ball Bearings:** 2 (to reduce friction and ensure smooth rotation)**Gears: 16T to 98T** (used for torque and speed adjustment)
  - **Electrical Components**
    a) **Generator: 50W DC Motor (1500 RPM)** (acts as the power-generating unit)
    b) **Boost Converters:** Used to step up the voltage from the wind turbine output to match the required system voltage
- **Motor testing:**
  a) No load voltage: 9.9V at 1300RPM
  b) Current:

S.NO	Resistance Value	Current Value
1	16hom	0.5A
2	12hom	0.61A
3	8.3hom	0.84A
4	5.9hom	1.22A
5	2.6hom	2.4A

Table 2: Motor Testing

- **Real time data of wind seed:**
  - Wind speed in m/s:

S.NO	Date	Minimum	Average	Maximum
1	18/12/2024	2.4	3.8	5.6
2	19/12/2024	2	3.3	4.6
3	20/12/2024	2.9	4.5	7.2
4	Total average	2.4	**3.9**	5.8

Table 3:Real-time Wind speed values

  - The above data gathered in the top roof of **Shivaji Bhuvan**

➢ Pictures of the implemented Wind turbine:

Fig 7: Turbine's Rotor

Fig 8: Turbine's Blade

Fig 9: Top View of the Gear Box and Bearing

Fig 10: Side View of the Gear Box and Bearing

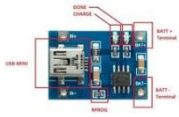
Fig 11: Full View of the Turbine

Implementation of the Smart Grid Setup:

- **List of the used components:**

SI.No	Components	Model	Specification	Quantity	Image
1.	Voltage sensor	Diymall DC 0-25V	voltage measures: 25V DC	8	
2.	Current sensor	ACS712	Operates at4.5-5.5V Rated O/p: 20A	8	
3.	Power Sensor	7SEMI INA260	I/p : 3-5V used as bidirectional current	4	
4.	Buck Converter	LM2596	I/P: 4.5-35V O/P:1.23-30V Switching Frequency: 150KHz	4	
5.	Boost Converter	MT308	Operating frquency : 150KHz	3	
6.	Buck-Boost Converter	LTC3780	Converts DC voltage from 5-32V to regulated output of 1-30V	1	
7.	Arduino	Mega	_____	1	
8.	NodemCU	ESP 32	_____	1	

9.	Battery	_____	12.8V/12Ah	1	
10	Solar Panel	_____	50W	1	
11	Load Side Solar Panels	_____	10W	2	
12	Micro Solar Panel	_____	3.5W	5	
13	Rectifier(SMPS)	_____	220V AC to 12V DC	1	
14	Inverter	_____	200W	1	
15	LCD Display	20*4	_____	3	
16	Boost Converter	XL6019	input: 3-30V output: 5-40V Switching frequency: 220kHz		
17	Jumper Wires	_____	_____	200	

18.	Buzzer	_____	5V	8	
19.	Diode	_____	10A	18	
20.	Relay	_____	5V	20	
21.	Charging Module	_____	5V	3	
22.	DC Motor	_____	5V	3	
23.	LED	_____	5V	8	
24.	Wind Turbine	_____	50W	1	
25.	Anemometer	GM816	_____	1	
26.	Light Sensor	BH1750	_____	1	

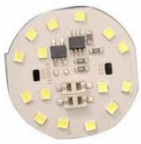
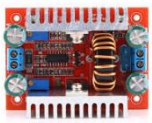
27	Temperature sensor	DHT11	_____	1	
28	LED	_____	8V	3	
29	Push Button	_____	5V	16	
30	Logical level converter	TXS0108E	_____	1	
31	Buck converter	XL4005	_____	1	
32	Boost converter	_____	400W-15A	1	
	Small battery	_____	3.8-2000mA	3	

Table 4: List of used components

- **Real time data of Solar Panel Voltage Values:**

S.NO	Date	Condition	Voc 1	2
1	16/12/2024	Sunny day	21V at 11:20 AM	20.7V at 4:00 PM
2	18/12/2024	Cloudy day	20V at 11:20 AM	19V at 4:00 PM

Table 5: Real time data of Solar Panel Voltage Values

- **Tested power consumption of the components:**

S.NO	Model number	No load current	losses	Maximum Voltage I/p	Minimum voltage I/P	Efficiency
1	LM2596 Buck converter	0.01A	1.5W	40V	3.3v - 0.006A	86.3%
2	XL6019E1 Boost converter	0.025A	0.9W	35V	3.5V-0.007A	89.8%
3	XL4005E1 Buck converter	0.02A	6.92W at full load	32V	5V-0.007A	85%
4	DHT11	0.005A 0.0015A	_____	5V 3.3V	_____	____
5	BH1750	0.00001	_____	_____	_____	____
6	Relay	0.005A off con 0.081A On con	_____	5V	_____	____
7	Voltage sensor	0.001	_____	16V	_____	____
8	LCD	0.05A	_____	5V	_____	____
9	Current sensor	0.011A 0.006A	_____	5V 3.3V	_____	____
10	Arduino Mega	0.03A 0.05A	_____	5V 7V	_____	____
11	ESP32	0.035A	_____	5V	_____	____

Table 6: Tested power consumption of the components:

The implementation of the smart grid system was carried out in a structured and systematic manner as per the circuit diagrams in the page 12 and 13, ensuring precise execution, integration, and optimization. The system consists of multiple energy sources, load types, and an advanced control mechanism for automation and monitoring.

➢ Wiring & Hardware Assembly

❖ **The implementation involved a** two-layered wiring system**:**

a) **Upper Layer - Electrical Circuit Wiring:** This layer handled power generation, storage, and distribution, ensuring a seamless energy flow through the system.

b) **Lower Layer - Control Circuit Wiring:** This layer managed monitoring, automation, and decision-making, integrating microcontrollers, sensors, and relays.

❖ **Electrical Circuit Wiring**

The electrical wiring was carefully executed to ensure safe and efficient power transmission. Key components included:

a) **Main Power Sources:**
   1. 50W **Solar Panel** for primary energy generation.
   2. 50W **Wind Turbine** for additional energy supply.
   3. 200W **Inverter** for DC-AC conversion.
   4. 60W **Rectifier** for grid power stabilization.
   5. 12.8V / 12Ah **Battery** for energy storage.

b) **Bus System:**
   1. A **Charging Bus** (12V) to store excess energy.
   2. A **Discharging Bus** (12V) to supply power to the loads.

c) **Voltage Regulation:**
   1. **Boost Converter:** Placed before the battery to step up 12V to 13.6V for efficient charging.
   2. **Buck Converters:** Used at the output to regulate voltage down to 12V for stable operation.
   3. **Additional Buck Converters:** Installed in industrial, overload, and short circuit loads to provide the required voltage.

d) **Load Distribution:**
   1. **On-Grid Load**: Connected to a 10W solar panel and the grid.
   2. **Fault Detection Loads**: Used for overvoltage and short circuit testing.
   3. **Industrial Load**: Dedicated load with a backup battery.

❖ **Control Circuit Wiring**

The control circuit ensured system automation and real-time monitoring. It included:

a) **Microcontrollers:**
   1. **Arduino Mega** for system control.

2. **ESP32** for remote monitoring.

b) **Sensors:**
Voltage, Current, and Power Sensors for real-time data collection.

c) **Relays:**
Automated switching between power sources based on system requirements.

d) **LCD Displays & Communication Modules:**
Provided live status updates of energy flow and load conditions.

e) **Power Supply for Control Components:**
1. **IoT Components**: Supplied with 5V.
2. **Arduino**: Supplied with 9V, both powered from the main battery.
3. All the components are connected to a common ground

➢ Integration of Power Sources & Load Distribution

After completing the wiring, the integration phase ensured each component functioned as expected.

- ❖ **Renewable Energy Integration:**
  Solar and wind power systems were connected and tested under various environmental conditions.
- ❖ **Battery Management:**
  Charging and discharging cycles were optimized to maintain system efficiency.
- ❖ **Load Connection:**
  Different loads were tested for stable power supply, ensuring no overvoltage or fluctuations.

➢ Control & Automation Setup

The system's intelligence was implemented using microcontroller programming and automation logic:

- ❖ **Data Collection & Monitoring:**
  Sensors continuously monitored voltage, current, and power flow.
- ❖ **Automated Switching:**
  Relays dynamically switched between solar, wind, battery, and grid power.
- ❖ **Remote Access:**
  ESP32 enabled real-time monitoring through an IoT-based dashboard.

➢ System Testing & Optimization

Multiple rounds of testing were conducted to refine system performance:

- ❖ **Load Testing:**
  Various loads were tested under different conditions to analyze energy distribution.

- **Fault Detection Mechanism:**
  Overvoltage and short circuit scenarios were simulated.
  System Optimization:
  Adjustments were made to improve efficiency, minimize energy losses, and enhance response time.

Pictures of the implemented setup:

Fig 12: Distributed Energy Sources (Industrial Load and On-Grid Load)

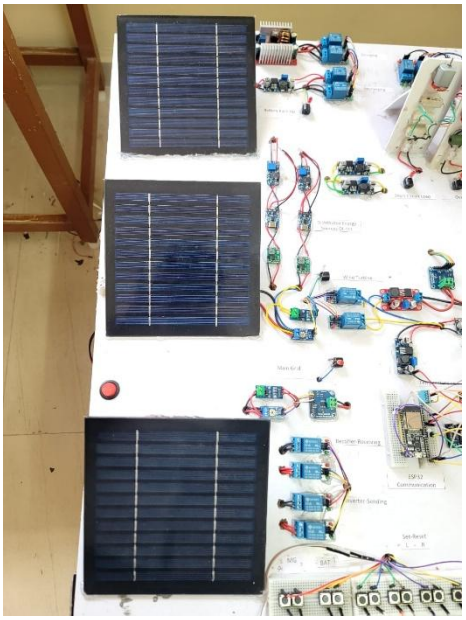


Fig 13: DES (Over Load and Short Circuit

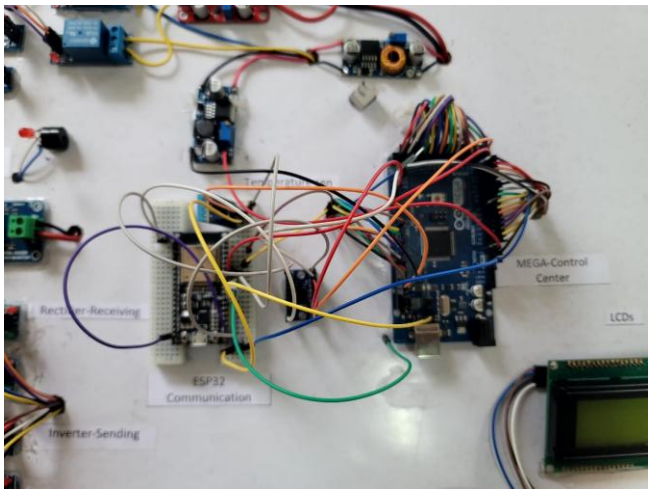


Fig 14: Control Center

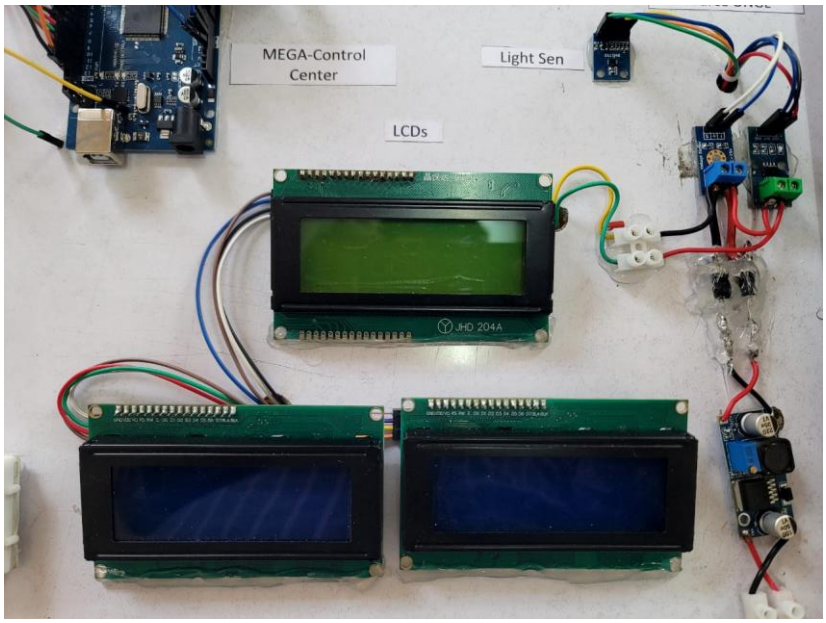


Fig 15: Monitoring

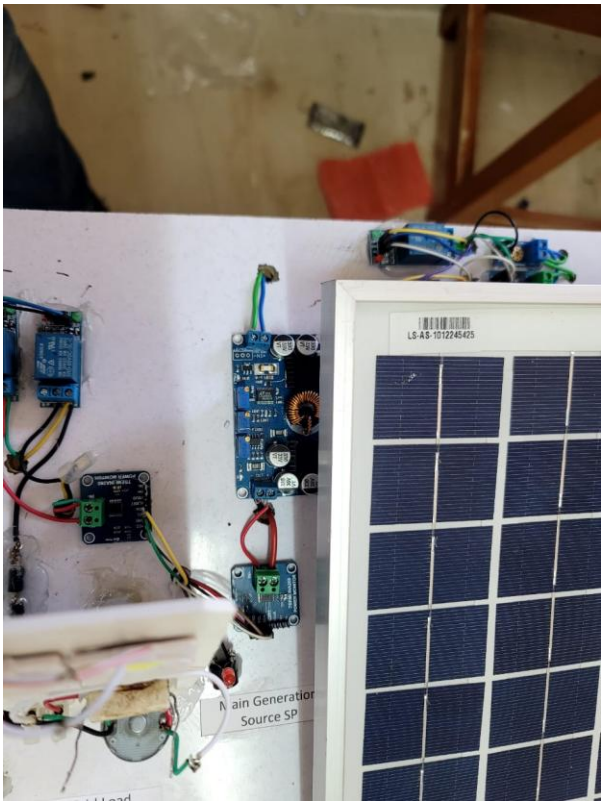


Fig 16:Main Solar Panel Setup

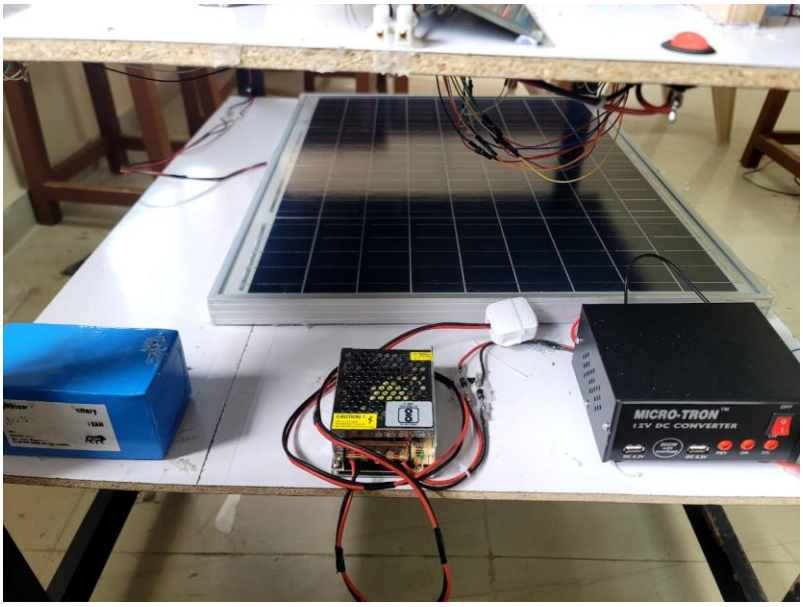


Fig 17: Battery-Rectifier-Inverter-Main solar panel

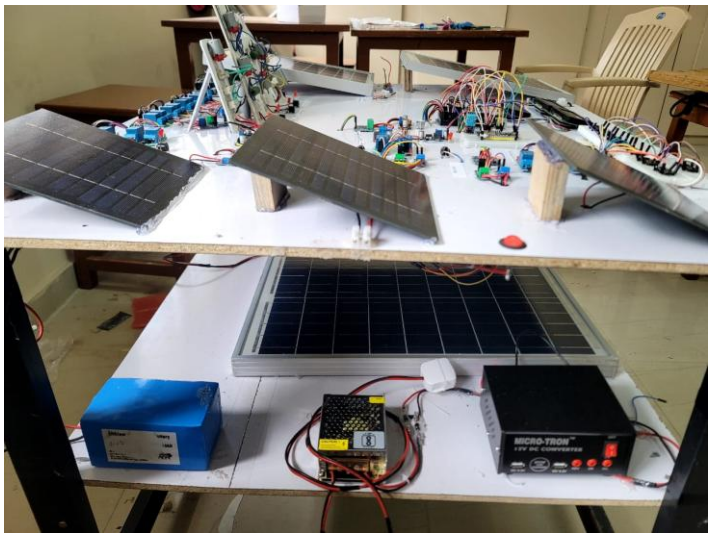


Fig 18: Side-view implementation

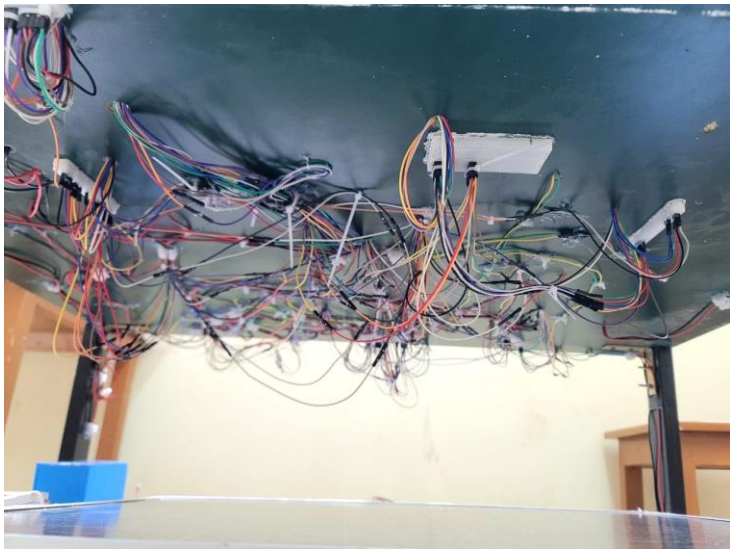


Fig 19: Wiring

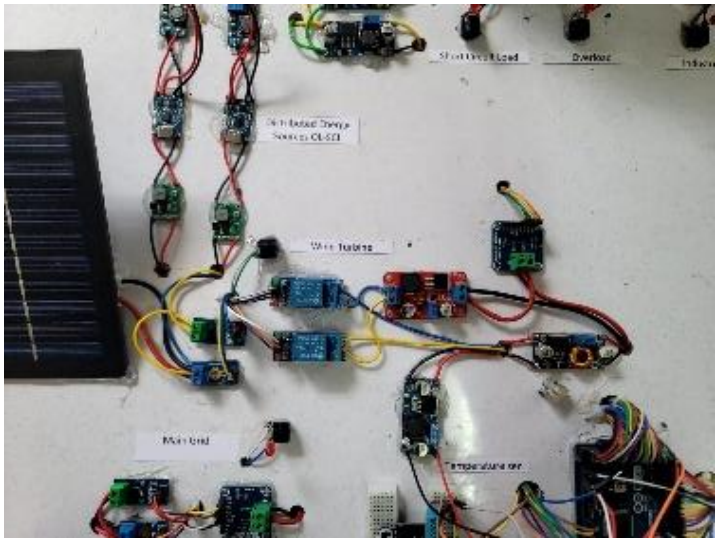


Fig 20: Wind-Turbine Setup

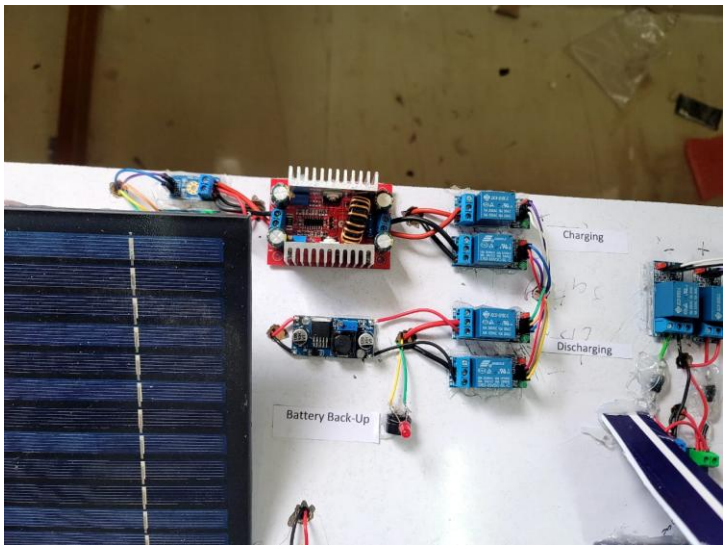


Fig 21: Battery Setup

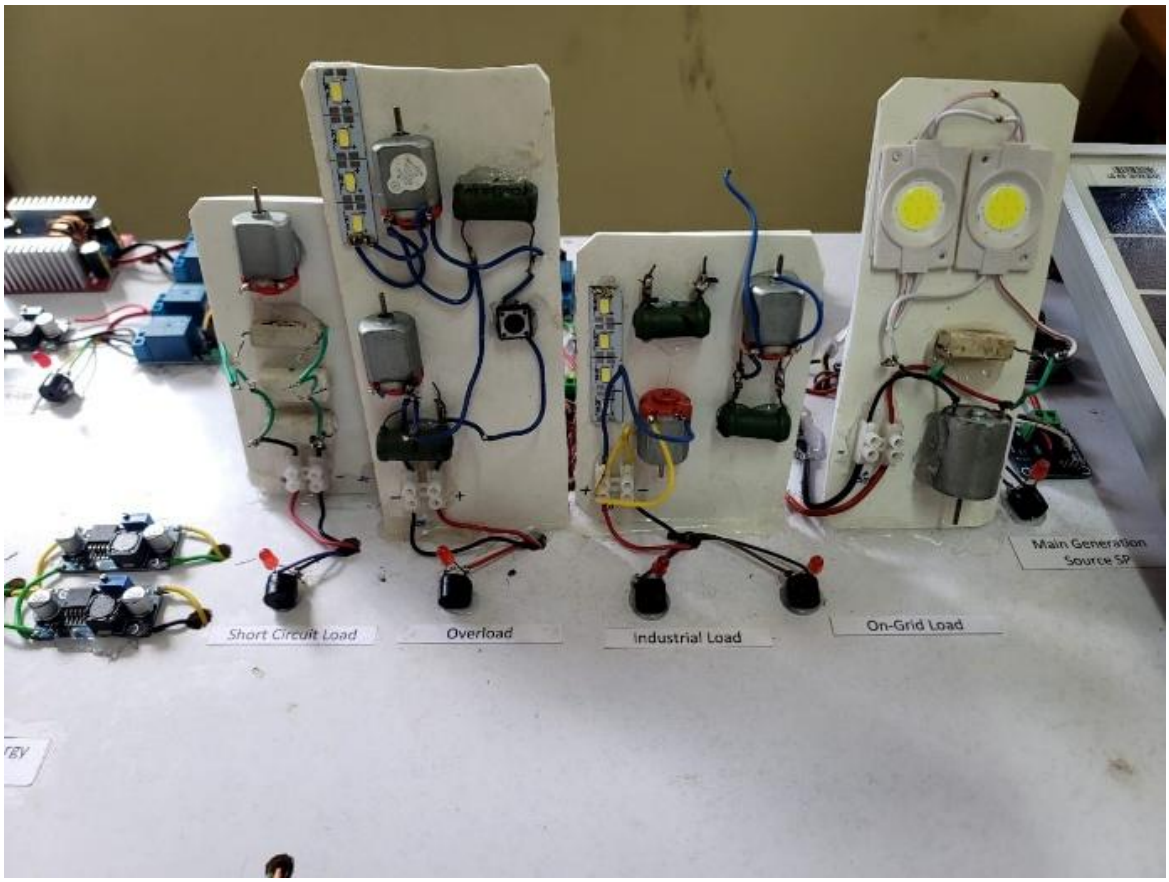


Fig 22: Different types of loads-ONGL-INDL-OV-SCL

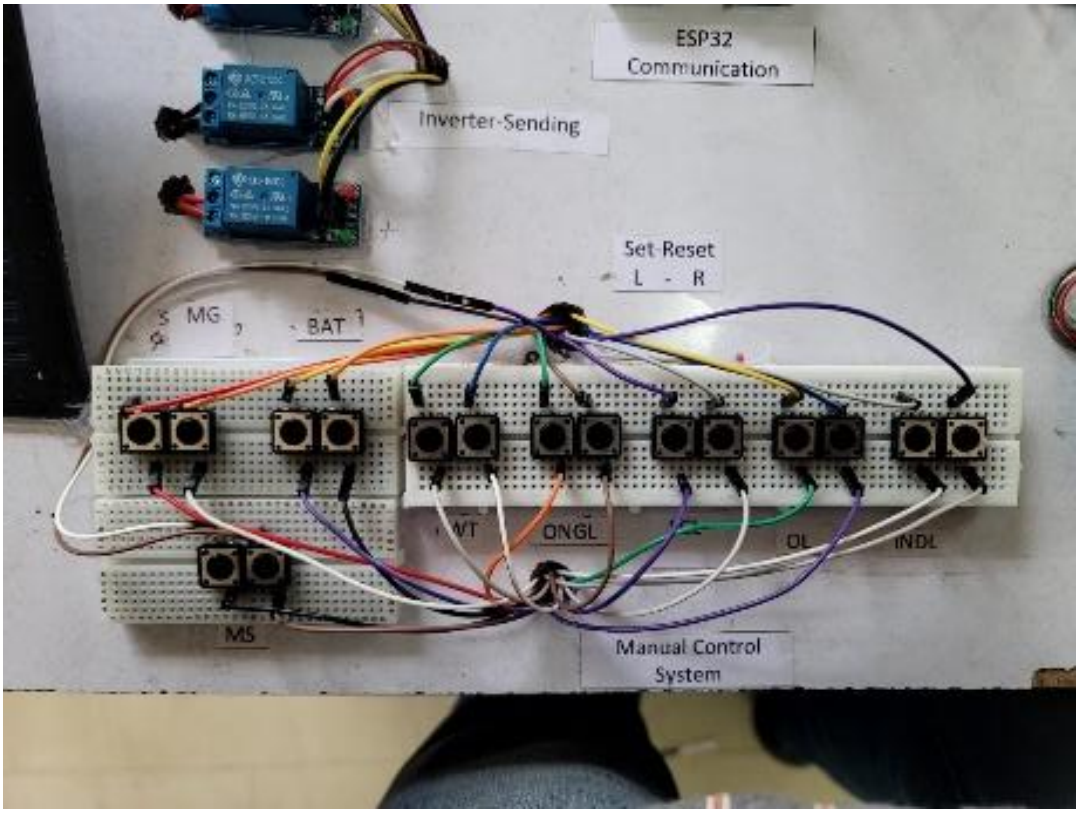


Fig 23: Manual Controlling system

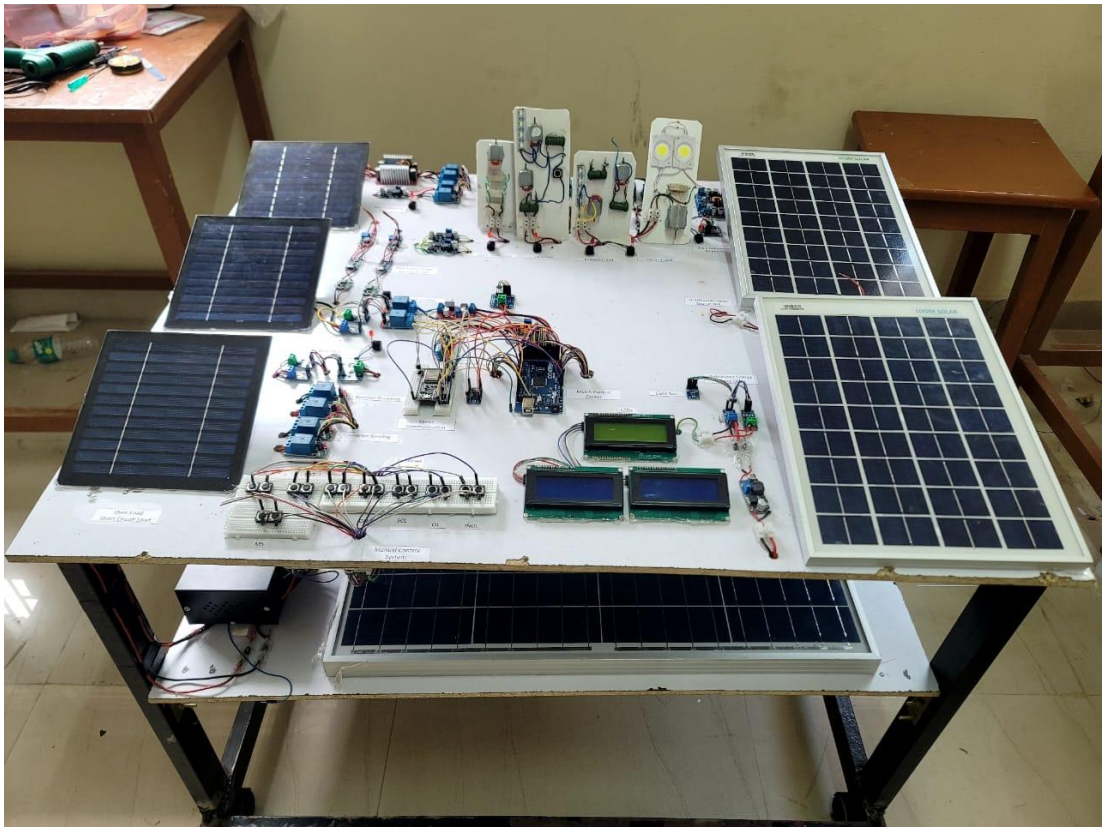


Fig 24: Entire setup

Coding Implementation

- **Flowchart**

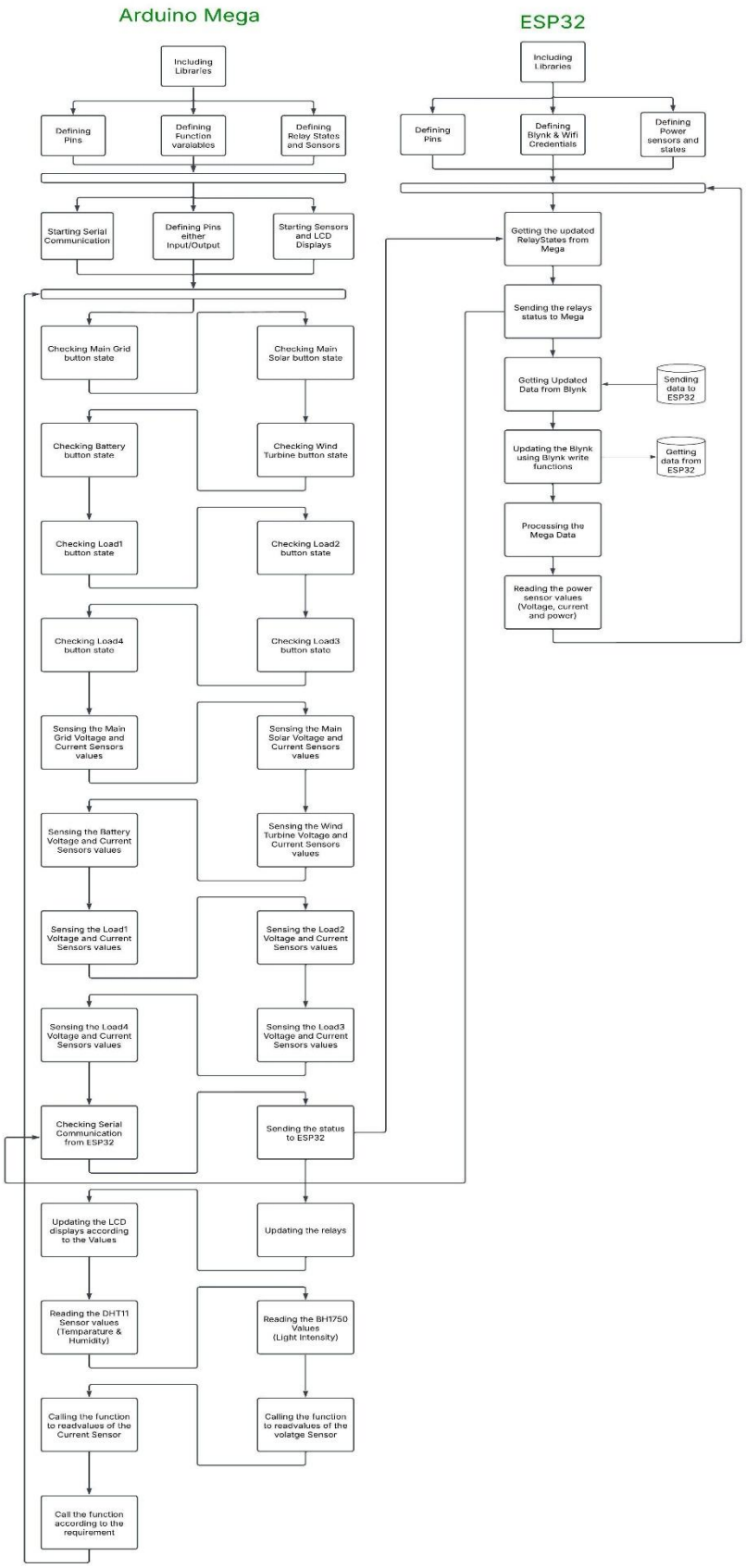


Fig 25: Code Flow Chart Block Diagram

- **Programming Language**
  1. The code was written in **C++**.
- **Software Used**
  1. **Arduino IDE**
- **Code Links**
  1. Arduino Mega code Link: [Mega code]
  2. Arduino Mega code pictures:

```
#include <DHT.h>
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <BH1750.h>

#define V_SEN_1_PIN A0
#define V_SEN_2_PIN A1
#define V_SEN_3_PIN A2
#define V_SEN_4_PIN A3
#define V_SEN_5_PIN A4
#define V_SEN_6_PIN A5
#define V_SEN_7_PIN A6
#define V_SEN_8_PIN A7

#define C_SEN_1_PIN A8
#define C_SEN_2_PIN A9
#define C_SEN_3_PIN A10
#define C_SEN_4_PIN A11
#define C_SEN_5_PIN A12
#define C_SEN_6_PIN A13
#define C_SEN_7_PIN A14
#define C_SEN_8_PIN A15

#define RELAY1 9
#define RELAY2 10
#define RELAY3 11
#define RELAY4 12
#define RELAY5 22
#define RELAY6 24
#define RELAY7 26
#define RELAY8 28
#define RELAY9 30
#define RELAY10 32
```

1

```
#define RELAY11 34
#define RELAY12 36
#define RELAY13 38
#define RELAY14 40
#define RELAY15 42
#define RELAY16 44
#define RELAY17 46
#define RELAY18 48
#define RELAY19 50
#define RELAY20 52

#define BUZZER1 0
#define BUZZER2 1
#define BUZZER3 2
#define BUZZER4 3
#define BUZZER5 4
#define BUZZER6 5
#define BUZZER7 6
#define BUZZER8 7

#define SET_BUTTON1 23
#define SET_BUTTON2 25
#define SET_BUTTON3 27
#define SET_BUTTON4 29
#define SET_BUTTON5 31
#define SET_BUTTON6 33
#define SET_BUTTON7 35
#define SET_BUTTON8 37

#define RESET_BUTTON1 39
#define RESET_BUTTON2 41
#define RESET_BUTTON3 43
#define RESET_BUTTON4 45
```

2

```
#define RESET_BUTTON5 47
#define RESET_BUTTON6 49
#define RESET_BUTTON7 51
#define RESET_BUTTON8 53

const float VOLTAGE_SCALING = 5.0 / 1023.0 * (25.0 / 5.0);
const float ACS712_SENSITIVITY = 0.1;
const int ACS712_ZERO_OFFSET = 512;

float Grid_Voltage = 0;
float Solar_Voltage = 0;
float Wind_Voltage = 0;
float Bat_Voltage = 0;
float Load1_Voltage = 0;
float Load2_Voltage = 0;
float Load3_Voltage = 0;
float Load4_Voltage = 0;

DHT dht(13, DHT11);

#define V_REF_C 5.0
#define SENSITIVITY_C 0.185
#define V_MID_C 2.5
BH1750 lightMeter(0x23);

bool relay1Active = true;
bool relay1State = false;
bool relay2State = false;
bool relay3State = false;
bool relay4State = false;

bool relay2Active = true;
bool relay5State = false;
```

3

Fig 26: Mega Code

```
bool relay6State = false;

bool relay3Active = true;
bool relay7State = false;
bool relay8State = false;

bool relay4Active = true;
bool relay9State = false;
bool relay10State = false;
bool relay11State = false;
bool relay12State = false;

bool relay5Active = true;
bool relay13State = false;
bool relay14State = false;

bool relay6Active = true;
bool relay15State = false;
bool relay16State = false;

bool relay7Active = true;
bool relay17State = false;
bool relay18State = false;

bool relay8Active = true;
bool relay19State = false;
bool relay20State = false;

LiquidCrystal_I2C lcd1(0x27, 20, 4);
LiquidCrystal_I2C lcd2(0x26, 20, 4);
LiquidCrystal_I2C lcd3(0x23, 20, 4);
```

4

```
> void Sen_Solar(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Wind(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Bat(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Load1(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Load2(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Load3(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Load4(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void checkSerial() {···
  }

> void sendStatusToESP() {···
  }

> void updateRelays() {···
  }

> void updateLCD() {···
  }
```

5

```
> void Sen_Solar(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Wind(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Bat(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Load1(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Load2(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Load3(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void Sen_Load4(float voltageThreshold, float currentThreshold, float voltageMin) {···
  }

> void checkSerial() {···
  }

> void sendStatusToESP() {···
  }

> void updateRelays() {···
  }

> void updateLCD() {···
  }
```

6

```
> void updateLCD() {···
  }

> void readDHT() {···
  }

> void readLightIntensity() {···
  }

> float readVoltage(int pin) {···
  }

> float readCurrent(int sensorPin) {···
  }

> void loop() {···
  }
```

7

3. ESP32 code Link: [ESP32]
4. ESP32 code pictures:

```
1   #define BLYNK_TEMPLATE_ID "TMPL3Bgw6LPkm"
2   #define BLYNK_TEMPLATE_NAME "Hii"
3   #define BLYNK_AUTH_TOKEN "06L3mrc50eDc8rbUfNvjSgbrrd9kCDJS"
4   #define BLYNK_PRINT Serial  // Enable Serial Debugging
5
6   #include <Wire.h>
7   #include <Adafruit_INA260.h>
8   #include <WiFi.h>
9   #include <BlynkSimpleEsp32.h>
10
11  char ssid[] = "sivakumar123";
12  char pass[] = "sivakumar";
13
14  Adafruit_INA260 ina260_grid_load;
15  Adafruit_INA260 ina260_wind;
16  Adafruit_INA260 ina260_on_grid;
17  Adafruit_INA260 ina260_solar;
18
19  BlynkTimer timer;
20  WidgetTerminal terminal(V1);
21
22  bool relayStates[20];
23  bool prevRelayStates[20];
24  bool gridState = false;
25  bool batteryState = false;
26
27 > void updateMegaRelays() {···
34  }
35  // Function to send relay state changes to Mega
36 > void sendRelayStateToMega(int relayNumber, bool state) {···
41  }
42  // BLYNK Switch Handlers with Parent Dependency
43 > BLYNK_WRITE(V20) {  // Grid State···
```

1

```
43 > BLYNK_WRITE(V20) {  // Grid State···
50   }
51 > BLYNK_WRITE(V21) {  // Grid Condition (Only works if Grid State is ON)···
57   }
58 > BLYNK_WRITE(V24) {  // Battery State···
65   }
66 > BLYNK_WRITE(V25) {  // Battery Condition (Only works if Battery State is ON)···
72   }
73   // Wind Turbine - Relay7 & Relay8
74 > BLYNK_WRITE(V23) {···
77   }
78   // Industrial Load - Relay19 & Relay20
79 > BLYNK_WRITE(V29) {···
82   }
83   // Commercial Load - Relay15 & Relay16
84 > BLYNK_WRITE(V27) {···
87   }
88   // Main Domestic Load - Relay17 & Relay18
89 > BLYNK_WRITE(V28) {···
92   }
93   // On Grid Load - Relay5 & Relay6
94 > BLYNK_WRITE(V26) {···
97   }
98   // Process incoming Serial data from Mega
99 > void processMegaData(String data) {···
148  }
149  // Read Power Sensors (ESP32 Side)
150 > void readPowerSensors() {···
183  }
184 > void setup() {···
200  }
201 > void loop() {···
211  }
```

2

Fig 27: ESP32 Code

5.2 Challenges faced and solutions implemented

1. Wind Turbine Challenges & Solutions

Challenge 1: High Cost of BLDC Motor

- Initially, we planned to use a **BLDC motor**, but due to its high cost, we opted for a **DC motor** instead.
- The selected motor was **100W, 2750 RPM, 12V**, but its performance needed optimization.

Solution:

- To optimize the motor, we performed **rewinding**.
- The original **winding had 13 turns per slot with thick wire**, so we reduced the wire thickness and increased the turns to **28 per slot**.
- This modification **decreased the RPM from 2750 to 1300** and reduced the power output to **50W at 12V**, making it more efficient for our application.

Challenge 2: Rotor Weight & Low Voltage Output

- The **initial rotor was made of metal with 10.3 m diameter**, **80 cm long and 10inches width blades**, making it excessively heavy.
- Due to the weight, the wind turbine could generate only **0.5V**, far below the required voltage.

Solution:

- We **reduced the rotor diameter from 1.03m to 85cm**.
- The **blade material was changed from metal to aluminum**, reducing weight significantly.
- The **blade length was shortened from 80cm to 60cm**, and the **width was reduced from 10 inches to 6 inches** to improve efficiency.

Challenge 3: Ball Bearing Damage Due to Welding

- The ball bearing was **welded directly**, causing damage due to excessive heat.

Solution:

- We implemented a **carrying cup** to protect the bearing while welding, preventing heat damage and ensuring smooth operation.

Challenge 4: High Cost of Required Gear Ratio

- The ideal gear ratio needed was **10 teeth to 130 teeth**, but the high cost made it unaffordable.

Solution:

- To reduce costs, we adjusted the gear ratio to **16 teeth to 98 teeth**, which was more affordable while still achieving a functional power transmission.

2. Smart Grid Setup Challenges & Solutions

1. **Fluctuations in Relay Power Supply:**
   - **Challenge:** Initially, the relays were powered directly from solar panels, causing fluctuations that damaged the boost converter used for battery charging due to uncontrolled power flow.
   - **Solution:** Relays and IoT components were instead powered with a stable 5V supply from the main battery, ensuring consistent power and preventing damage.
2. **Overloaded Buck Converter:**

- **Challenge:** The relays were initially powered by a 2A buck converter, but the large number of connected components exceeded its capacity, causing overheating and potential failure.
- **Solution:** The 2A buck converter was replaced with a 5A buck converter, ensuring better performance and protecting IoT components from voltage spikes.

3. Code Challenges and Solutions

Challenge 1 : Finding Proper Hardware for Required Analog and Digital Pins

Solution:

- Use pin mapping diagrams of Arduino Mega and ESP32 to allocate pins efficiently.
- Utilize I2C expanders or multiplexers for additional digital/analog pins if required.

Challenge 2 : Properly Defining the Address of INA260 Sensors and 16x4 LCD Displays with I2C

Solution:

- Run an I2C Scanner sketch to detect and verify I2C addresses.
- Use unique addresses or an I2C multiplexer (TCA9548A) to prevent conflicts.

Challenge 3 : Differentiating the Analog and Digital Pins for Each Hardware

Solution:

- Maintain a pin allocation table to track assignments clearly.
- Define pins using #define or const int to improve readability and avoid duplication.

Challenge 3 : Defining Each and Every Pin, Variable, Function, and Nested Function

Solution:

- Use meaningful names for pins, variables, and functions for better organization.
- Keep functions modular and reusable to simplify debugging and modifications.

Challenge 4 : Understanding the Flow of Each Function and Modifying According to Our Requirement

Solution:

- Develop flowcharts or pseudo-code before implementing the functions.
- Add clear comments and maintain proper indentation for better readability.

Challenge 5 : Sending Data to ESP32 from Arduino Mega and Simultaneously to Blynk from ESP32

Solution:

- Use Hardware Serial or Software Serial for stable UART communication.
- Implement timing control (millis()) and error checking to ensure smooth data transmission.

Chapter 6: Results

6.1 outcomes

The smart grid system successfully achieved all objectives:

1. **Scalability & Flexibility** – Integrated multiple power sources (solar, wind, battery, and grid) to ensure a stable and reliable energy supply for urban areas.
2. **Renewable Energy Integration** – Solar and wind power reduced dependence on fossil fuels, lowering carbon emissions and promoting sustainability.
3. **IoT-Based Monitoring & Fault Detection** – Real-time data acquisition, two-way communication, and automated fault detection enhanced grid reliability.
4. **Real-Time Control & Optimization** – Intelligent power switching ensured continuous supply and efficient load management.

All operations were executed automatically using **sensors and relays**, which responded dynamically to pre-set values, ensuring seamless energy management.

Fig 28: Final Project Integration overview

Generation Side Results

1. Main Solar Panel

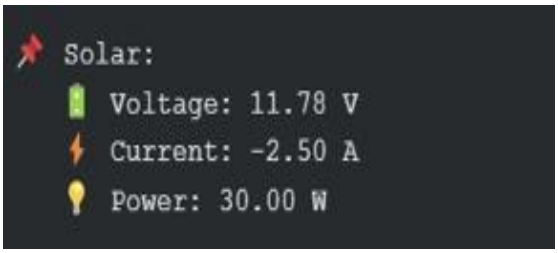
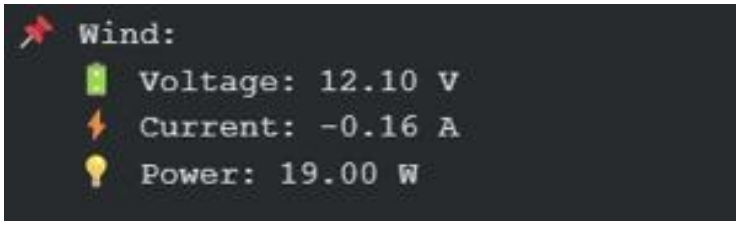


Fig 29: Main Solar Panel Results

The solar panel generated 30W, contributing significantly to the smart grid's renewable energy mix. It adjusted power output based on grid requirements, reducing dependence on conventional energy sources.

2. Wind Turbine



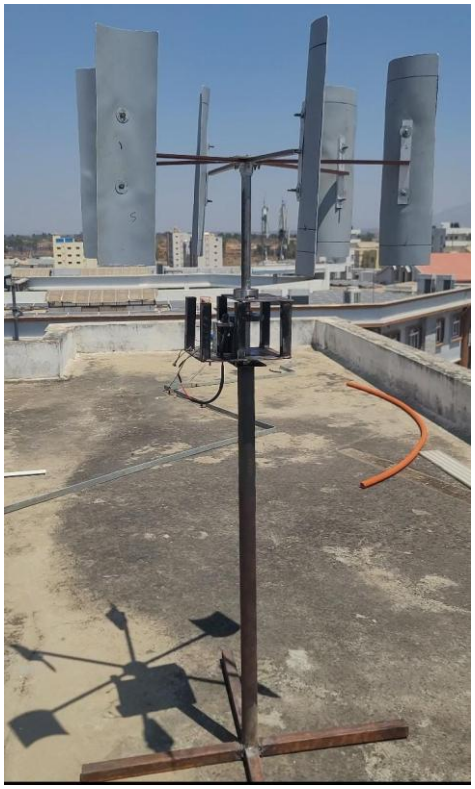


Fig 30: Wind turbine Results

The wind turbine generated 19W, supplementing solar power. The low current value indicates moderate wind speeds during the test. The combined use of solar and wind enhanced energy stability and availability.

3. Battery Performance

a) Battery Charging

```
Battery

Voltage:  13.50 V
Current:  -1.81 A
Power:    -24 W
Battery Percentage: 80.00 %
Battery Charging
```

b) Battery Discharging

```
Voltage:  13.36 V
Current:  -0.93 A
Power:    -12 W
Battery Percentage: 70.00 %
Battery Discharging
```

Fig 31: Battery Results

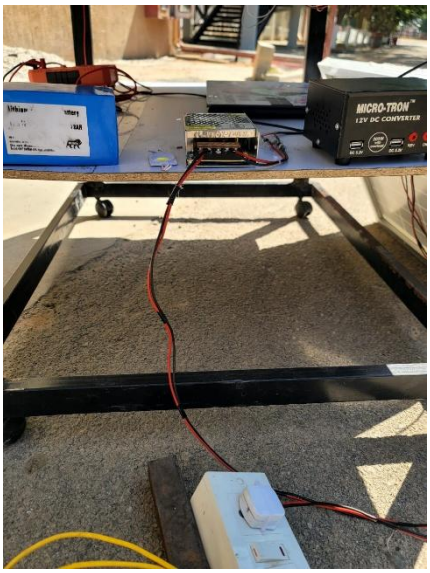
The battery efficiently stored excess energy and supplied power when needed. Its reliable charge-discharge cycles ensured grid stability and reduced dependence on the main grid.

4. Main Grid Contribution

a) Receiving Mode

```
Main Grid:
Voltage: 11.35 V
Current: 2.61 A
Power: 29.65 W

Status: Receiving
```



b) Sending Mode

```
Main Grid:
Voltage: 9.47 V
Current: -4.71 A
Power: 44.84 W

Status: Sending
```

Fig 32: Main Grid Results

The grid acted as both a backup and distributor. It received 29.65W when renewable generation was low and supplied 44.84W back to the system during excess generation. This bidirectional energy exchange improved efficiency and cost savings.

Load Side Results

1. **On-Grid Load Performance**
   a) **Sending Power to grid**

```
Grid Load:
Voltage: 12.02 V
Current: -0.27 A
Power: 3.20 W
Status: Sending
```

   b) **Receiving Power from grid**

```
On Grid Load:
Voltage: 11.74 V
Current: -0.26 A
Power: 3.08 W
Status: Receiving
```

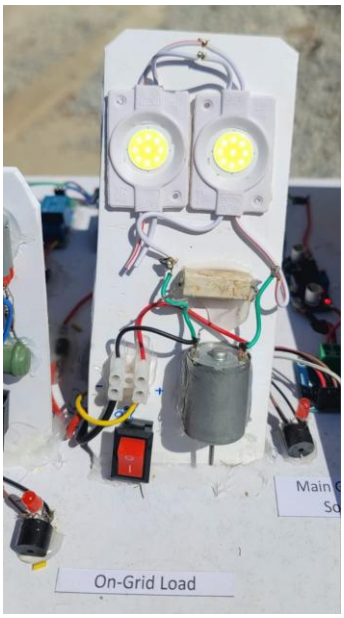


Fig 33: On Grid load Results

The on-grid load managed power distribution efficiently, maintaining stability and minimizing fluctuations. The system dynamically switched between receiving and sending power, optimizing energy usage and reducing costs.

2. **Industrial Load**

```
Industrial Load

Voltage:  5.42 V
Current:  3.96 A
Power:    21 W
```

Fig 34: Industrial load Results

The industrial load consumed 21W, demonstrating the grid's capability to supply high-demand consumers reliably. This was achieved using both solar energy and grid power for cost optimization.

3. **Overload Condition**

```
Over Load

Voltage:  5.36 V
Current:  2.54 A
Power:    13 W

Over Load Load2
```

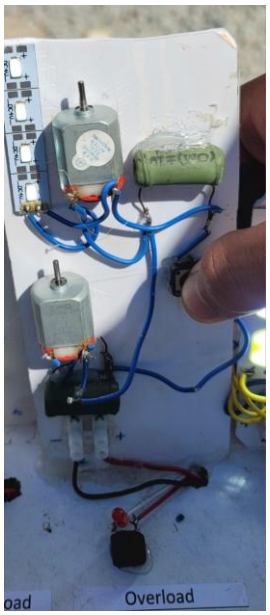


Fig 35: Overload Results

The system successfully detected and managed an overload condition using relays and sensors. Automated regulation prevented system failure and ensured uninterrupted power to other loads.

4. **Short Circuit Load:**

```
Fault Load

Voltage:  7.10 V
Current:  6.16 A
Power:    43 W

Short Circuit Load3
```

Fig 36: Short-circuit Results

The short circuit protection system responded effectively by disconnecting the affected section, preventing damage due to high current surges. This aligns with the objective of **enhanced fault detection and protection**.

Monitoring System Results

The smart grid monitoring system, equipped with sensors and relays, continuously tracks power generation, consumption, and environmental parameters. The LCD displays provide real-time data on the performance of different power sources, battery status, and environmental factors like temperature and light intensity.

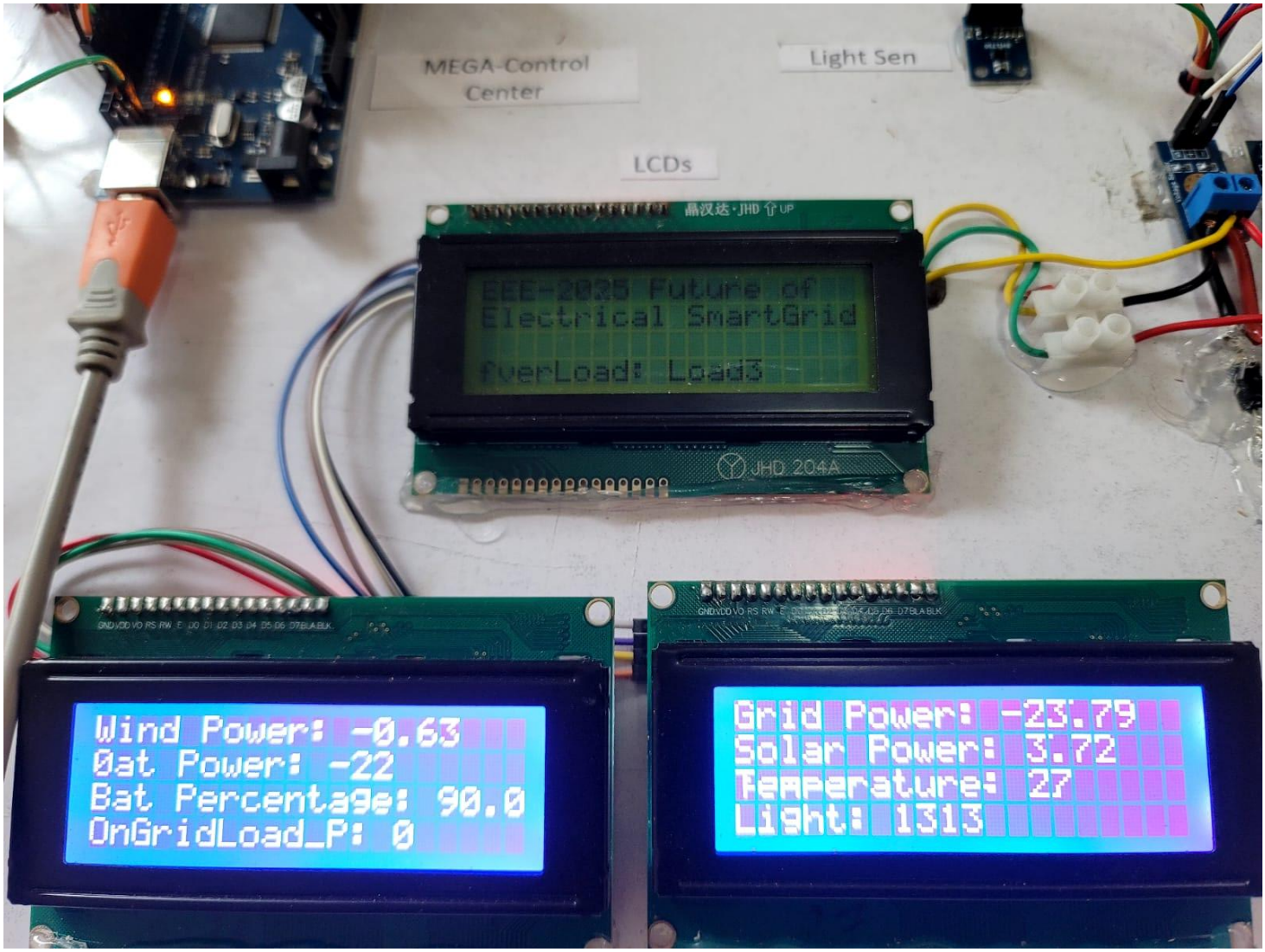


Fig 37: Monitoring System Results

Power Generation & Consumption Monitoring

1. **Wind Power**: -0.63 W
   - Indicates that the wind turbine is not actively generating power at the moment. The negative value suggests minimal or no wind energy contribution during the observation period.
2. **Solar Power**: 3.72 W
   - Shows the amount of power being generated by the solar panel. This indicates that solar energy is actively contributing to the smart grid.
3. **Grid Power**: -23.79 W

- The system is drawing 23.79W from the grid, indicating a demand for additional power due to lower renewable energy generation at that moment.

4. **Battery Power**: -22 W
   - The battery is discharging 22W to support the grid or connected loads, ensuring a continuous power supply.
5. **Battery Percentage**: 90.0%
   - Displays the current charge level of the battery, indicating sufficient stored energy for backup and grid support.
6. **On-Grid Load Power**: 0 W
   - No power is currently being supplied to the on-grid load, possibly due to a lack of demand or automatic switching to another power source.

Environmental Monitoring

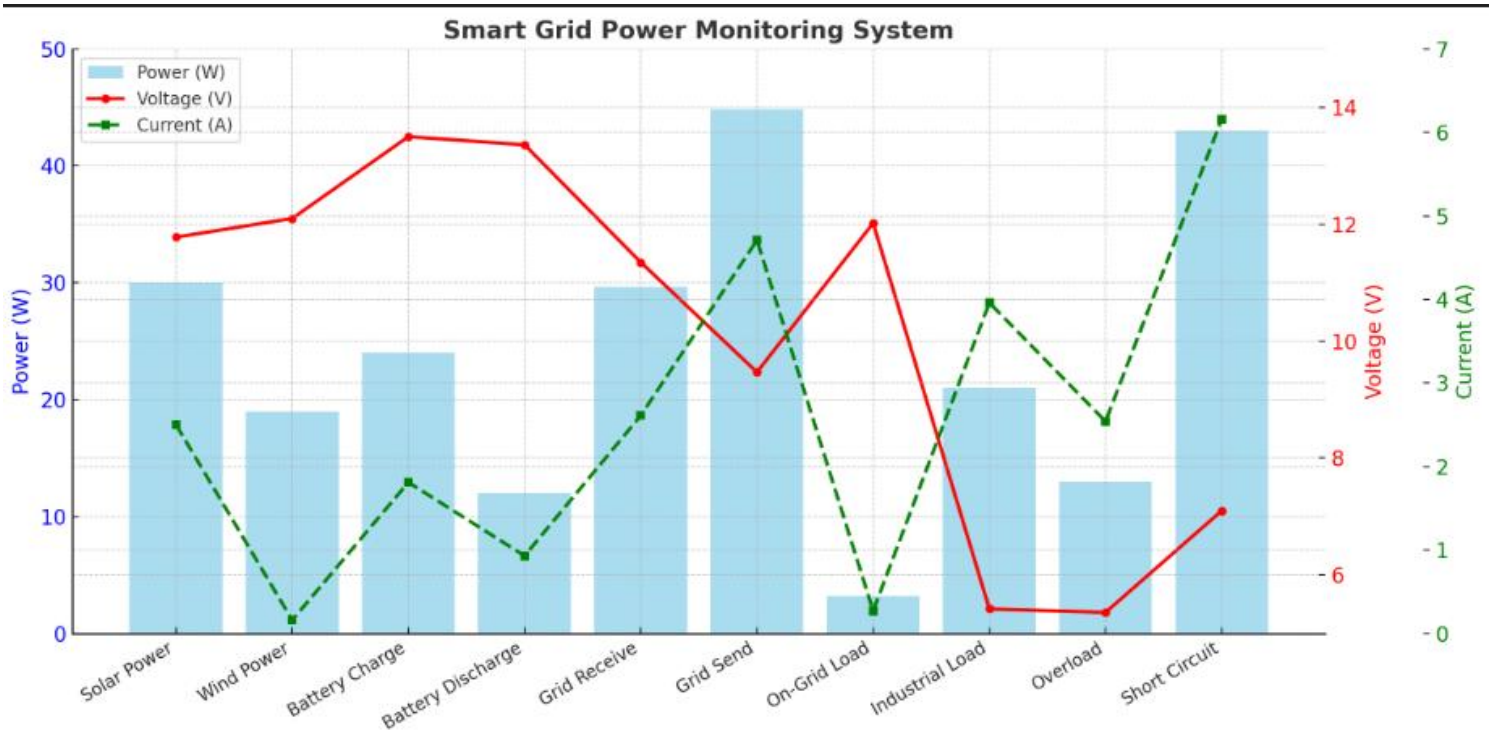
1. **Temperature**: 27.2°C
   - Represents the ambient temperature in the system's operating environment, which can influence the efficiency of solar panels and battery performance.
2. **Light Intensity**: 1313
   - Measures the intensity of light, which directly affects solar panel performance. A high value suggests good sunlight conditions for optimal solar energy generation.

Automated Operation

All energy management and fault-handling processes were executed **automatically** through **sensors and relays**. These components continuously monitored voltage, current, and power levels, taking real-time actions based on **pre-set thresholds**. This automation ensured an intelligent and efficient smart grid system, reducing human intervention while optimizing performance.

6.2 Interpretation of results

This section analyzes the power generation, storage, and load distribution performance of the smart grid system based on the recorded values.



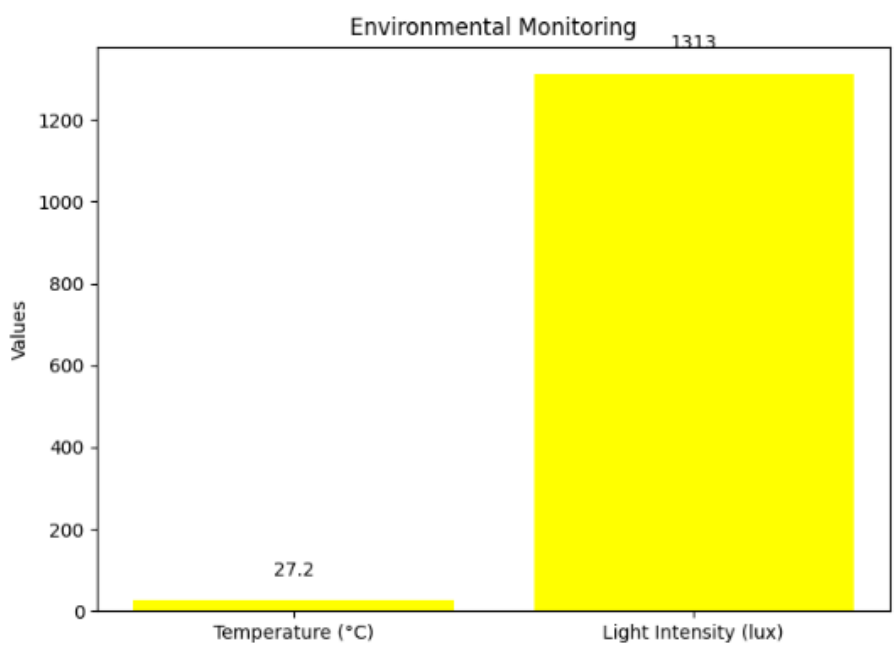


Fig 38: Smart Grid Performance Analysis

1. Generation Side Analysis

a) **Main Solar Panel**

- **Interpretation:** The solar panel generated 30W, playing a crucial role in renewable energy supply. It adjusted output based on grid demand, reducing reliance on conventional sources.

b) **Wind Turbine**

- **Interpretation:** The wind turbine produced 19W, supplementing solar energy. The low current suggests moderate wind speeds during operation. This combination improved system stability.

c) **Battery Performance**

- **Interpretation:** The battery efficiently stored excess energy and discharged when required. Its stable charge-discharge cycles ensured uninterrupted power supply and minimized dependency on the grid.

d) **Main Grid Contribution**

- **Interpretation:** The grid acted as both a backup and a distributor, receiving 29.65W when renewable generation was low and sending 44.84W during excess generation. This bidirectional energy exchange improved efficiency and reduced operational costs.

2. Load Side Analysis

a) **On-Grid Load Performance**

- **Interpretation:** The on-grid load efficiently managed power flow, dynamically switching between sending and receiving power. This ensured optimized energy usage and cost reduction.

b) **Industrial Load**

- **Interpretation:** The industrial load consumed 21W, demonstrating the system's capability to support high-demand consumers by balancing between solar and grid power.

c) **Overload Condition**

- **Interpretation:** The system detected and controlled overload conditions using relays and sensors, preventing failures and ensuring continuous operation.

d) **Short Circuit Protection**

- **Interpretation:** The short circuit protection system responded effectively, disconnecting the affected section to prevent damage from high current surges. This aligns with smart grid safety objectives.

3. Environmental Monitoring

a) **Temperature**

- **Interpretation:** Represents ambient temperature, which influences solar panel efficiency and battery performance.

b) **Light Intensity**

- **Interpretation:** Indicates strong sunlight, enabling optimal solar power generation.

6.3 Comparison with existing literature or technologies

Feature	Traditional Grid	Proposed Smart Grid Model
Power Generation	Centralized, mostly fossil fuel-based	Decentralized, integrates solar & wind energy
Energy Storage	Limited or absent	Battery storage for backup & peak shaving
Grid Contribution	One-way power flow from grid to users	Bi-directional flow (users can send power to the grid)
Demand Response	Fixed supply, no real-time control	Adaptive load control based on demand and generation
Fault Detection	Manual detection, slow response	Real-time monitoring with automated fault detection
Load Management	No smart control, prone to overload	Intelligent distribution & load balancing
Efficiency	High transmission losses	Reduced losses with localized generation
Monitoring System	Basic SCADA, limited remote access	IoT-based real-time monitoring & control
Grid Resilience	Vulnerable to blackouts	Self-healing with automated fault isolation
Environmental Impact	High carbon emissions	Low emissions due to renewable integration

Table 7: Traditional grid VS Smart grid

Chapter 7: Conclusion

The successful implementation of a smart grid model integrating solar, wind, battery storage, and grid contribution with hardware deployment and IoT-based monitoring has demonstrated significant improvements over traditional power systems. The proposed system enhances efficiency, reliability, and sustainability by utilizing renewable energy sources, real-time data acquisition, and automated control mechanisms.

Key outcomes from the project include:

- Successful hardware implementation of the smart grid system, validating its practical feasibility.
- Real-time IoT-based monitoring and control, improving system responsiveness and energy management.
- Effective integration of solar and wind power, ensuring continuous renewable energy supply.
- Battery storage optimization, providing efficient energy storage and seamless power transition during fluctuations.
- Bidirectional power flow capability, allowing energy reception and injection into the grid, enhancing flexibility.
- Improved fault detection and load management, ensuring grid stability and minimizing power losses.

Compared to a traditional grid, our hardware-implemented smart grid system has proven to be more efficient, resilient, and adaptable, with lower carbon emissions, reduced transmission losses, and improved fault recovery. These advancements establish it as a practical and scalable solution for future energy systems.

Chapter 8 : Future Work

- For future development, the smart grid system should be enhanced with Artificial Intelligence (AI) for fully automated operation. AI can optimize energy distribution, predict demand fluctuations, and enhance fault detection without human intervention. Implementing machine learning algorithms will allow the system to analyze energy patterns, forecast power consumption, and adjust renewable energy utilization dynamically.
- Additionally, integrating blockchain technology for secure and transparent energy transactions can enhance grid reliability. Expanding the system to support vehicle-to-grid (V2G) technology will allow electric vehicles to participate in energy exchange, improving grid stability.
- Future research can also focus on edge computing for faster data processing and cybersecurity measures to protect against grid cyberattacks. Moreover, scalability tests should be conducted to ensure the system's efficiency in large-scale deployments. By incorporating these advancements, the smart grid can evolve into a self-sustaining, intelligent, and highly resilient energy network, paving the way for the future of sustainable urban energy solutions.

References

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Solar power integration in Urban areas: A review of design innovations and efficiency enhancements