Memorial University of Newfoundland
(Faculty of Engineering and Applied Science)

Department of Electrical and Computer Engineering

Design and Analysis of a Hybrid Power System and IoT SCADA System for Remote Sites

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Presentation Outline

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- **Simulation, Performance Analysis, and Optimization**
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- **Dynamic Modeling and Simulation**
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- **Open Source IoT-Based SCADA Using HTTP and TCP/IP Protocols**
  - System Architecture and Implementation
  - Experimental Validation

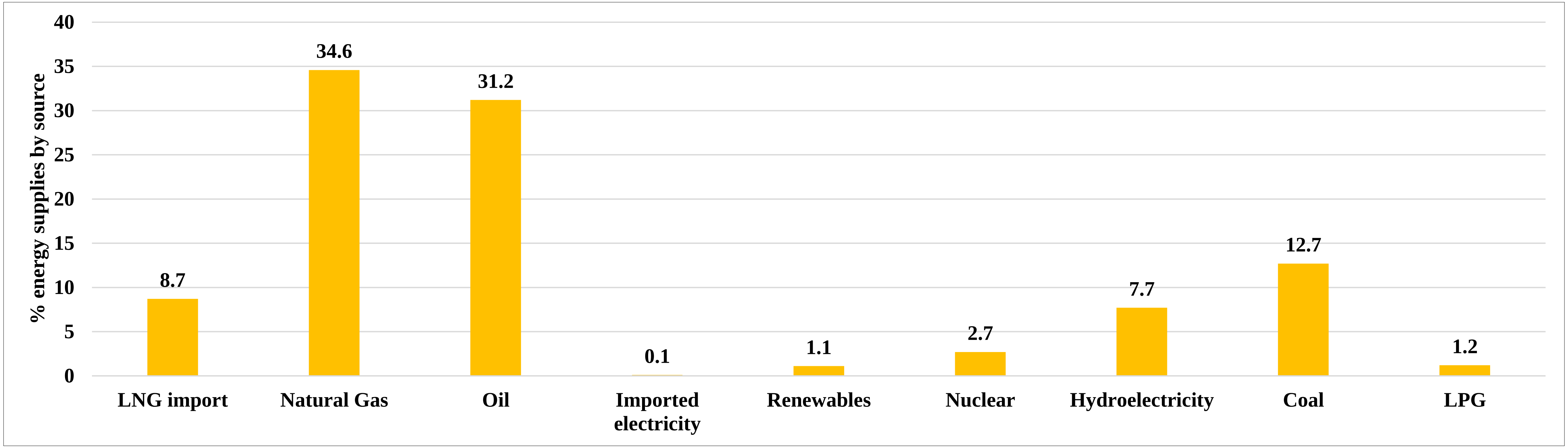
- **Conclusion**

- **Future Direction**

Background Context

- **The Energy Crisis**

- **Fossil Fuel Dependency**
- Predominance of fossil fuels in energy production in developing countries like Pakistan.
- **Environmental Issues Caused by Fossil Fuels**
- Fossil fuels significantly contribute to CO_2 emissions, global warming, and deforestation.
- Increased frequency of natural disasters linked to climate change.



Energy Mix of Pakistan

Background

- **Deforestation**
  - Climate change, driven by fossil fuel use, has increased the frequency and severity of floods in Pakistan.
  - Deforestation worsens the risk of natural disasters like floods.

Economic Issues Caused by Fossil Fuels

- **High Power Generation Costs**
  - Fossil fuel-based power generation is expensive, especially in the long term.
  - The cost of importing fossil fuels increases the economic burden on developing countries.

- **Electricity Shortages and Unreliable Power Supply**
  - The demand for electricity in Pakistan grows annually.
  - Frequent power outages, sometimes lasting up to 12 hours a day, disrupt daily life and economic activities.

Economic loss impact due to floods in Pakistan in 2022

Province	Damage (Million USD)	Loss (Million USD)	Requirement for Rehabilitation (Million USD)
Baluchistan	1625	2516	2286
KPK (Khyber Pakhtunkhwa)	935	658	780
Punjab	515	566	746
Sindh	9068	11,376	7860

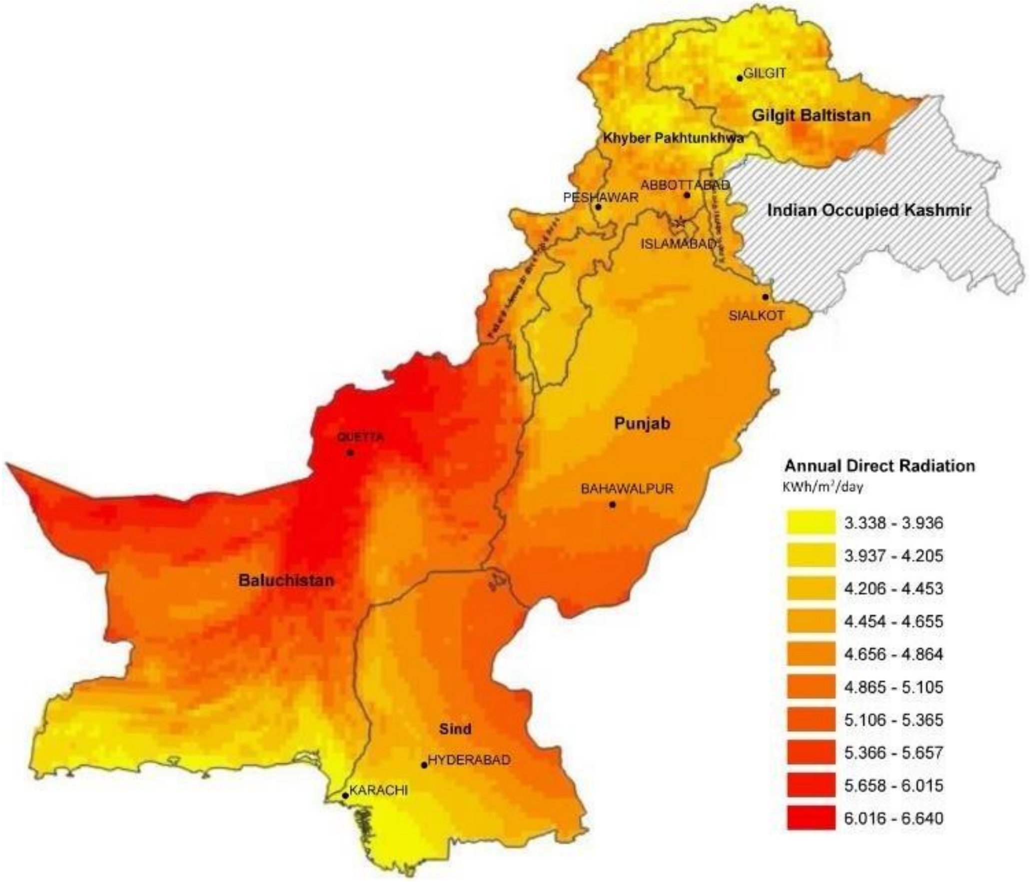
Background

Transition to Renewable Energy

- **Hybrid Power Systems**:
- Integrating renewable energy sources, such as solar and wind, with traditional generators.

- **Untapped Renewable Potential**:
- Pakistan has significant potential for renewable energy.
- 100,000 MW from coal, 56,000 MW from hydro, 150,000 MW from wind, and 50,000 MW from solar.
- Baluchistan (7.0 kWh/m² per day), Sindh (6.0-6.5 kWh/m² per day), Punjab and Khyber Pakhtunkhwa (5.5-6.0 kWh/m² per day).

- **Economic and Social Benefits**:
- Transitioning to renewables can improve living standards, support economic development, and reduce the environmental impact.



Literature Review

Reviewed Paper	Description
Iqbal & Iqbal (2019)	Stand-alone PV system design and performance evaluation for rural off-grid applications in Pakistan.
Aghenta & Iqbal (2019)	IoT-based SCADA system for photovoltaic monitoring, leveraging Arduino and web-based dashboards for remote control.
Akhtar et al. (2020)	Advancements in solar reflector technology, emphasizing enhanced efficiency and cost-benefit analysis for solar thermal systems in Pakistan.
Bakht et al. (2022)	Echo-economic modeling of hybrid energy systems, combining solar PV, wind, and batteries to mitigate load shedding in Pakistan.
He & Iqbal (2024)	SCADA system development using open-source components for real-time monitoring of photovoltaic systems.

Research Objectives

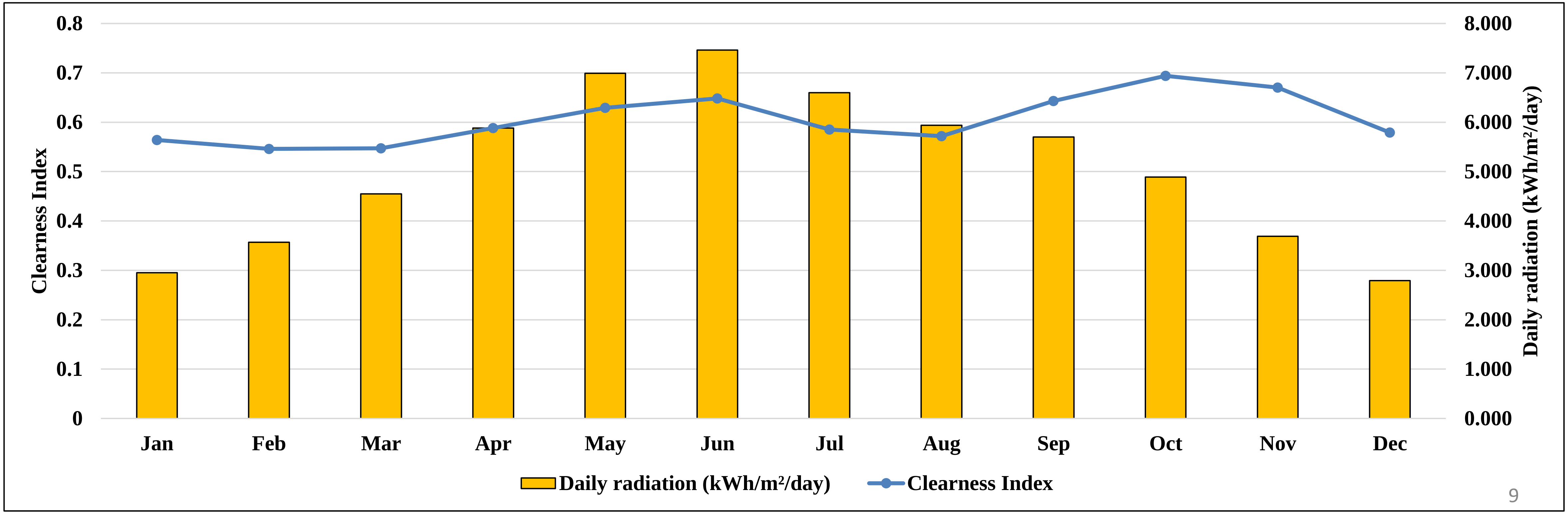
- **Environmental Impact Mitigation:** Evaluate the potential for electricity generation from solar energy to reduce greenhouse gas emissions and flood risks in developing countries.
- **Hybrid Power System Design:** Develop a reliable and cost-effective hybrid power system tailored for rural areas in Pakistan.
- **Dynamic System Analysis:** Investigate the performance of the hybrid power system under varying load conditions and environmental changes, validated through Hardware-in-the-Loop (HIL) testing.
- **IoT-Based SCADA Implementation:** Design and implement a low-cost, open-source IoT-based SCADA system for remote monitoring and control, utilizing diverse communication protocols.

Simulation, Performance Analysis, and Optimization of Off-Grid Hybrid Power Systems

Site Analysis and Optimization

- **Site Selection Criteria**
  - Evaluation of renewable resource availability, environmental conditions, and economic viability for optimal hybrid power system design.

- **Solar Horizontal Irradiance (SHI)**
  - SHI ranges from 2.79 kWh/m²/day to 7.46 kWh/m²/day, with a clearness index between 0.546 and 0.694.



Selected Site Overview

- **Location:**

  Berru Bandi, rural area of Abbottabad District, Pakistan (Coordinates: 34°16′38″ N 73°15′18″ E).
- **Altitude:**

  1456.79 meters above sea level.
- **Challenges:**

  Limited road access and basic amenities, and reliance on diesel generators contribute to high CO_2 emissions.

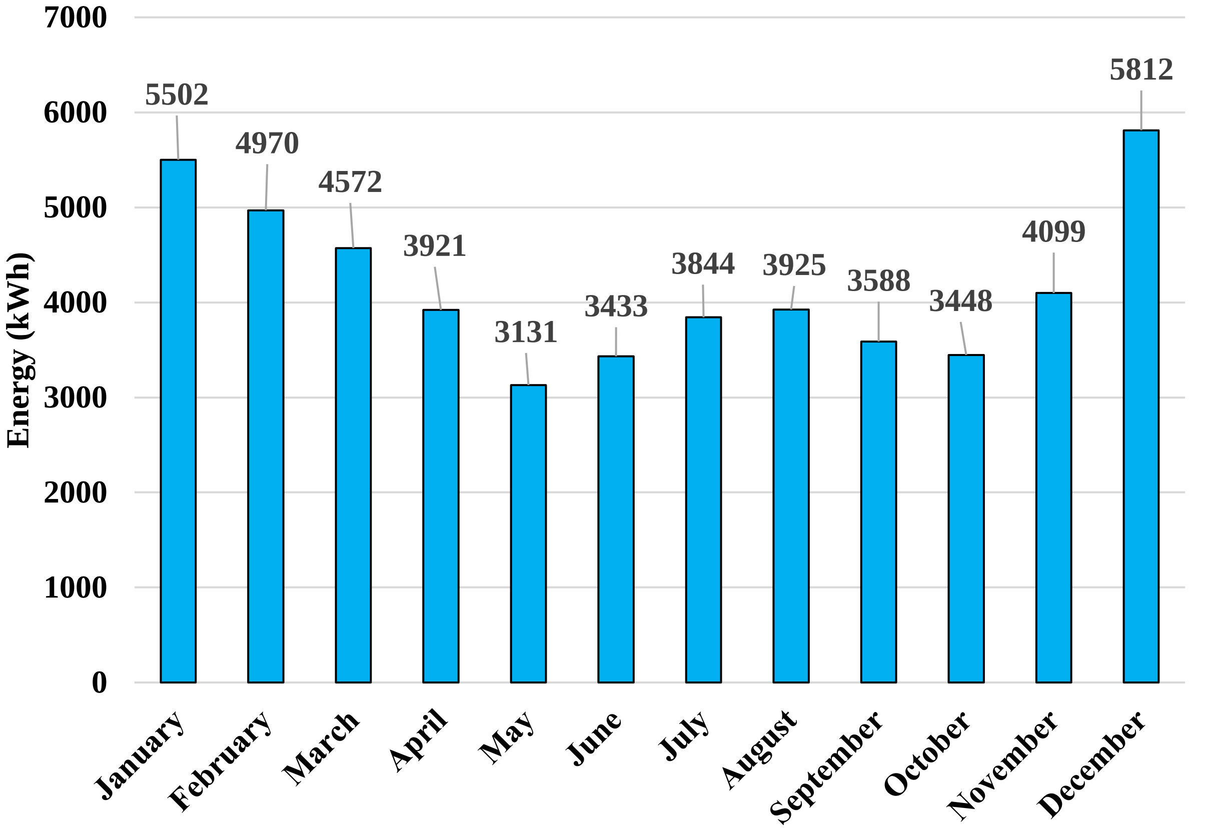
Google Earth view

Actual view

Analysis of Electrical Load

Appliances Description	**Unit's Quantity**	**Installed Unit Load Rated Power Watts (W)**	**Aggregate Connected Load (kW)**
LED Lights	100	30	3
Ceiling Fan	30	75	2.25
Iron	8	1000	8
Washing Machine	10	700	7
Refrigerator	10	750	7.5
Television	10	200	2
Electric Heater	8	500	4
Electric Geyser	8	1000	8
Water Suction Pump	1	5000	5
Total Connected Load	**46.75 KW**		

Appliances Description and Total Connected Load



Monthly Electricity Consumption

Performance Analysis of System Using PVsyst Software

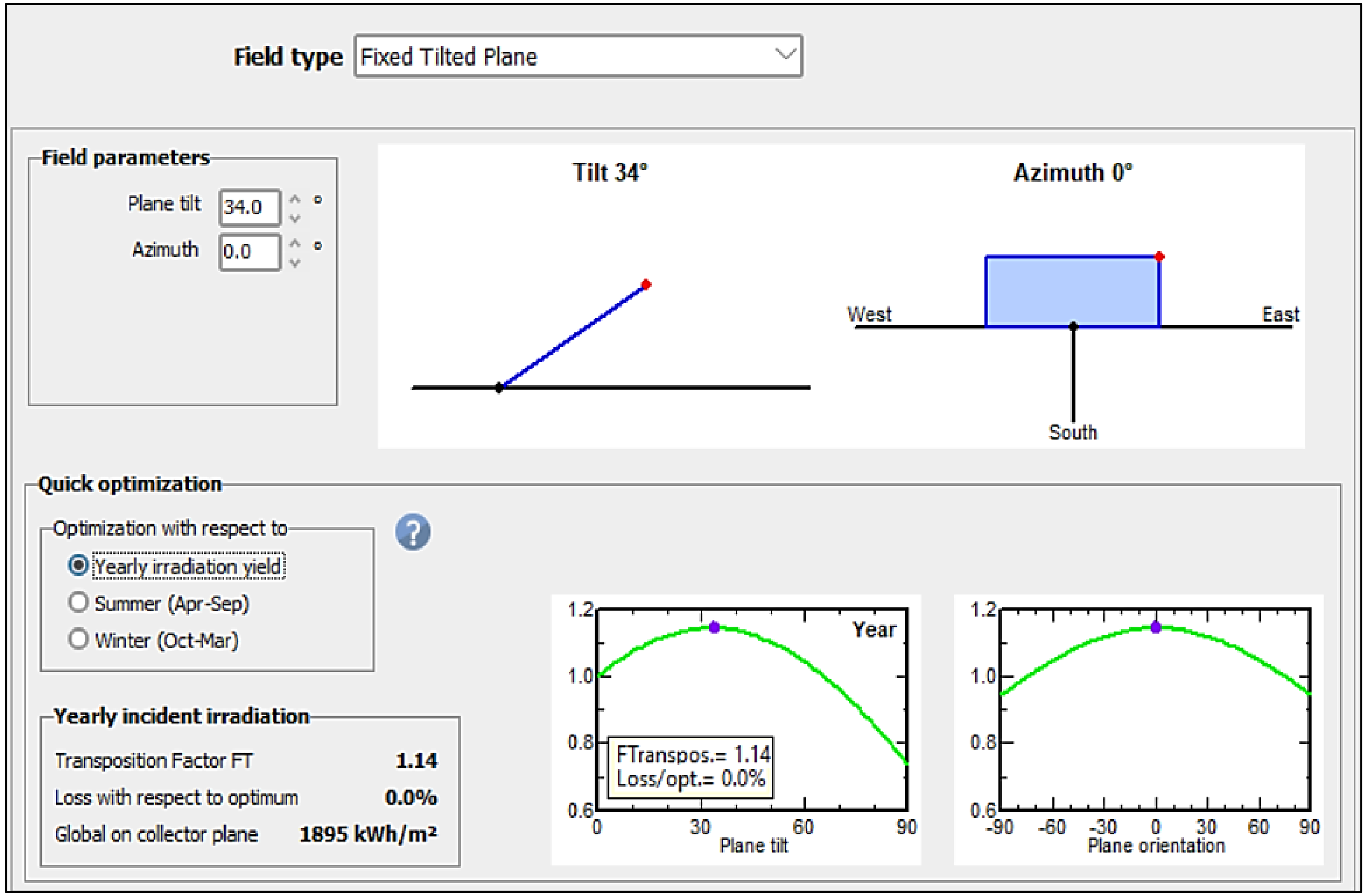
- **Tilt angle:** 34°

- **Yearly global horizontal radiation:** 1657.8 kWh/m².
- **Diffuse horizontal radiation:** 702.48 kWh/m².
- **Average ambient temperature:** 14.29 °C.

- **Surplus energy:** 35.93 MWh/year.

- **Backup generator fuel consumption** estimate of 5551 L.

- **The community's actual usage** of over 75,000 L.



Performance Analysis of System Using PVsyst Software

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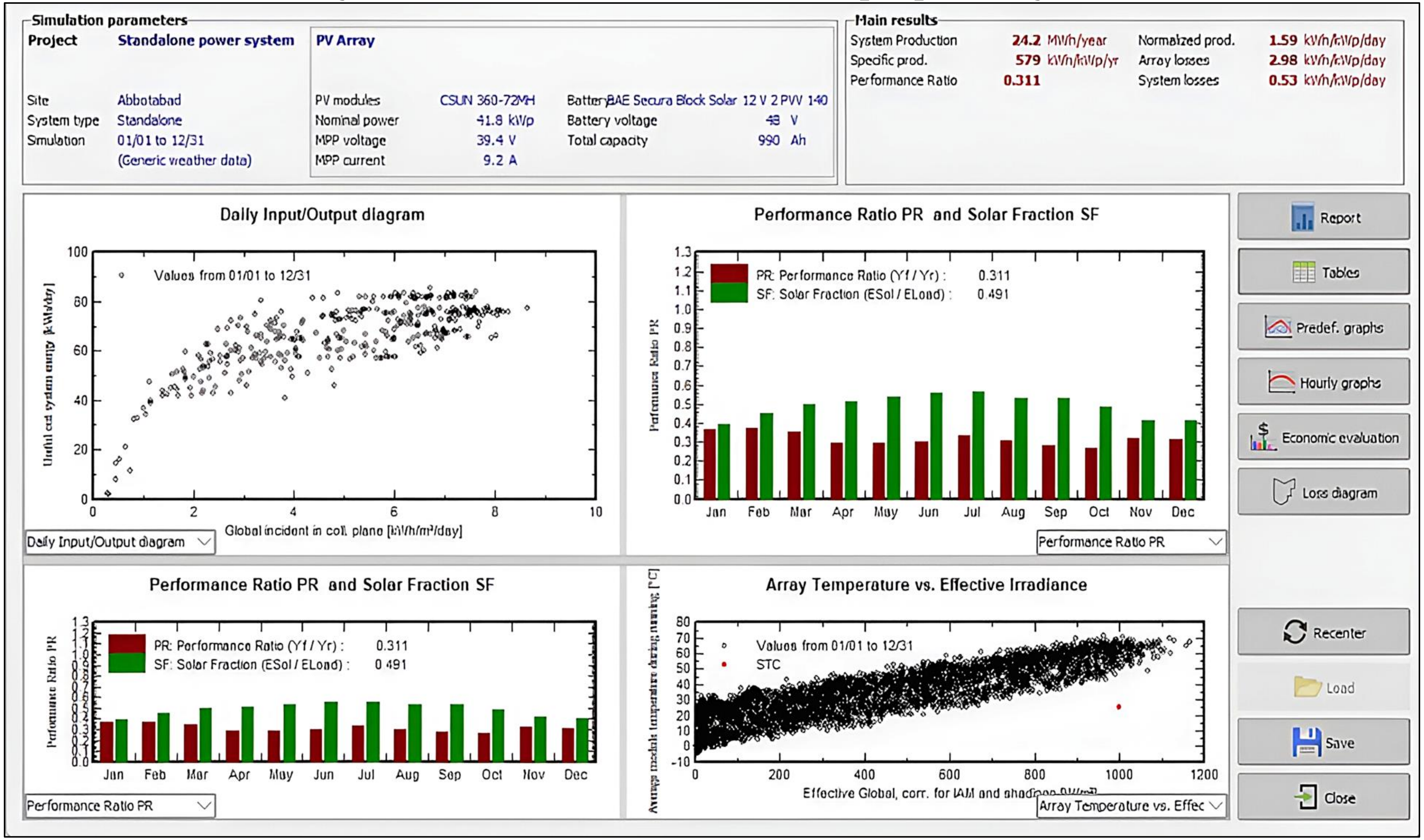
Renewable energy generation and consumption based on predefined parameters.

Month	Glob Hor [kWh/m²]	Glob Eff [kWh/m²]	Diff Hor [kWh/m²]	E Array [kWh]	E User [kWh]	Unused Energy [kWh]	Fuel BU [Liters]
January	70.7	105.4	29.42	4418	2556	1935	542
February	85.3	107.6	45.44	4510	2462	1948	452
March	123.8	138.4	67.86	5799	2868	2643	470
April	163.7	165.7	68.20	6943	2802	3479	439
May	197	179.2	78.54	7510	2978	3634	433
June	199.2	173.8	78	7282	2949	3410	413
July	183.8	163.8	90.40	6865	3057	2895	425
August	175.4	170	82.13	7125	2967	3268	447
September	161.9	179.6	59.60	7524	2881	3696	437
October	134.2	176.9	41.38	7413	2818	3855	481
November	85.2	124	34.35	5198	2507	2572	493
December	78.1	126.9	27.16	5316	2571	2600	519
Total	1658.3	1811.3	702.48	75,903	33,416	35,953	5551

Performance Analysis of System Using PVsyst Software

PVsyst simulation outcomes for the proposed system.



HPS Design and Optimization Using HOMER Pro

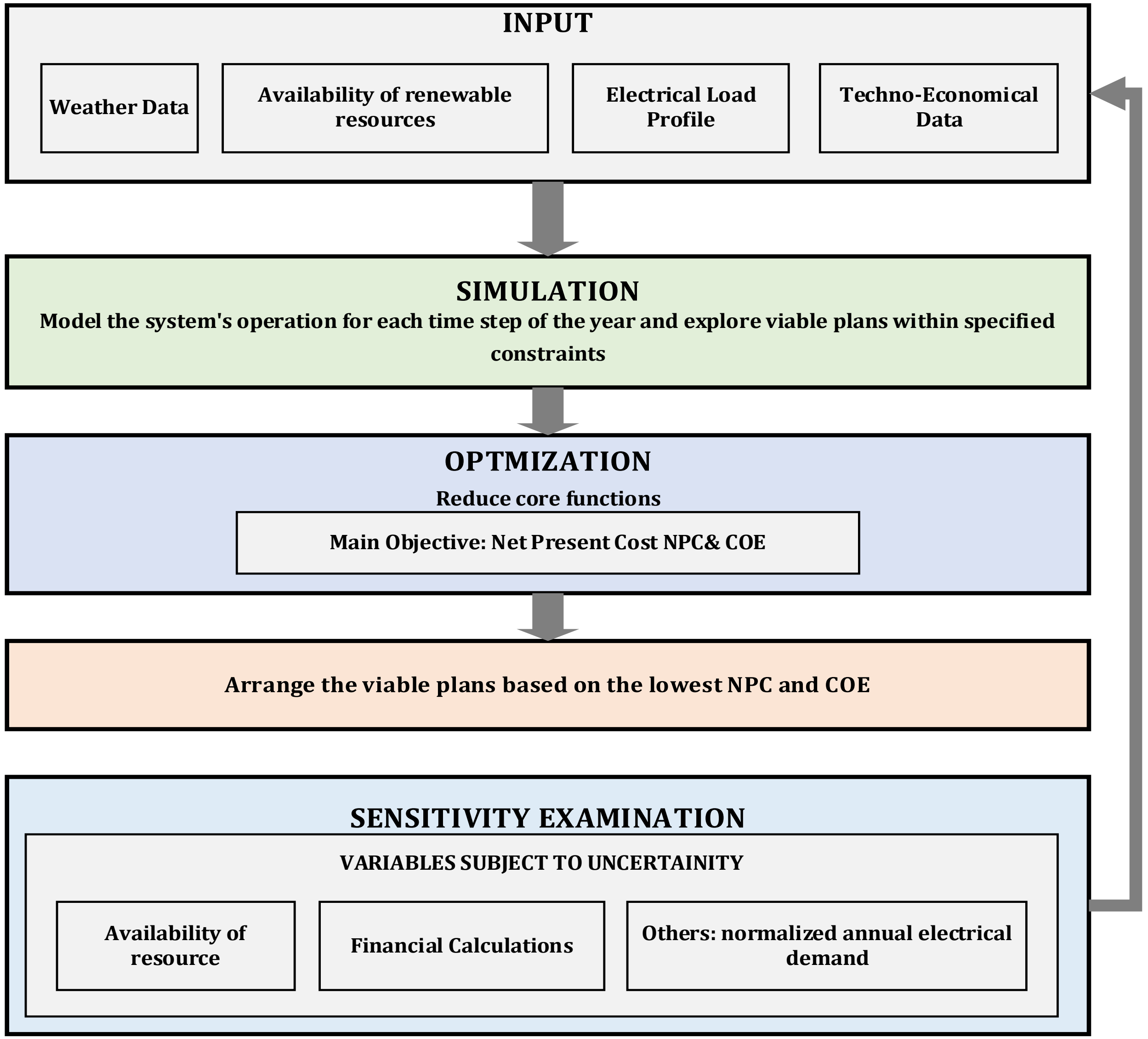
- The design of the hybrid power system is executed using HOMER Pro, developed by the American National Renewable Energy Laboratory in 1993.

- HOMER Pro is a system modeling tool used to evaluate various component combinations for both grid-connected and off-grid systems.

- It performs three key functions: simulation, optimization, and detailed analysis of planned energy systems.

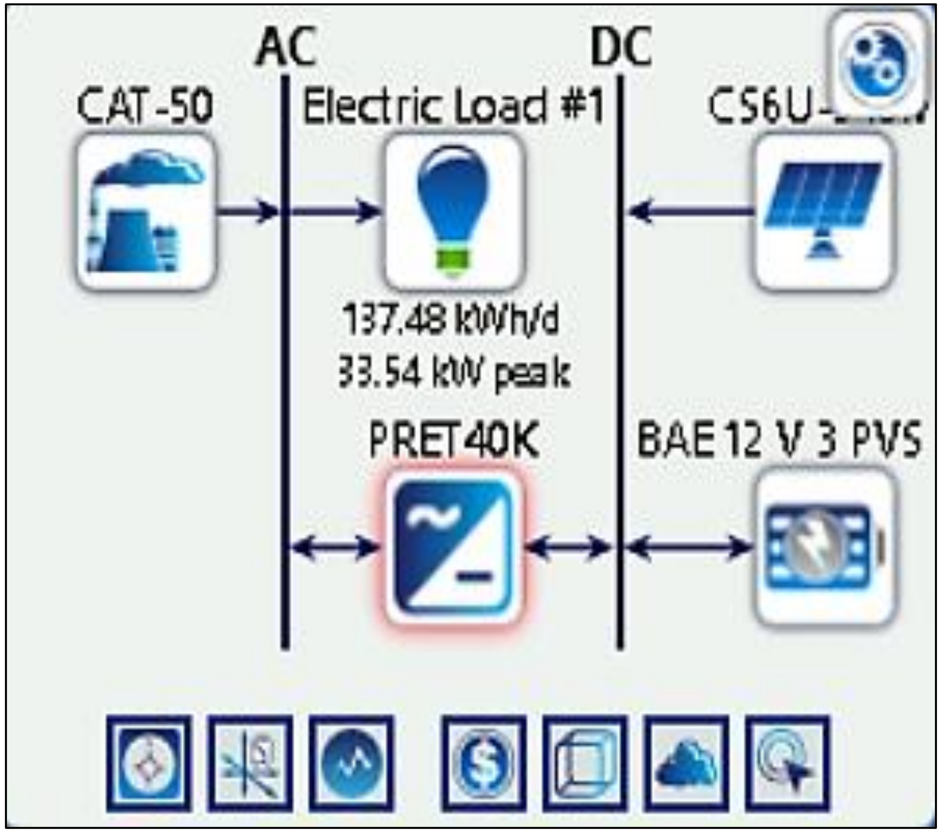
- During simulation, HOMER Pro conducts hour-by-hour assessments throughout the year to evaluate the technological feasibility of proposed systems.

- The software evaluates key life cycle costs including acquisition, repair, service, and maintenance.



System Design

- The load profile determined above for the summer and winter months is given as input to Homer Pro.
- The annual average load per day is computed as 137.48 kWh/day.
- The Peak Load is 33.54 kW peak.



$$\text{Diversity factor} = \sum \frac{\text{Individual maximum demand}}{\text{maximum demand of the aggregated system}}$$

Electricity Generation Analysis

Simulation Results

System Architecture: PRETTL REFUsol40K (38.3 kW)
CanadianSolar MaxPower CS6U-340M (69.3 kW) HOMER Cycle Charging
BAE SECURA SOLAR 12 V 3 PVS 210 (210 strings)

Total NPC:	$102,310.00
Levelized COE:	$0.1578
Operating Cost:	$2,093.01

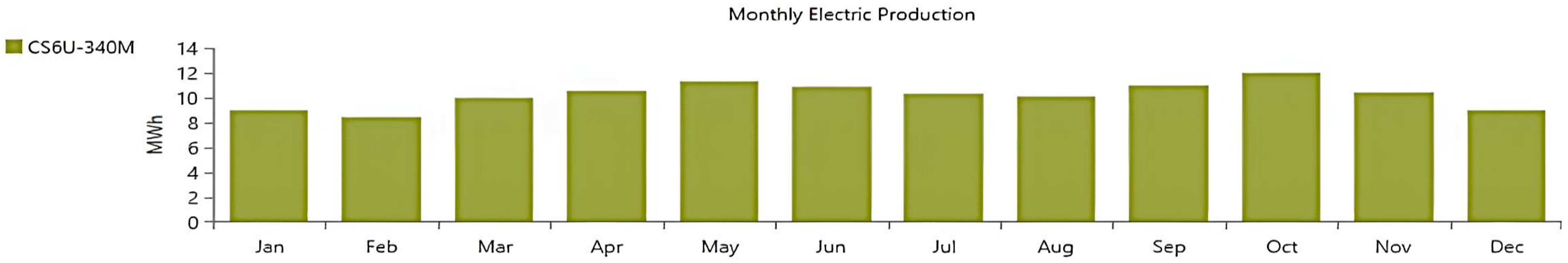
PRETTL REFUsol40K Emissions
Cost Summary Cash Flow Compare Economics Electrical Renewable Penetration BAE SECURA SOLAR 12 V 3 PVS 210 CanadianSolar MaxPower CS6U-340M

Production	kWh/yr
CanadianSolar MaxPower CS6U-340M	123,077
Total	123,077

Consumption	kWh/yr	%
AC Primary Load	50,149	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	50,149	100

Quantity	kWh/yr	%
Excess Electricity	67,237	54.6
Unmet Electric Load	31.2	0.0621
Capacity Shortage	46.1	0.0919

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	4,916	%



Create Proposal Time Series Plot Other...

Results of system optimization in HOMER Pro.

System Structure	Solar Panel (kW)	Diesel Genset (kW)	Battery Bank (No.)	Converter (kW)	NPC (USD)	COE (USD)	Operating expenses (USD/Year)	Primary Investment (USD)
PV-BB-Converter	69.3		210	38.3	0.102 M	0.158	2093	75,253
PV-Genset-BB-Converter	60.5	40	187	38.1	0.104 M	0.161	2391	73,452
PV-Genset-Converter	300	40		40.4	1.70 M	2.62	118,520	166,710
Genset		40		40.4	2.44 M	3.77	188,407	166,710

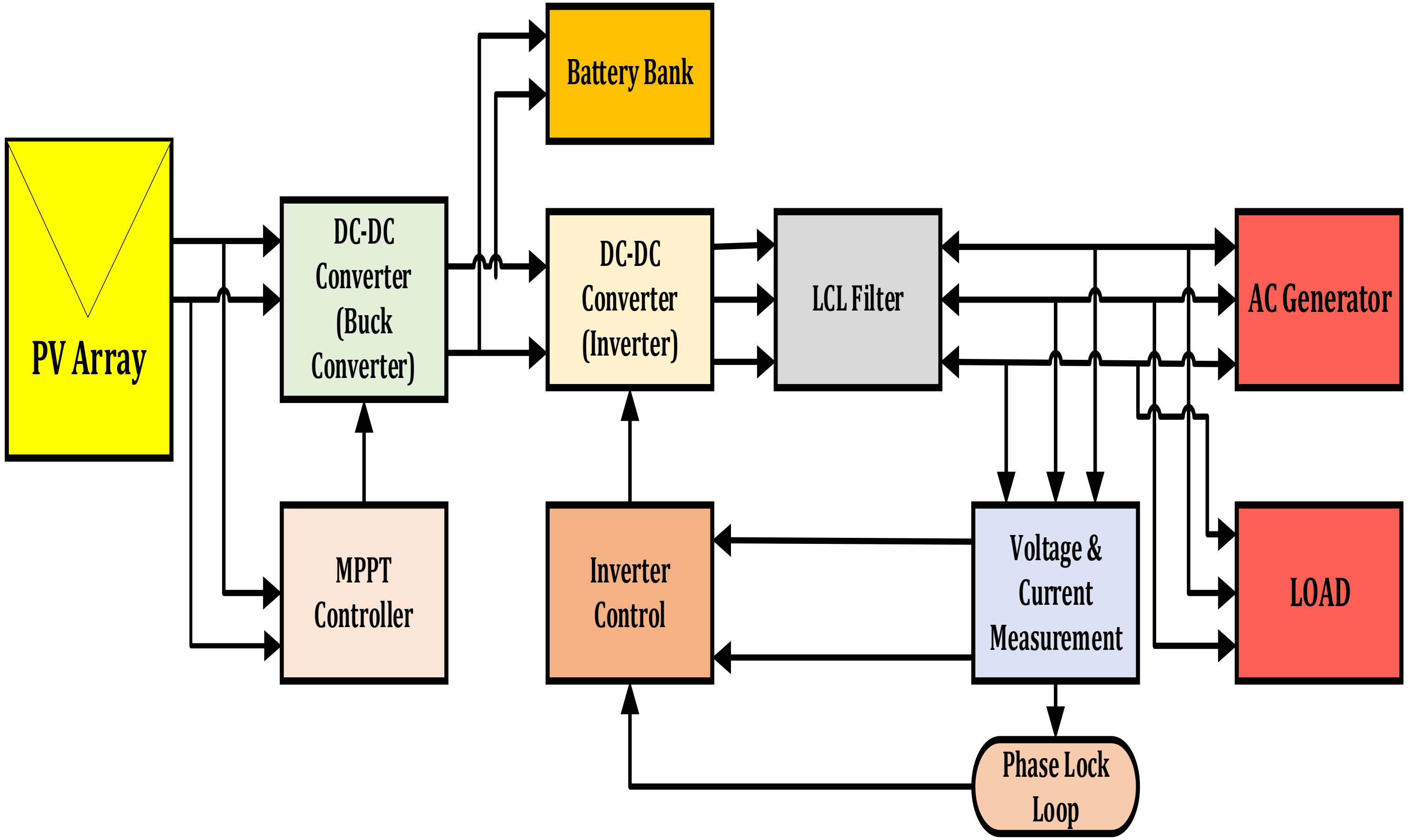
Sensitivity analysis by variations in the solar GHI.

Solar Irradiance ($kWh/m^2/day$)	System Design	PV (kW)	Diesel Genset (kW)	Battery Bank (No. of Batteries)	Converter (Kw)	NPC (USD)	COE (USD/kWh)	Operating Cost (USD/year)	Initial Capital (USD)	Renewable Energy Fraction (%)	CO2 Emissions (kg/year)
0	DG	0	40	0	0	12.1 M	18.60	931,949	17,014	0	102,531
1	PV-DG-BB-Converter	404	40	216	45.6	371,294	0.572	8540	260,896	99.7	184
2	PV-BB-Converter	197	0	260	90.3	207,804	0.320	4252	152,839	100	0
3	PV-BB-Converter	115	0	273	122	152,857	0.236	3130	112,839	100	0
4	PV-BB-Converter	93.3	0	227	90	125,222	0.193	2564	92,077	100	0
5.08	PV-BB-Converter	69.3	0	210	38.3	102,310	0.158	2093	75,253	100	0
6	PV-BB-Converter	67.3	0	180	72.1	94,518	0.146	1935	69,497	100	0
7	PV-BB-Converter	55.5	0	176	54.5	84,533	0.130	1731	62,162	100	0
8	PV-BB-Converter	44.1	0	183	65.1	78,358	0.121	1605	57,612	100	0
9	PV-BB-Converter	40.8	0	176	61.9	74,174	0.114	1519	54,535	100	0
10	PV-BB-Converter	49.2	0	136	73.7	70,747	0.109	1450	52,006	100	0
11	PV-BB-Converter	43	0	136	64.9	66,039	0.102	1353	48,547	100	0

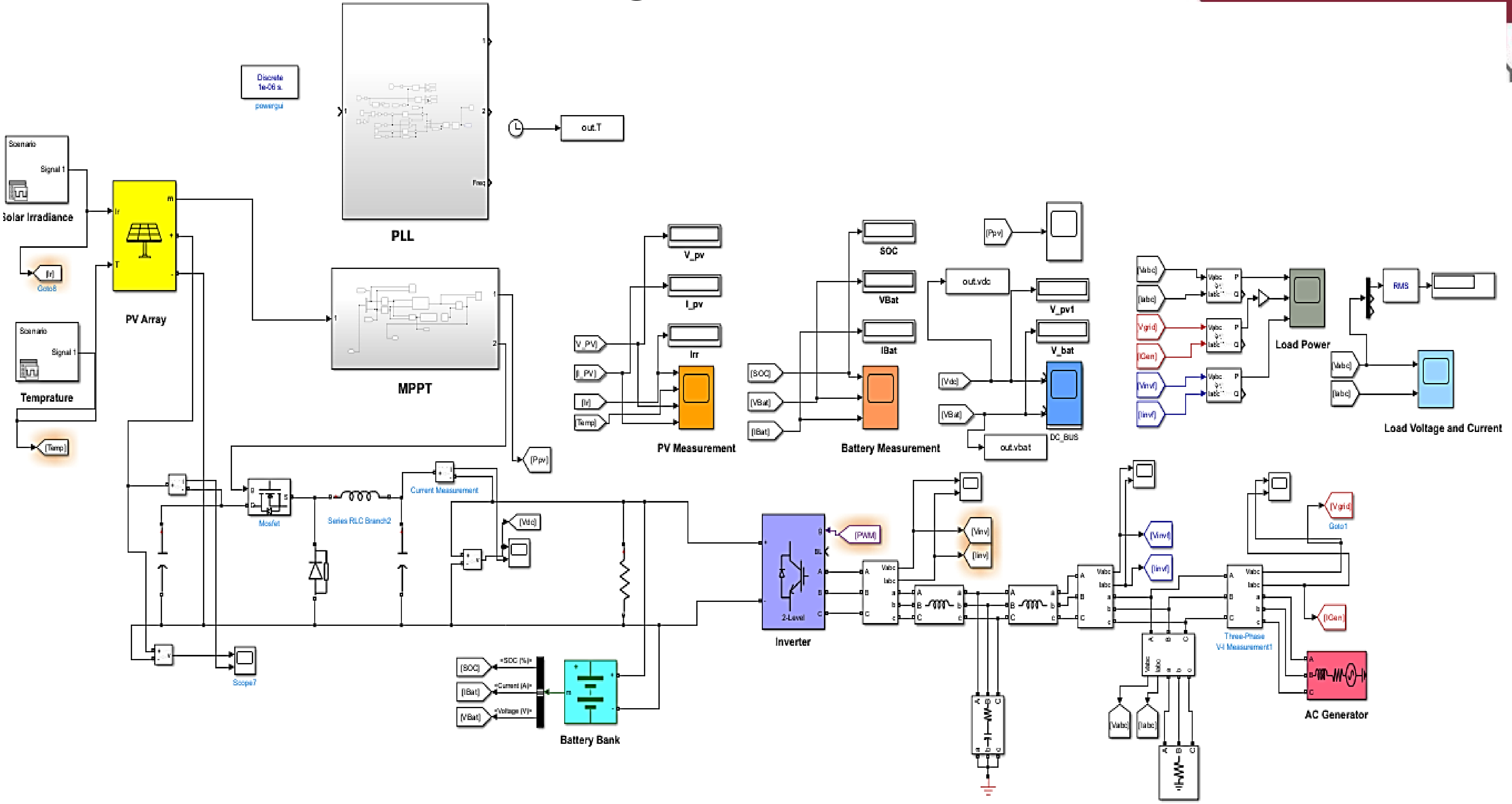
Dynamic System Modeling in MATLAB/Simulink

MATLAB/Simulink Modeling

- The primary building blocks used to model the hybrid power system
- PV Panels
- MPPT Controller
- DC-DC Converter (Buck Converter)
- DC-AC Inverter
- LCL Filter
- Battery Bank and its Charge Controller
- PLL Loop
- Synchronous Generator
- Variable Load



MATLAB/Simulink Modeling



MATLAB/Simulink Modeling

- The dynamic modeling of a photovoltaic (PV) system involves simulating its performance under varying atmospheric conditions based on the ASTM G173 spectrum.

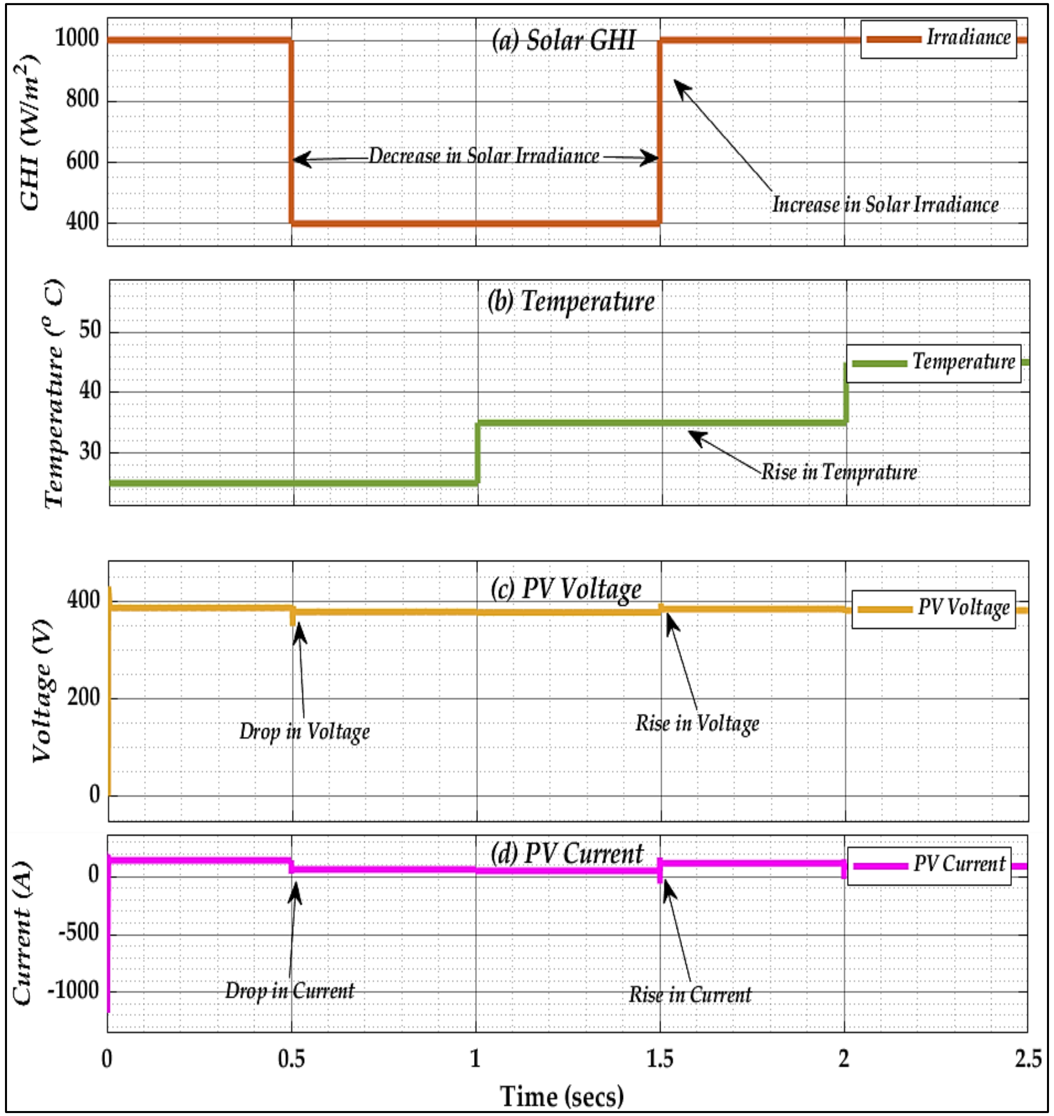
- An initial irradiance value of around 1000 W/m^2 is typically set to simulate standard solar radiation conditions.

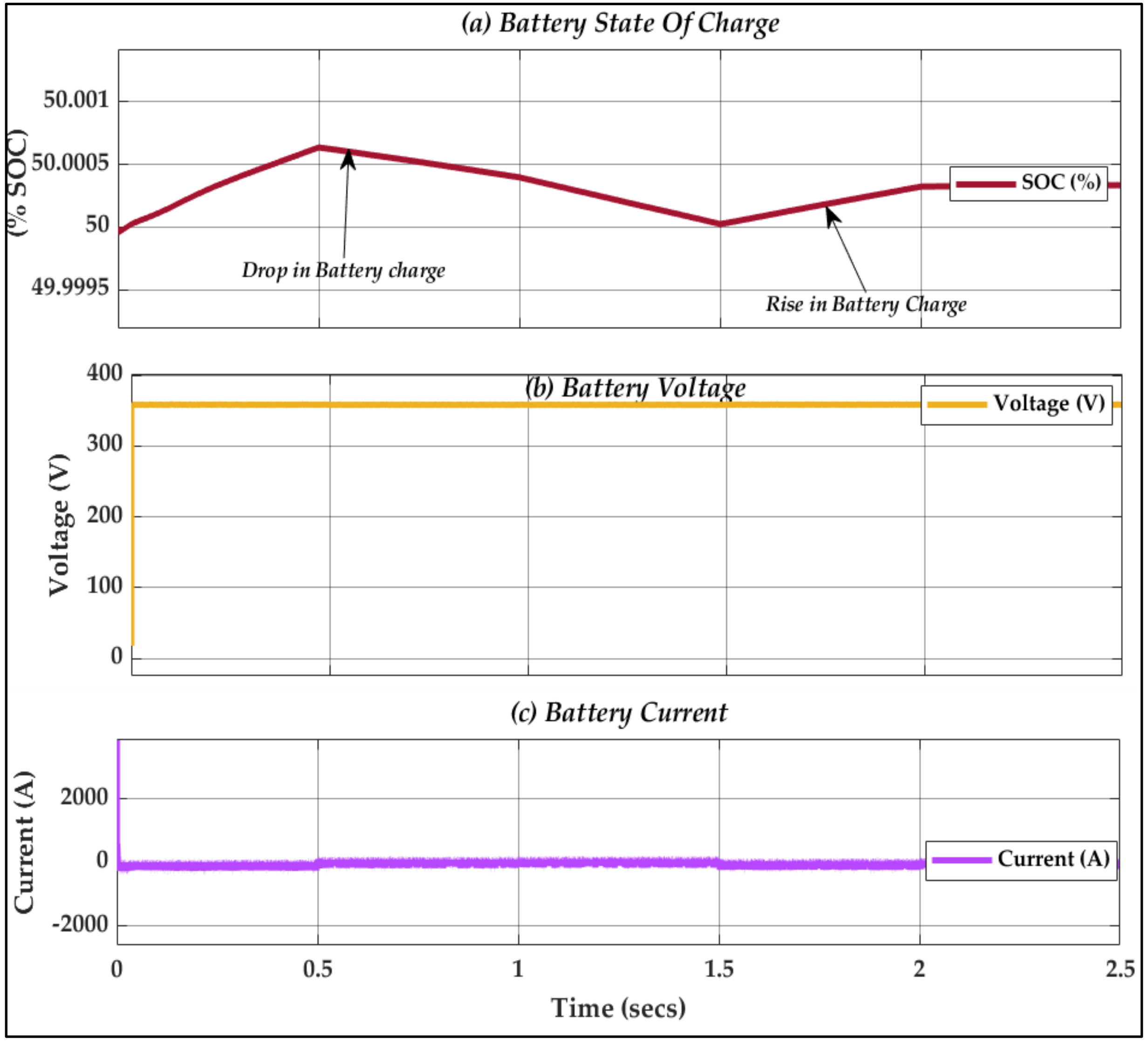
- Solar cell temperatures in simulations may fluctuate between 25°C and 60°C, with higher temperatures potentially increasing current output due to enhanced electron excitation.

- As irradiance levels decrease, voltage and current levels drop, while increased temperatures also result in reduced current and voltage.

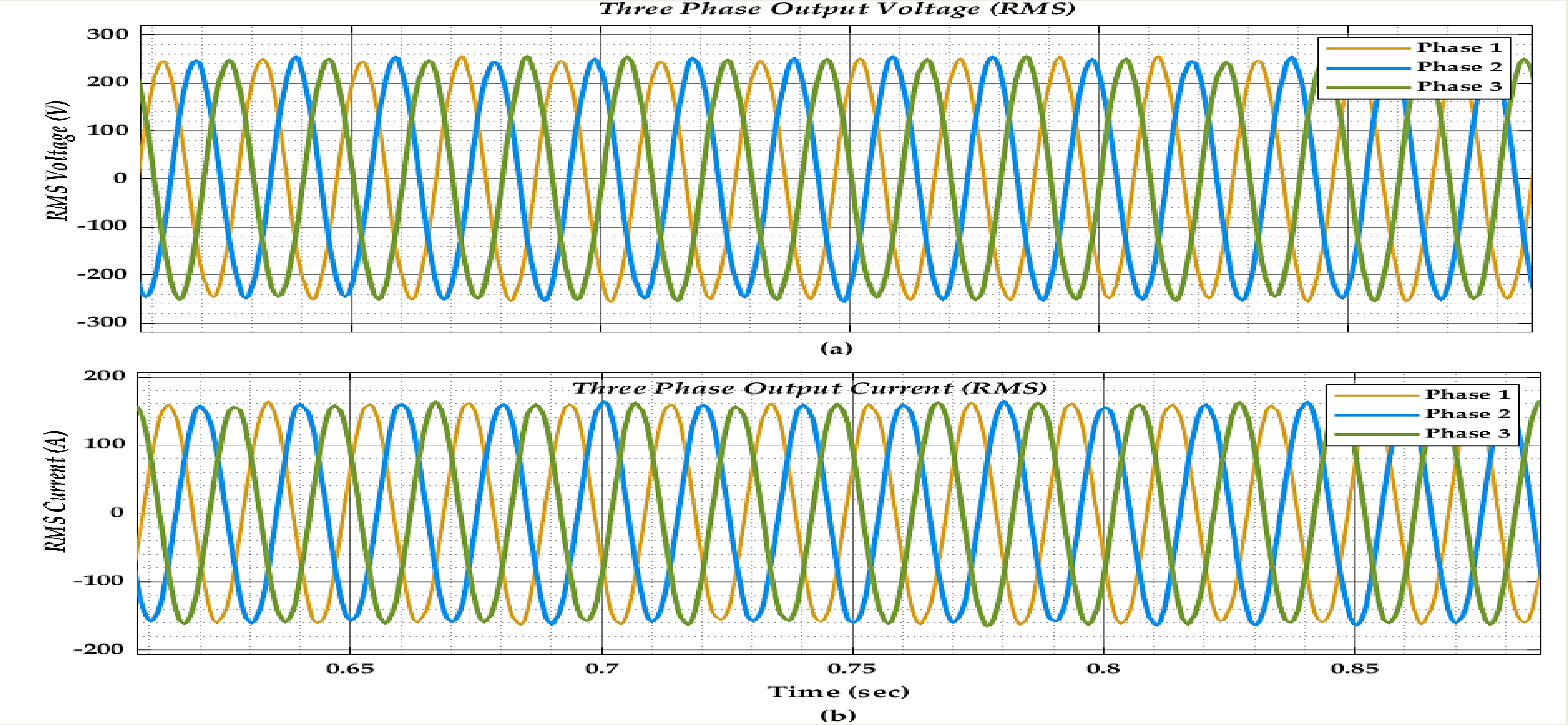
- Conversely, higher GHI levels lead to increased voltage output from the PV array.

Dynamic Response and State of Battery Charge





Three-Phase Output Voltage



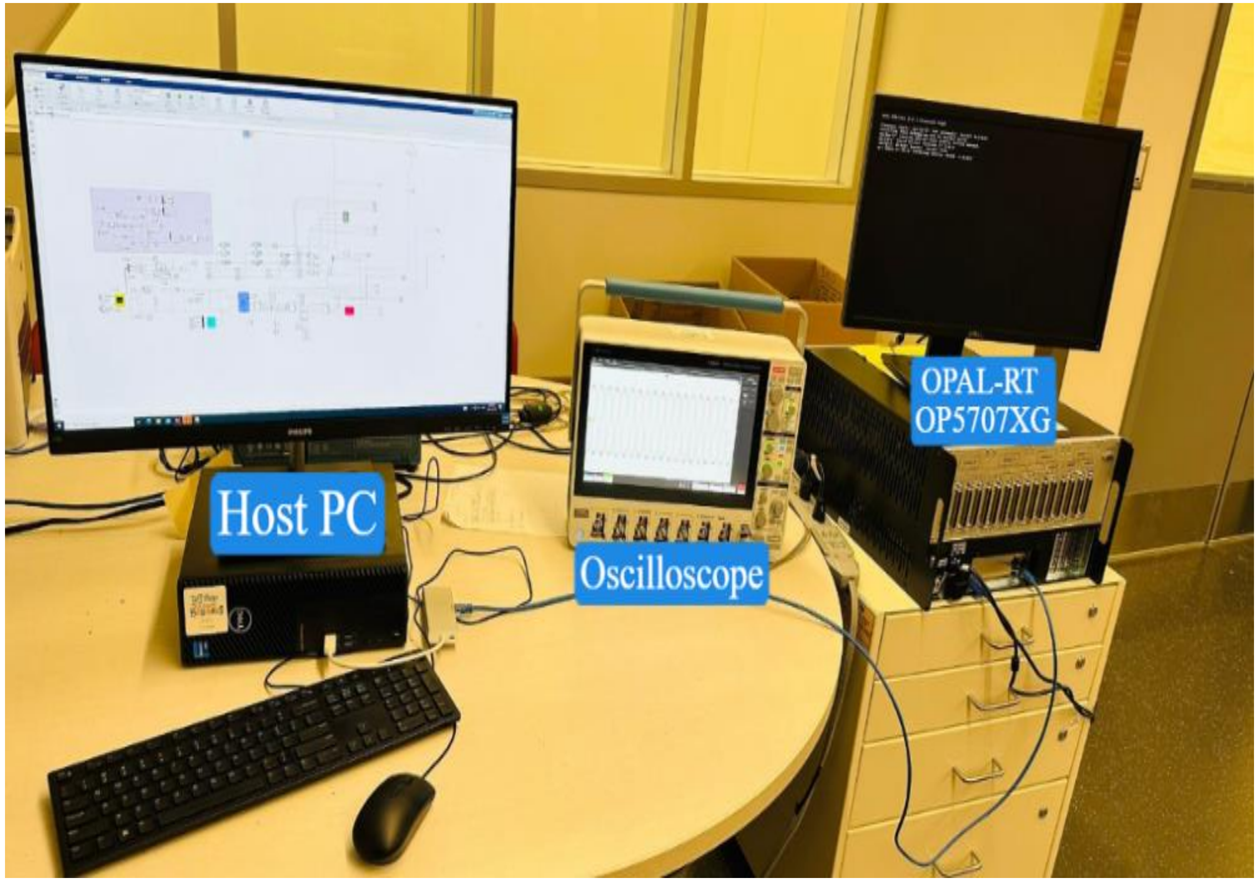
Experimental Validation Using Hardware in Loop

- The OP5707XG by OPAL-RT Technologies is an advanced real-time simulator that uses FPGA technology to provide fast and accurate simulations with minimal latency.

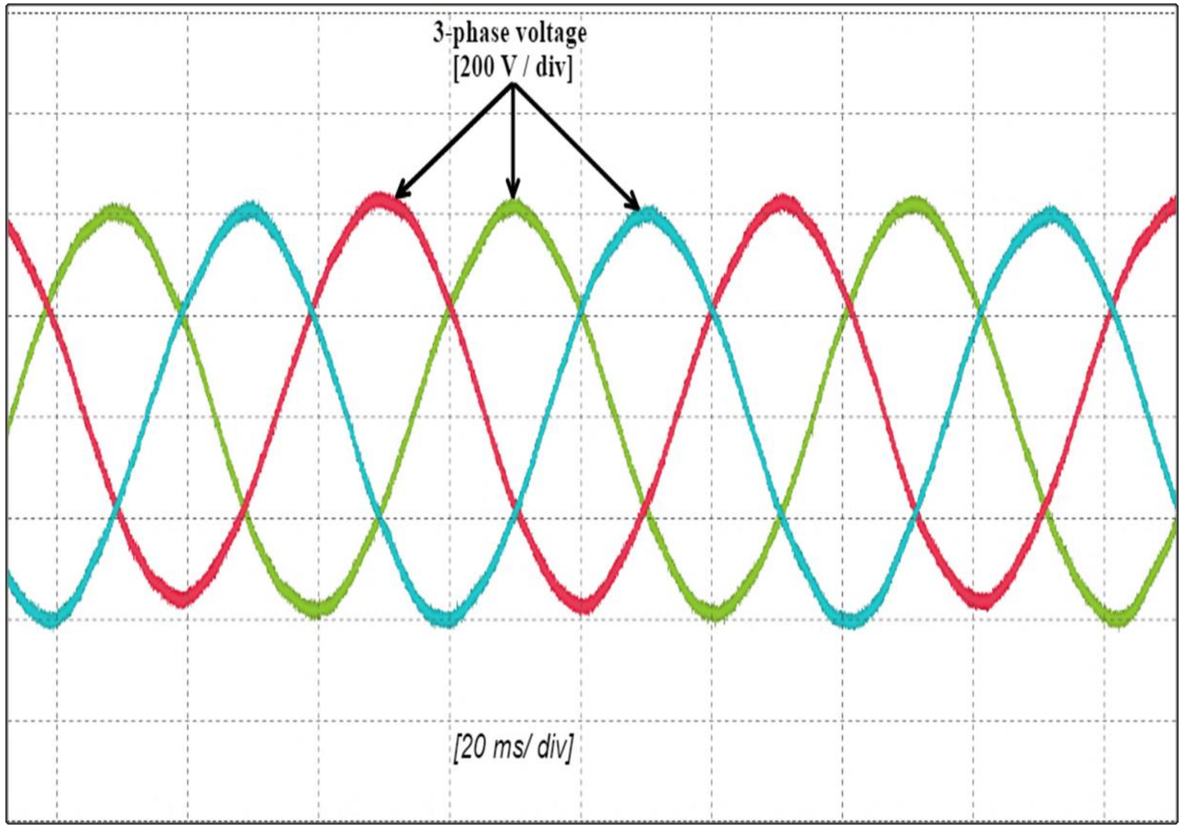
- It is particularly effective in hardware-in-the-loop (HIL) checking for various applications, including photovoltaic (PV) systems.

- The simulator features powerful processors and precise input/output (I/O) interfaces, which are vital for accurately replicating load current and voltage dynamics.

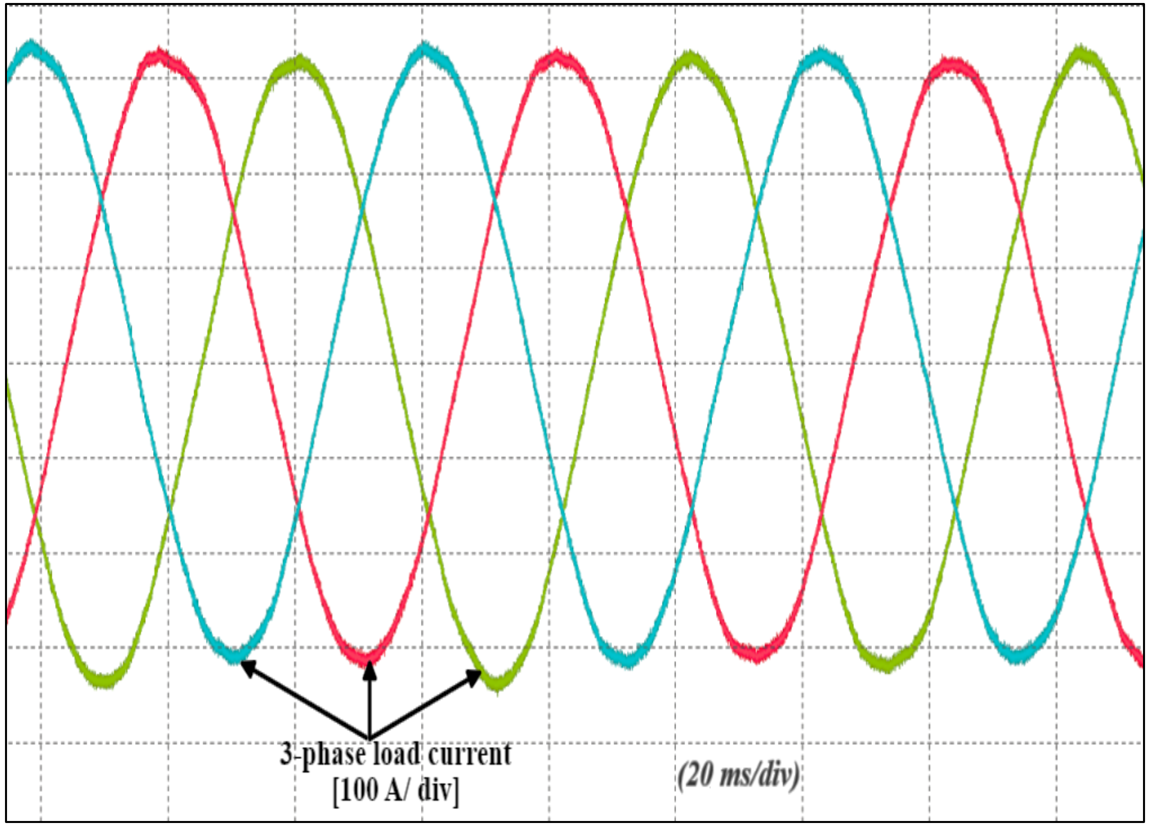
- This accurate replication is essential for optimizing the performance of PV systems in real-time.



Experimental Validation Using Hardware in Loop



Three-phase output load voltage



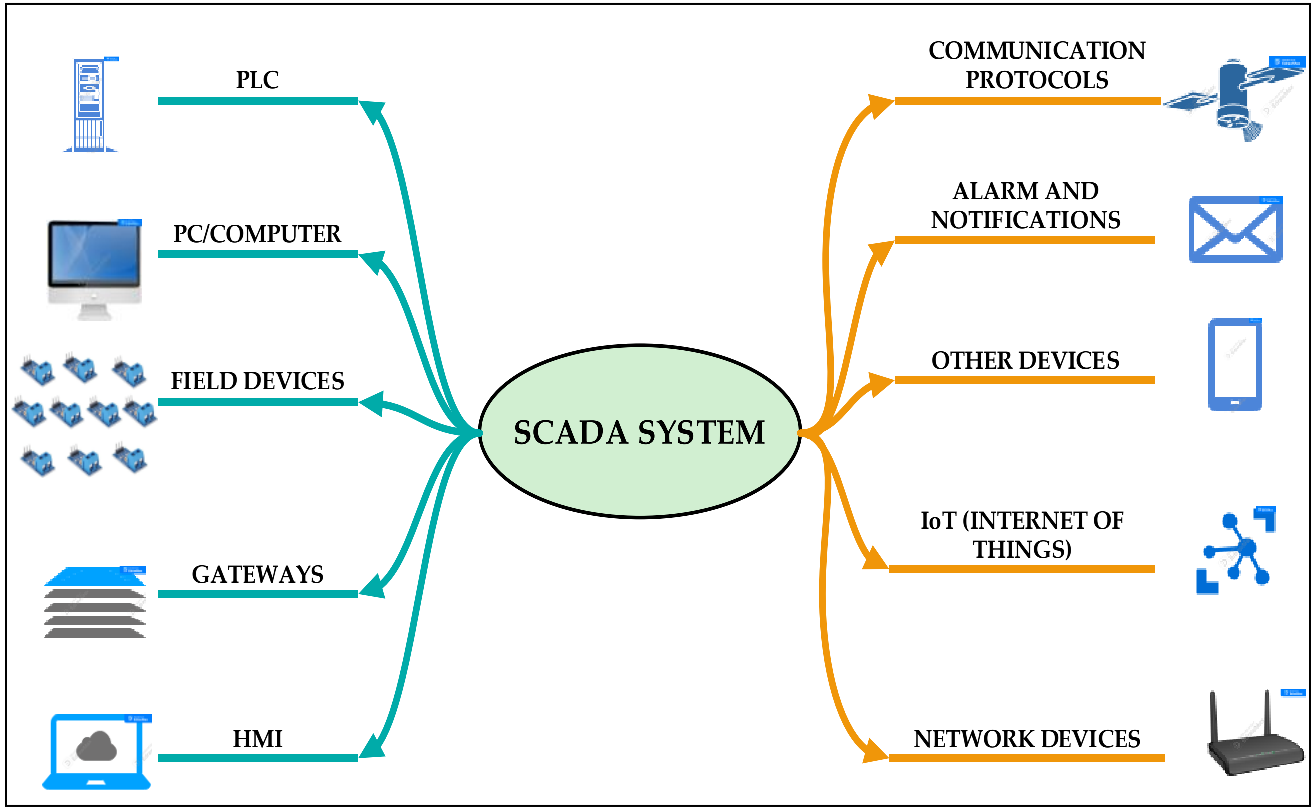
Three-phase output load current

Open Source IoT-Based SCADA using HTTP and TCP/IP Protocols

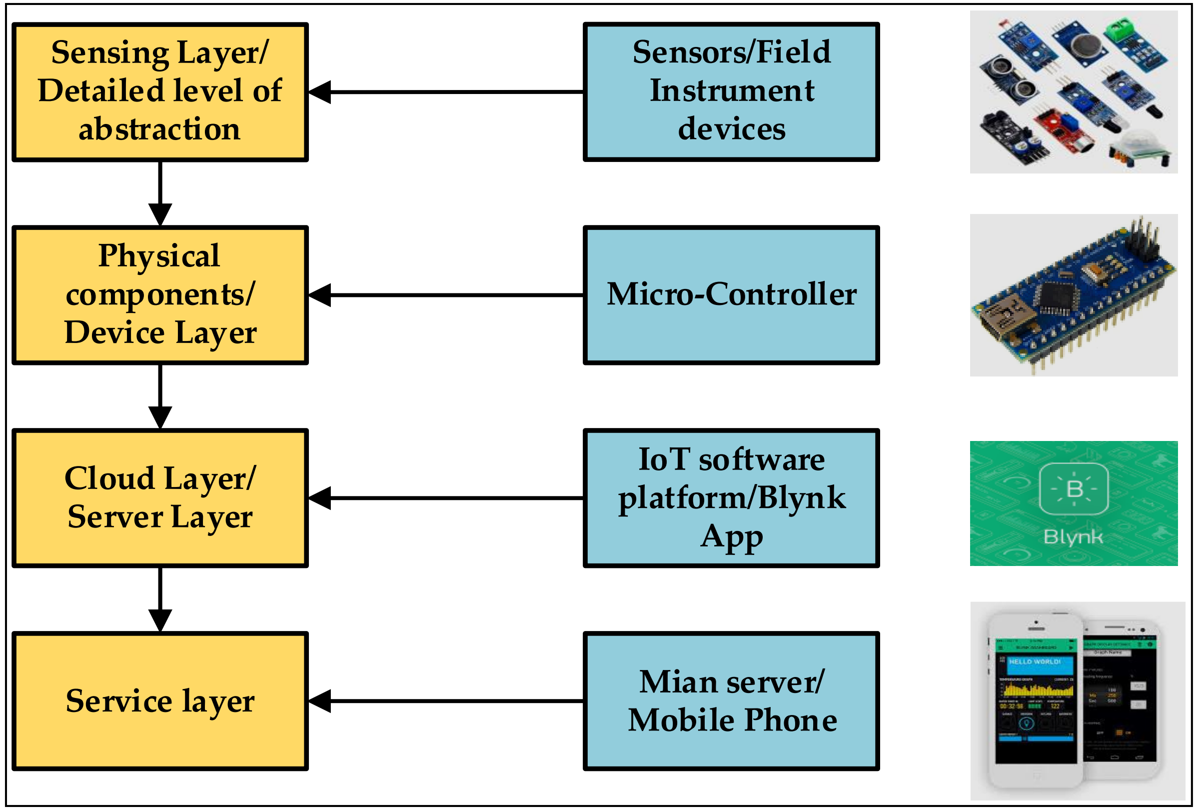
Proposed System Description

- **System Architecture**
- **Utilization of Open-Source Platforms**
- **Data Transfer Mechanism**
- **Low Cost and Low Powered**
- **Dual-Mode Communication**
- **Enhanced Remote Monitoring and Notification System**

Structure and Layer Scheme of SCADA System



Structure of SCADA System



Layer Scheme of SCAD system

Components of the System

- **Microcontrollers:**
- **Arduino Nano**: Central processing unit managing sensor data and communication.
- **ESP-32:** High-performance SoC enabling Wi-Fi and Bluetooth connectivity.

- **Sensors:**
- **Voltage Sensor (ZMPT101B):** Monitors voltage levels.
- **Current Sensor (ACS712):** Measures electrical current.

- **Communication Modules:**
- **GSM SIM800L:** Facilitates remote communication over mobile networks.

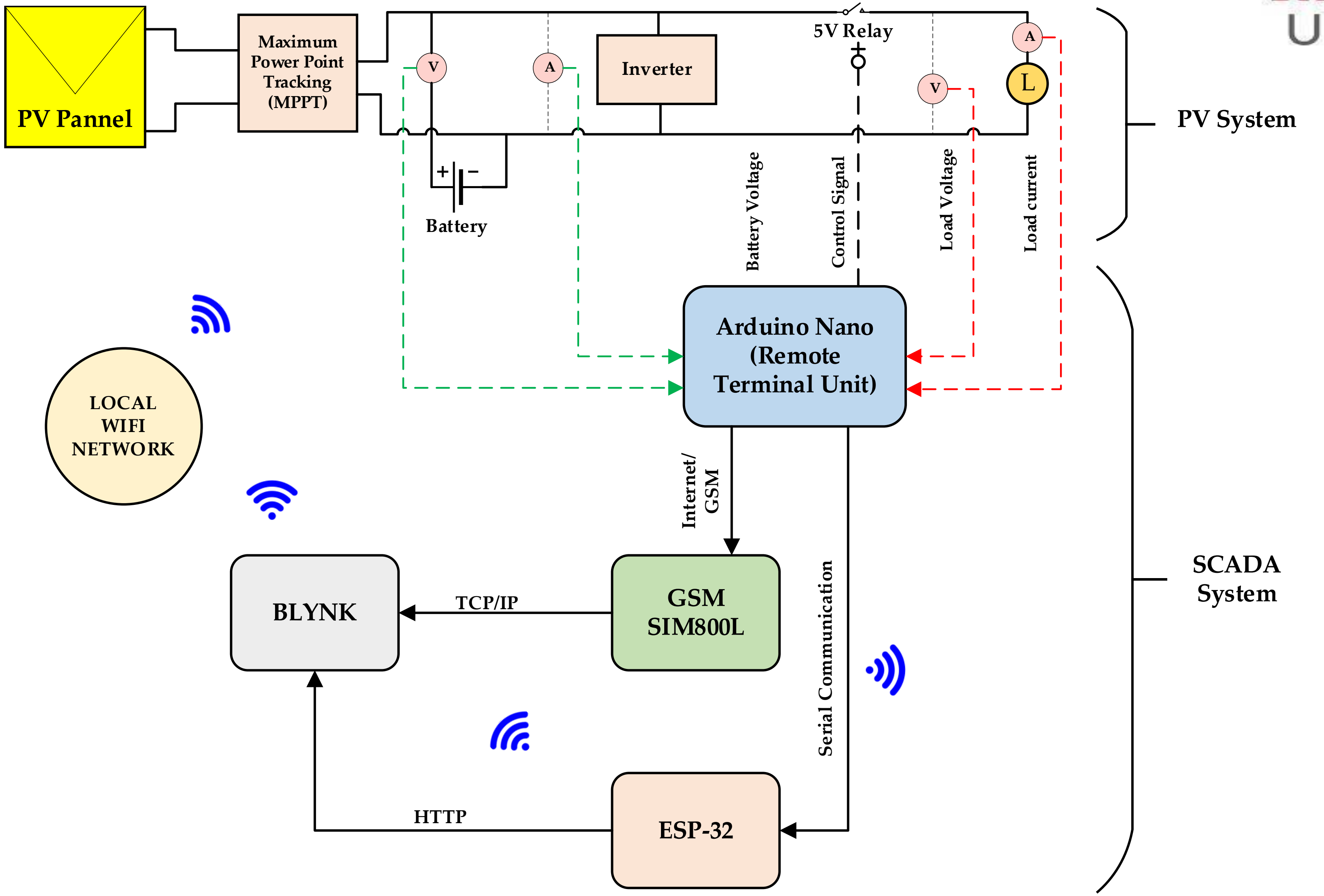
- **Control Relays:**
- **5V Single Channel Relay:** Controls switching operations. - Software and Integration:

- **Arduino IDE:** Development environment for coding and uploading to microcontrollers.

- **Blynk 2.0 App and Web Console:** Interface for real-time monitoring and control.

- **Twilio API:** Enables SMS notifications for remote system alerts.

Design of the Proposed System



Arduino Nano

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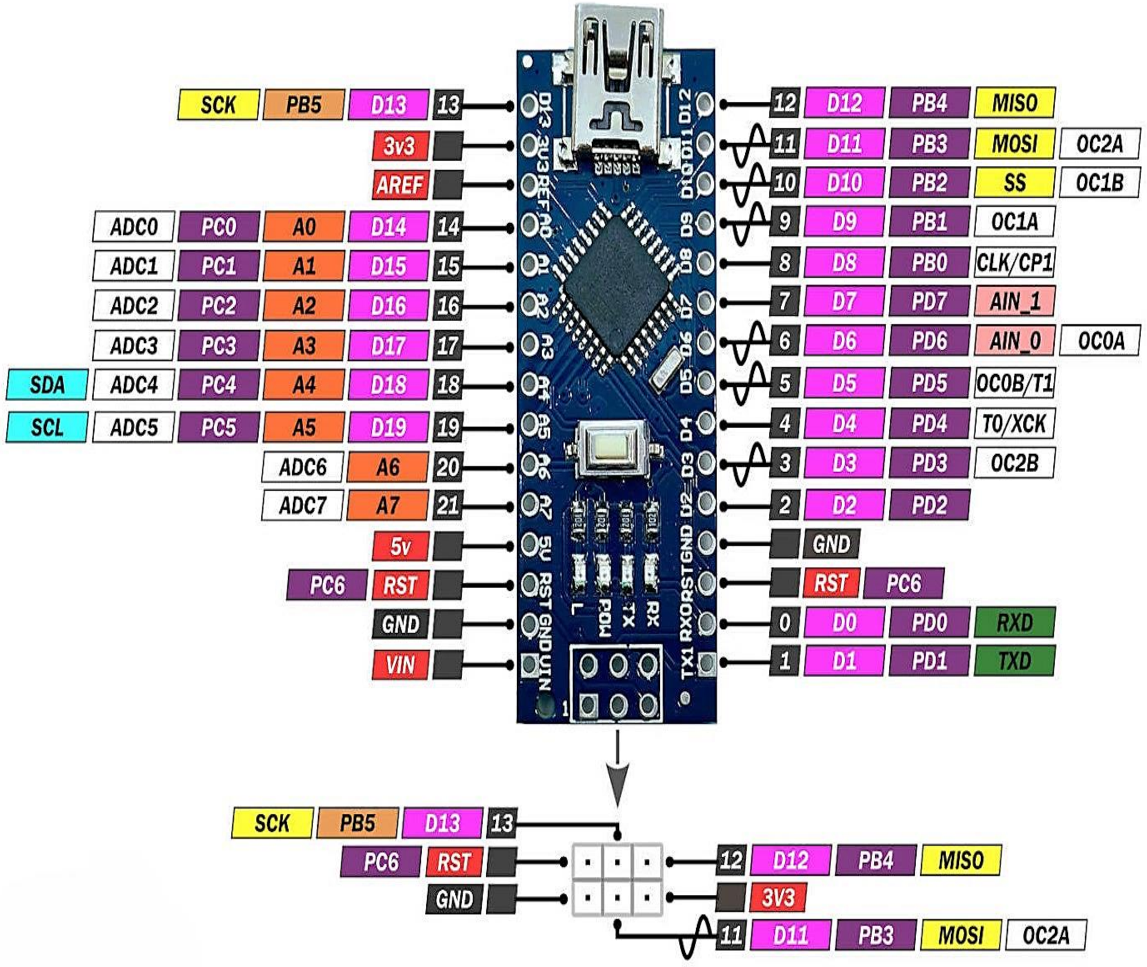
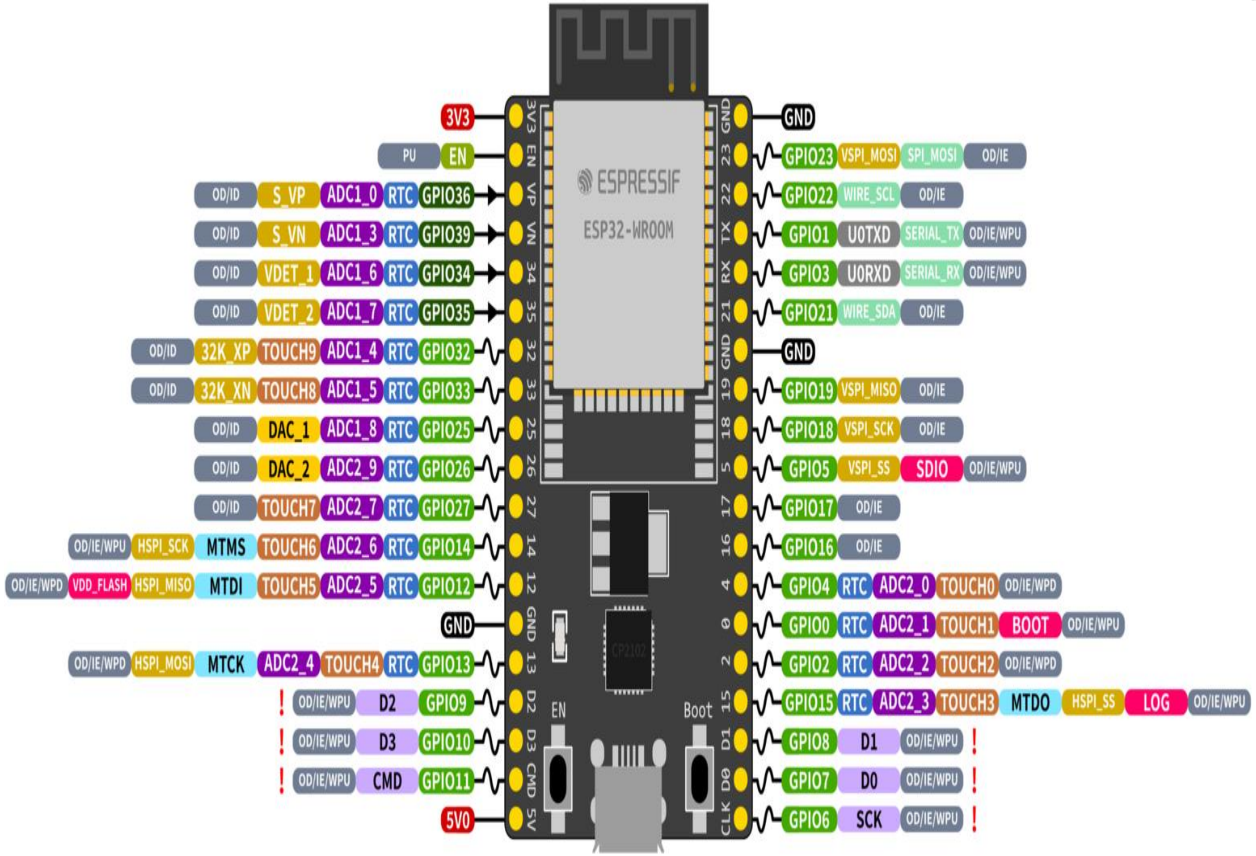
Specifications	Details
Microcontroller	ATmega328P
Operating Voltage & clock speed	5V & 16 MHz
Input Voltage	7-12 V
Digital I/O pins	14 (of which 6 provided PWM)
PWM digital I/O pins	6 (D3,D5,D6,D9,D10,D11)
Analog Input pins	8 (A0 to A7)
Flash memory	32 KB of which 2 KB used by the bootloader
EPROM	1 KB (ATmega328P)
Communication	UART,12C,SPI, Mini-USB

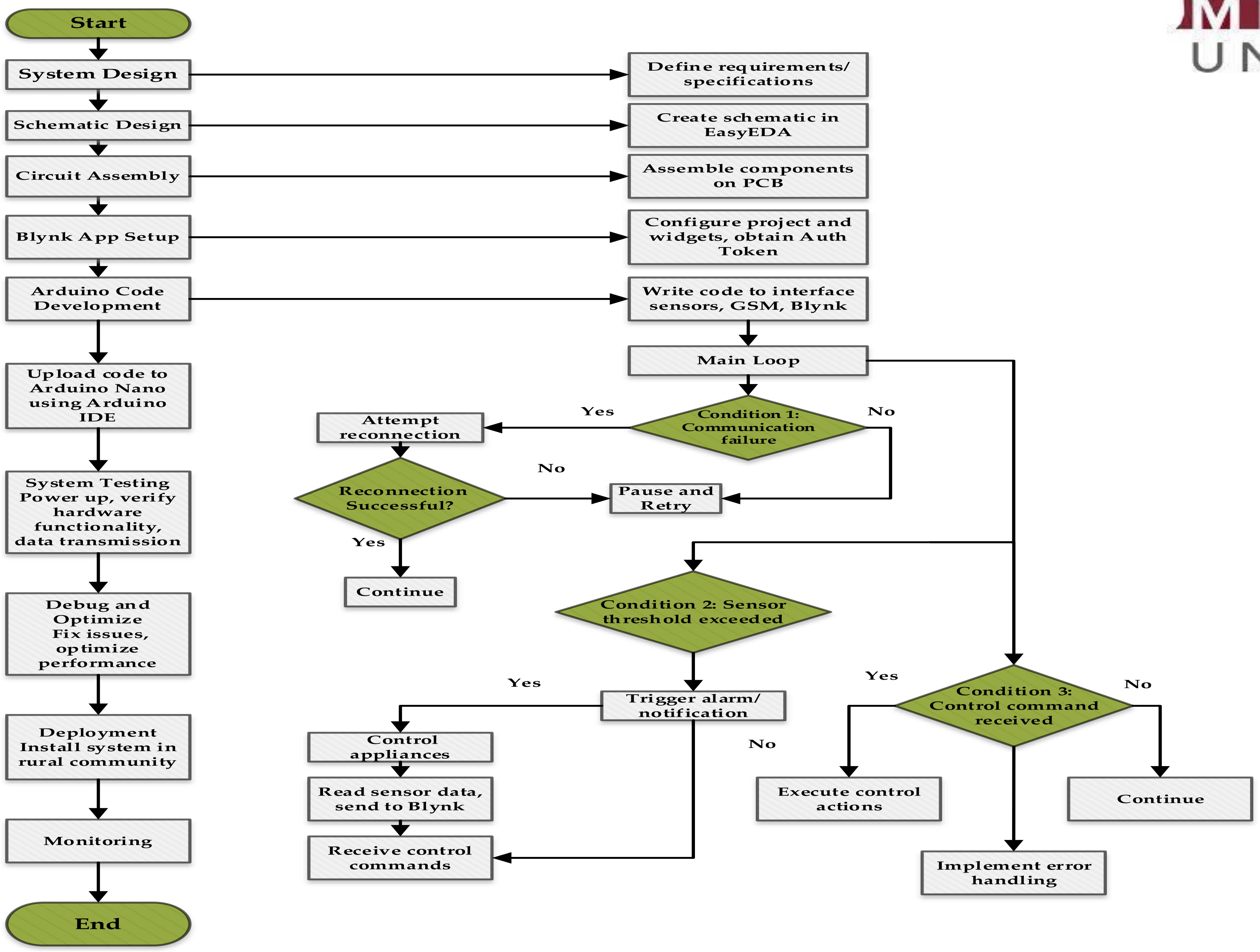


ESP-32 System on Chip (SOC) Microcontroller

Specifications	Details
Processor	Xtensa dual-core 32-bit LX6, up to 240 MHz
Wi-fi	IEEE 802.11 b/g/n, 2.4 GHz
Supply Voltage	3.3 Volts
GPIO Pins	34 GPIO pins
Analog Channels	18 channels (12-bit SAR ADCs)
Digital to Analog	2 channels (8-bit DACs)
Communication Interfaces	SPI, I2C, I2S, UART, CAN, PWM, ADC, DAC



Flow chart of System Working

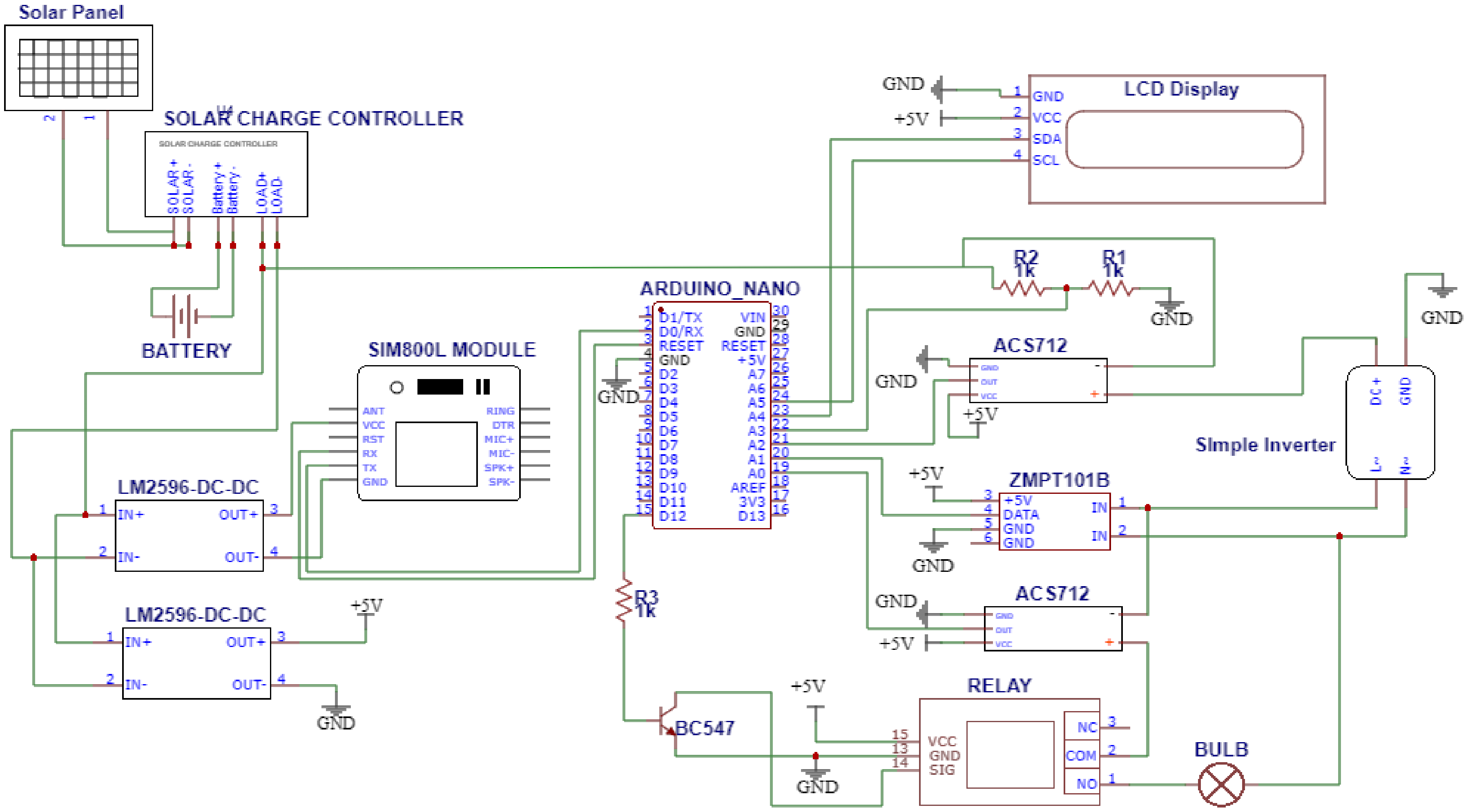


Implementation Strategy

- The IoT system was developed using an Arduino Nano, interfaced with a GSM module (SIM800L) for communication, and integrated with the Blynk app for monitoring.

- The system also incorporates an ESP-32 microcontroller for enhanced connectivity and real-time data transmission, utilizing the Blynk console for remote control.

Arduino Nano with a GSM module SIM800L interfaced with the Blynk app.



Pin Layout

Description	Analog/ Digital	Arduino Nano Pin#
GSM SIM800L	Digital	2,3
PV Voltage	Analog	22
LCD Display	Analog	23,24
ACS 712 Current sensors	Analog	21,19
ZMPT101B	Analog	20
5V Relay	Digital	15

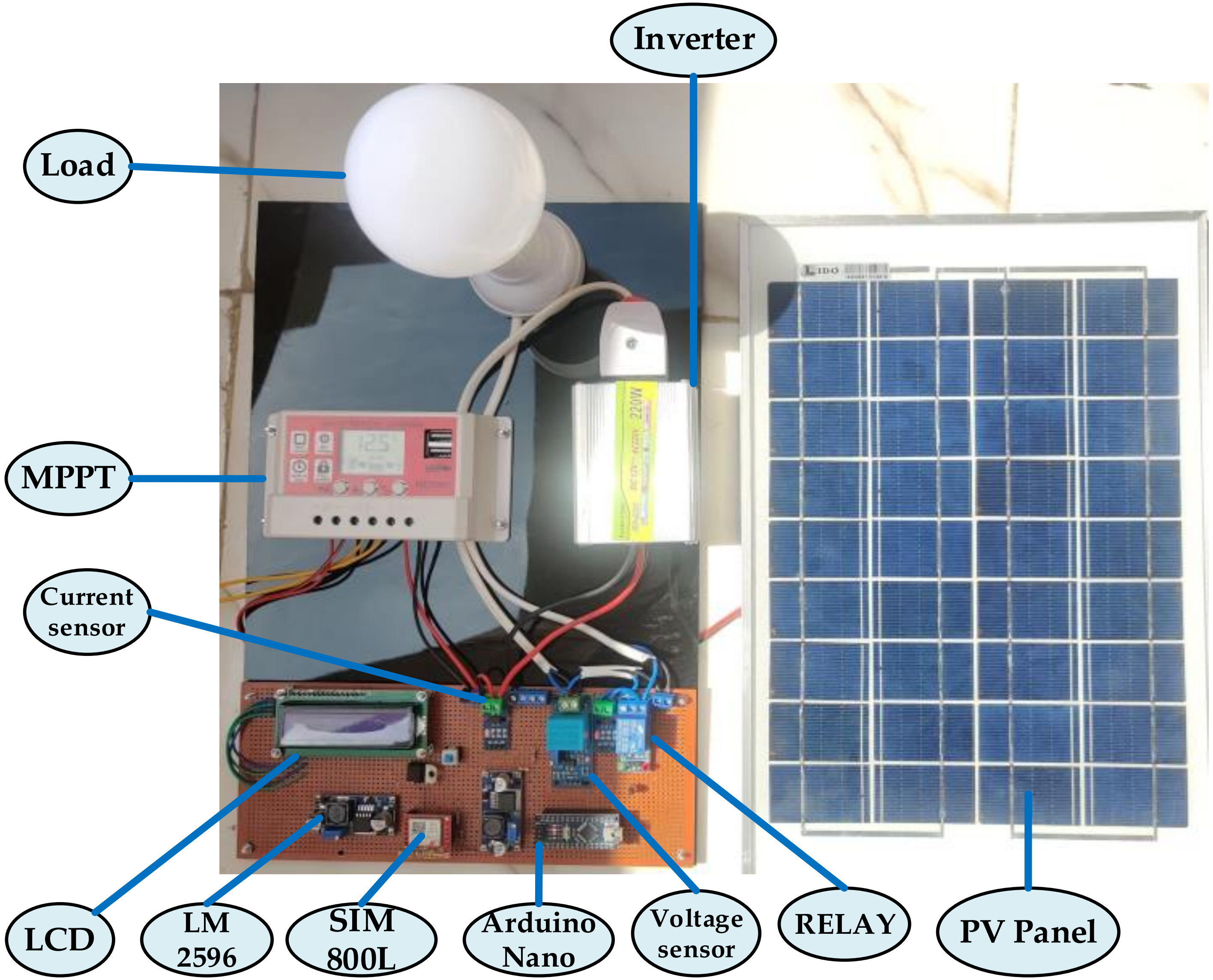
Algorithm of the Proposed System

- **Start**

- **Initialization**: Include libraries, define pins and constants, initialize GSM, LCD, and sensor sensitivity.
- **Setup Function**: Initialize serial communication, GSM, and LCD; connect to Blynk; set pin modes; turn off relay.
- **Main Loop**: Run Blynk, measure DC voltage and current, measure AC voltage and current, update LCD.
- **Function: takeDCvol**: Read and calculate DC voltage; delay 500 ms.
- **Function: takeDCcur**: Read and calculate DC current; print to serial monitor; delay 500 ms.
- **Function: takeACvol**: Get RMS AC voltage; adjust range; print to serial monitor; delay 500 ms.
- **Function: takeACcur**: Get peak-to-peak AC voltage, calculate RMS current; adjust range; print to serial monitor; delay 500 ms.
- **Function: blynkupdate**: Update Blynk virtual pins with sensor readings.
- **Function: LCD update**: Clear LCD; display DC and AC voltage/current values.
- **BLYNK_WRITE Function**: Check V4 value; control relay accordingly.
- **Function: getVPP1**: Read and calculate peak-to-peak voltage; return value.

- **End**

Hardware Setup and Commissioning with Blynk App



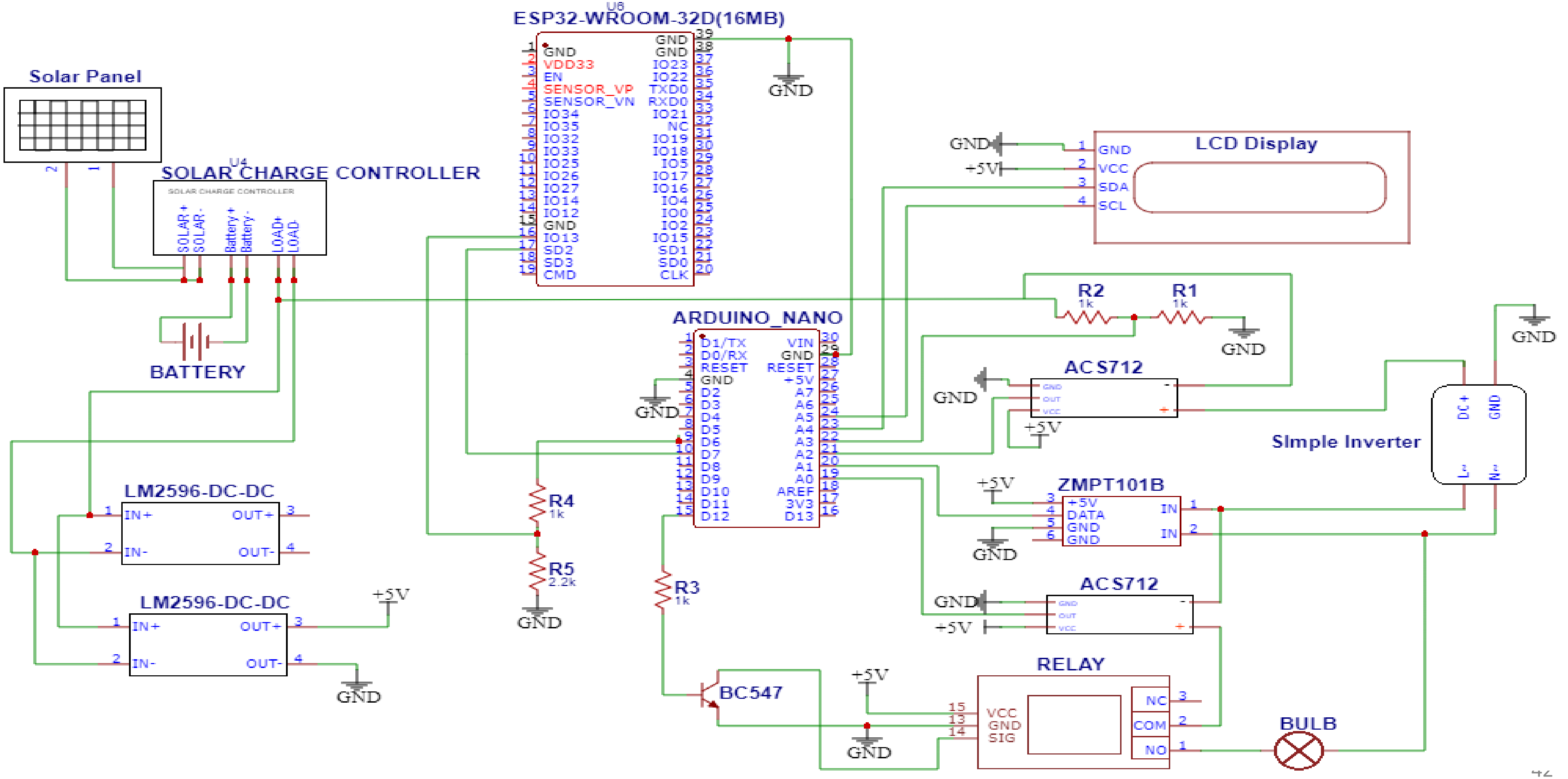
Hardware setup using GSM and Arduino Nano

FID’s values on LCD

PV system FIDs values on the Blynk App Dashboard

PV system FIDs Monitoring on the Blynk App mobile interface

Arduino Nano Serially Interfaced with an ESP-32, Utilizing the Blynk Console.



Hardware Setup

Experimental Setup Location

- Conducted at the Electrical and Computer Engineering Laboratory, Memorial University of Newfoundland and Labrador (MUN), Canada.

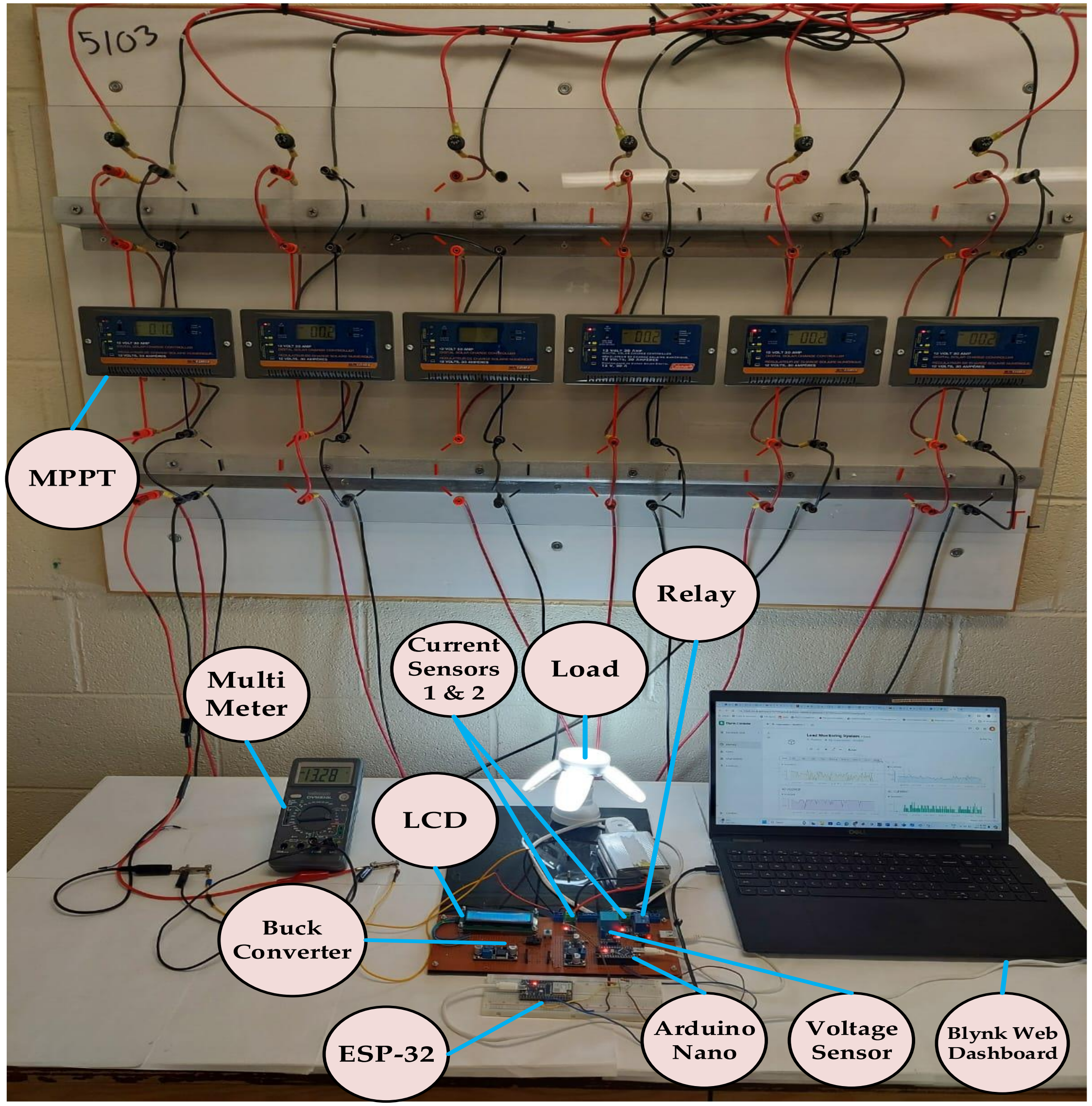
PV Panel Configuration

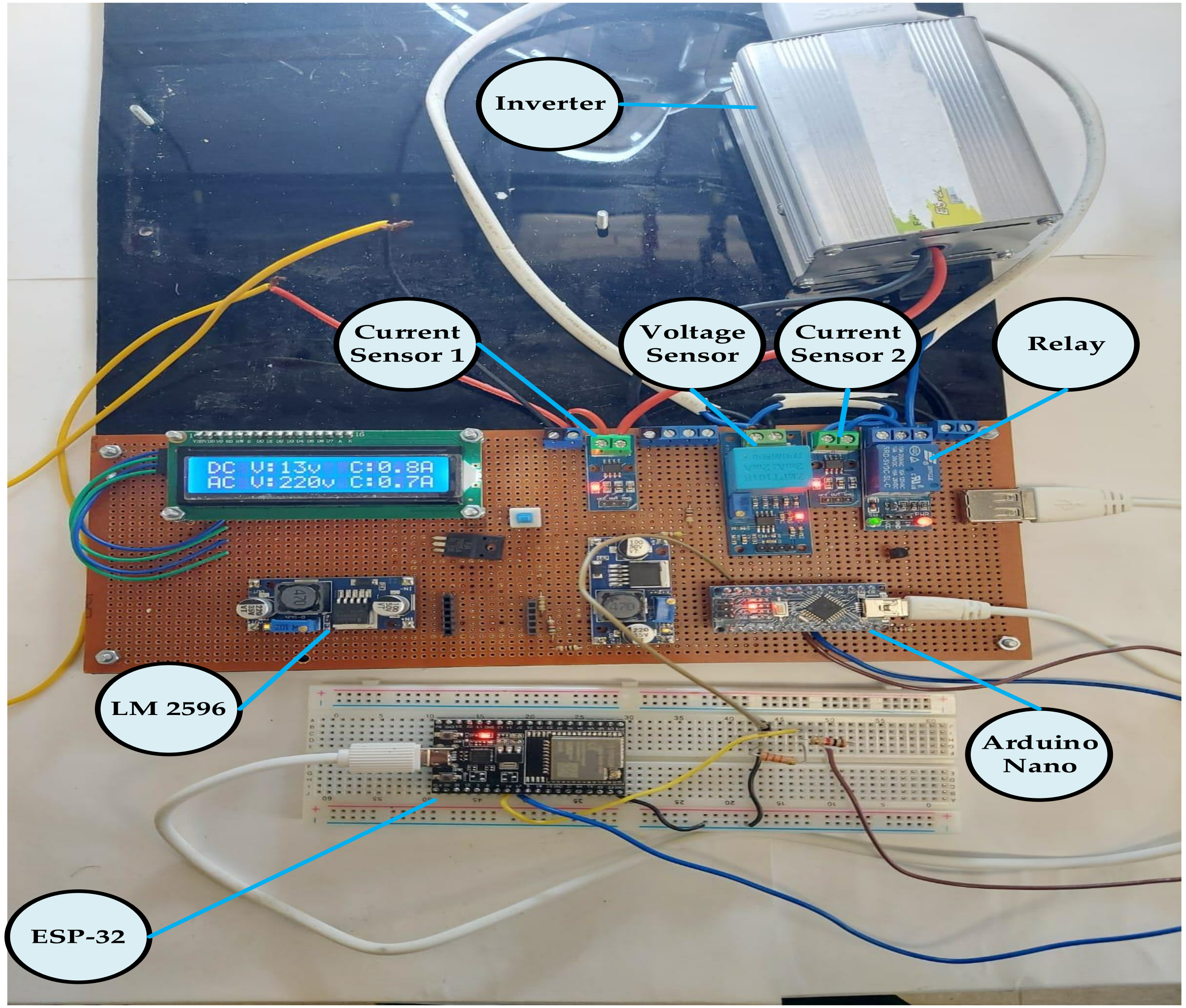
- Twelve PV panels, each generating 130 Watts with a maximum current of 7.6 Amperes.
- For SCADA system evaluation, two PV panels are used to monitor and control electrical load.

Additional System Components:

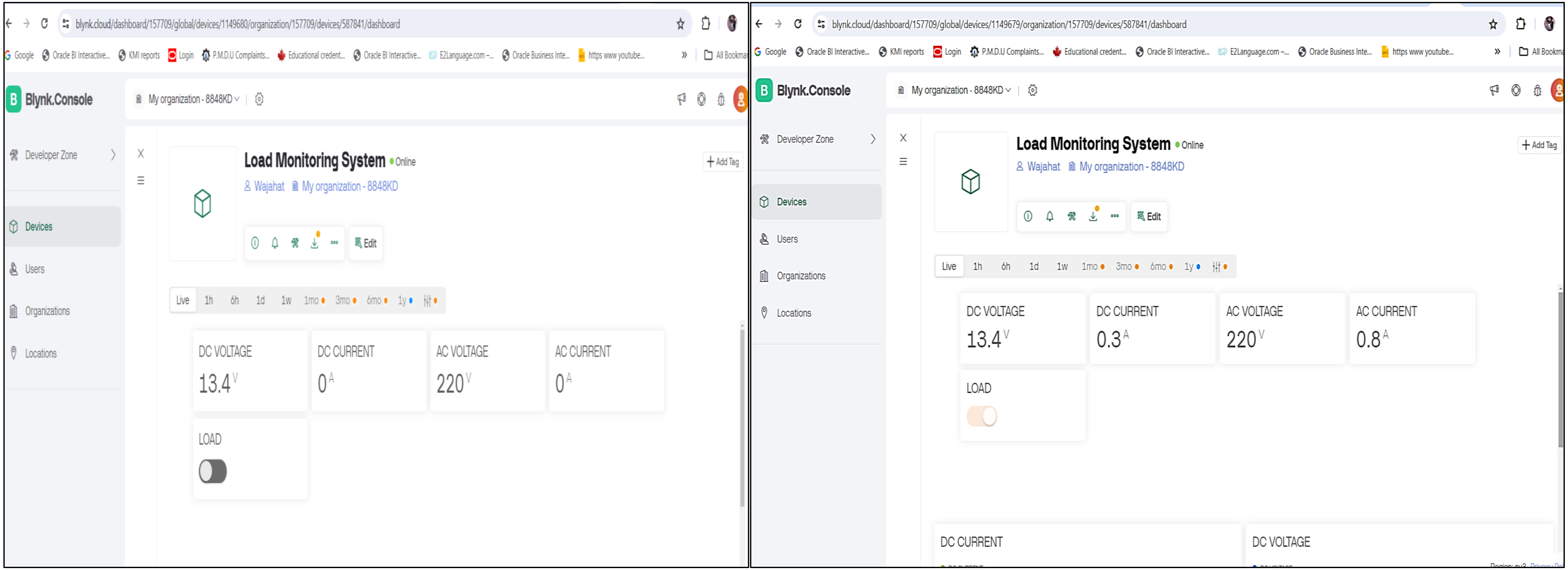
- Includes Maximum PowerPoint Tracking (MPPT) for optimizing energy production.
- Equipped with a battery bank consisting of six 12V, 25A lead-acid batteries.

Hardware Setup



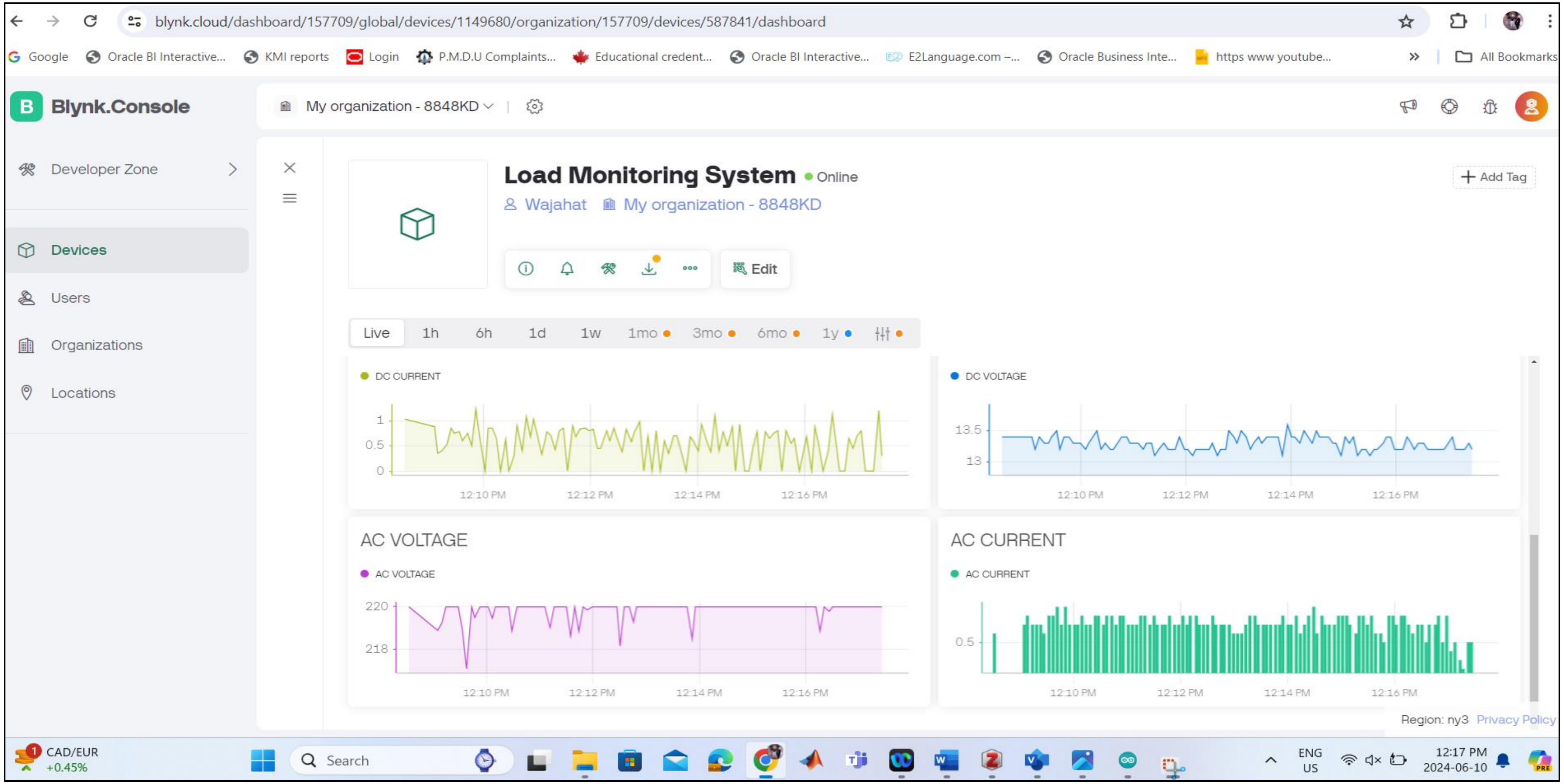


Blynk Console Dashboard ESP-32 and Arduino Nano



Status of the Blynk web dashboard interface in the “OFF” and “ON” states.

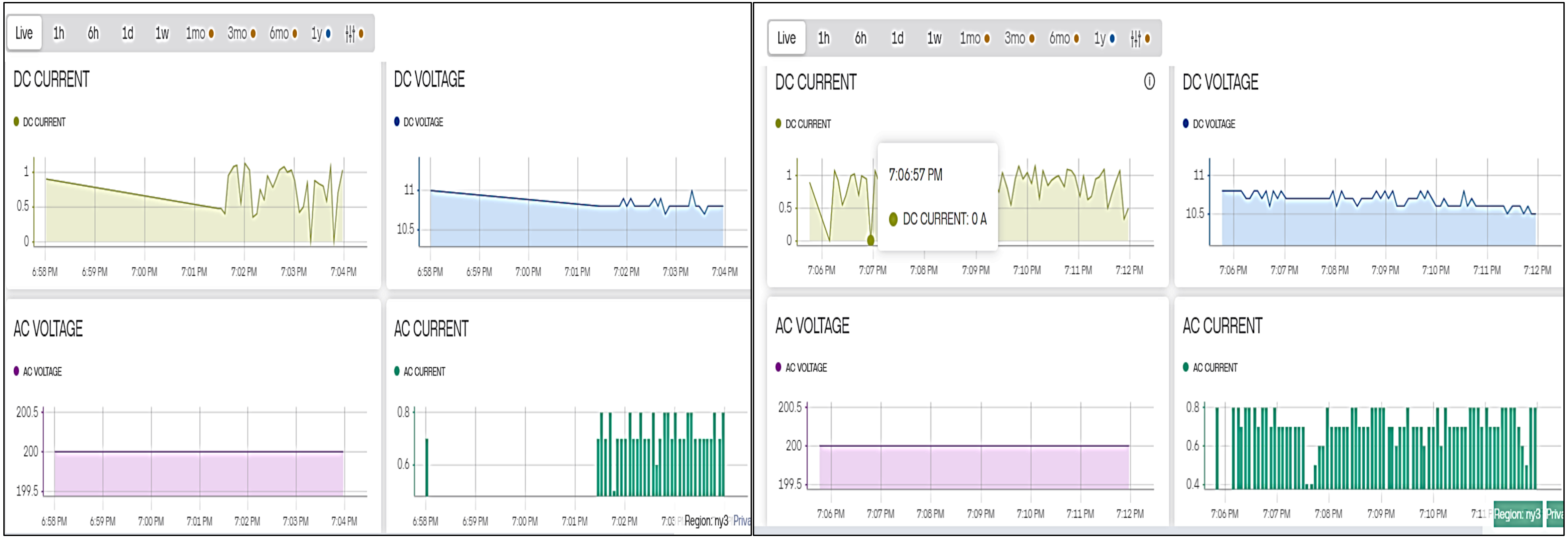
Blynk Console Dashboard ESP-32 and Arduino Nano



Monitoring and Control of the PV system on the Blynk Console Dashboard

System Performance Under Varied Weather Conditions

- **Robustness Assessment**
- The system's resilience was tested across different weather conditions, demonstrating consistent performance in maintaining energy generation and system stability despite fluctuations in environmental factors.



Monitoring and Notifications System

➢ **On-Site Monitoring:**

• **LCD Display:** Real-time updates on key system parameters, including DC and AC voltage and current, with immediate fault detection and reporting.

➢ **Remote Alerts:**

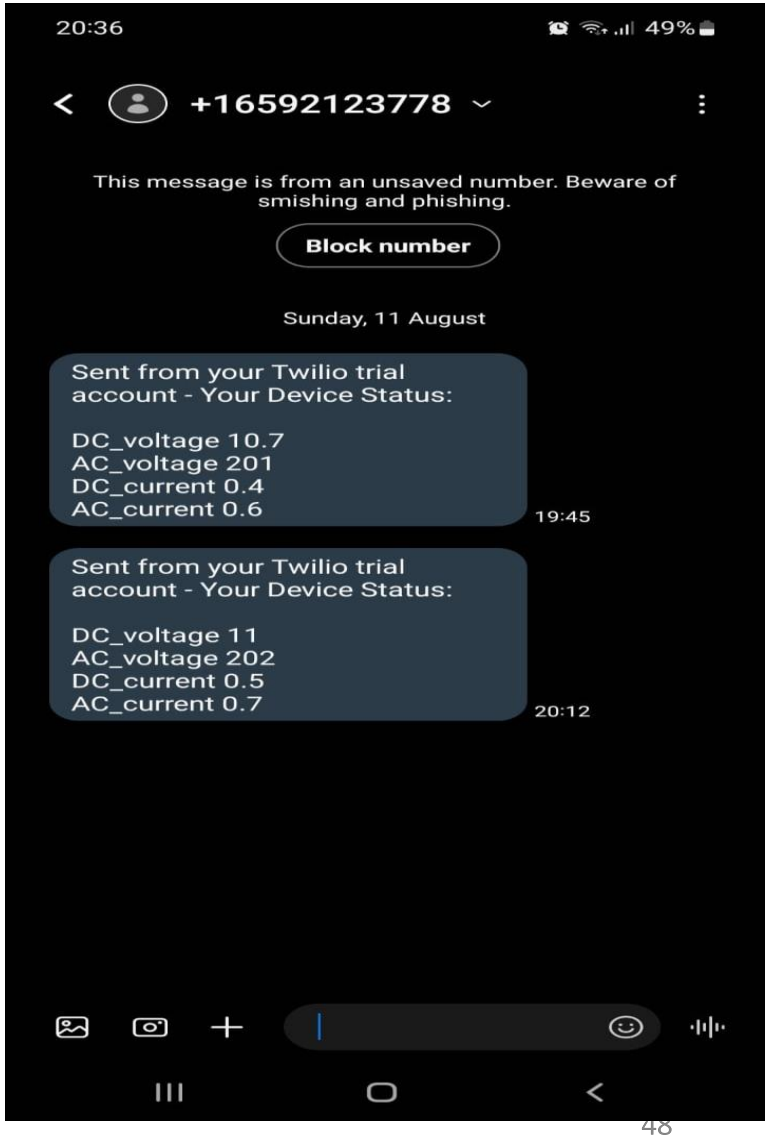
• **SMS Notifications:** Real-time alerts sent to users via SMS, enabling prompt response to system status changes or faults.

➢ **Twilio API Integration:**

•Provides robust and reliable communication for system alerts.

➢ **Communication Enhancement:**

• **Twilio Integration:** Enhances the system's ability to respond quickly to operational issues, ensuring efficient management of the PV system.



Conclusion

- **Innovative Hybrid Power System:** The study introduces a hybrid power system designed to meet the energy needs of remote and isolated locations, emphasizing its ability to provide consistent and sustainable electricity.

- **System Components:** The hybrid power system integrates solar panels, MPPT, a DC-AC inverter, a buck converter, a diesel generator, battery storage, and an electrical load.

- **Performance Analysis:** Performance and optimal configurations are assessed using PVsyst and HOMER Pro software, with dynamic modeling conducted in MATLAB Simulink.

- **Experimental Validation:** Hardware-in-the-loop simulations with the OP5707XG simulator confirm the system's reliability in delivering consistent power.

- **HOMER Pro:** The second phase focuses on a hybrid power system for a remote community, resulting in a renewable energy fraction of 100%, an energy cost reduction to $0.158 per kWh, and substantial annual operating cost savings.

- **SCADA System Development:** The third phase involves designing a comprehensive SCADA system with FIDs, an RTU, and an MTU, using GSM SIM800L and ESP-32 for remote monitoring and control.

Conclusion

• **Real-Time Monitoring:** The SCADA system offers real-time monitoring and control of key parameters like battery and load voltage and current, with data visualization through the Blynk app and LCD.

• **Cost-Effective Solution:** The SCADA system is economical with a total cost of CAD 35.52, no ongoing expenses, and low power consumption, demonstrating versatility and accuracy in real-time data management.

• **Sustainability and Efficiency:** The research contributes to sustainable energy solutions and IoT-based SCADA systems, aligning with global efforts to adopt renewable energy sources and enhance resource management.

Future Work

- **Advanced Optimization Techniques:** Explore genetic algorithms and machine learning-based methods to enhance system efficiency and reduce costs.

- **Emerging Technologies Integration:** Incorporate advanced energy storage solutions to further improve the performance of the hybrid power system.

- **Expanded SCADA Capabilities:** Enhance SCADA systems to integrate a broader range of energy sources and use predictive analytics to optimize energy consumption and generation.

- **Cybersecurity Measures:** Strengthen cybersecurity protocols for IoT components to improve the reliability and security of the energy management system.

List of Publications

- Khalid, W.; Awais, Q.; Jamil, M.; Khan, A.A. Dynamic Simulation and Optimization of Off-Grid Hybrid Power Systems for Sustainable Rural Development. Electronics 2024, 13, 2487. https://doi.org/10.3390/electronics13132487.

- Khalid, W.; Jamil, M.; Khan, A.A.; Awais, Q. Open-Source Internet of Things-Based Supervisory Control and Data Acquisition System for Photovoltaic Monitoring and Control Using HTTP and TCP/IP Protocols. *Energies* **2024**, *17*, 4083. https://doi.org/10.3390/en17164083

- W. Khalid and M. Jamil, "Hybrid Power System Design and Dynamic Modeling of Signal Repeater Station on Natural Gas Transmission Network," *2024 12th International Conference on Smart Grid (icSmartGrid)*, Setubal, Portugal, 2024, pp. 412-417, doi: 10.1109/icSmartGrid61824.2024.10578153.


ANY
QUESTIONS?