Faculty of Engineering
and Applied Science

Memorial University
of Newfoundland

Open Source SCADA Systems for Small Renewable Power Generation

M.Eng Student: Lawrence O. Aghenta
Thesis Supervisor: Prof. M. Tariq Iqbal

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Overview:

Open Source SCADA Systems for Small Renewable Power Generation

Introduction:

Motivation:

1. The distributed nature of Power Generation infrastructures

2. High cost of Commercial SCADA systems: Economically unjustifiable for smaller applications.

3. Interoperability issues, high power consumption, & the need for expensive standard communication systems in Commercial SCADA solutions.

4. The need for a cost-effective, reliable, secure, timely, flexible & sophisticated coordinated data monitoring and control system: Open Source SCADA

Introduction:

Objectives, Challenges and Work Around:

a. Objectives:

- To design, model & dynamically simulate a Small Hybrid Power System.
- To study some proven Commercial SCADA Systems & Open Source SCADA packages.
- To study and test the available open source Internet of Things (IoT) platforms & use the best options.
- To design some low-cost, low-power, reliable, secure IoT-based Open Source SCADA systems.
- To test the designed Open Source SCADA systems with a Small Renewable Power Generation system with ESS.

b. **Challenges:**

- Site for the Hybrid Power System Design.
- Choice of SCADA components to meet low-power objective.
- Security Strategies to meet security objective.
- Complexity of the entire system

c. **Work Around:**

- A House in Nigeria was chosen for the Hybrid Power System Design.
- Tested Multiple components, and IoT Platforms.
- The main data server was locally installed, self-managed and self-hosted on own private network.
- Simple solutions proposed to overcome the complexity of the entire system.

SCADA:

SCADA: Description & Basic Elements

- Supervisory
- Control
- And
- Data
- Acquisition

SCADA: Basic Elements

Field Instrumentation Devices (FIDs)

Sensors and Actuators connected to the process system being managed

Remote Terminal Units (RTUs)

Local collection points for gathering reports from FIDs (sensors)

Communications Network

Protocol needed to transfer data to and from different sites (Connects RTUs to MTU)

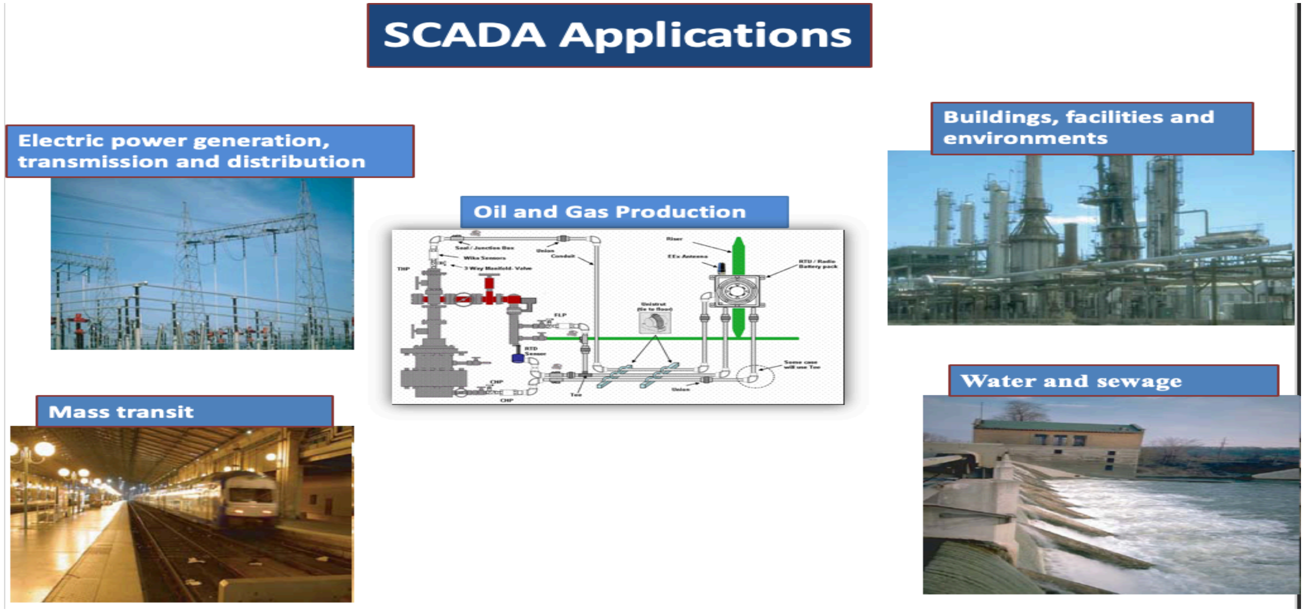
Master Terminal Unit (MTU)

Collecting information gathered by the remote stations to generate the necessary actions (HMI)

SCADA:

SCADA: Basic Functions

- Data Acquisition
- Networked Data Communication
- Data Presentation
- Monitoring/Control



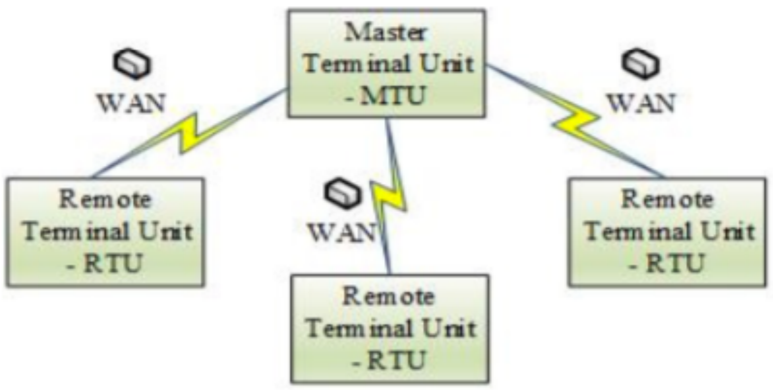
SCADA: Architectures (Generations)

- Monolithic
  - 1st Generation
- Distributed
  - 2nd Generation
- Networked
  - 3rd Generation
- Internet of Things
  - 4th Generation

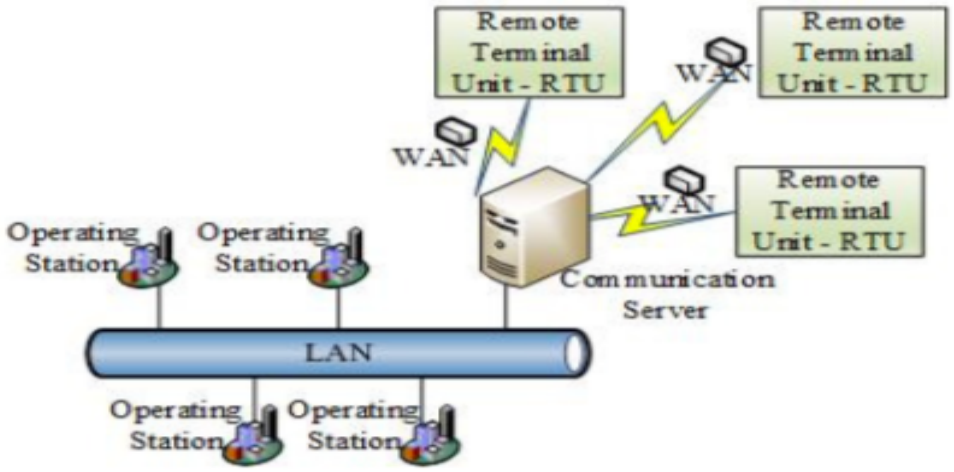
SCADA:

SCADA: Architectures (Generations)

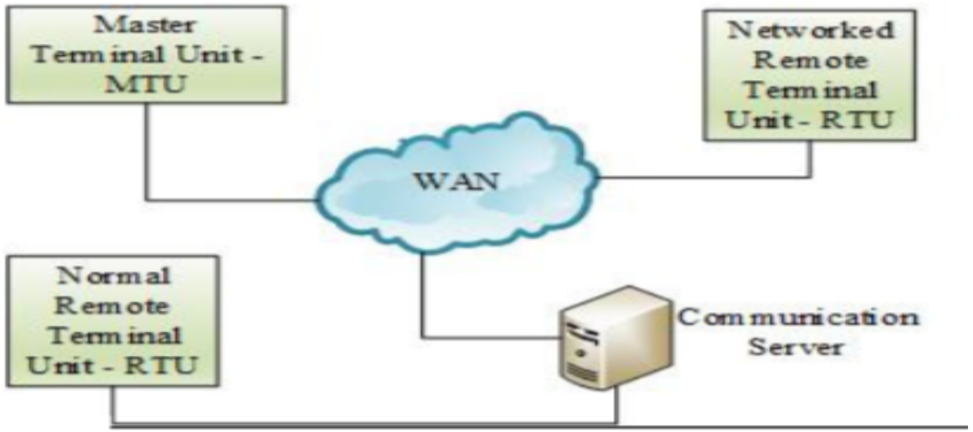
1st Generation - Monolithic SCADA:



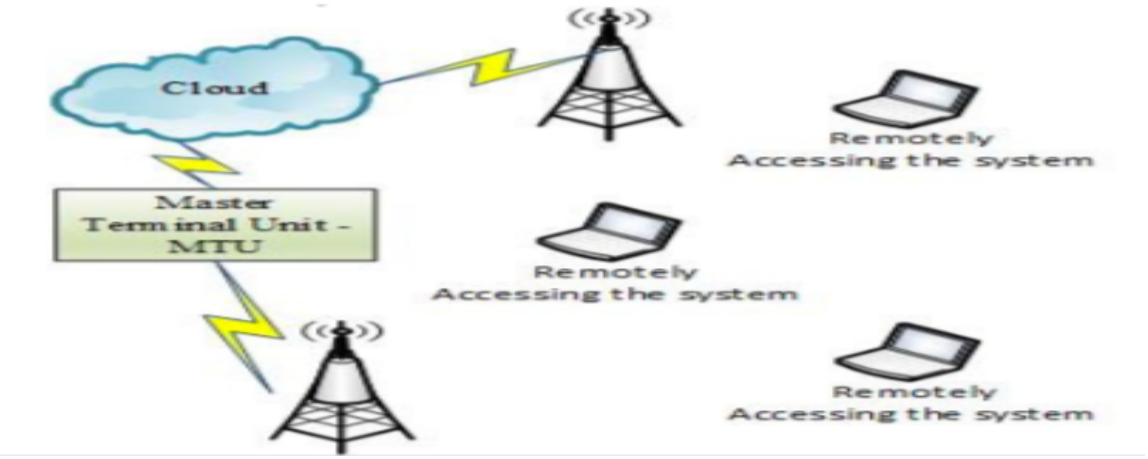
2nd Generation - Distributed SCADA:



3rd Generation - Networked SCADA:



4th Generation – Internet of Things (IoT)-based SCADA:



SCADA:

Desired Characteristics:

- Dynamism; flexibility.
- Retrofit; upgrading/updating
- Ease of Use/Ease of Installation
- Reliability and Availability
- Low Power Consumption
- Security: various attacks are possible; Security techniques must be decided and implemented.

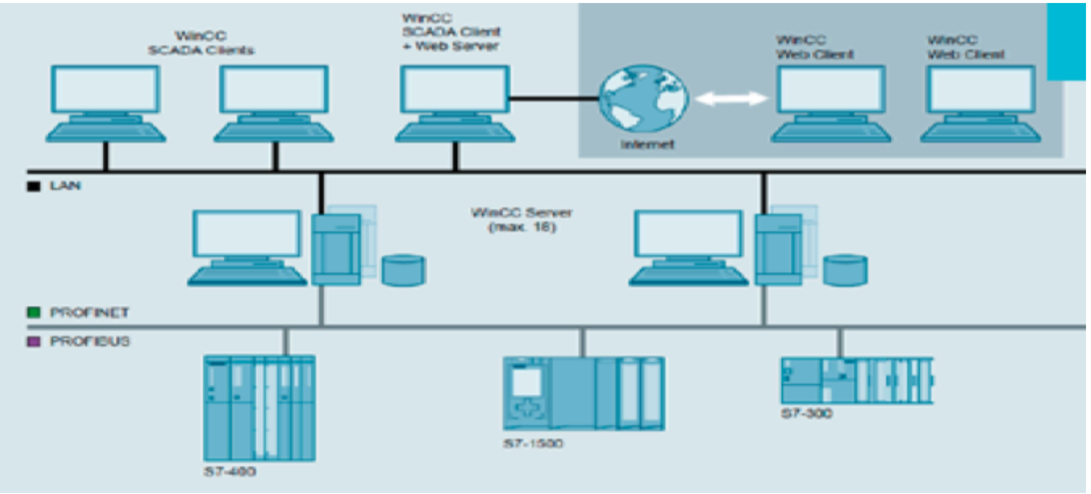
Classes of SCADA:

- Proprietary (Commercial) SCADA; e.g. Siemens, ABB, GE, Wonderware, Schneider Electric, etc.
- Open Source SCADA

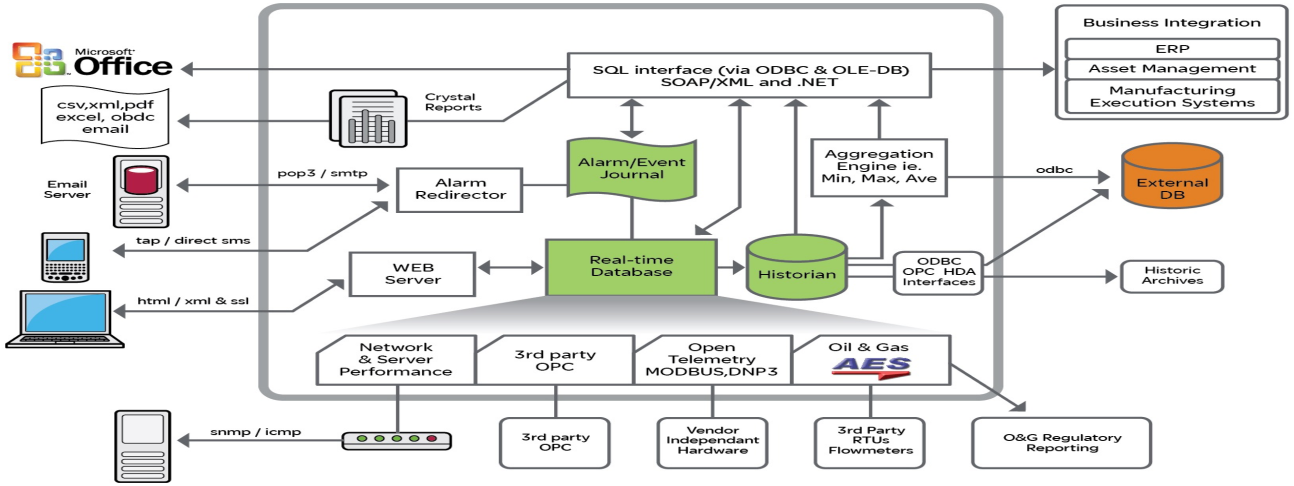
SCADA:

Some Studied Commercial SCADA Solutions:

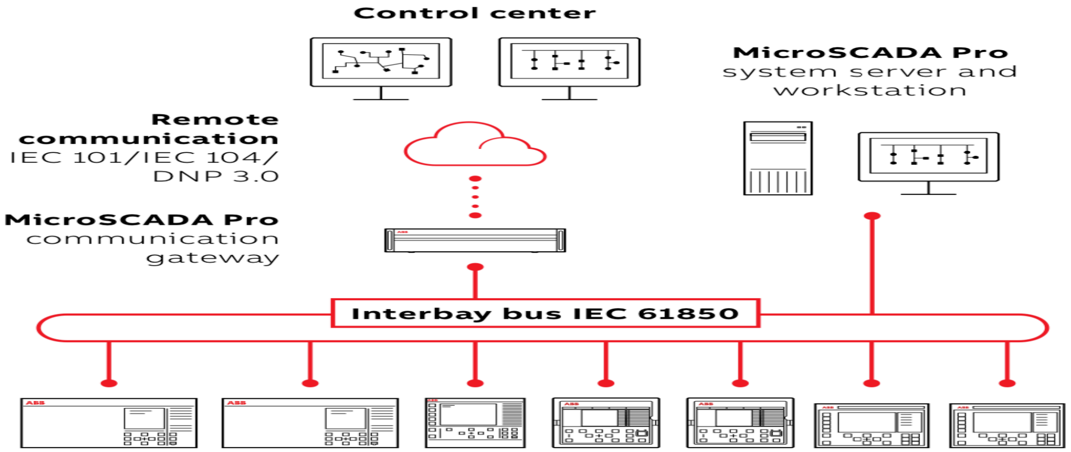
1. SIMATIC WinCC: Siemens



2. ClearSCADA: Schneider Electric



3. MicroSCADA Pro: Allen Bradley



4. Ovation SCADA: Emerson

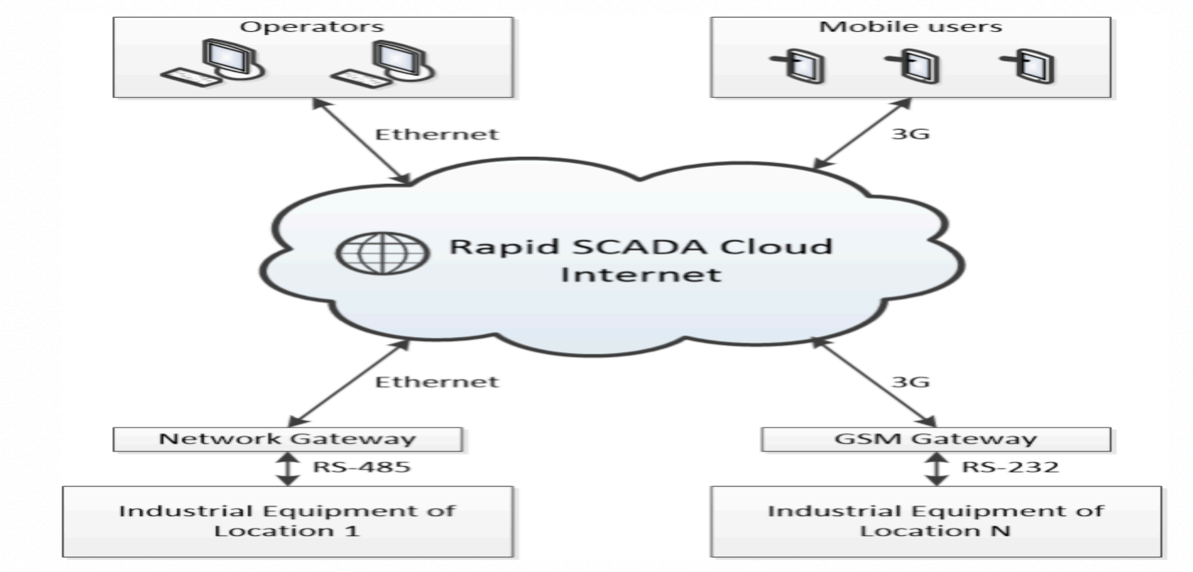
Specifications

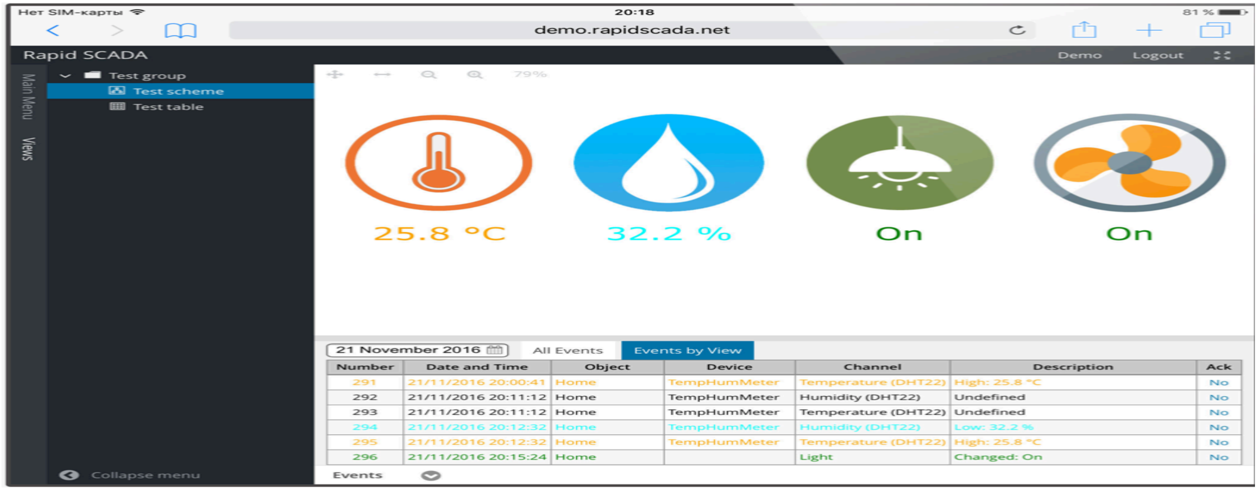
SCADA Communication Server Specifications	
Hardware Platform	Windows
Standard Communication Protocols	Modbus (Master/Slave), Allen-Bradley DF-1, Allen-Bradley EIP, DNP3 (Client/Server), IEC61850, IEC60870-101, IEC60870-104, GE GSM, Turbine Control Interface, OPC UA (Client/Server)
Communication Media	Leased lines, dial-up telephones, microwave, licensed and unlicensed radio, spread spectrum packet radio, public switched networks, satellites, cellular, Ethernet (LAN and WLAN)
Redundancy Scheme	Primary and backup; supports dual redundant configuration
Number of Simultaneous Communication Channels	Up to 32 per server

SCADA:

Some Studied Open Source SCADA Solutions:

1. Rapid SCADA





2. Tango SCADA

Motivation:

- Extreme Electricity shortage and prolonged periods of power outages in Nigeria.
- Abundant Solar Irradiation in Nigeria (an average of 17.3 $MJ/m^2/day$ (4.81$KWh/m^2/day$) in Benin City).
- Modelling and Simulation is the necessary first step in design, optimization and performance analysis.
- A Case Study of a Hybrid Power System with a Small Renewable Power Generation.

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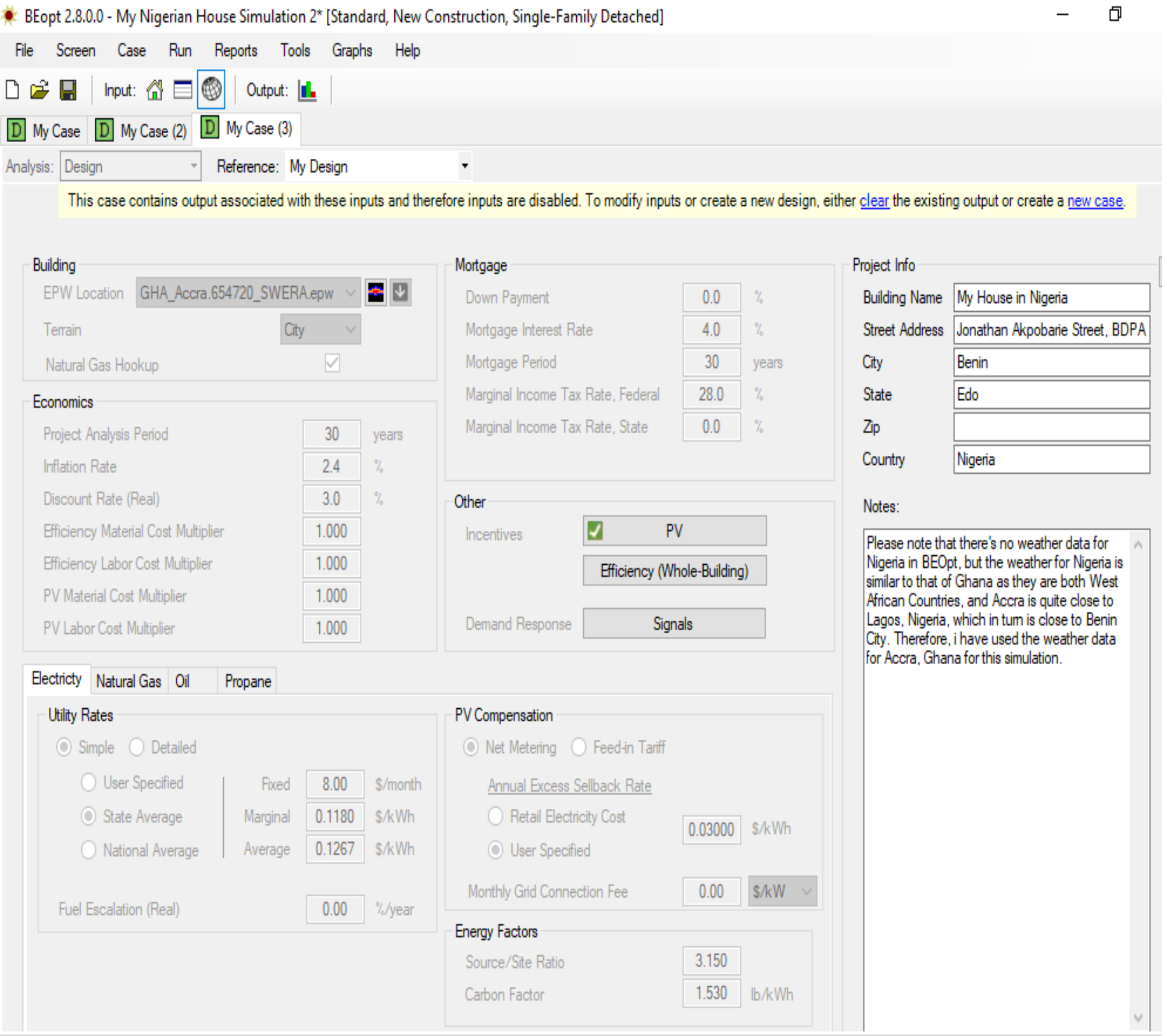
Project Steps:

- House Energy Needs determination: Thermal Modelling and Analyses using BEOpt software
- System Sizing, Optimum Design Technology and Cost Analyses using HOMER Pro software
- Dynamic/Mathematical model of each of the subsystems (components).
- Matlab/Simulink Simulation of the Proposed PV System Component of the Hybrid Power System
- Simulation results.

Design and Simulation of a Hybrid Power System for a House in Nigeria:

House Energy Needs Determination: Thermal Modelling and Analysis (BEOpt):

Site Screen & House Picture:

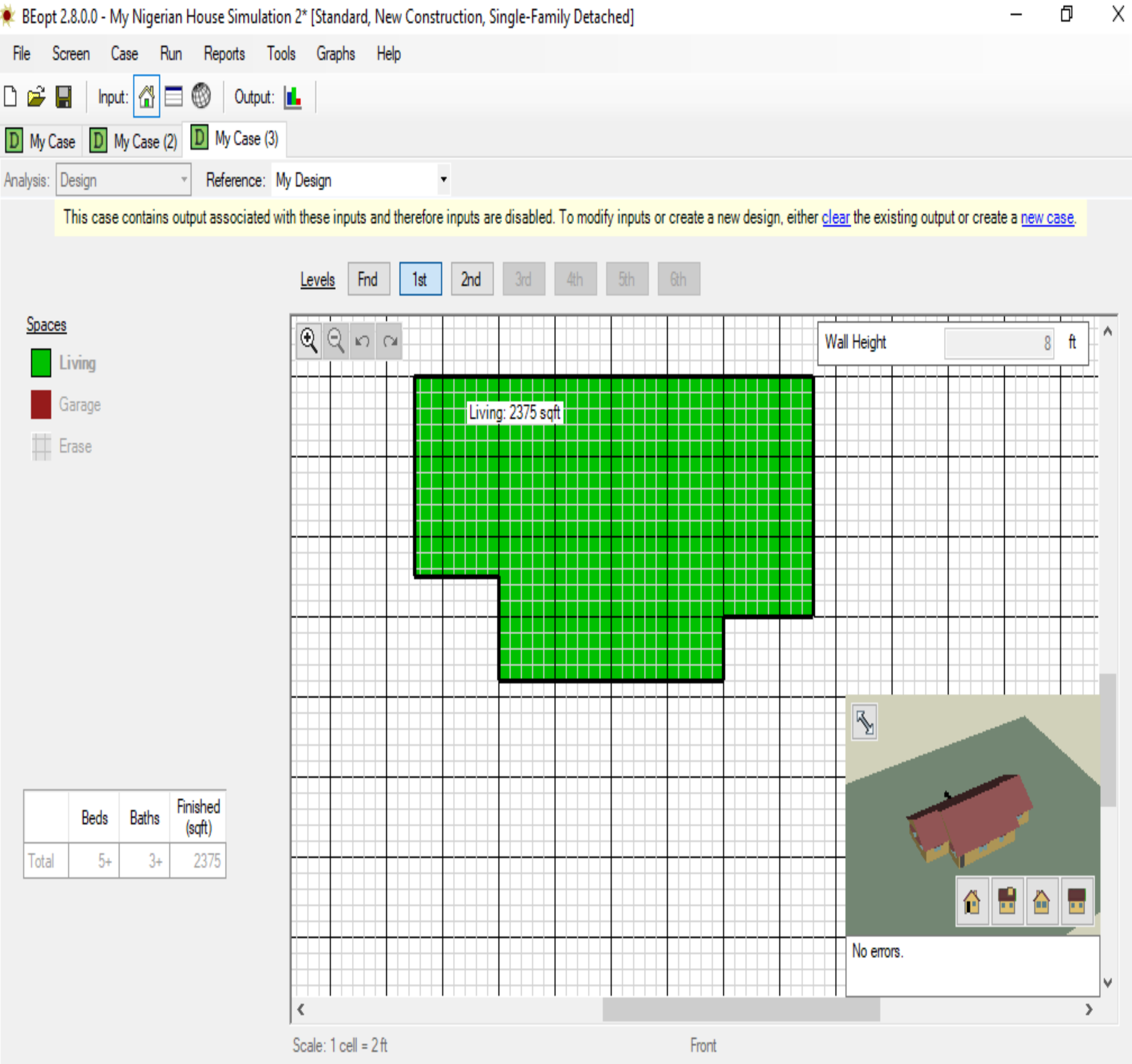


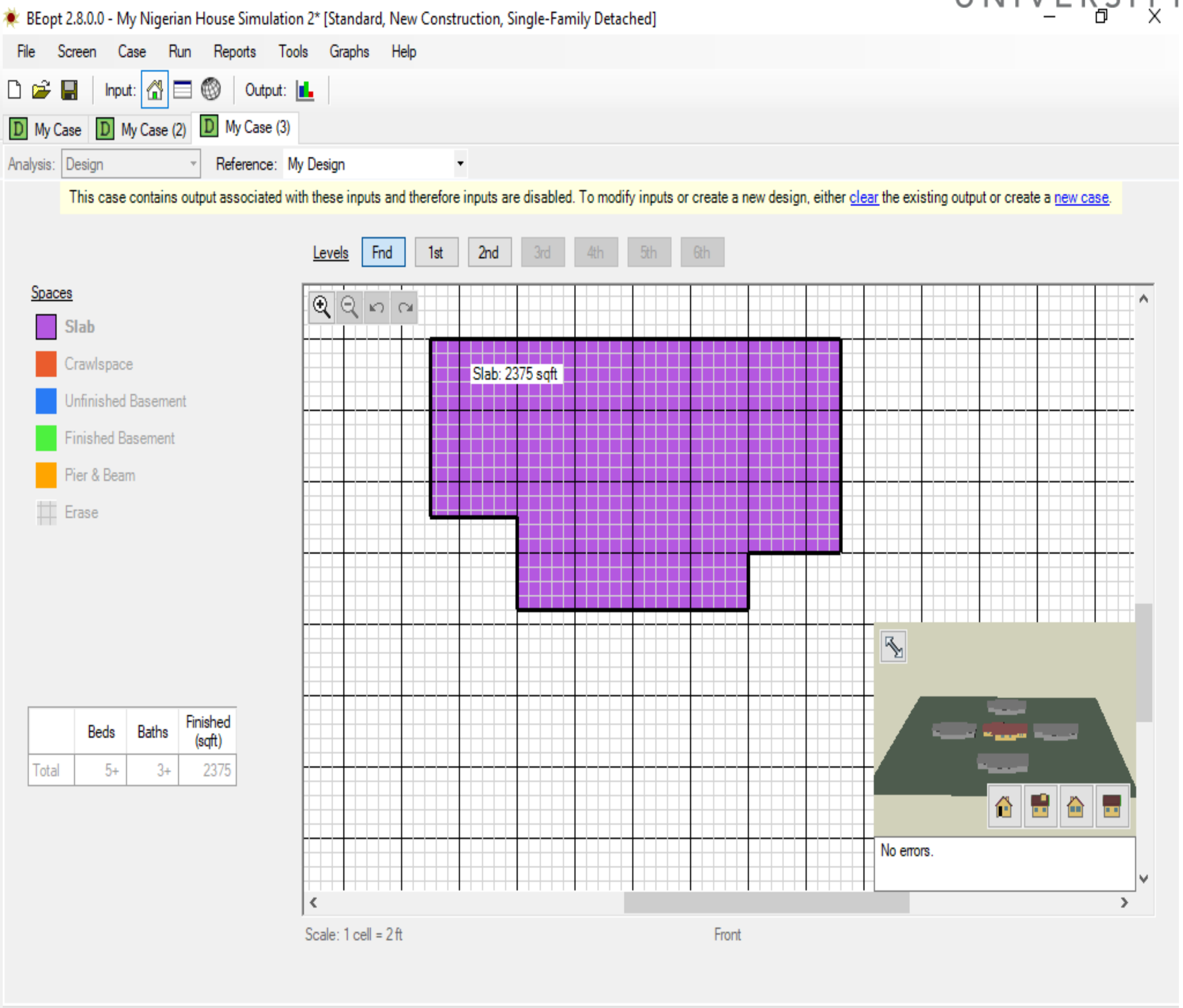
Side View of the Chosen House

Design and Simulation of a Hybrid Power System for a House in Nigeria:

House Energy Needs Determination: Thermal Modelling and Analysis (BEOpt):

Main Floor and Building Foundation:

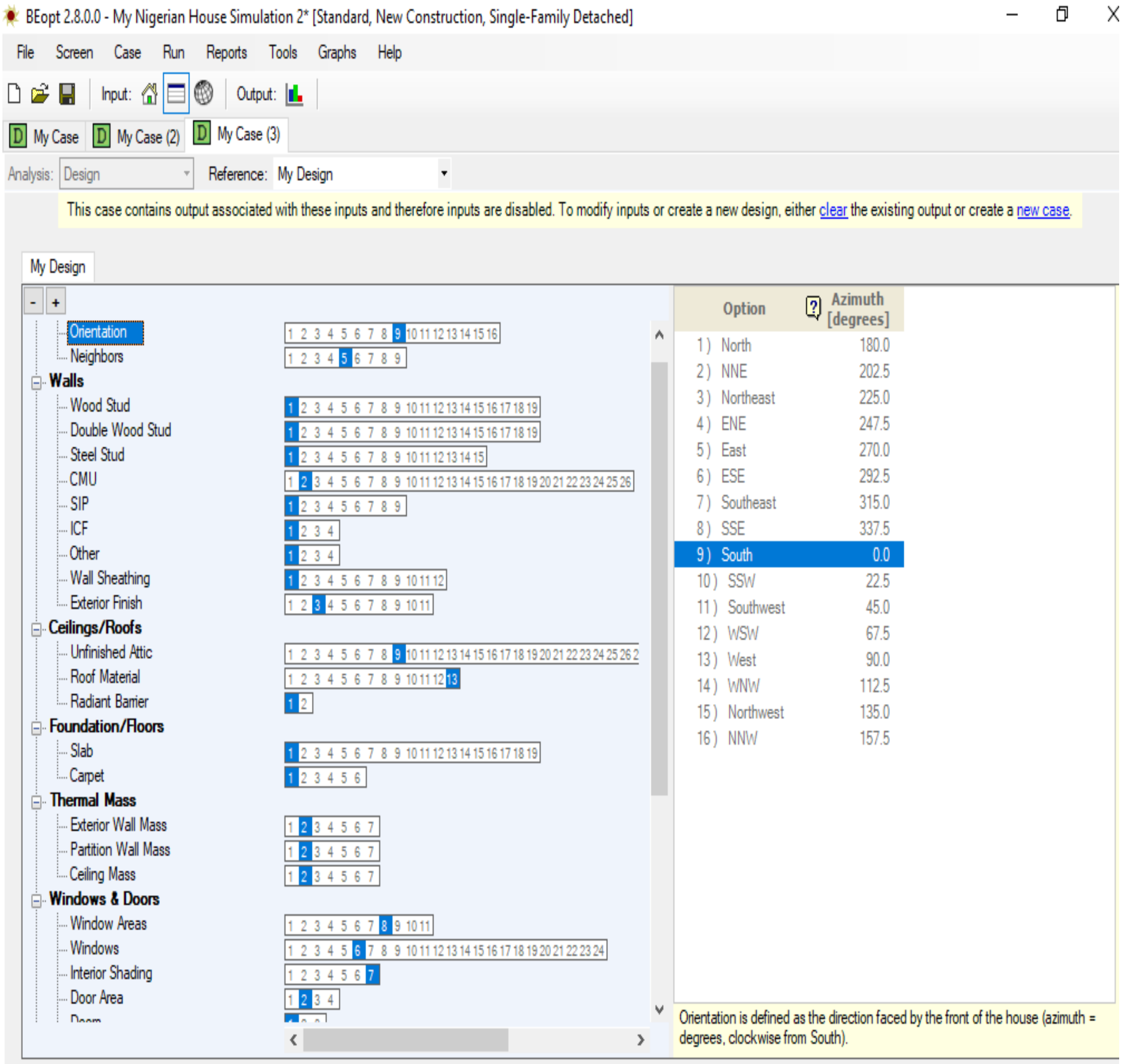




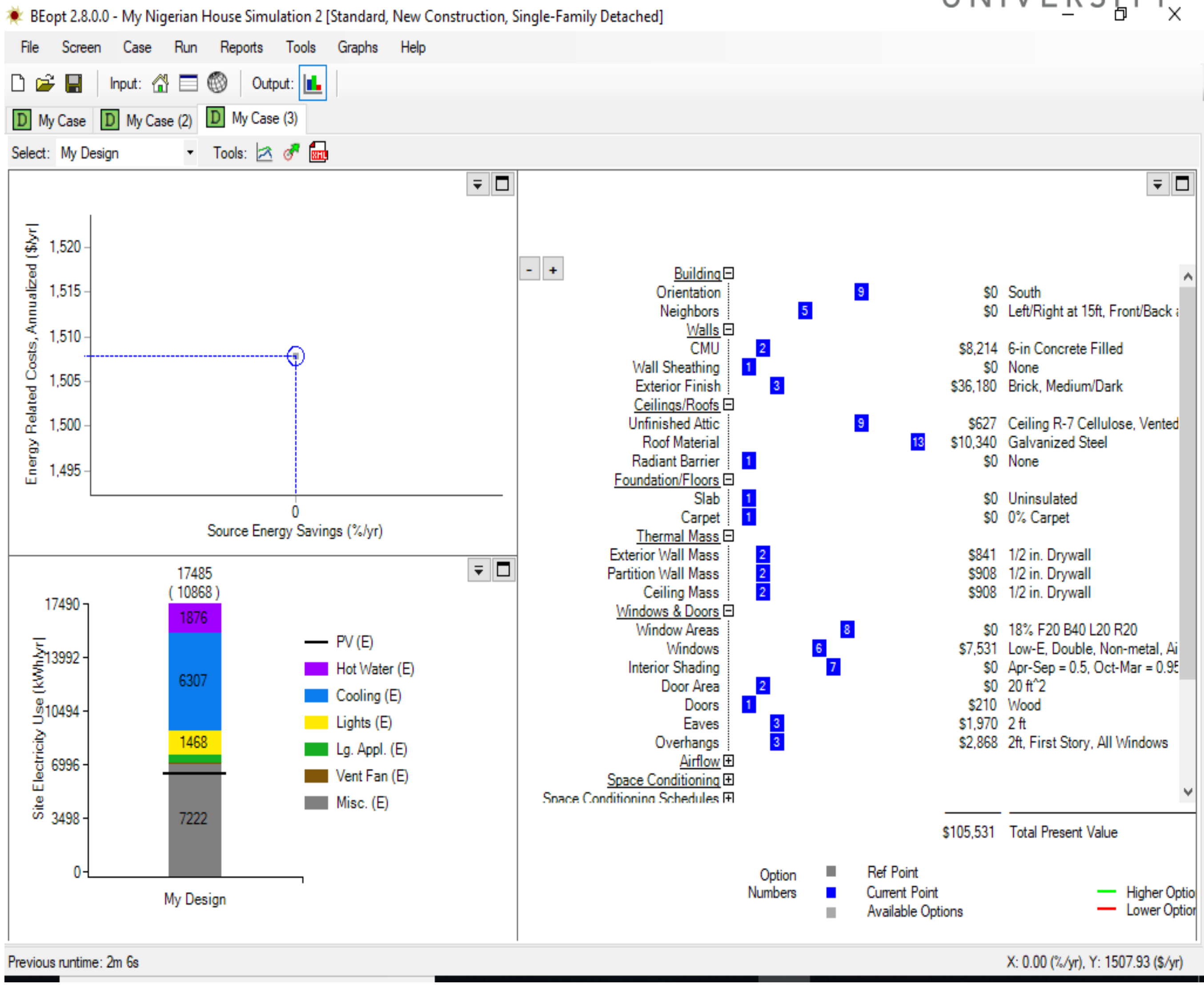
Design and Simulation of a Hybrid Power System for a House in Nigeria:

House Energy Needs Determination: Thermal Modelling and Analysis (BEOpt):

Sample Modelling Outputs:

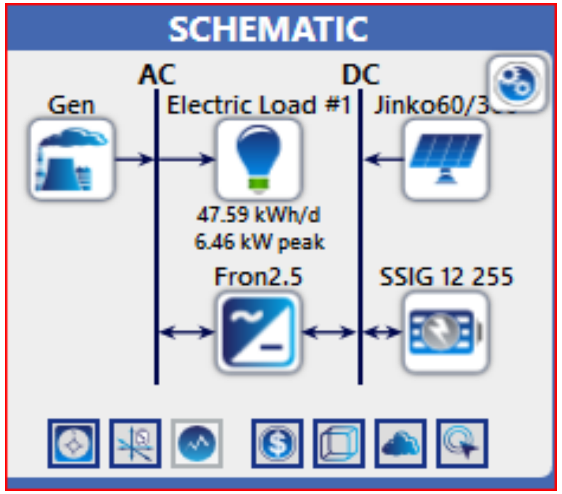


House Energy Needs:



System Sizing, Optimum Technology and Cost: HOMER Pro:

- The generated BEOpt Annual Hourly Load Data exported into HOMER Pro for HPS Sizing, and optimum system design.
- HOMER (Hybrid Optimization of Multiple Energy Resources) software was developed by the National Renewable Energy Laboratory.
- HOMER models micropower systems with single or multiple power sources: e.g. Photovoltaics, Wind turbines, etc.
- HOMER, the micropower optimization model, helps to design off-grid and grid-connected systems.
- HOMER analyses help to answer design questions e.g: Components size? Most cost effective technology? etc.
- HOMER simulates various configurations to find the least cost combinations that meet electrical and thermal loads.

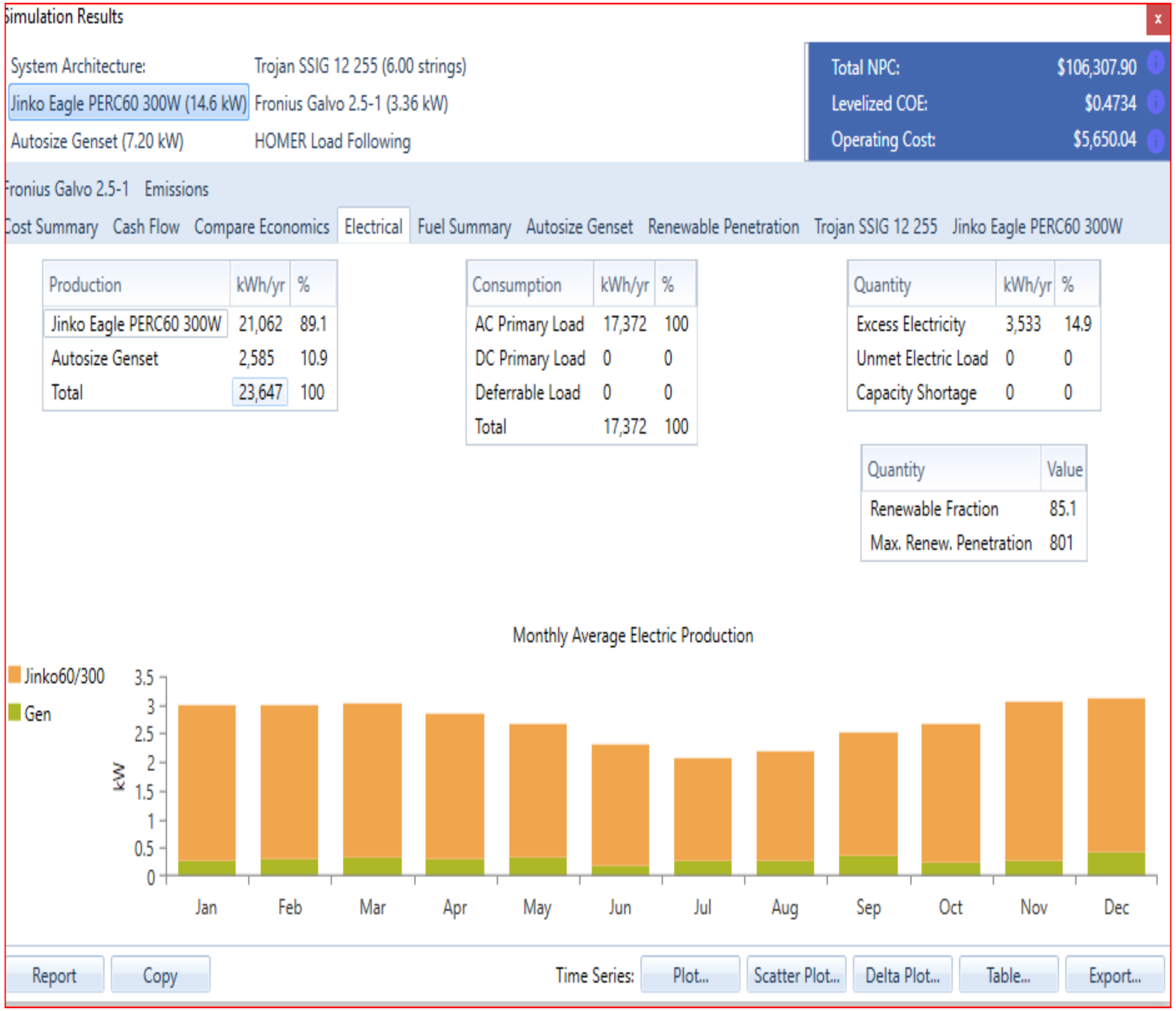


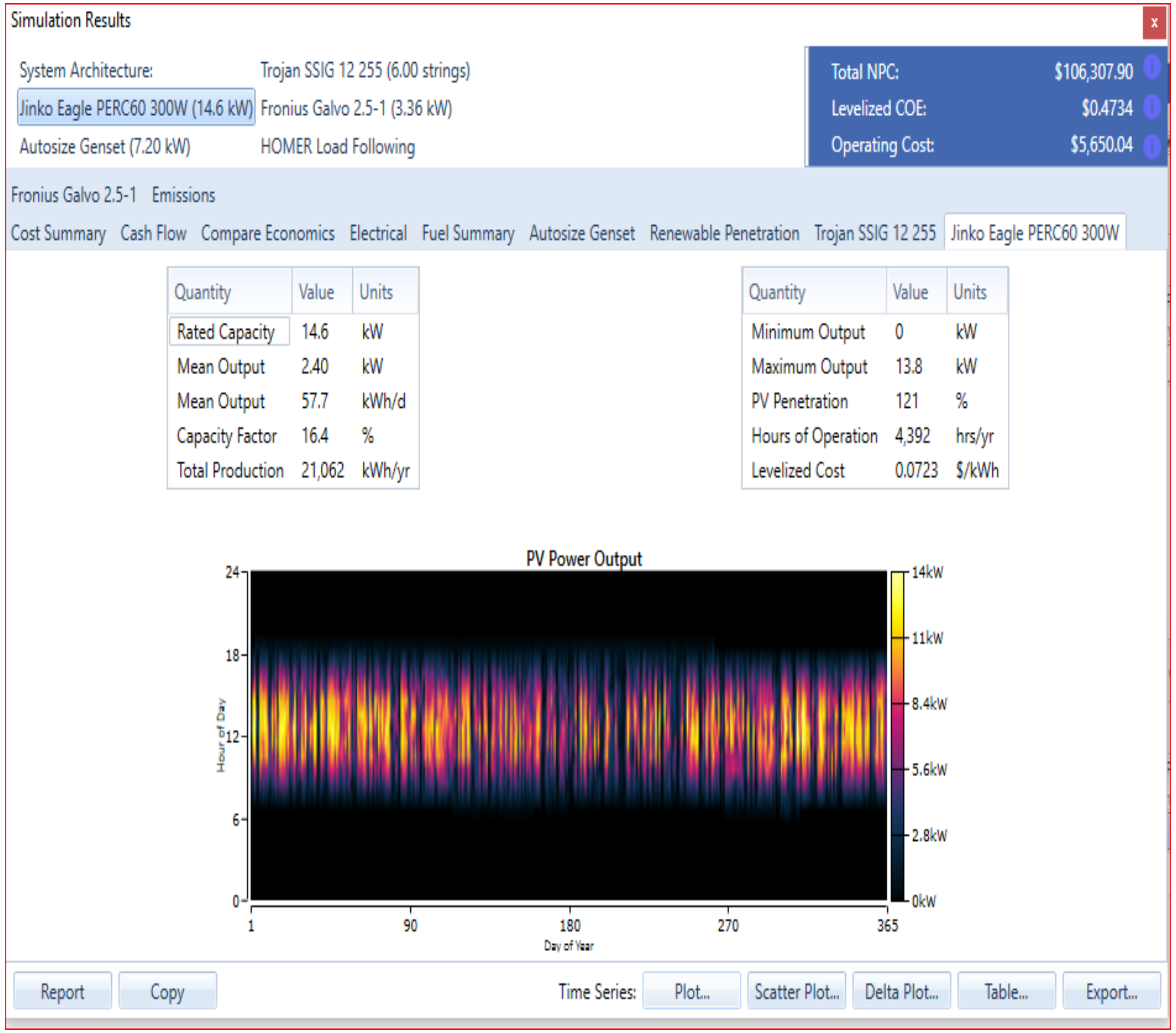
Hybrid Power System Components & Layout

Design and Simulation of a Hybrid Power System for a House in Nigeria:

System Sizing, Optimum Technology and Cost: HOMER Pro:

HOMER Simulation Results:





Design and Simulation of a Hybrid Power System for a House in Nigeria:

System Sizing, Optimum Technology and Cost: HOMER Pro:

HOMER Simulation Results:

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Simulation Results

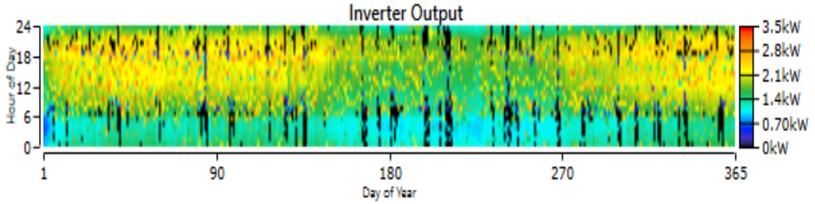
System Architecture: Trojan SSIG 12 255 (6.00 strings)
Jinko Eagle PERC60 300W (14.6 kW) Fronius Galvo 2.5-1 (3.36 kW)
Autosize Genset (7.20 kW) HOMER Load Following

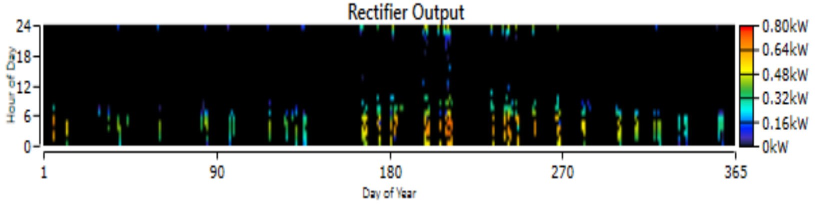
Total NPC: $106,307.90
Levelized COE: $0.4734
Operating Cost: $5,650.04

Cost Summary | Cash Flow | Compare Economics | Electrical | Fuel Summary | Autosize Genset | Renewable Penetration | Trojan SSIG 12 255 | Jinko Eagle PERC60 300W | Fronius Galvo 2.5-1 | Emissions

Quantity	Inverter	Rectifier	Units
Capacity	3.36	3.36	kW
Mean Output	1.70	0.0161	kW
Minimum Output	0	0	kW
Maximum Output	3.36	0.759	kW
Capacity Factor	50.8	0.479	%

Quantity	Inverter	Rectifier	Units
Hours of Operation	8,086	383	hrs/yr
Energy Out	14,935	141	kWh/yr
Energy In	15,721	148	kWh/yr
Losses	786	7.42	kWh/yr





Report | Copy | Time Series: | Plot... | Scatter Plot... | Delta Plot... | Table... | Export...

Simulation Results

System Architecture: Trojan SSIG 12 255 (6.00 strings)
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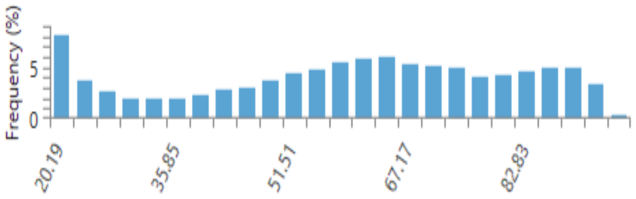
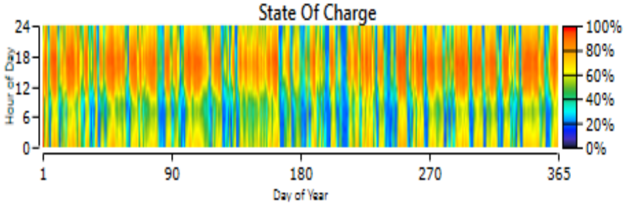
Fronius Galvo 2.5-1 | Emissions | Cost Summary | Cash Flow | Compare Economics | Electrical | Fuel Summary | Autosize Genset | Renewable Penetration | Trojan SSIG 12 255 | Jinko Eagle PERC60 300W

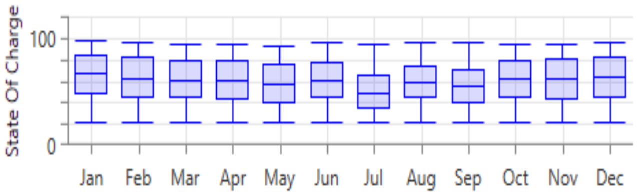
Quantity	Value	Units
Batteries	24.0	qty.
String Size	4.00	batteries
Strings in Parallel	6.00	strings
Bus Voltage	48.0	V

Quantity	Value	Units
Autonomy	29.9	hr
Storage Wear Cost	0.302	$/kWh
Nominal Capacity	74.1	kWh
Usable Nominal Capacity	59.3	kWh
Lifetime Throughput	44,448	kWh
Expected Life	5.02	yr

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	9,875	kWh/yr
Energy Out	7,927	kWh/yr
Storage Depletion	30.0	kWh/yr
Losses	1,978	kWh/yr
Annual Throughput	8,863	kWh/yr





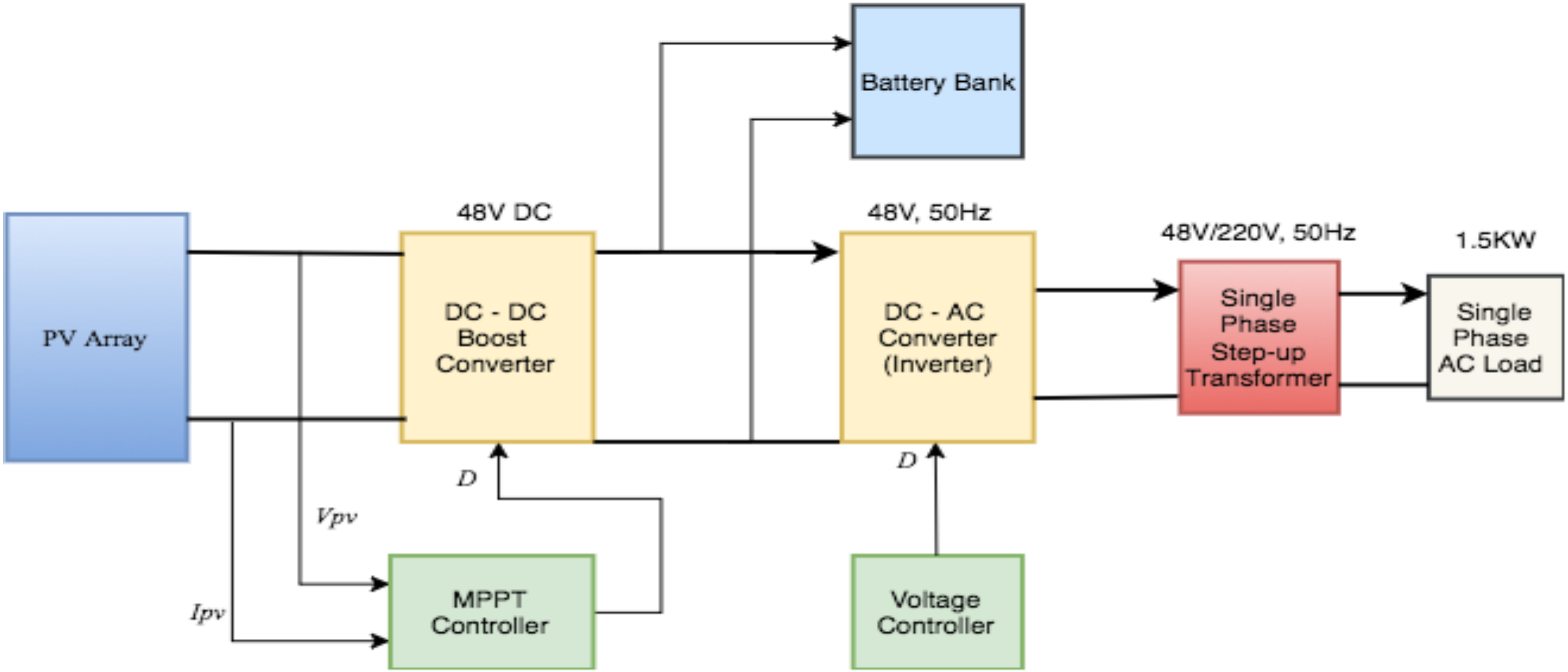


Report | Copy | Time Series: | Plot... | Scatter Plot... | Delta Plot... | Table... | Export...

Design and Simulation of a Hybrid Power System for a House in Nigeria:

Dynamic/Mathematical model of each of the subsystems (components):

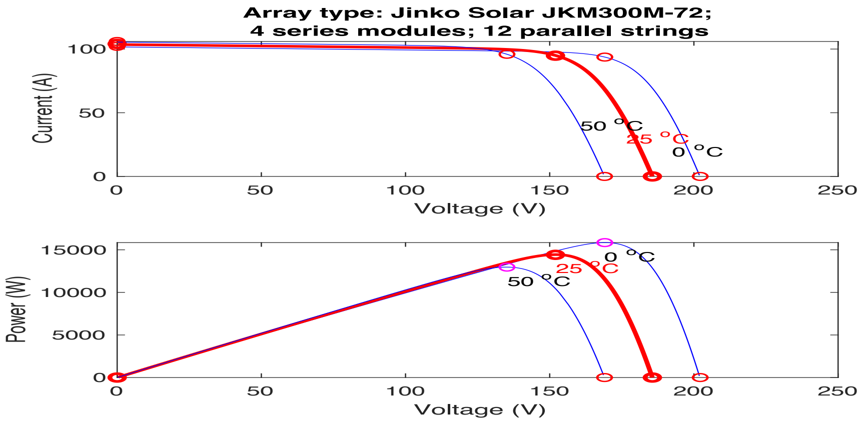
Block Diagram of PV System Components:



Design and Simulation of a Hybrid Power System for a House in Nigeria:

Dynamic/Mathematical model of each of the subsystems (components): Overview

- Jinko Solar JMK300M-72 PV Array: 4 strings of 12 panels PV modules. (12x4x300 = 14.4KW)



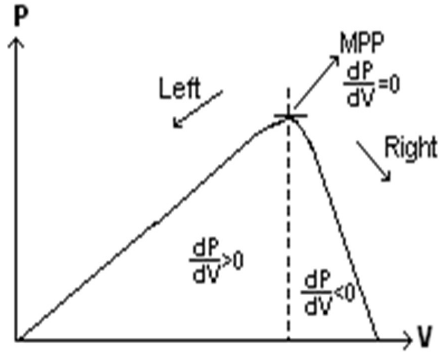
- The converter stabilizes and steps up (boosts) the DC Voltage from the PV Array to a fixed DC Voltage output.
- The converter provides the DC bus voltage (48V) for charging the Battery.
- The output voltage of the DC – DC Boost Converter is fed into the Inverter for conversion to AC voltage.
- The single phase voltage source inverter converts the fixed DC Voltage (48V) into a single-phase AC voltage (48V) with fixed frequency of 50Hz.
- The single-phase Step-up transformer steps up the 48V Inverter output to 220V AC at 50Hz for household loads
- Trojan SSIG 12 255 Lead Acid Batteries: 48V Bus Voltage, 1542Ah Capacity, 29.9 hrs Autonomy,

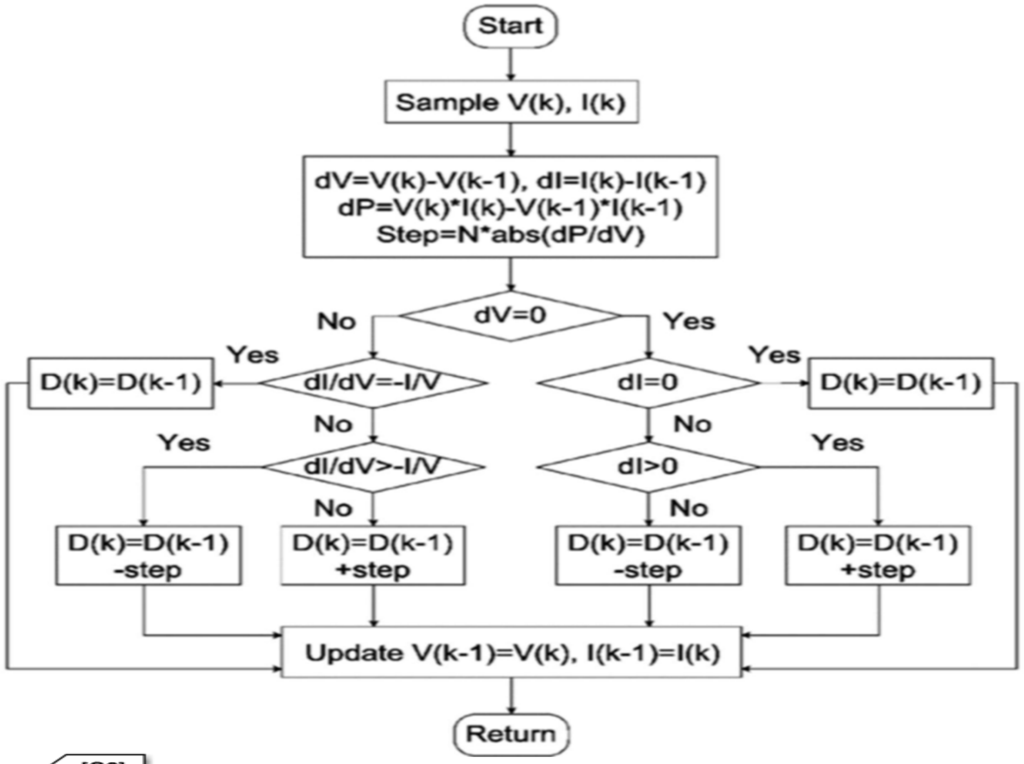
Dynamic/Mathematical model of each of the subsystems (components): Controls

Incremental Conductance MPPT Algorithm and Inverter Voltage Control:

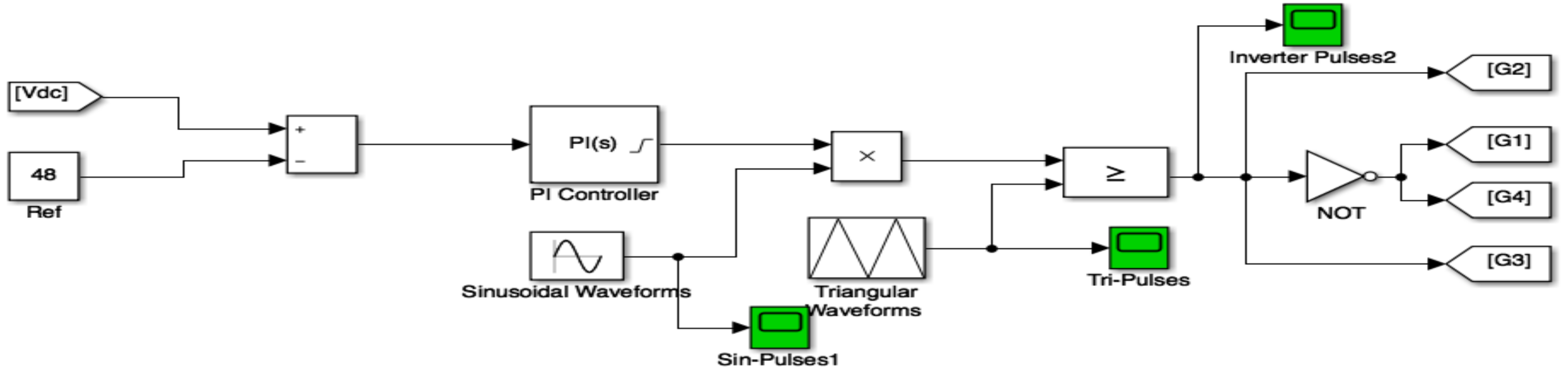
$$P = V * I$$

$$\frac{dP}{dV} = \frac{d(I * V)}{dV} = V * \frac{dI}{dV} + I$$



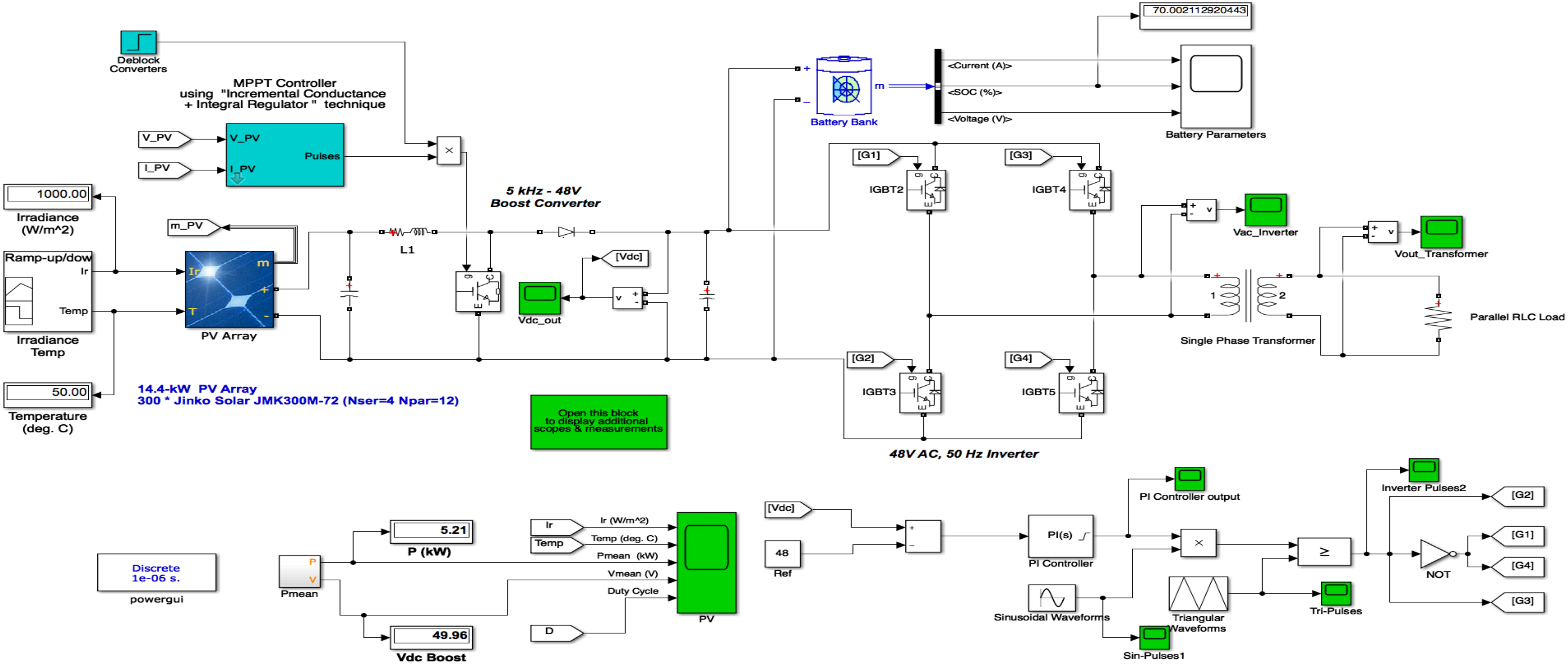


- dI/dV = incremental conductance. & I/V = panel conductance
- Incremental and Panel conductance are determined.
- DC – DC Boost Converter Duty Cycle, D is adjusted until:
- dI/dV = -I/V or dP/dV=0 = MPPT



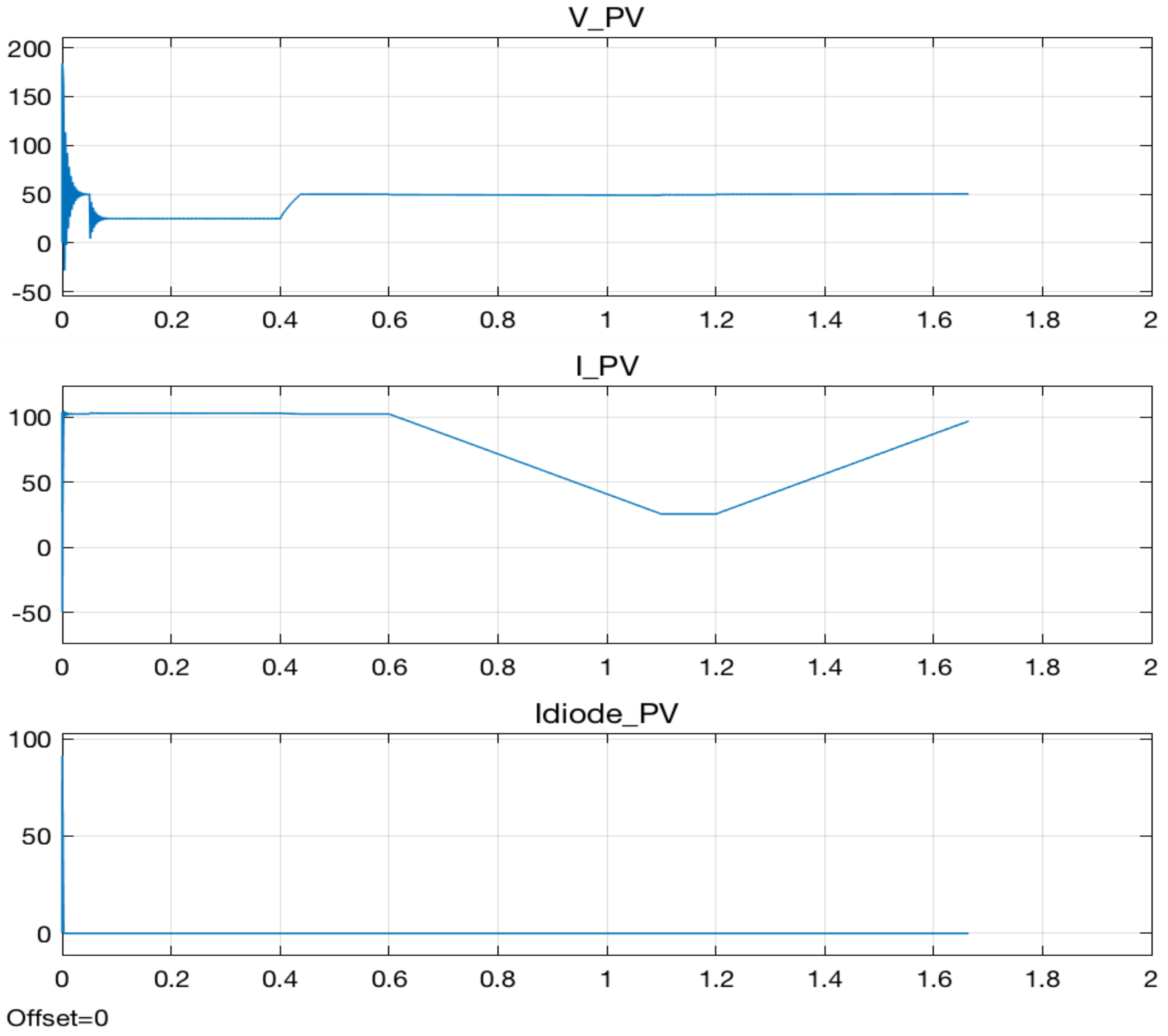
Design and Simulation of a Hybrid Power System for a House in Nigeria:

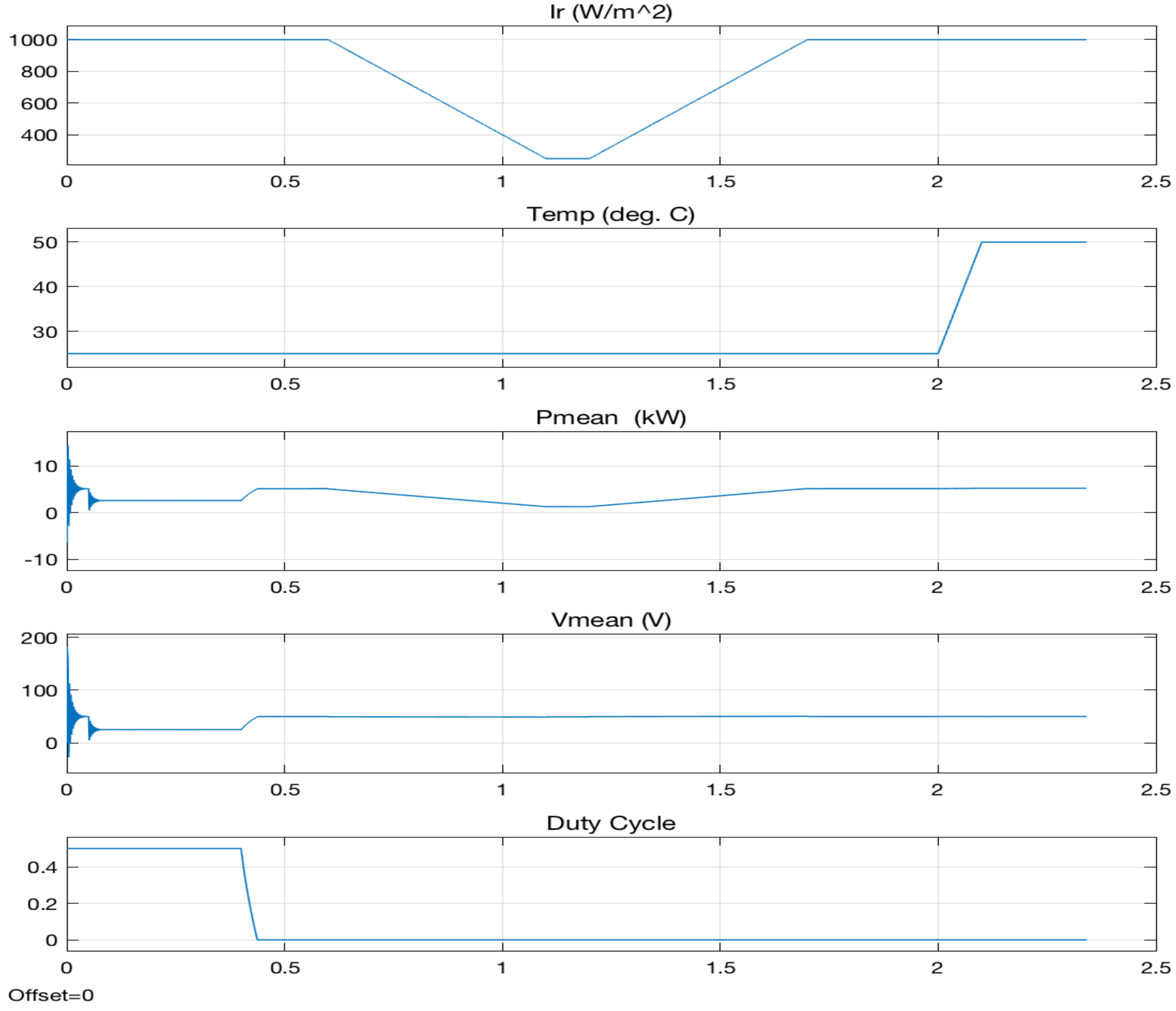
Matlab/Simulink Simulation of the PV System Components of the HPS



Design and Simulation of a Hybrid Power System for a House in Nigeria:

Simulation Results:





Design and Simulation of a Hybrid Power System for a House in Nigeria:

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Simulation Results:

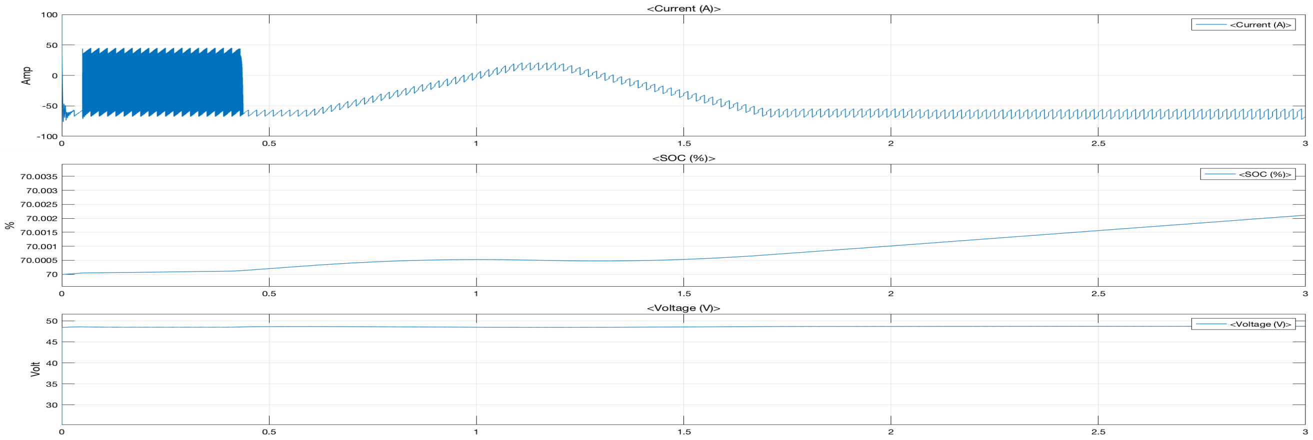

Fig.: Battery I, SOC & V

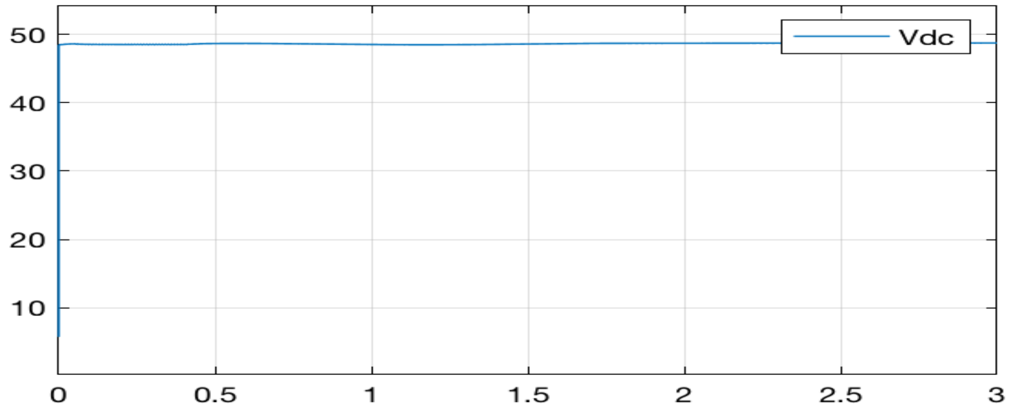

Fig.: DC – DC Boost Converter Output Voltage

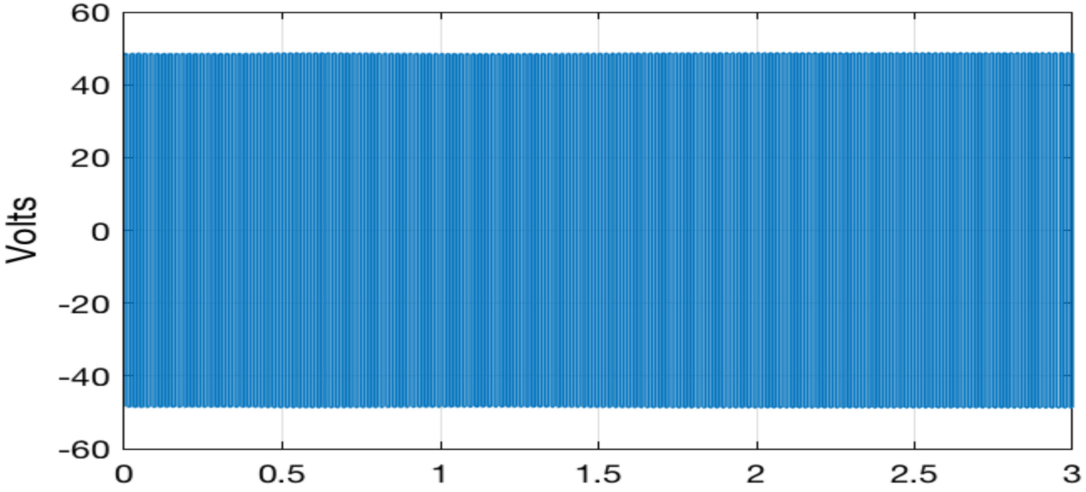

Fig.: Inverter Output Voltage

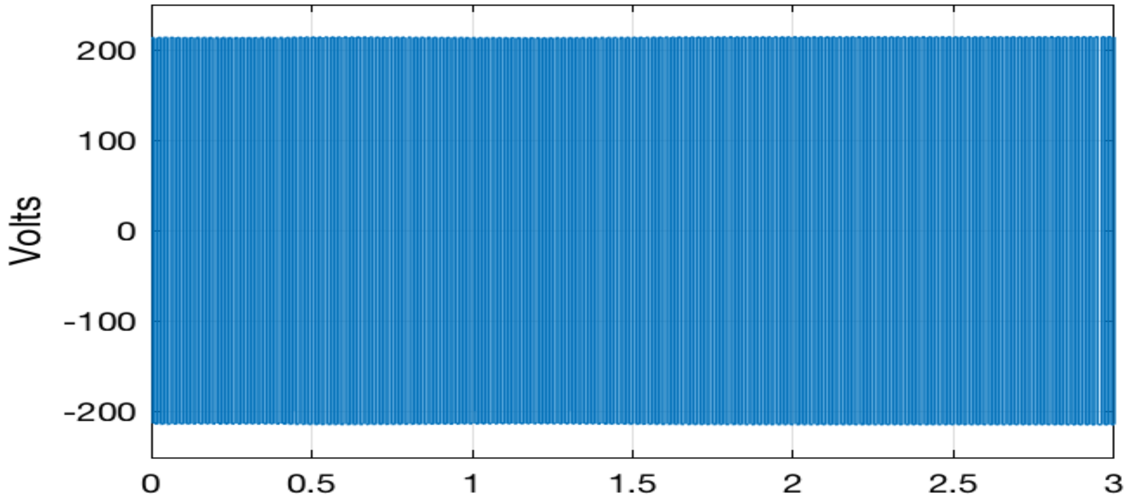

Fig.: Transformer Output Voltage: Load Voltage

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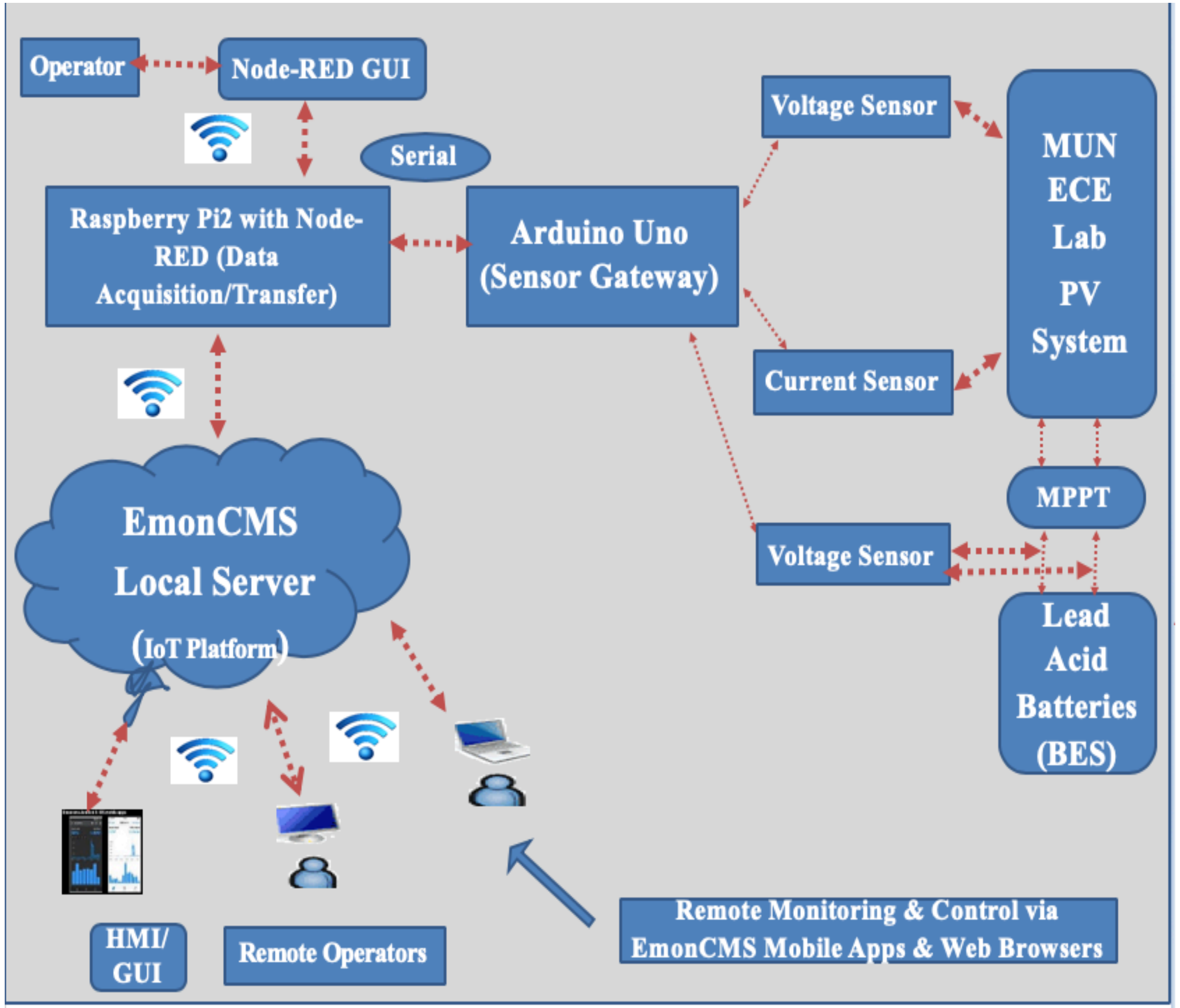
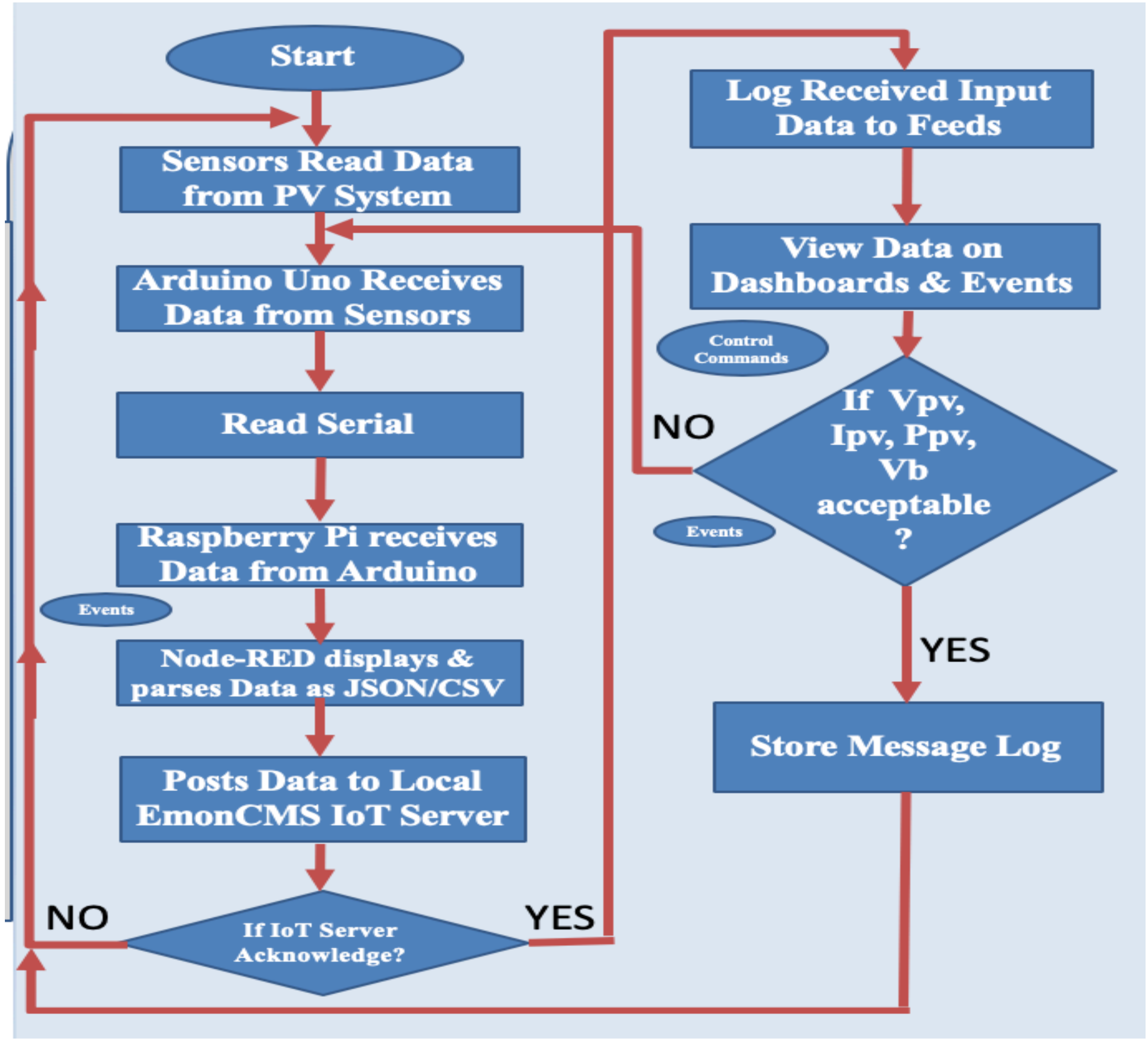
Components of SCADA 1 System:

- A Small Renewable Power Generation System (Solar PV System with ESS).
- Sensors (Current, Voltage.): FIDs
- Arduino Uno R3 Microcontroller: RTU
- Raspberry Pi2 Single-Board Computer: RTU
- Node-RED Programming Tool: SCADA Communication/Data Transfer
- EMONCMS Local Server IoT Platform: MTU
- Computers and Mobile Devices: HMIs/GUIs

System Configuration & Flow Chart:

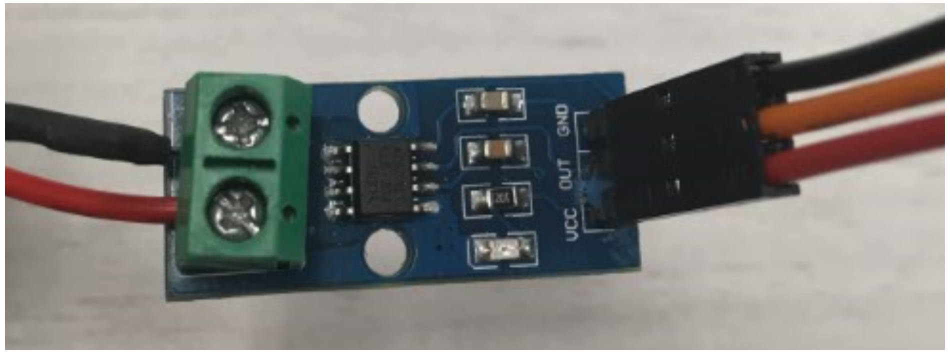


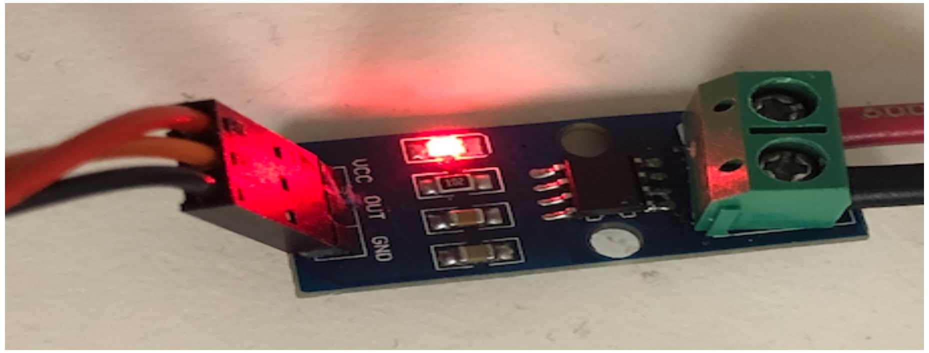


Field Instrumentation Devices: Sensors

The ACS 712 Hall Effect Current Sensor:

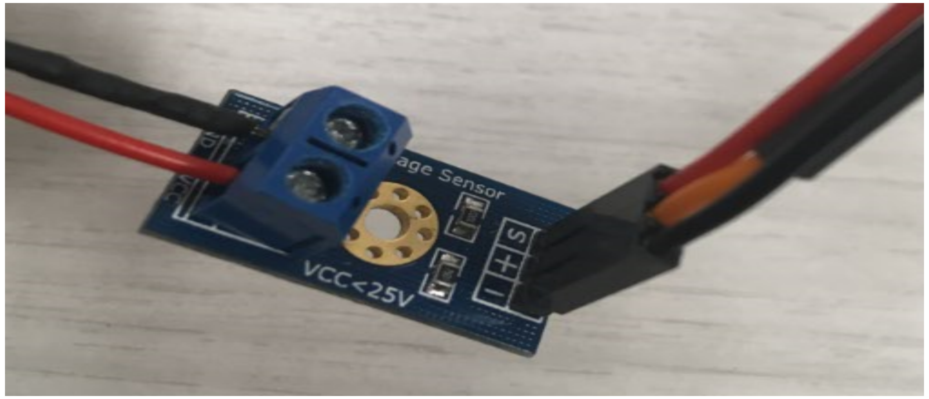
- Hall Effect-Based Linear Current Sensor, 5.0 V single supply operation, 66 to 185 mV/A output sensitivity, Low cost
- Output voltage proportional to AC or DC currents, Nearly zero magnetic hysteresis
- Used to measure the DC Current from the solar PV System (the 30A Model was used for this application)





The MH Electronic Voltage Sensor Module:

- Two modules used.
- Detects the supply voltage from 0.025 to 25V
- Analog input, Low Cost
- Uses the concept of Voltage Divider to measure the supply voltage



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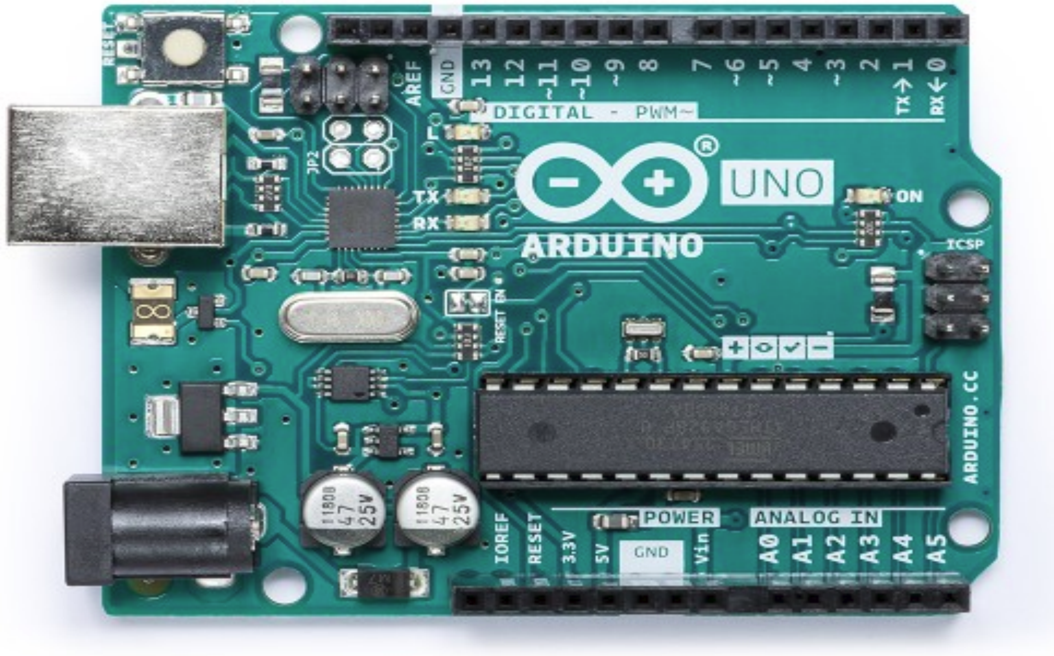
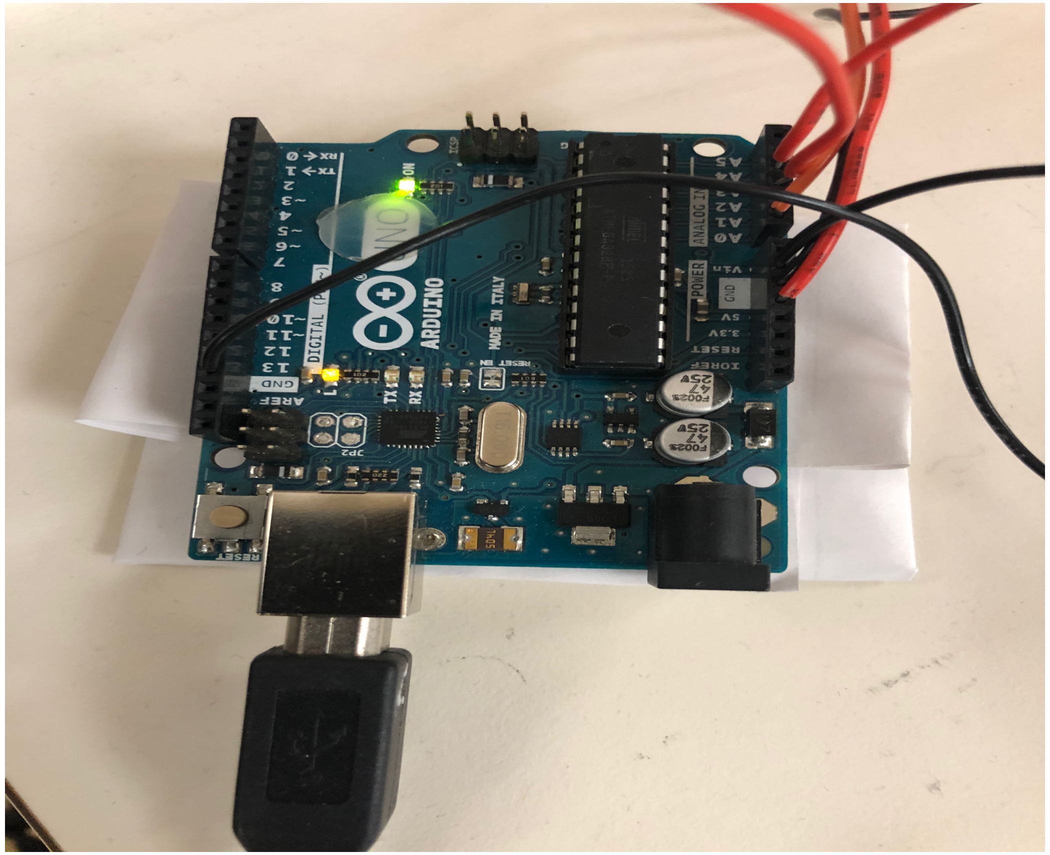
Arduino Uno R3 Microcontroller: RTU

- A microcontroller board based on the ATmega328P.; Version R3 used
- 14 digital input/output pins, 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button.
- Programmed to measure DC Current & Voltage from the PV Panel.

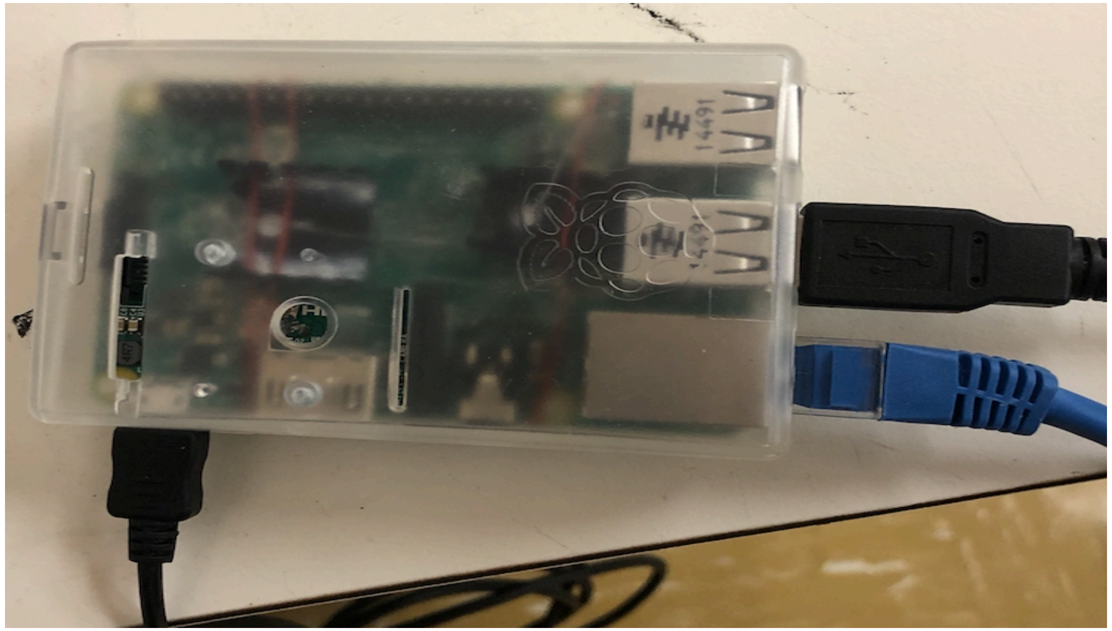


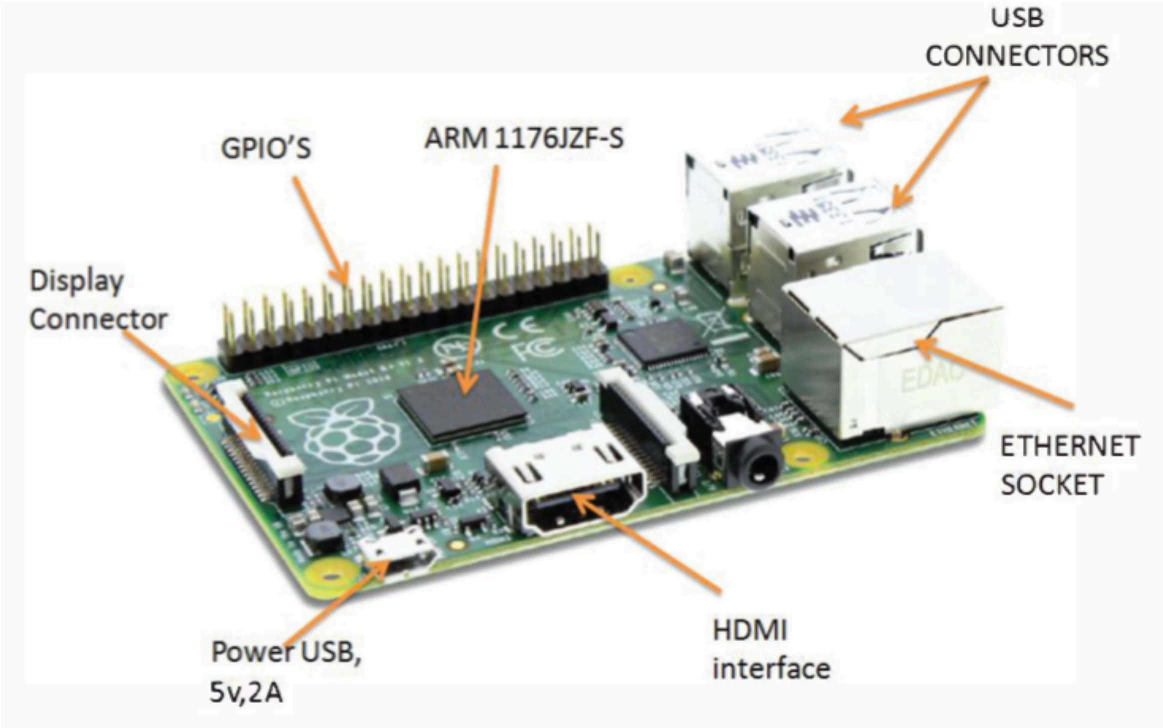


Open Source SCADA 1 Design: IoT-based, Emoncms, Arduino Uno, Raspberry Pi, Node-RED & Ethernet

Raspberry Pi Single-Board Computer: RTU

- A single-board computer device with BCM2836 quad core ARMv7 processor
- Hosted the Node-RED Programming Tool for parsing data to Emoncms IoT Platform
- Connected to MUN Network via an Ethernet cable.
- Arduino Uno board connected to the RPi via a USB cable.



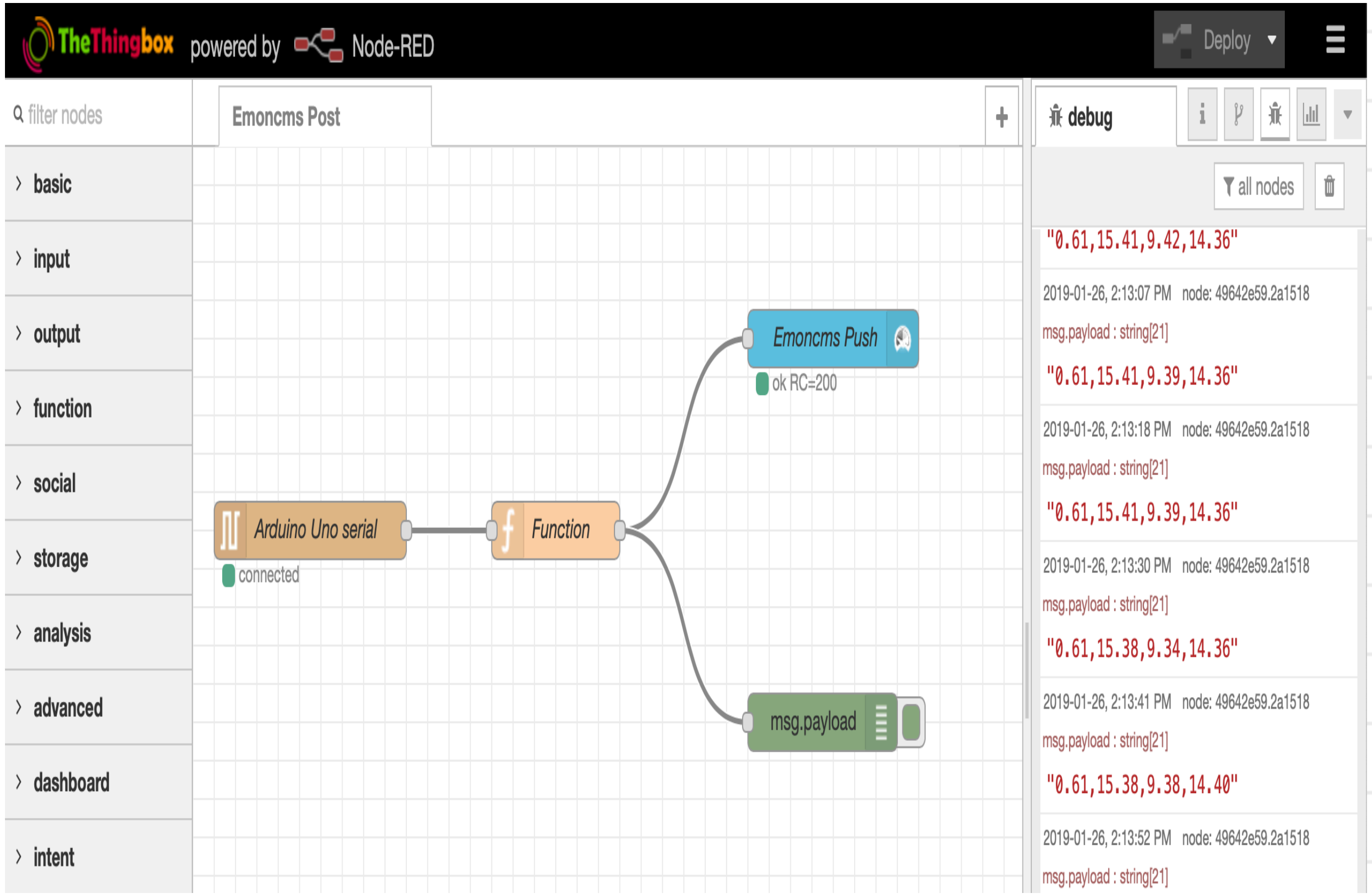


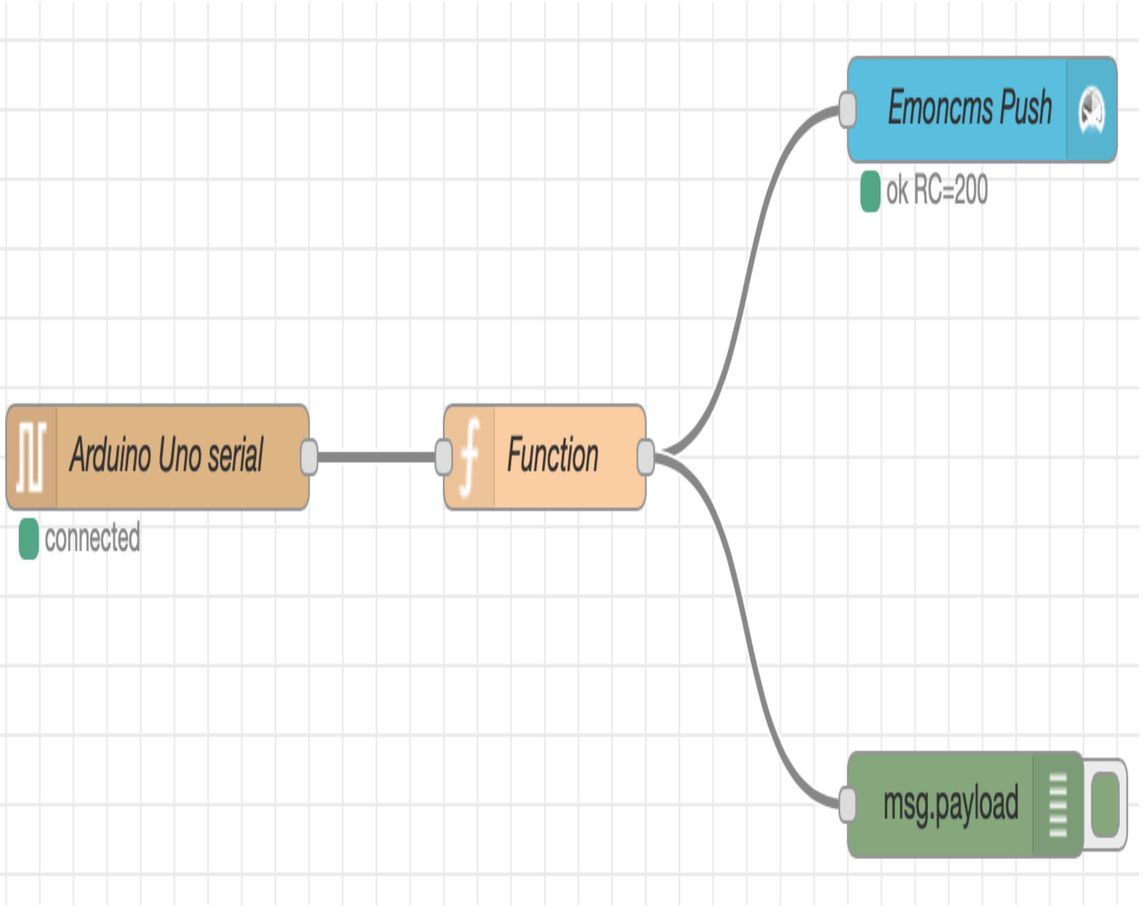
Open Source SCADA 1 Design: IoT-based, Emoncms, Arduino Uno, Raspberry Pi, Node-RED & Ethernet

SCADA Communication Channel: Ethernet + Node-RED

Node-RED Programming Tool:

- An open source programming tool for wiring together hardware devices, APIs & online services (IoT)
- Flows written to acquire Arduino Sensor Data via Serial, and Post to Emoncms IoT Server.





EMONCMS Local Server IoT Platform (MTU): Introduction to EMONCMS

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- A powerful open-source web-app for processing, logging & visualising energy data, temperature, etc.
- Allows Users to create customized reports in the form of charts, data logs & alarms (local, email, web, and mobile apps) for remote data monitoring and control.
- Part of the OpenEnergyMonitor.org project.
- Both Local and Web-Server options available.
- Free Local Server Software option for various Operating Systems.
- Locally installed on Jetson TK1 Dev. Kit Linux Machine; Data Security technique.
- Server Self-managed and Self-hosted on Private Network (MUN Network); Data Security technique.

Open Source SCADA 1 Design: IoT-based, Emoncms, Arduino Uno, Raspberry Pi, Node-RED & Ethernet

Hardware Implementation & Experimental Setup on a Small Renewable Power Generation System:

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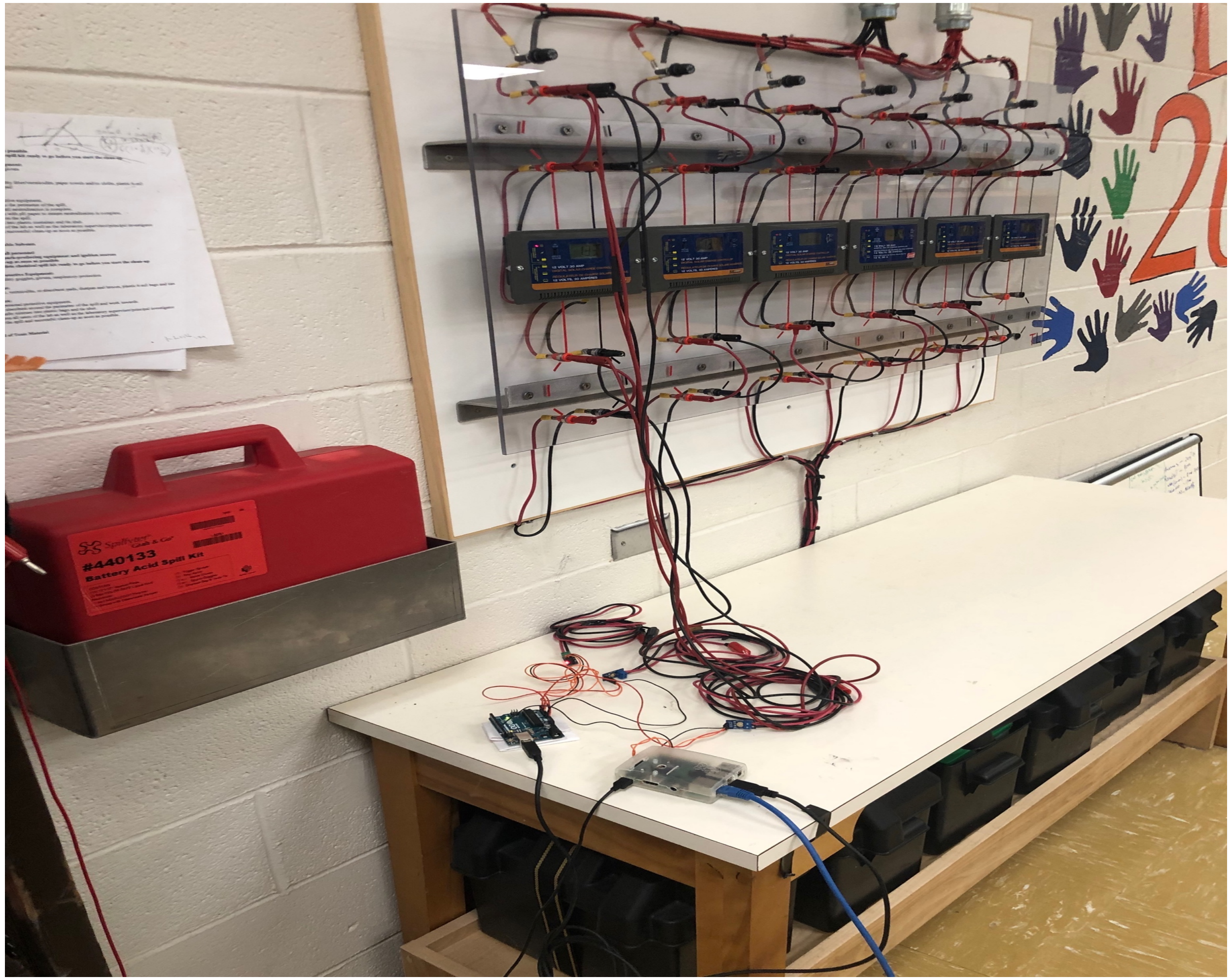
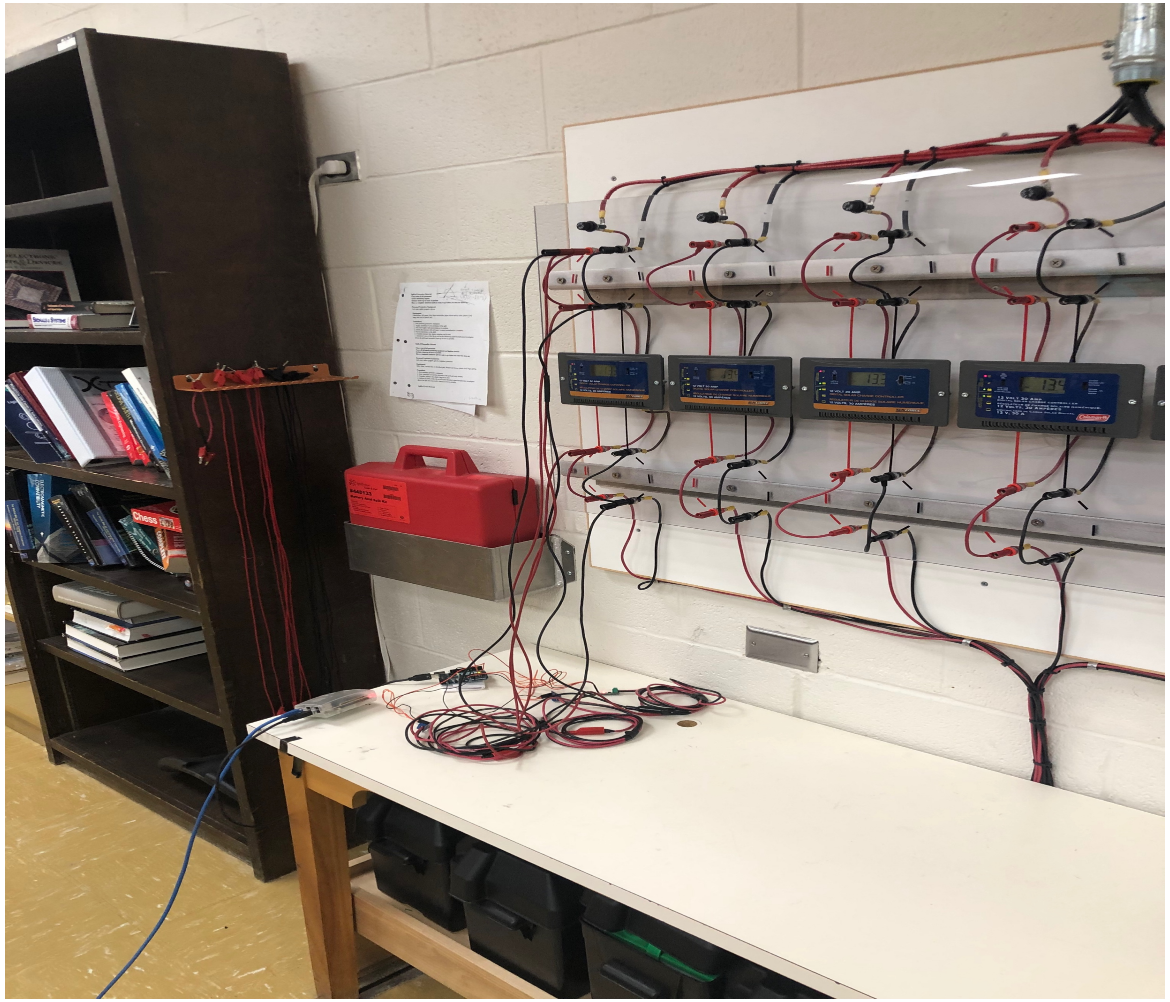
- Hardware Prototype designed & set up in MUN ECE Laboratory for PV System Monitoring & Supervisory Control:





Acquired PV System Data on Emoncms IoT Platform:

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Dashboards Apps Extra Setup Logout

Inputs

Input API Help

Node 1 inactive

Node 10 5s

Node	Key	Name	Process list	Updated	Value
10	1	PV Current	Log to feed	5s	0.6
10	2	PV Voltage	Log to feed	5s	15.48
10	3	PV Power	Log to feed	5s	9.28
10	4	Battery Voltage	Log to feed	5s	14.4

Dashboards Apps Extra Setup Logout

Feeds

Feed API Help

Node 1 301KB inactive

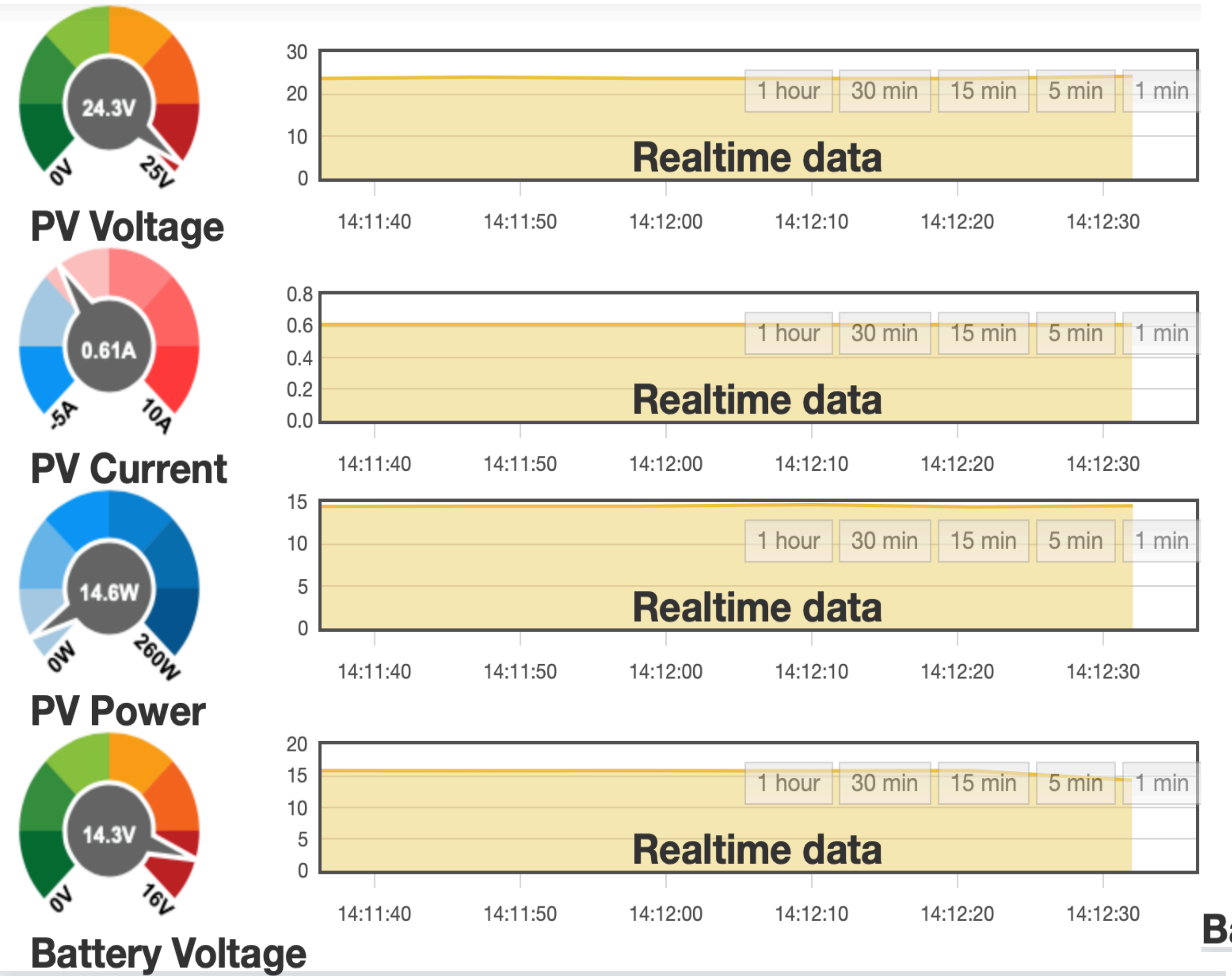
Node 10 0B 8s

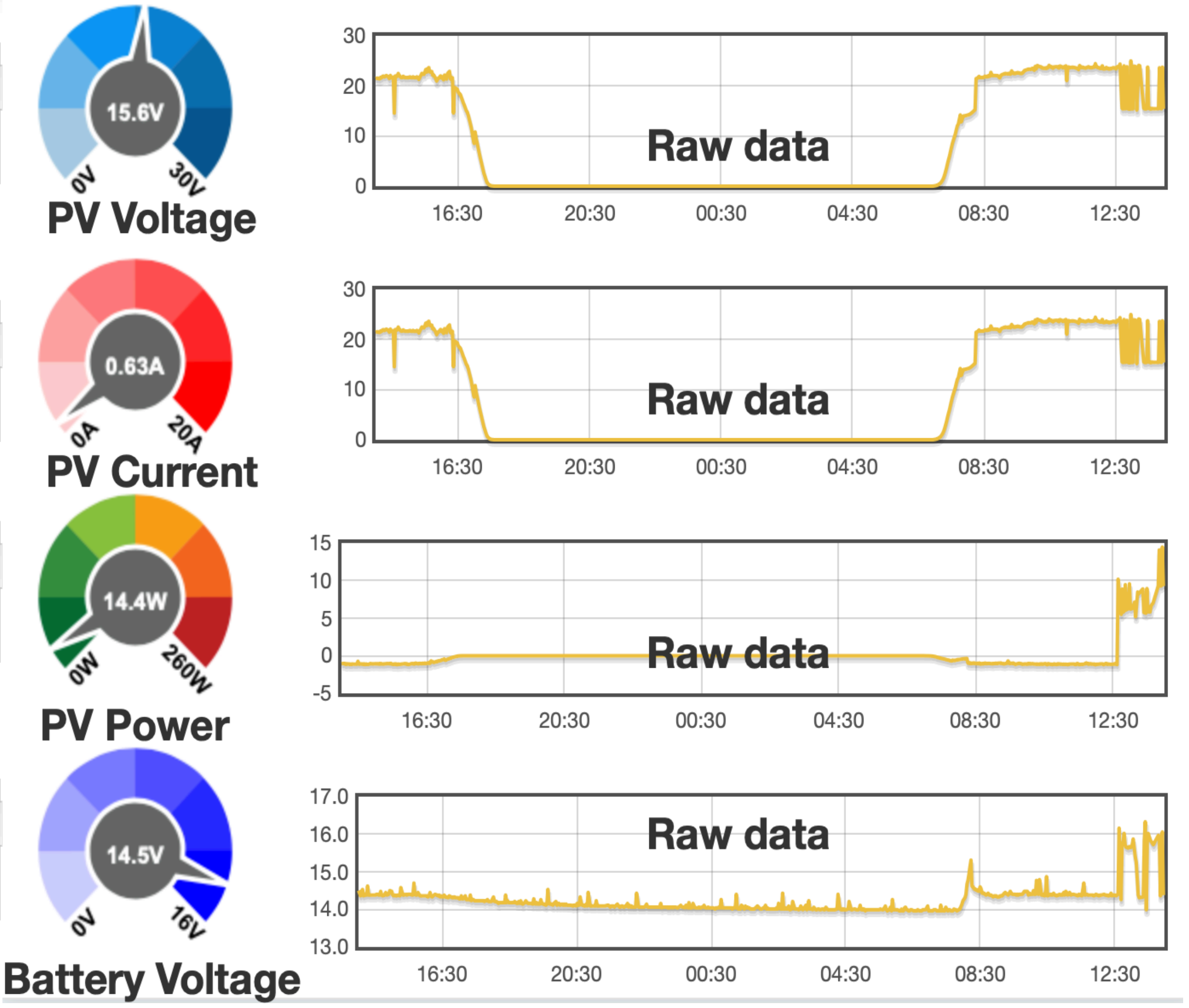
Id	Tag	Name	Process list	Public	Datatype	Engine	Size	Updated	Value
24	...	PV Power_W			REALTIME	PHPFINA	n/a	8s	9.28
15	...	PV Current_A			REALTIME	PHPFINA	n/a	8s	0.6
19	...	PV Voltage_V			REALTIME	PHPFINA	n/a	8s	15.5
25	...	Battery Voltage_V			REALTIME	PHPFINA	n/a	8s	14.4

Refresh feed size New virtual feed

Open Source SCADA 1 Design: IoT-based, Emoncms, Arduino Uno, Raspberry Pi, Node-RED & Ethernet

Human Machine Interface: Operator Dashboards and Events: Emoncms IoT Platform:

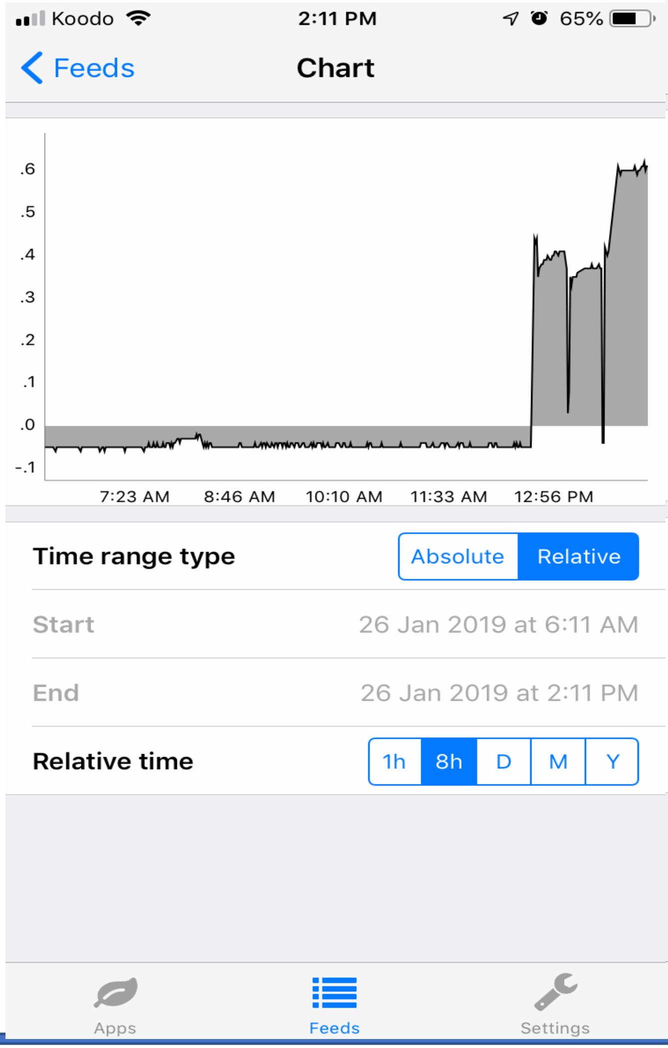


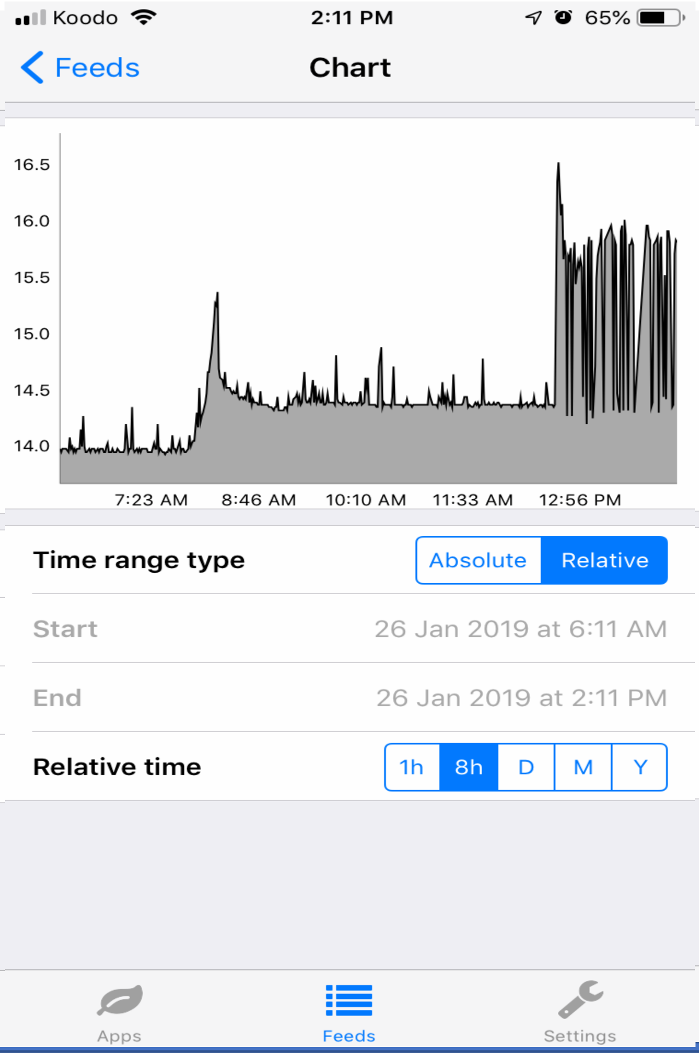


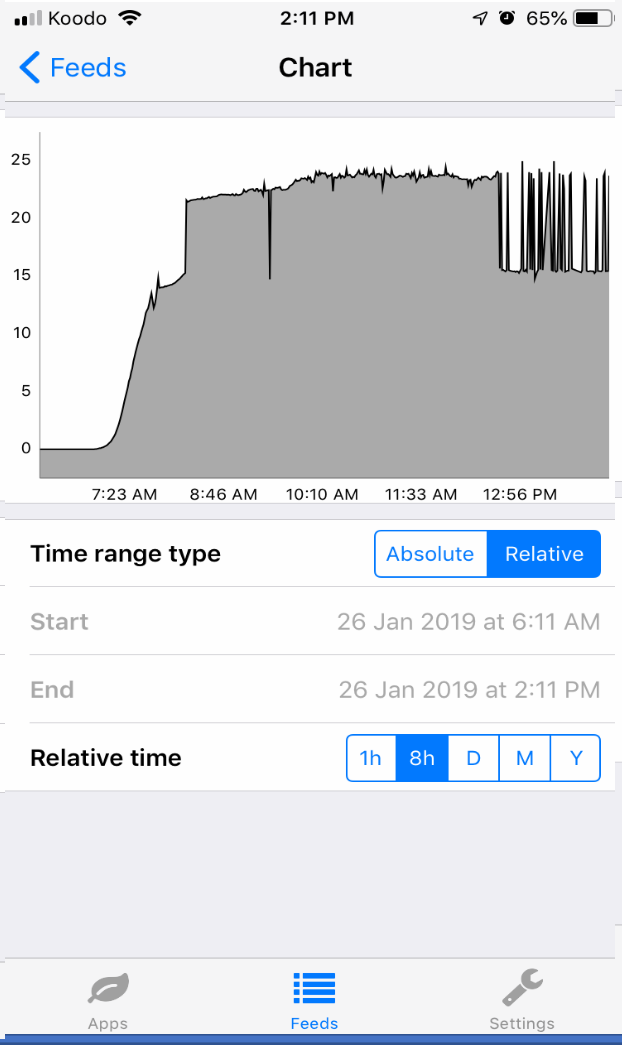
Open Source SCADA 1 Design: IoT-based, Emoncms, Arduino Uno, Raspberry Pi, Node-RED & Ethernet

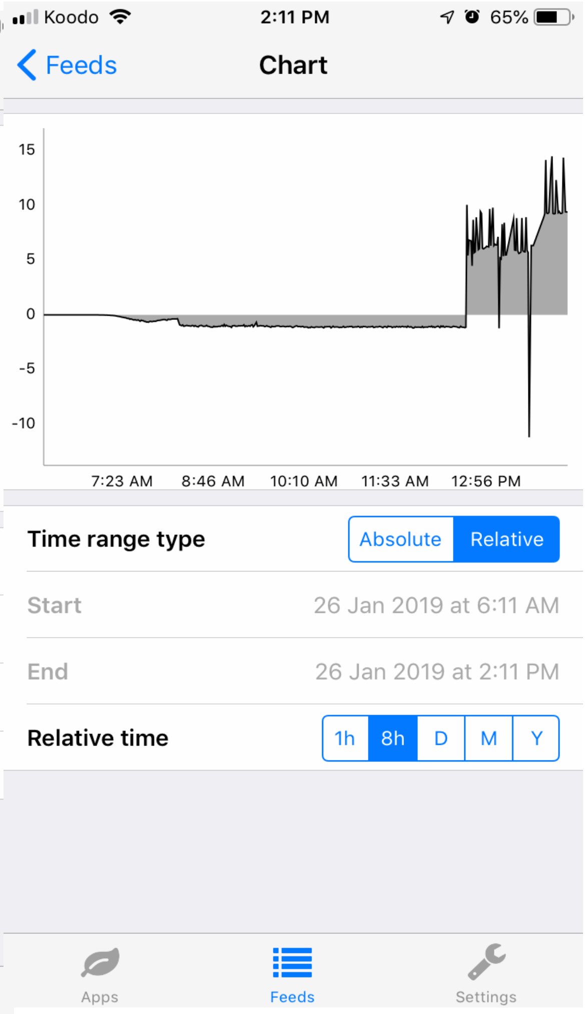
Human Machine Interface: Operator Dashboards and Events: Emoncms IoT Mobile App Platform:

- Screenshots of PV Current, Voltage & Power from EMONCMS Mobile App:









Conclusions: Some Key Features of SCADA 1:

- IoT-based, Secure, Reliable, Low-cost, Low-Power, & Open Source
- Reporting, Remote Data Monitoring & Supervisory Control, Data Acquisition, Historic Data Storage & Trending, etc.

Table A.1: Bill of Materials.

S/N	COMPONENT	QTY	PRICE (CAD)
1	Emoncms Server (Jetson TK1 Dev. Kit)	1	250.00
2	Emoncms Software	1	00.00
3	Node-RED Software	1	00.00
4	Raspberry Pi 2 B	1	45.95
5	Arduino Uno	1	29.00
6	Current Sensor	1	5.25
7	Voltage Sensor	2	11.98
8	8GB SD Card	1	12.66
9	Miscellaneous (Wires, Boxes, etc.)	1	50.00
	Grand Total:		**$ 404.84 CAD**

Table A.2: Power consumption of hardware components.

S/N	HARDWARE	POWER (W)
1	Raspberry Pi 2 + Arduino Uno + Sensors	2.4
2	Emoncms Server	2.7
	Total Power Consumption :	**5.1 W**

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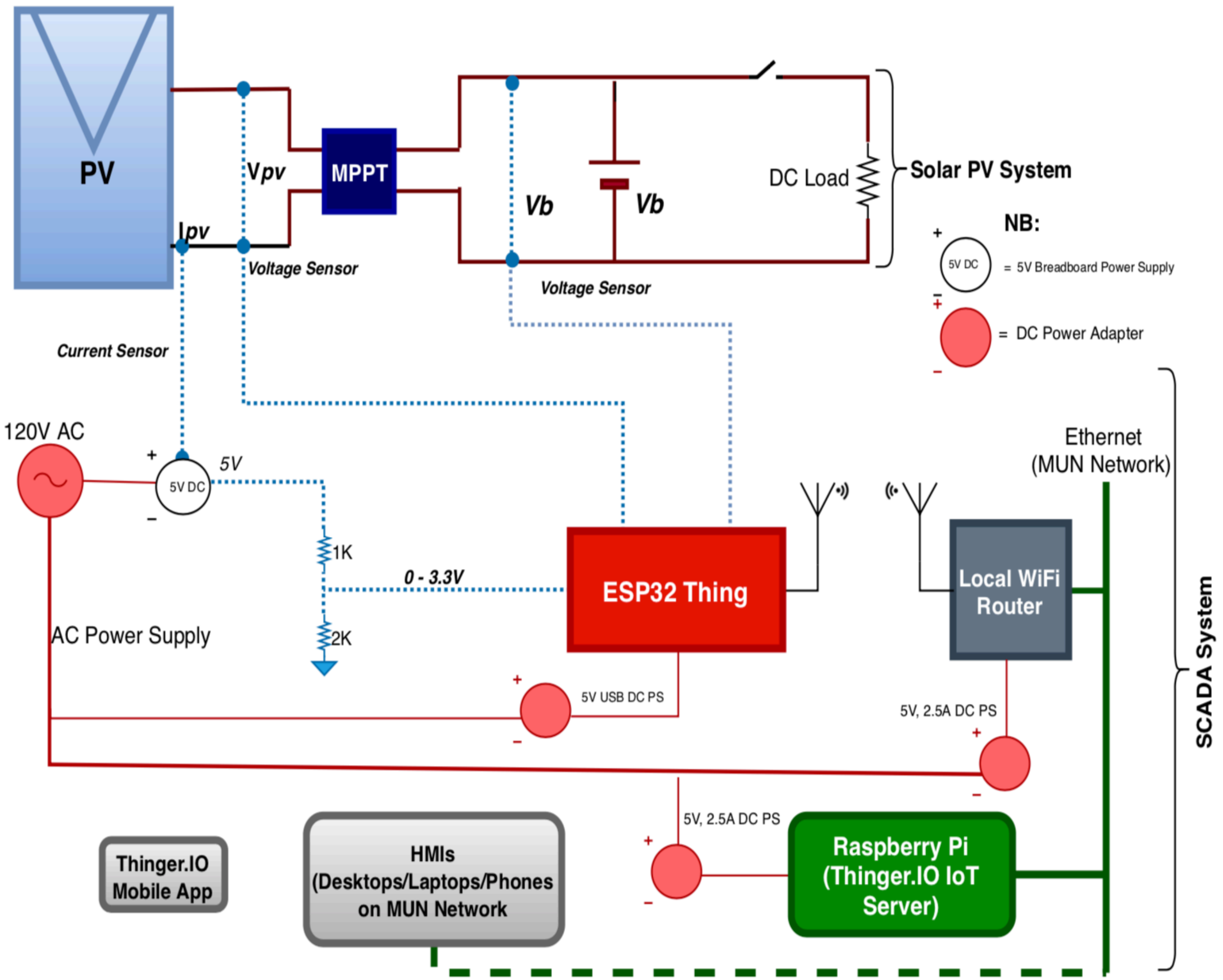
Components of SCADA 2 System:

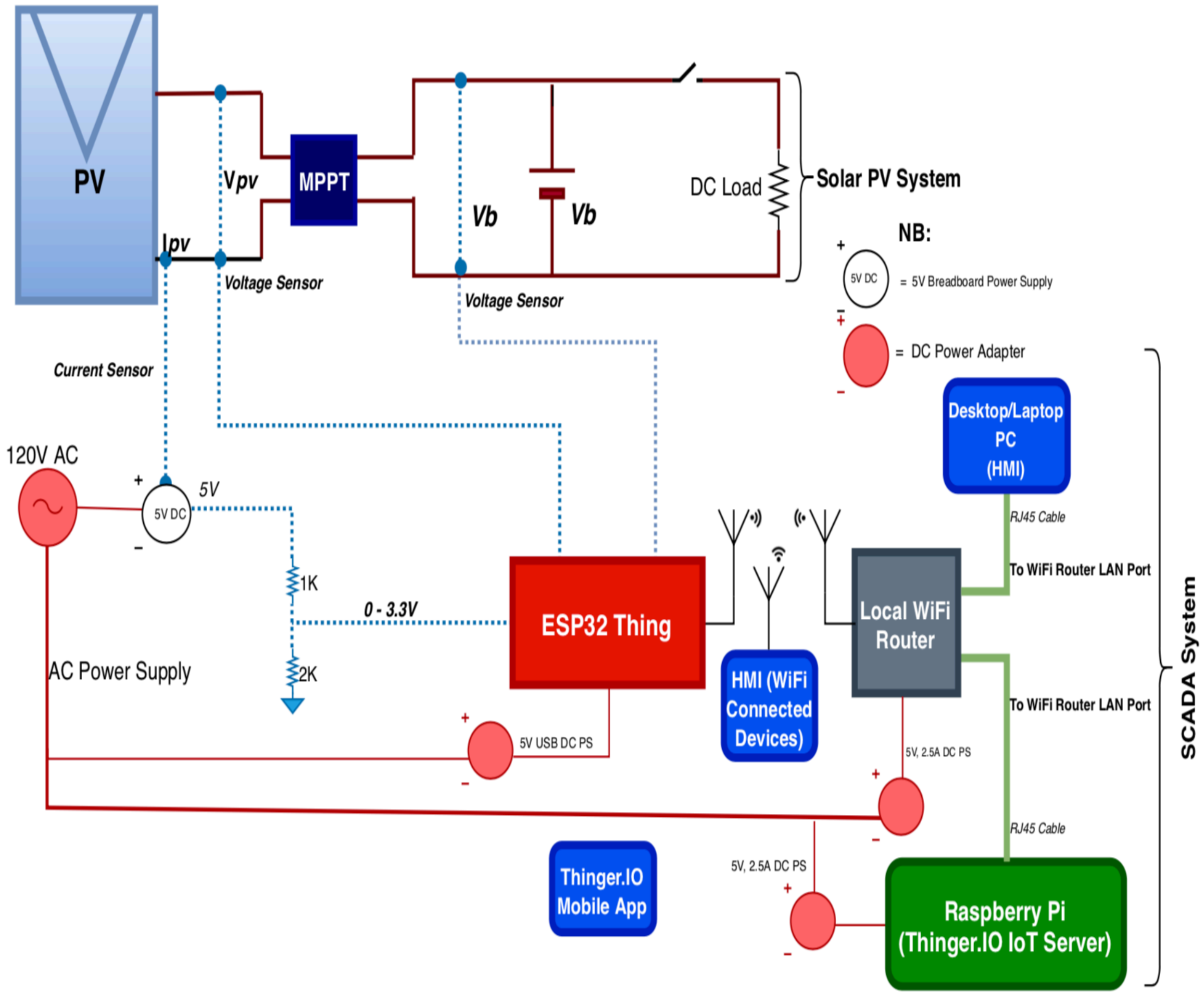
- A Small Renewable Power Generation System (Solar PV System with ESS).
- Sensors (Current, Voltage.): FIDs
- ESP32 Thing Micro-controller: RTU
- Raspberry Pi2 machine (Thinger.IO IoT Server): MTU
- Wi-Fi Router: SCADA Communication/Data Transfer
- Computers and Mobile Devices: HMIs/GUIs

Open Source SCADA 2 Design: IoT-based, Thinger.IO, Raspberry Pi, ESP32 Thing & Wi-Fi

System Configurations; Two Configurations considered



Configuration A: MUN Network (Internet Required)

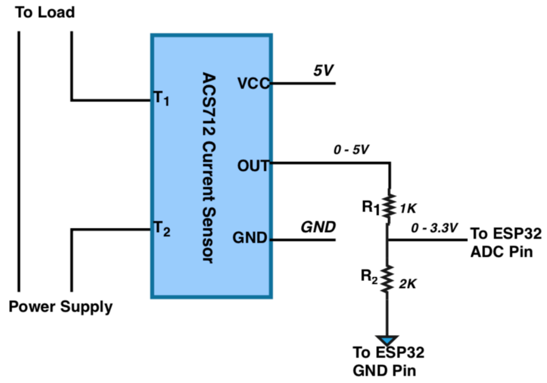


Configuration B: Private Industrial Network created (Internet Optional)

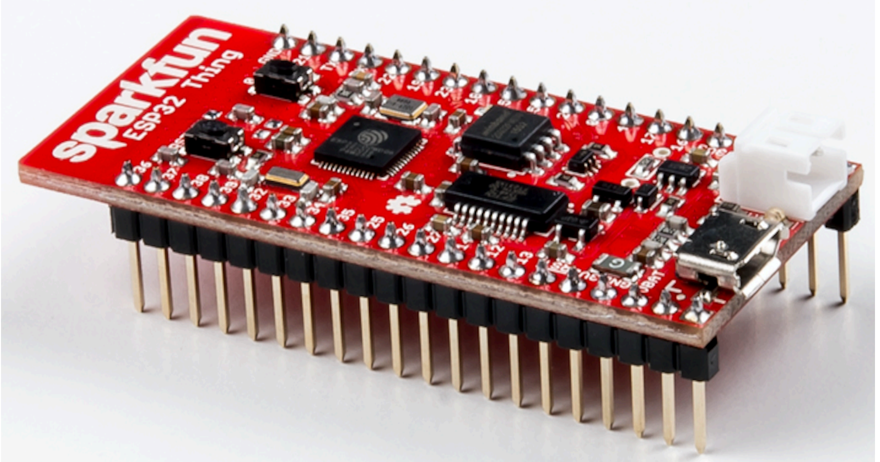
Open Source SCADA 2 Design: IoT-based, Thinger.IO, Raspberry Pi, ESP32 Thing & Wi-Fi

Field Instrumentation Devices: Same Sensors as in SCADA 1

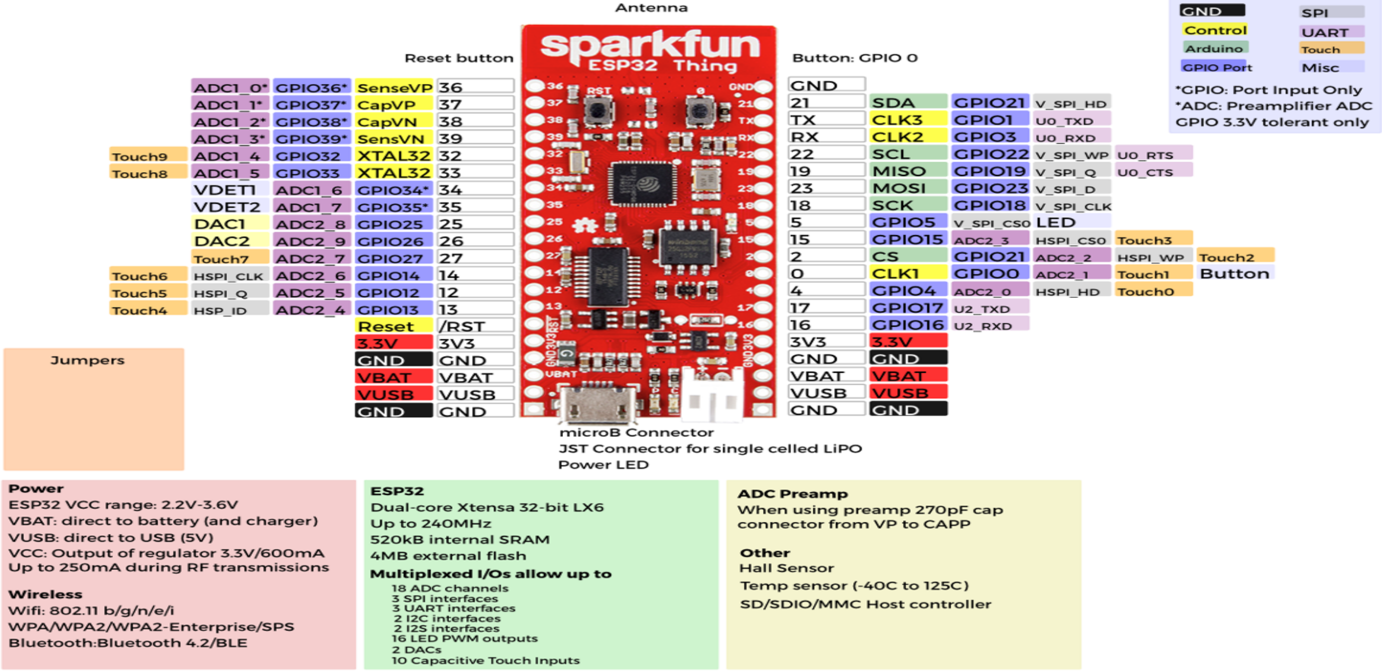
ESP32 Thing Micro-controller: RTU



- Low-Cost ($20), Low-Power (0.5W) Micro-controller for IoT Projects
- Supports Wi-Fi, 30 Input/Output Pins
- 5 V Power Supply, 2. 2 V to 3.6 V ((3.3 V) ADC Signal Voltage
- Programmed with Arduino IDE to measure & acquire Sensor PV Data & parse data over Wi-Fi to Thinger.IO IoT Server

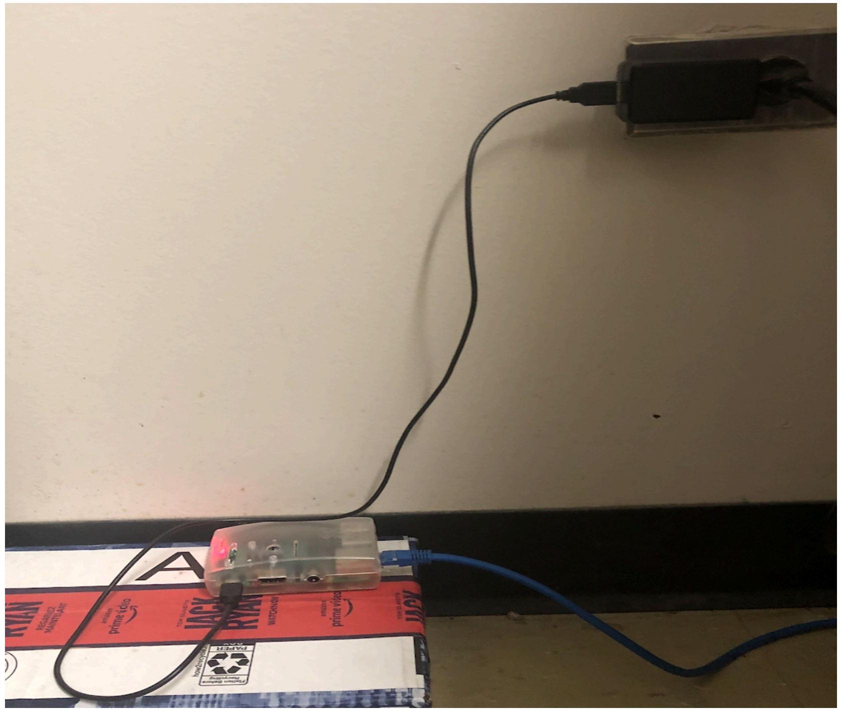


SparkFun ESP32 Thing (DEV-13907)



Raspberry Pi Single-Board Computer: MTU

- Hosted the Thinger.IO IoT Server
- Connected to MUN Network via an Ethernet cable in Configuration A.
- Connected to Wi-Fi Router LAN Port via an Ethernet cable in Configuration B.



SCADA Communication Channel: Wi-Fi Router for Private Wi-Fi Network

- D-Link Router (DI-524 Airplus G) used to create a private Wi-Fi Network

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Thinger.IO IoT Server: Overview

- A Powerful Open Source platform for the Internet of Things; supported by GitHub
- Supports REST API for controlling & reading smart devices; e.g: sensors
- Uses HTTP methods like OPTIONS, GET, PUT, POST, and DELETE.
- Specific response of each resource gotten in JSON/XML format.
- Allows integration of Arduino-compatible hardware; e.g: ESP32
- Both Web-Server and Self-Hosted options available
- Connected Devices identified with Unique Identifier and Credentials
- Cloud Console shows Google Maps of Connected Devices
- Allows an operator to define 4 resources (Input, Output, Input/Output, Callback resources)
- Supports Real-time visualization dashboards & charts for remote monitoring
- Supervisory Controls possible using Endpoints (emails, HTTP Requests, etc)
- Free Android & iOS Apps for Server integration available

Thinger.IO IoT Server: Configurations

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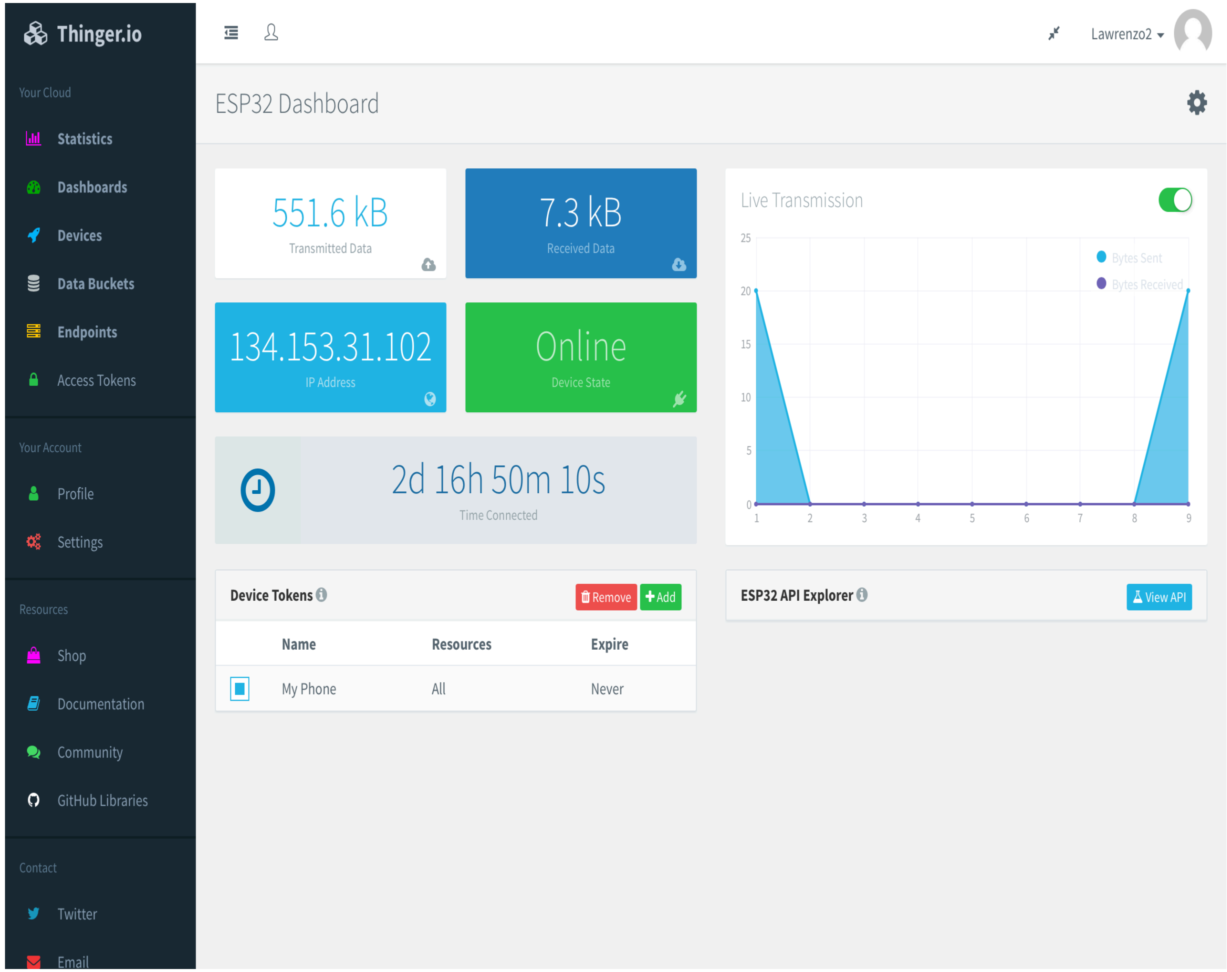
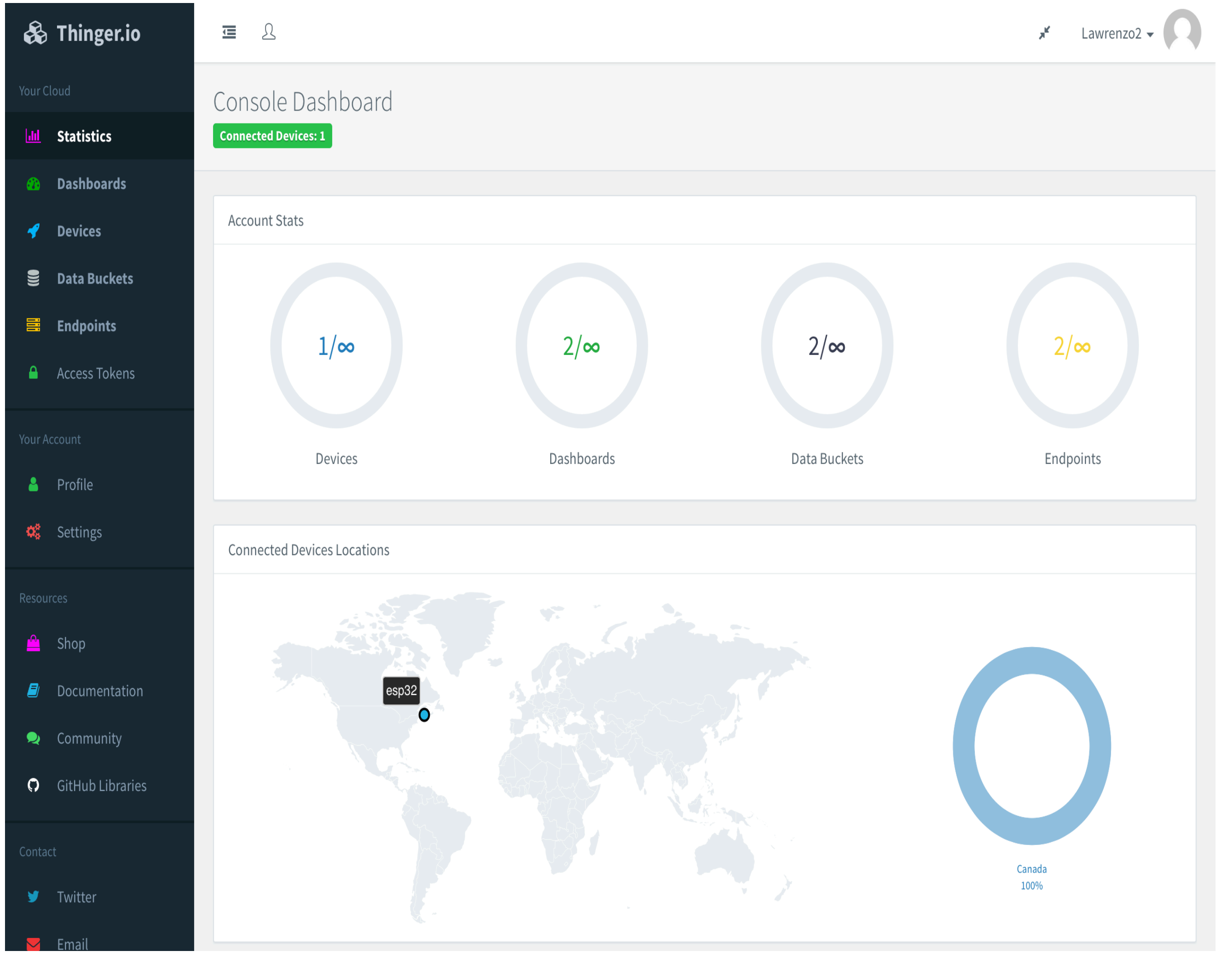
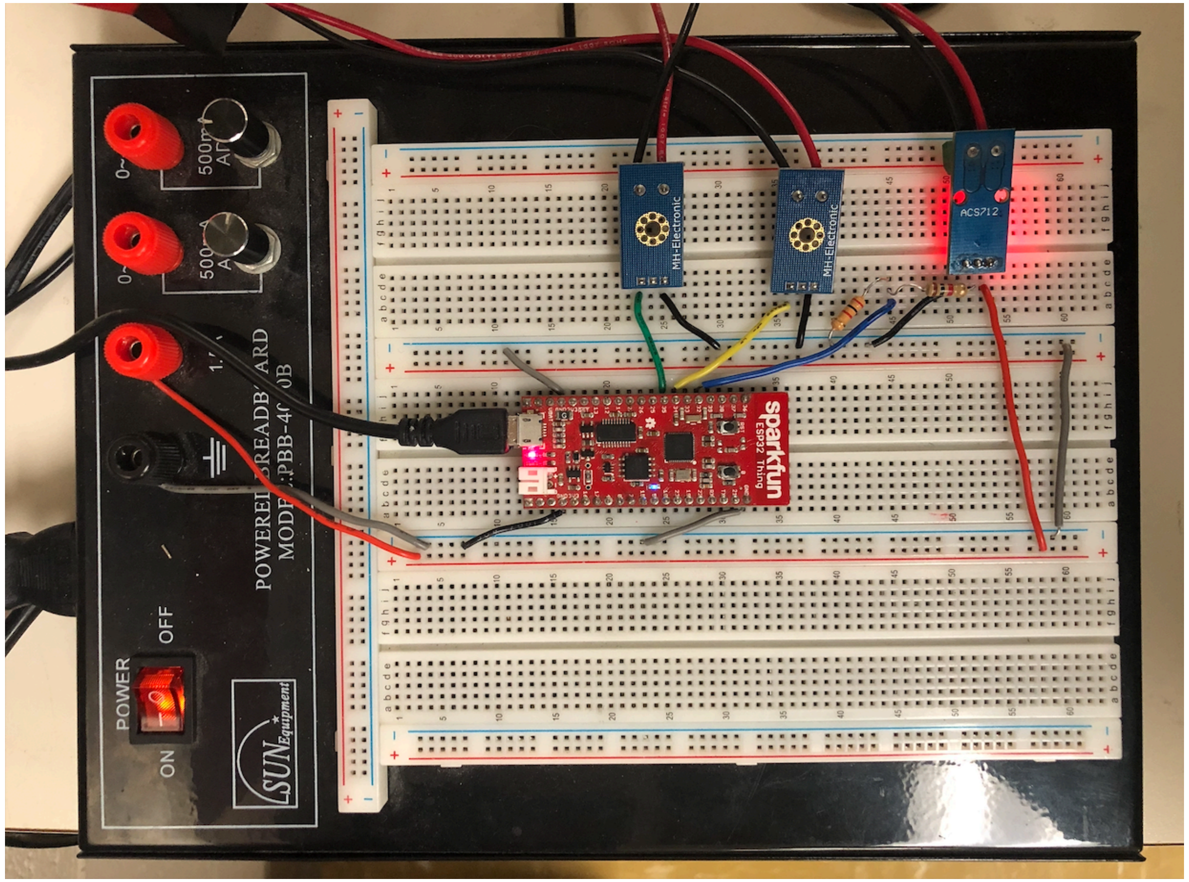
- Main Data Server installed on a Local Machine (Rpi), Self-hosted, Self-managed on private networks

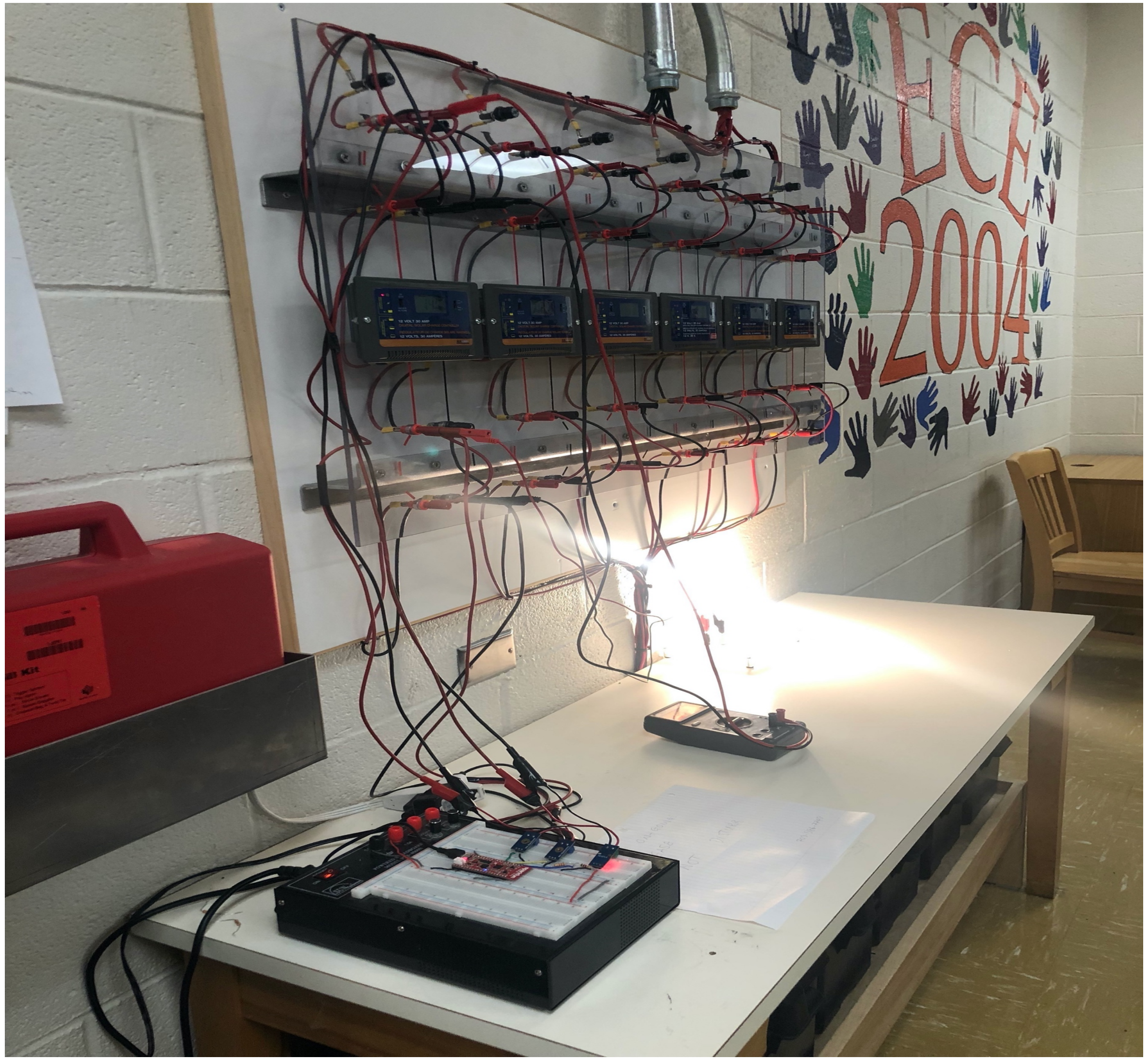




Prototype Design & Experimental Setup:

- Hardware implemented & System Set up on a Small Renewable Power Generation System (Solar PV System) at MUN ECE Lab:





Implementation Methodology & Flow Chart:

Algorithm 1: Data Logging Algorithm:

Initialization;

1. Read Sensor Values on Analog Pins 32, 34 and 35, and Calculate Values for Pins 32 × 34;
2. Display the above Values on Arduino IDE Serial Monitor;
3. Connect to Local Wi-Fi Network with Wi-Fi Name and Password;
4. Connect to Thinger.IO Local Server IP Address;
5. Identify the specified Thinger.IO Account Name, Device ID and Credentials;
6. Post Sensor Data to the specified Thinger.IO Device;

while *Thinger.IO Server Acknowledges Data Receipt* **do**

  7. Display Sensor Data on Thinger.IO Cloud Console, and;
  8. Display "Ok" on Arduino IDE Serial Monitor;

  if *No Data Receipt Acknowledgement from Thinger.IO Server* **then**

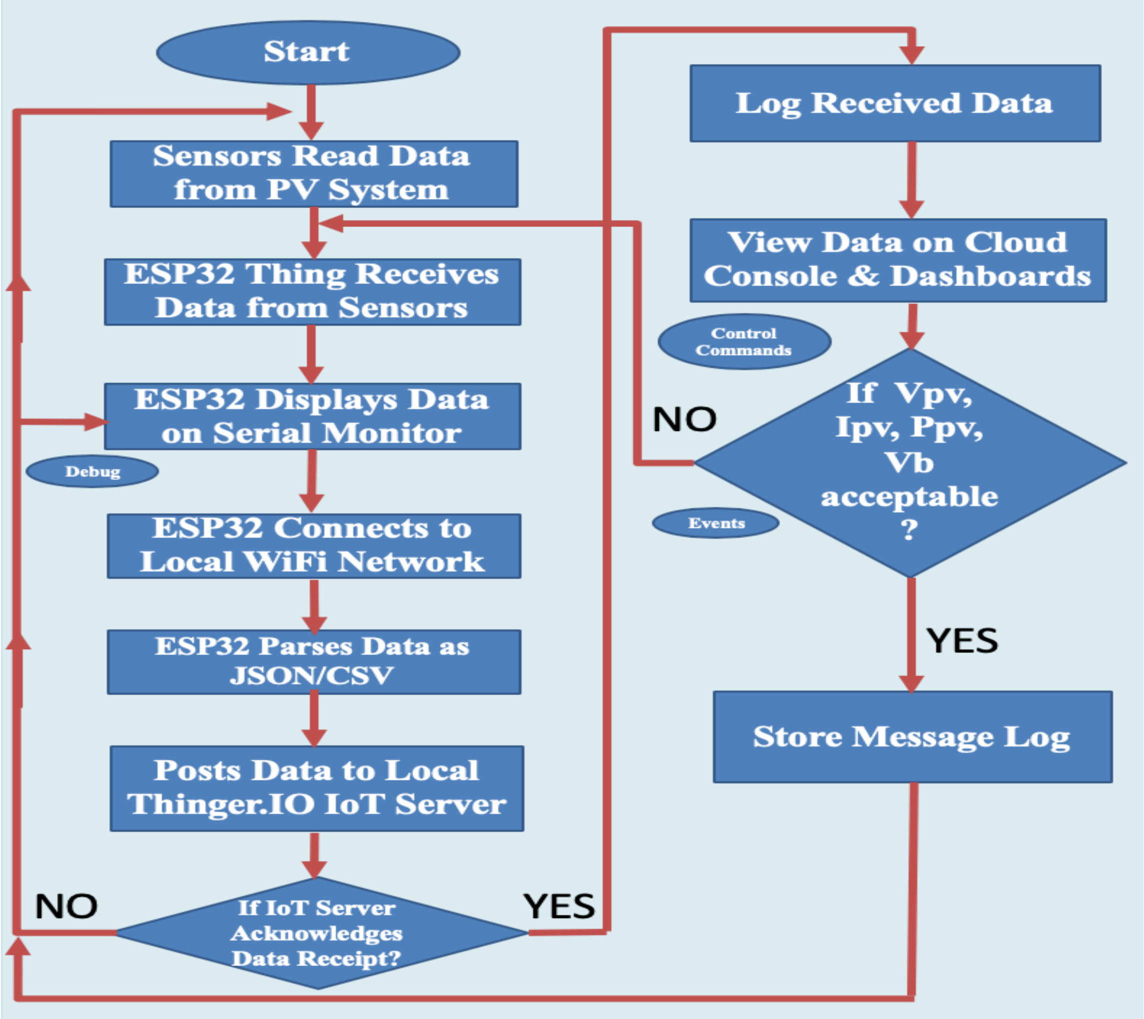
    9. Display Debug/Error Message on Arduino IDE Serial Monitor;

  else

    10. Go to Step 1;

  end

end



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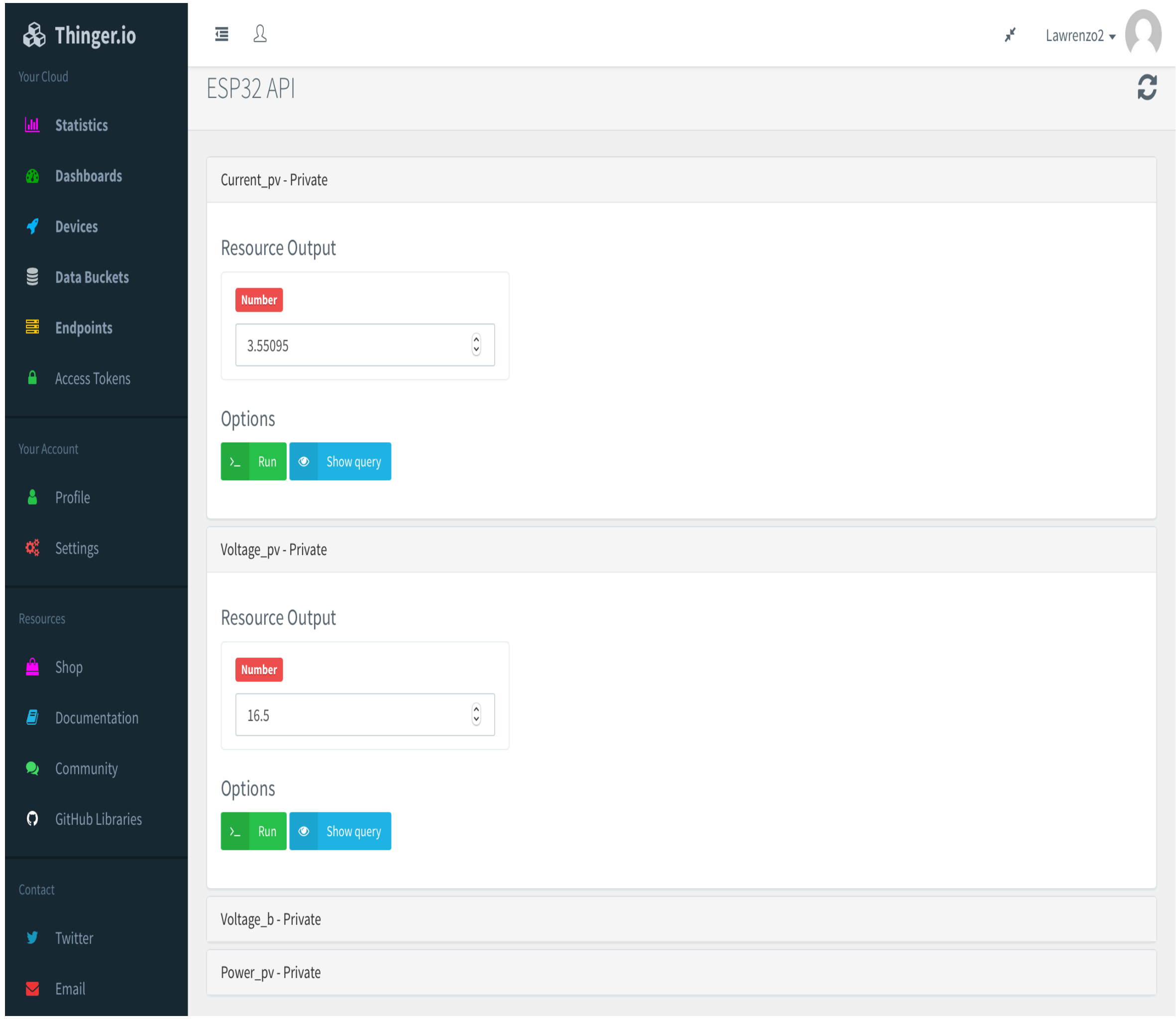
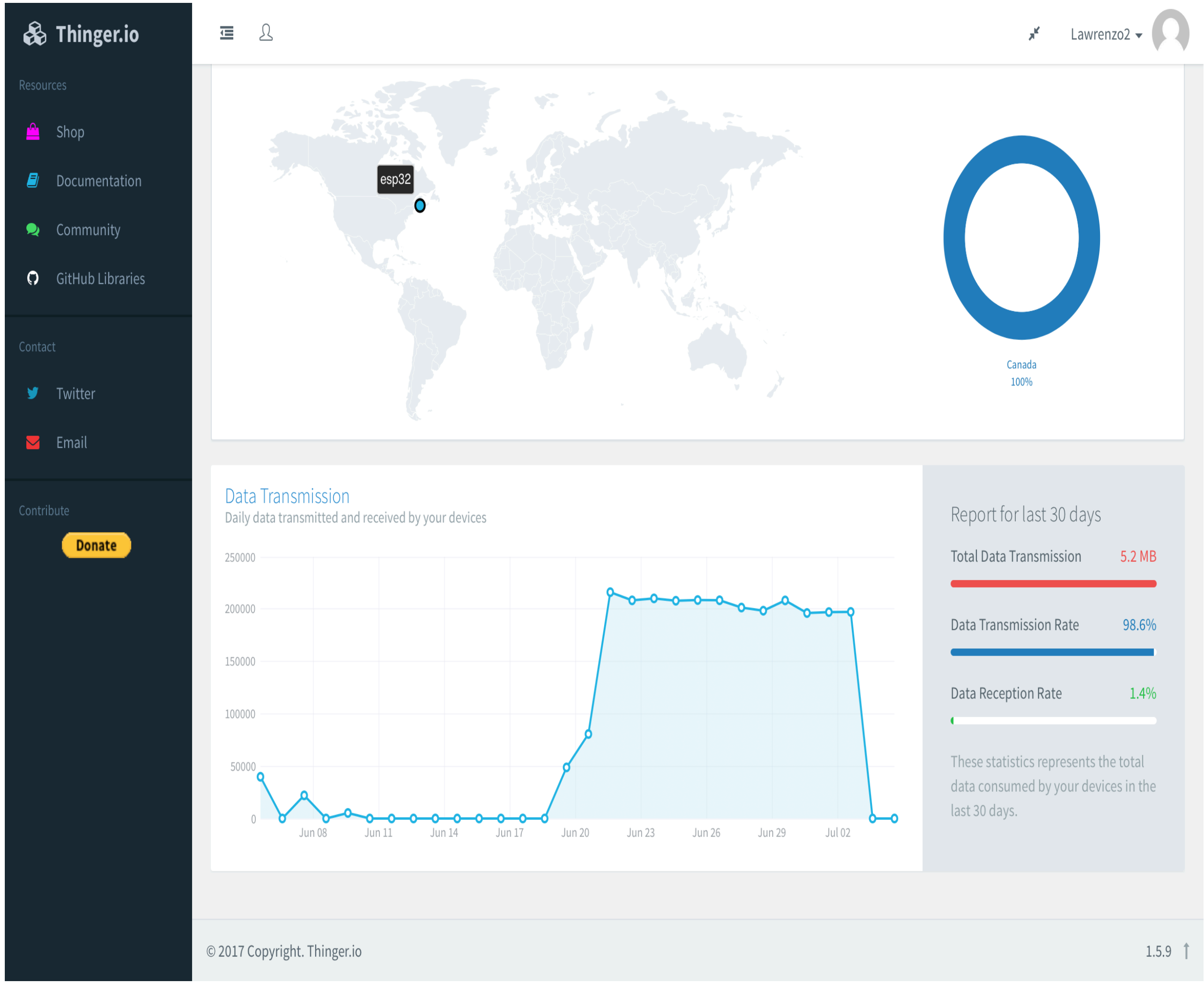
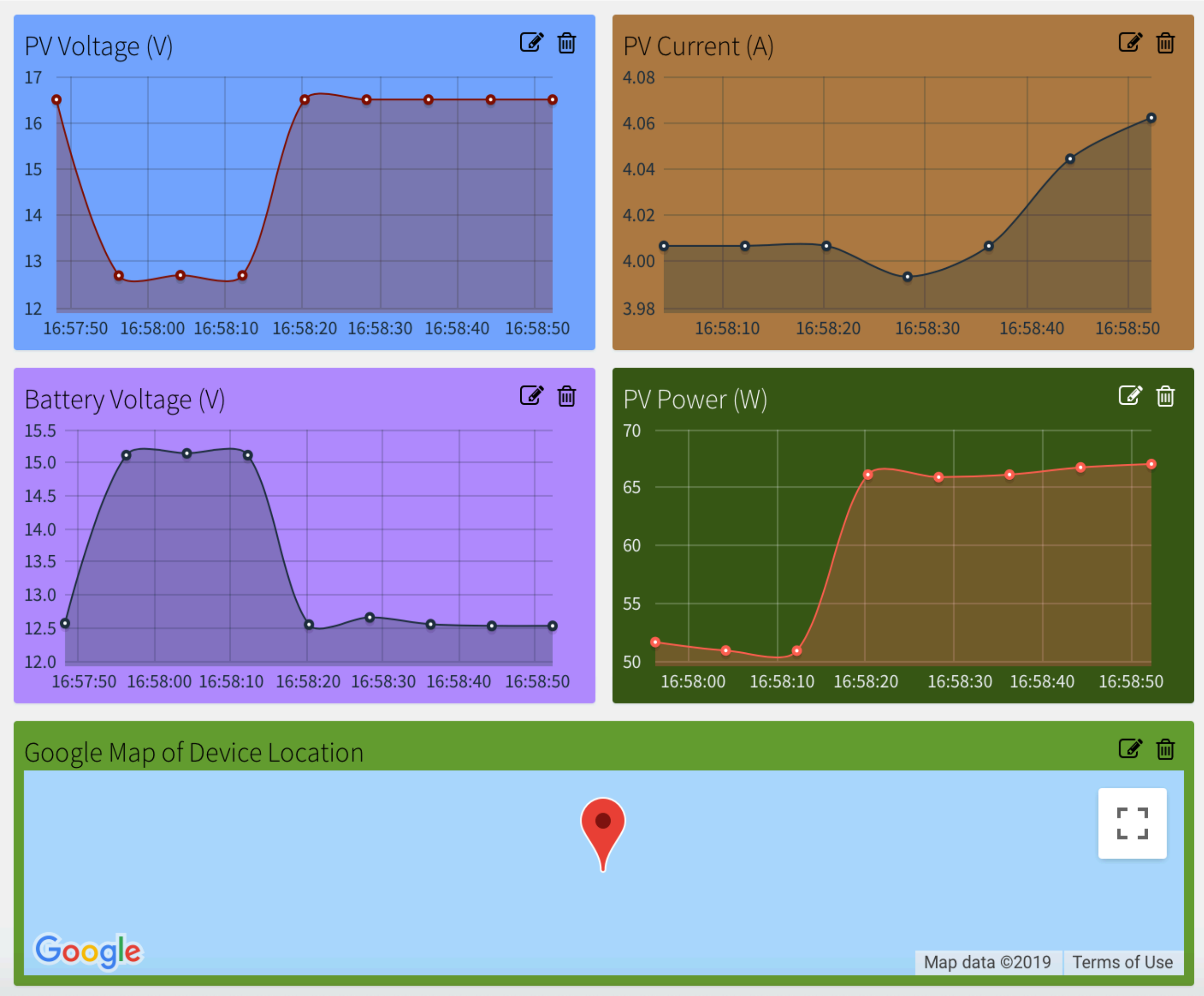
Data Logging & Historic Storage:

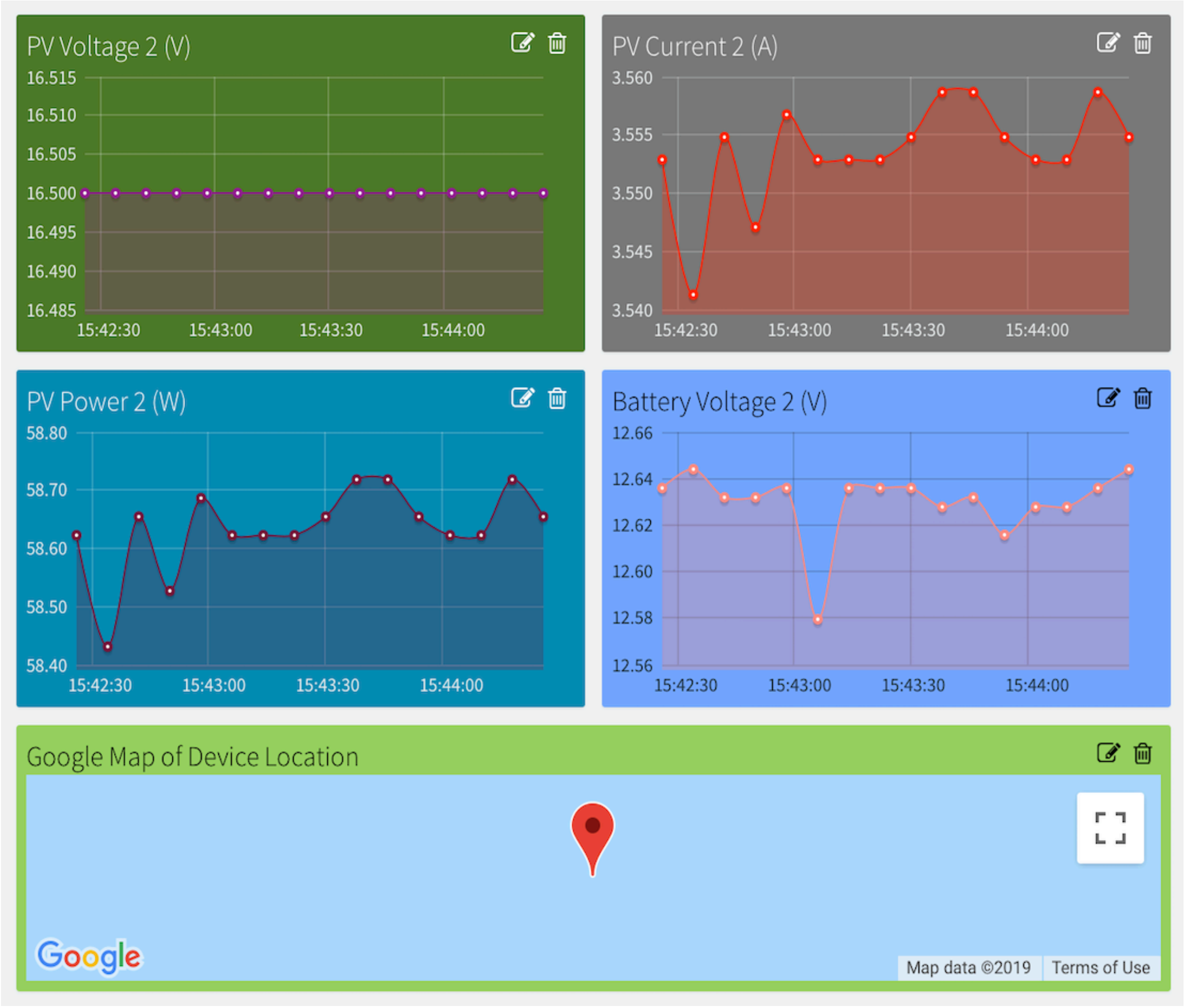




Open Source SCADA 2 Design: IoT-based, Thinger.IO, Raspberry Pi, ESP32 Thing & Wi-Fi

Human Machine Interface (HMI): PV Data Monitoring & Supervisory Control:





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Conclusions: Some Key Features of SCADA 2:

- IoT-based, Secure, Reliable, Low-cost, Low-Power, & Open Source
- Reporting, Remote Data Monitoring & Supervisory Control, Data Acquisition, Historic Data Storage & Trending, etc.

Table 4.1: Bill of Materials.

S/N	COMPONENT	QTY	PRICE (CAD)
1	Thinger.IO RPi ISO Image	1	15.62
2	Raspberry Pi 2 B	1	45.95
3	ESP32 Thing	1	31.90
4	Current Sensor	1	5.25
5	Voltage Sensor	2	11.98
6	D-Link D1-524 Wireless Router	1	98.51
7	8GB SD Card	1	12.66
8	Miscellaneous (Breadboard, Resistors, Wires, Boxes, etc.)	1	70.00
	Grand Total:		**$ 291.87 CAD**

Table 4.2: Power consumption of hardware components.

S/N	HARDWARE	POWER (W)
1	Raspberry Pi 2 B	1.7
2	ESP32 Thing (alone)	0.5
3	Breadboard (with Sensors, ESP32, Resistors, etc. connected)	3.3
4	D-Link D1-524 Wireless Router	4.4
	Total Power Consumption (less ESP32 alone):	**9.4 W**

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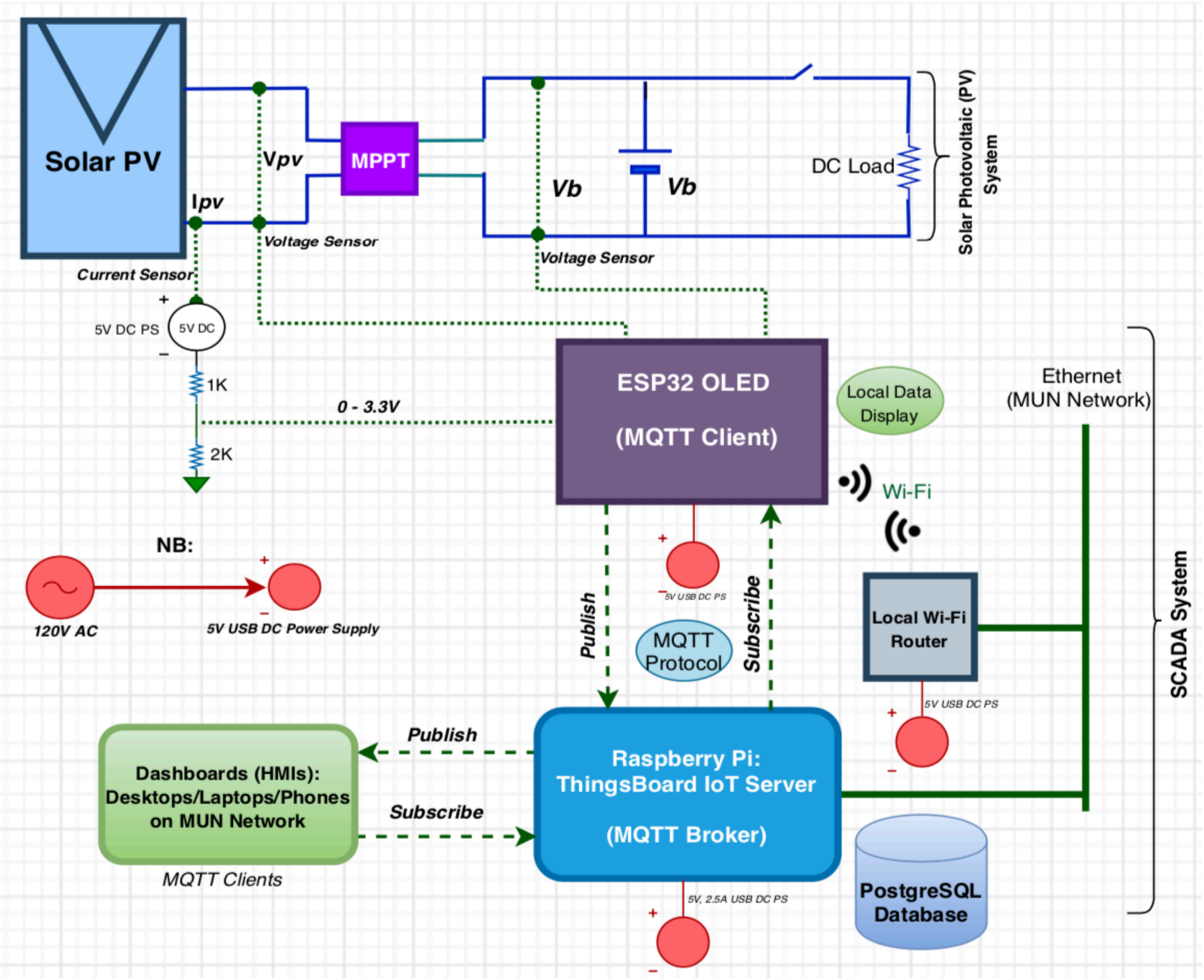
Components of SCADA 3 System:

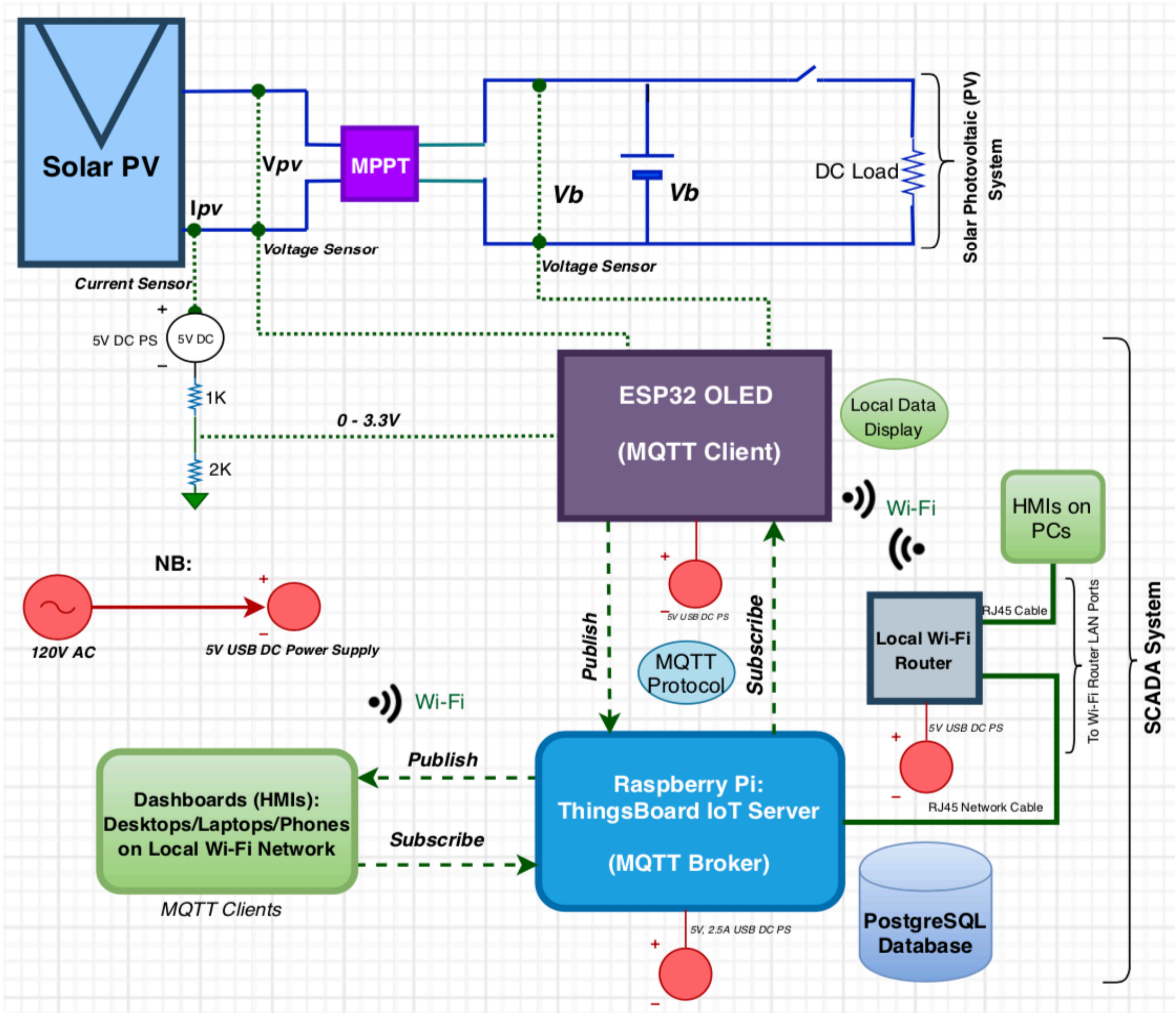
- A Small Renewable Power Generation System (Solar PV System with ESS).
- Sensors (Current, Voltage.): FIDs
- ESP32 with OLED Micro-controller: RTU
- Wi-Fi Router: SCADA Communication Network
- MQTT Protocol: Data Transfer
- Raspberry Pi2 machine (ThingsBoard IoT Server): MTU
- Computers and Mobile Devices: HMIs/GUIs

Open Source SCADA 3 Design: IoT-based, ThingsBoard, Raspberry Pi, ESP32 with OLED, Wi-Fi & MQTT Protocol

System Configurations; Two Configurations considered



Configuration A: MUN Network (Internet Required)

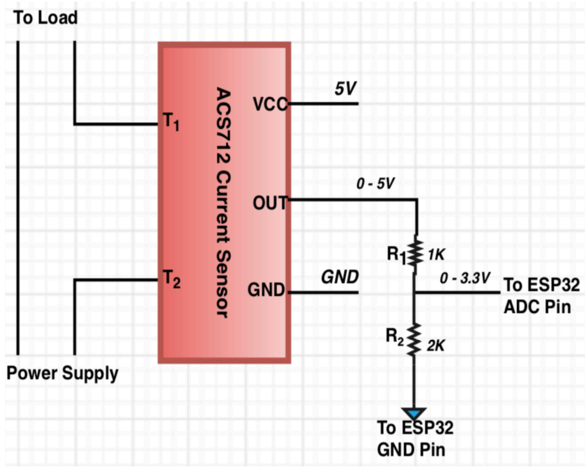


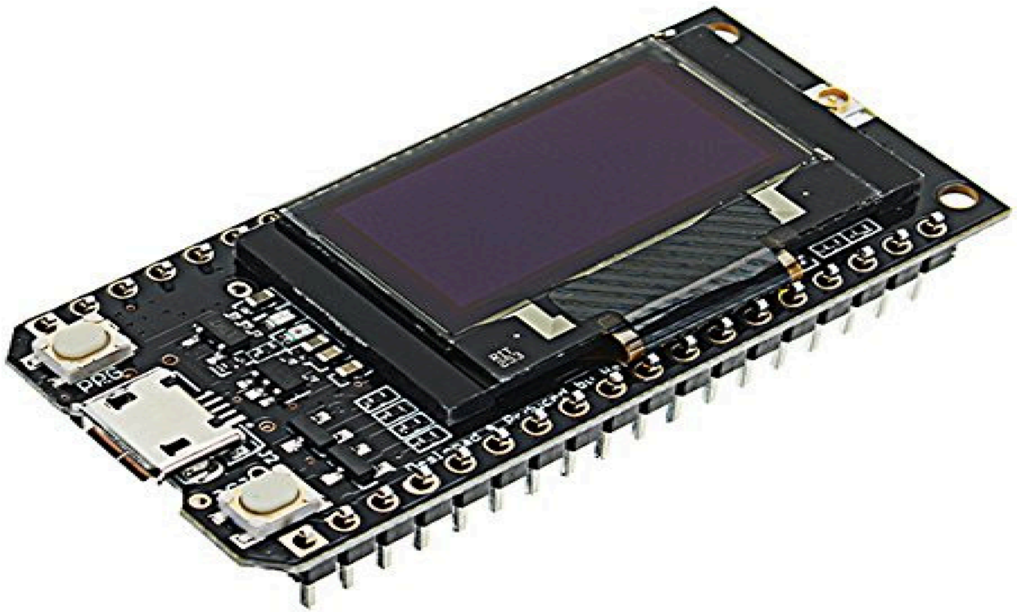
Configuration B: Private Industrial Network created (Internet Optional)

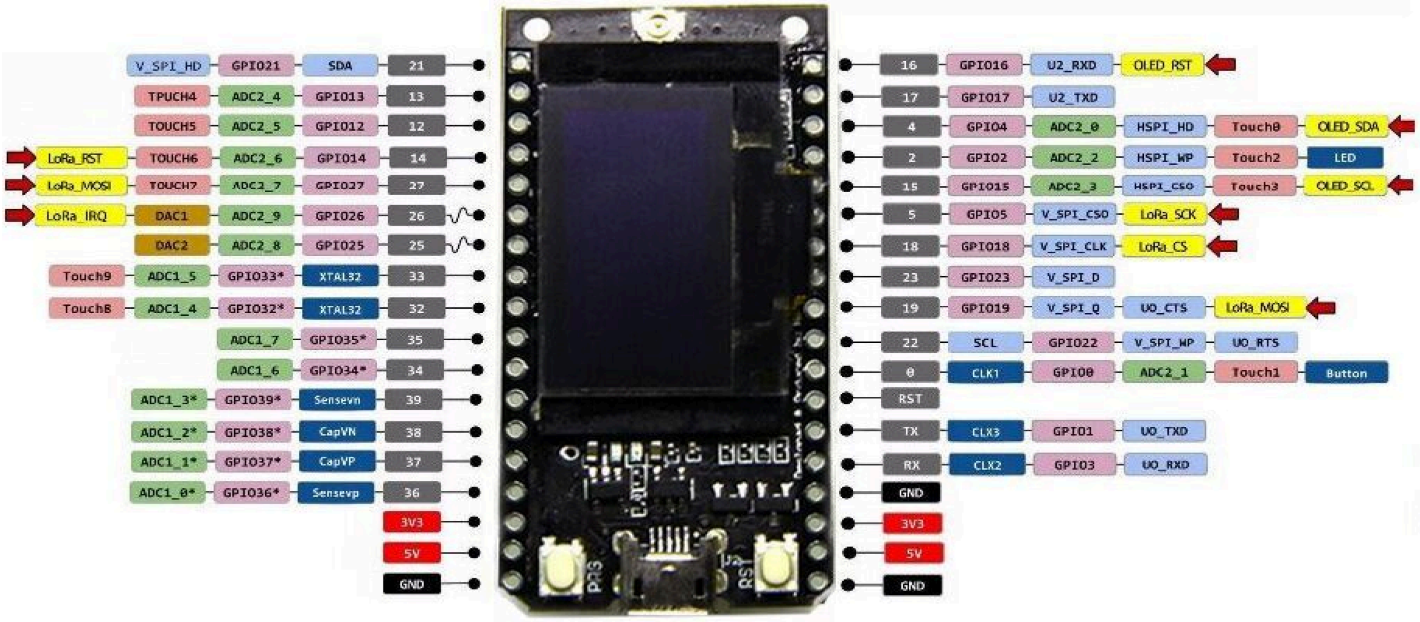
Field Instrumentation Devices: Same Sensors as in SCADA 1

ESP32 with OLED: RTU

- TTGO ESP32 LoRa32 micro-controller board with 0.96 inch OLED display
- 18 ADC pins and over 30 GPIO pins (I/O Pins), Supports Wi-Fi
- Low-Cost ($20), Low-Power (0.9W) Micro-controller for IoT Projects
- 5 V Power Supply, 1. 8 V to 3.7 V ((3.3 V) ADC Signal Voltage
- Programmed as an MQTT Client using Arduino IDE & MQTT Client Library (PubSubClient).

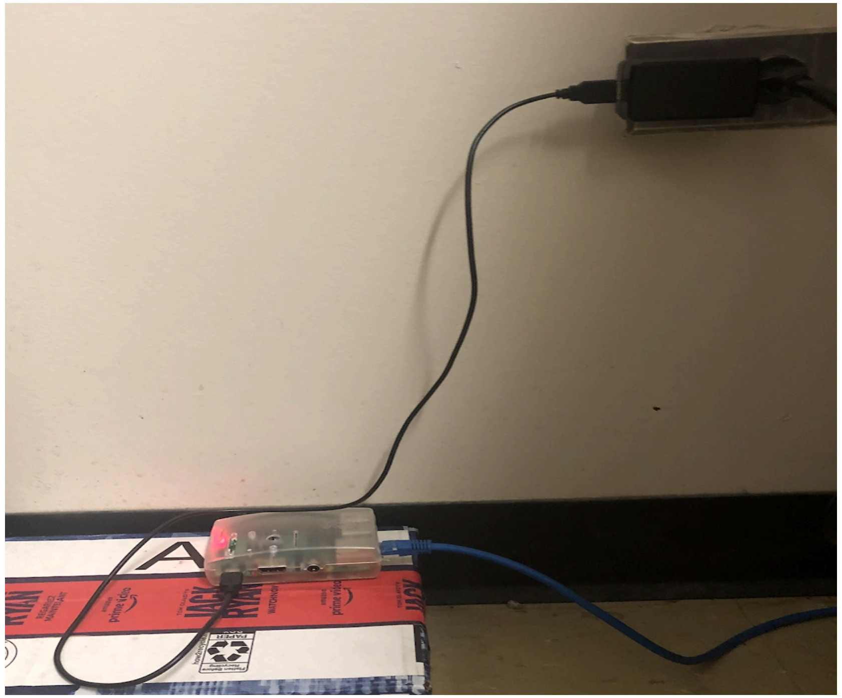






Raspberry Pi Single-Board Computer: MTU

- ThingsBoard IoT Server & PostgreSQL Database installed on the Raspberry Pi
- Connected to MUN Network via an Ethernet cable in Configuration A.
- Connected to Wi-Fi Router LAN Port via an Ethernet cable in Configuration B.



SCADA Communication Channel: Wi-Fi Router for Private Wi-Fi Network:

- D-Link Router (DI-524 Airplus G) used to createa private Wi-Fi Network

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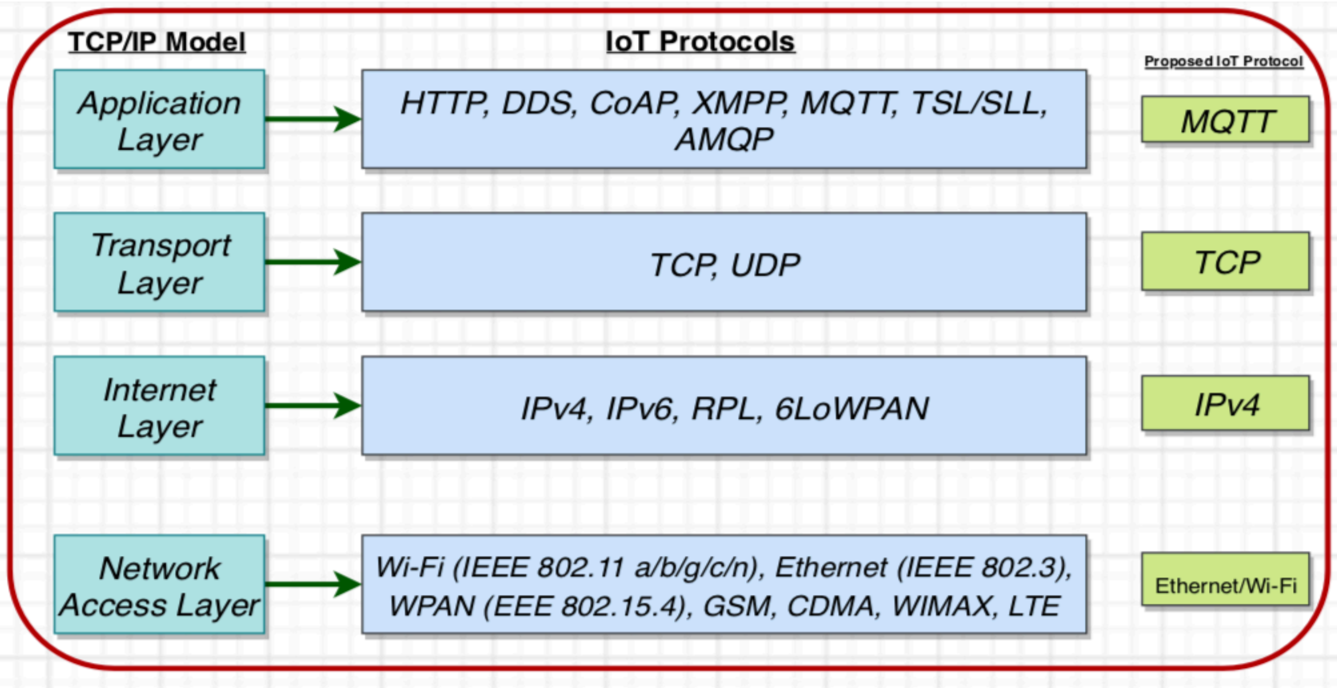
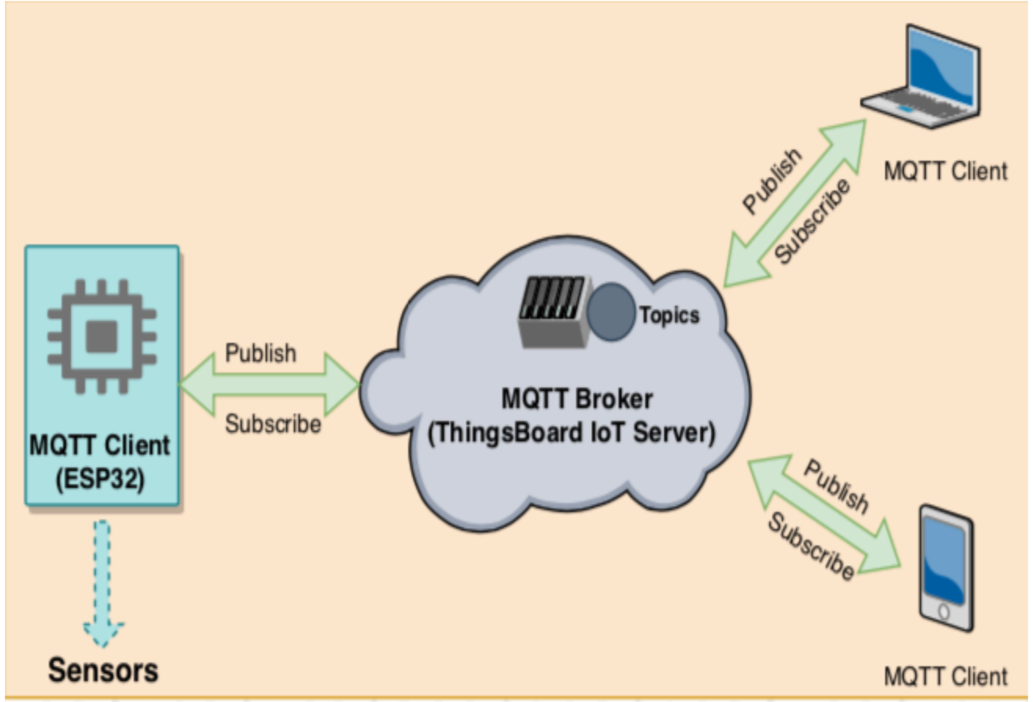
Internet of Things (IoT) & MQTT Protocol: Overview

- A reliable communication is necessary in an IoT-based application like SCADA
- IoT Technologies use the four layers of the general TCP/IP model.
- Important choice for IoT-based SCADA: communication protocols, message encoding format, & the web/IoT platform
- MQTT: a lightweight M2M data communication protocol; supports applications with limited resources, e.g low bandwidth
- MQTT Protocol Implemented over TCP/IP Wi-Fi for sensor data transfer.



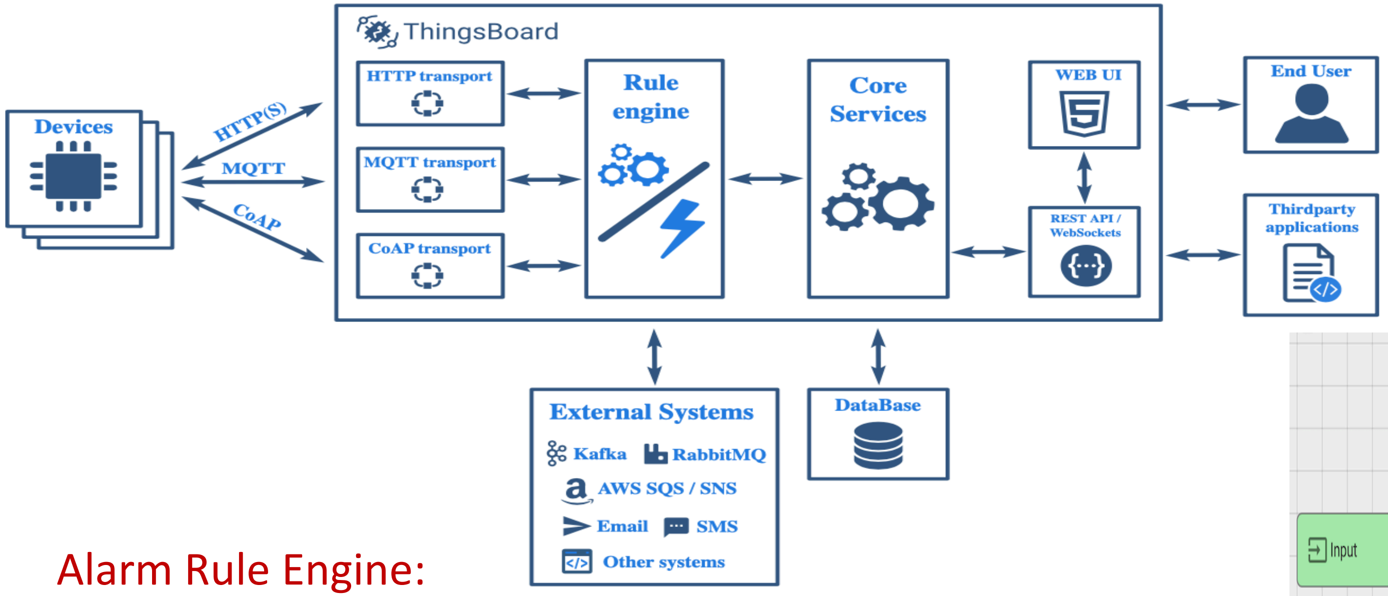


ThingsBoard IoT Server: Overview

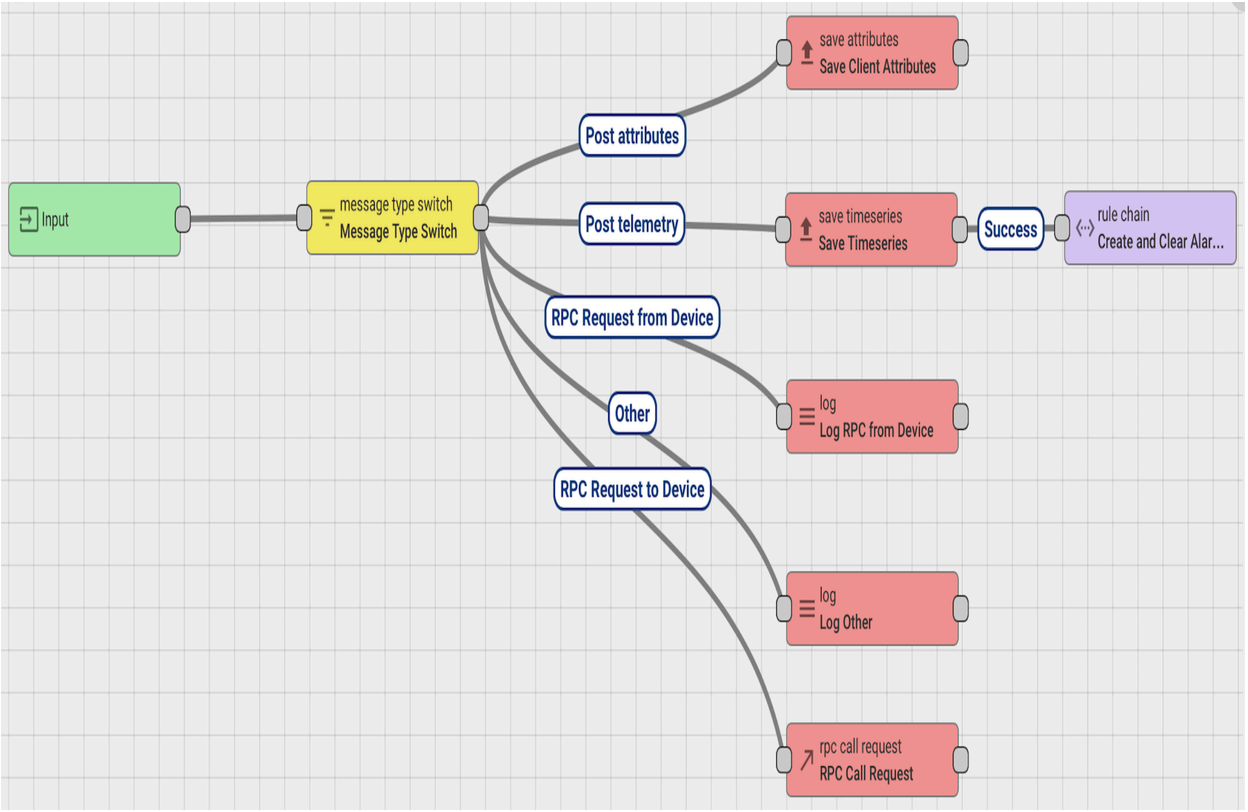
- An Open Source IoT Platform for data collection, processing, visualization & device management
- 100% Support for standard IoT protocols, e.g.; MQTT, CoAP, etc.
- Live Demo (Web), Cloud Server (e.g.; AWS) & On-premise Server options available.
- Supports various hardware integration, e.g.; ESP32, Arduino, ESP8266, etc.
- Supports customizable real-time dashboards for data visualization, alarms, device management, etc.
- Server nodes act as MQTT Broker that supports QoS levels 0 & 1
- Uses Database to store Entities (e.g.; devices, dashboards) & Telemetry Data (e.g.; Sensor Readings)
- Supports 3 different Database options; SQL (e.g.; Postgres), NoSQL (e.g.; Cassandra), & Hybrid
- Stores received values as Telemetries: Time-series key-value pairs.
- Community & Professional Editions available: Community Edition used (Free & supported by GitHub)
- On-premise Server option installed on a Raspberry Pi alongside PostgreSQL Database: Data Security strategy.

Open Source SCADA 3 Design: IoT-based, ThingsBoard, Raspberry Pi, ESP32 with OLED, Wi-Fi & MQTT Protocol

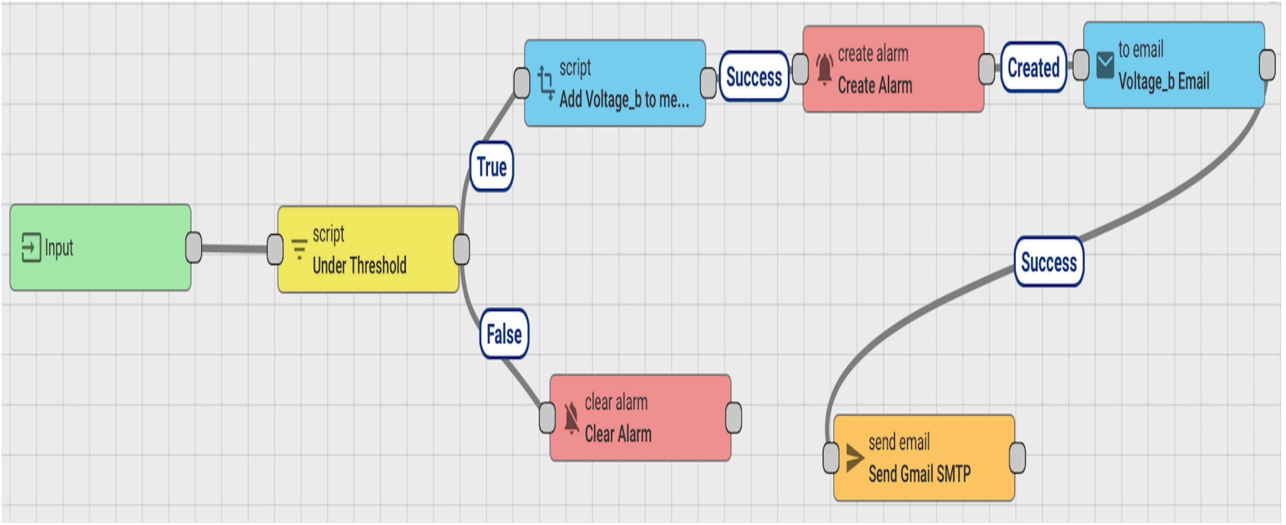
ThingsBoard IoT Server: Architecture



System Rule Engine:



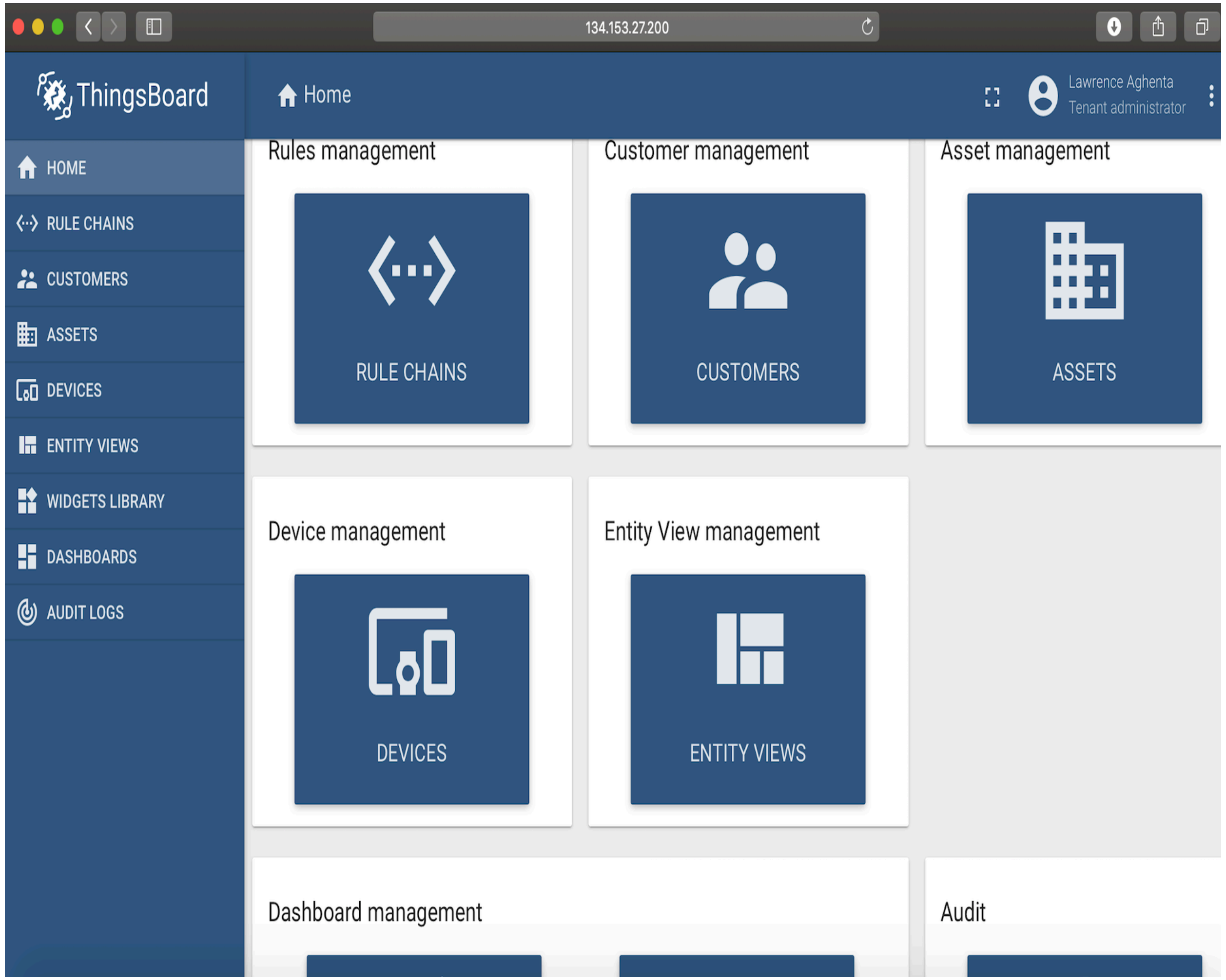
Alarm Rule Engine:



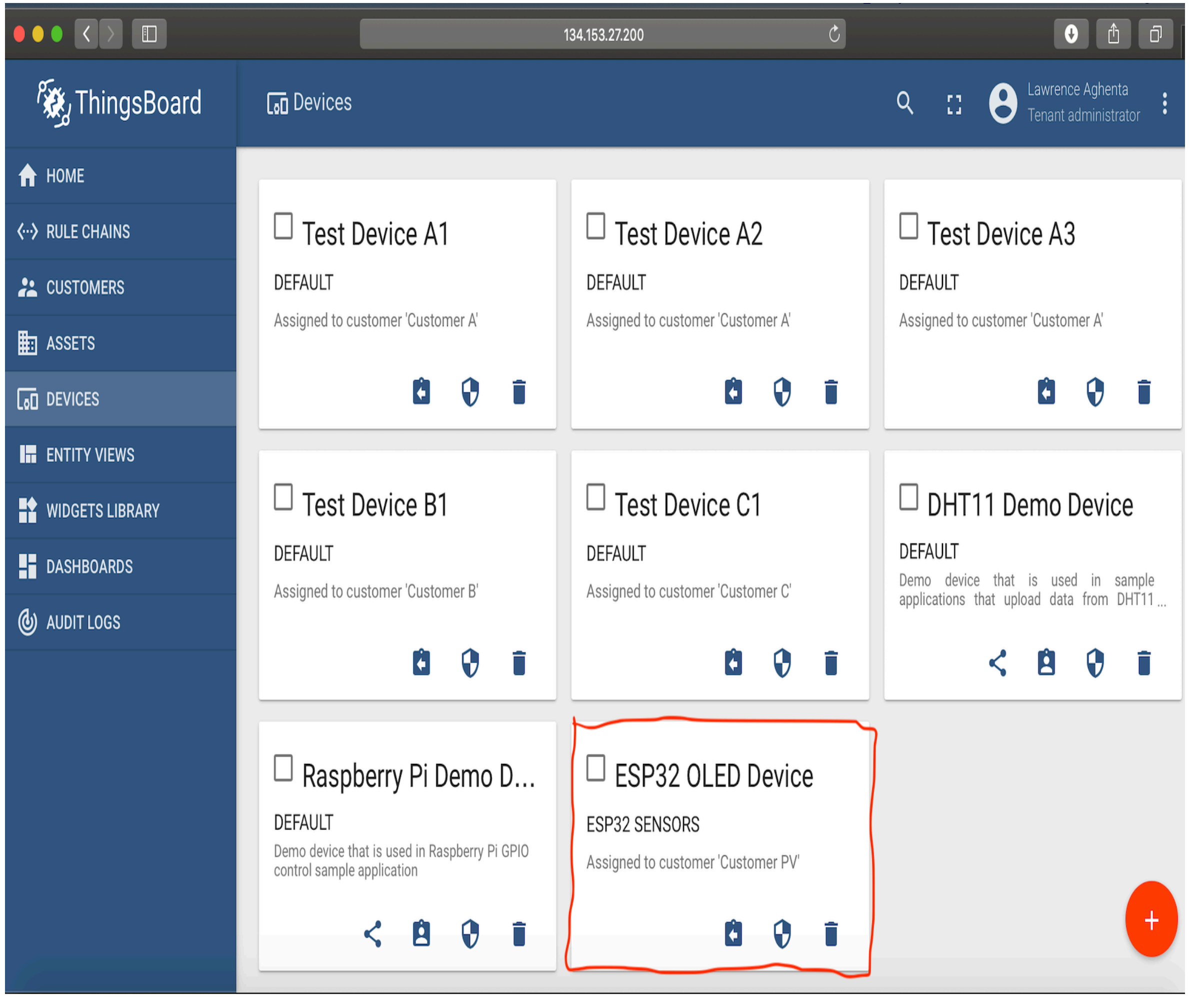
Open Source SCADA 3 Design: IoT-based, ThingsBoard, Raspberry Pi, ESP32 with OLED, Wi-Fi & MQTT Protocol

ThingsBoard IoT Server: Local Server Configuration

Rpi-installed ThingsBoard Server Platform:



Connected ESP32 OLED Device:



Open Source SCADA 3 Design: IoT-based, ThingsBoard, Raspberry Pi, ESP32 with OLED, Wi-Fi & MQTT Protocol

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Implementation Methodology:

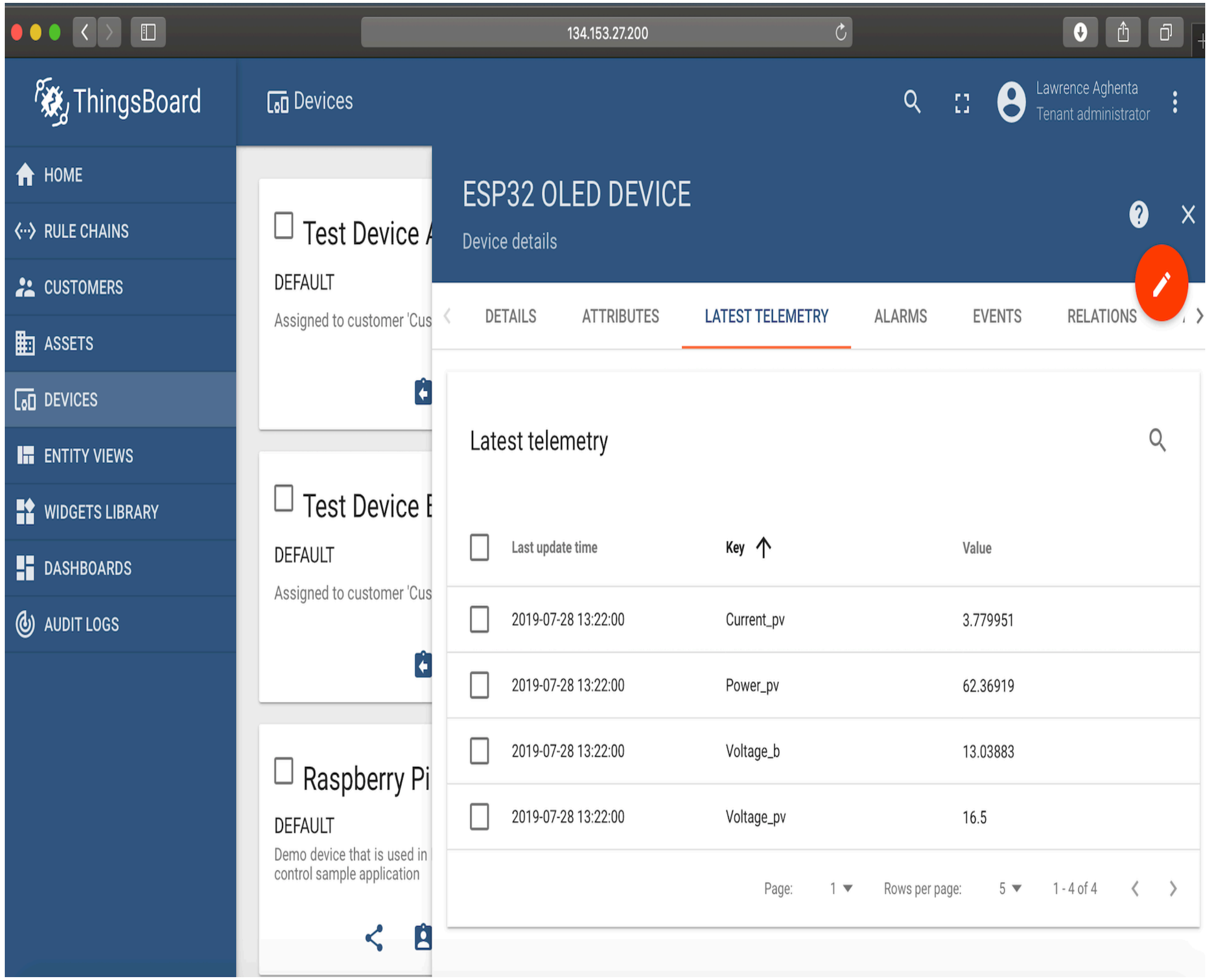
Algorithm 2: Data acquisition and logging algorithm:

Initialization;
1. Analog sensors measure and collect PV system data;
2. ESP32 reads sensor values on analog Pins 32, 34 and 35, and calculates values for Pins 32×34;
3. ESP32 displays the above values on Arduino IDE Serial Monitor and ESP32 OLED Screen;
4. ESP32 connects to local TCP/IP Wi-Fi Network with Wi-Fi Name and Password;
5. ESP32 MQTT Client identifies the local ThingsBoard IoT Server (MQTT Broker) via the Server IP Address;
6. ESP32 MQTT Client publishes sensor data to MQTT Broker over the TCP/IP Wi-Fi connectivity;
7. ThingsBoard Server displays data as Telemetry Messages on the specified Device using the Device Name and Access Token;
8. ThingsBoard Server Node logs the Telemetry Messages to Dashboards for data visualization;

while *ThingsBoard Server acknowledges data receipt* **do**
- 9. Display sensor data on ThingsBoard Server Node, Dashboards and ESP32 OLED Screen, and;
- 10. Display "DONE" on Arduino IDE Serial Monitor;
- **if** *No data receipt acknowledgement from ThingsBoard Server Node* **then**
  - 11. Display "FAILED......retrying in 5 seconds" on Arduino IDE Serial Monitor;
- **else**
  - 12. Go to step 1;
- **end**

end

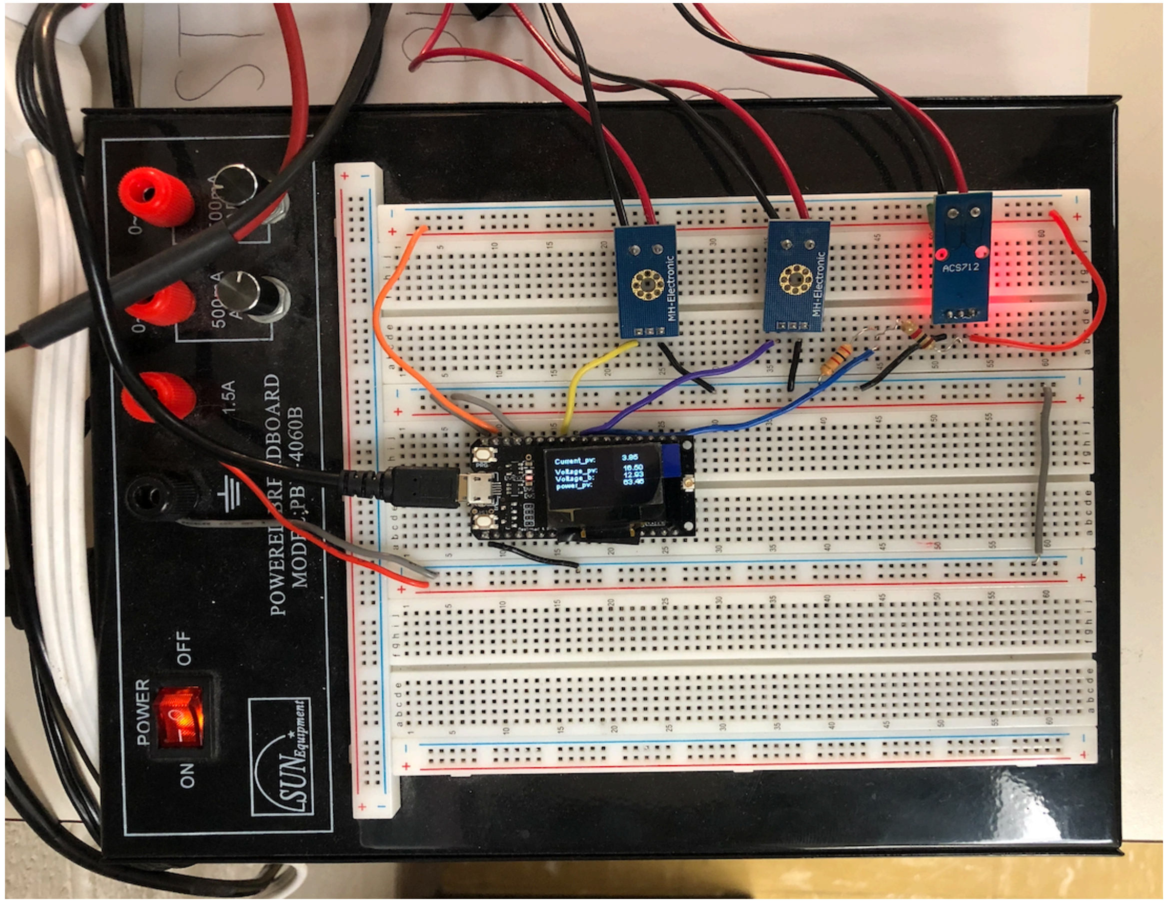
Real-time PV Data Posting:



Open Source SCADA 3 Design: IoT-based, ThingsBoard, Raspberry Pi, ESP32 with OLED, Wi-Fi & MQTT Protocol

Prototype Design & Experimental Setup:

- Hardware implemented & System Set up on a Small Renewable Power Generation System (Solar PV System) at MUN ECE Lab:



Open Source SCADA 3 Design: IoT-based, ThingsBoard, Raspberry Pi, ESP32 with OLED, Wi-Fi & MQTT Protocol

Human Machine Interface (HMI): PV Data Monitoring & Supervisory Control:

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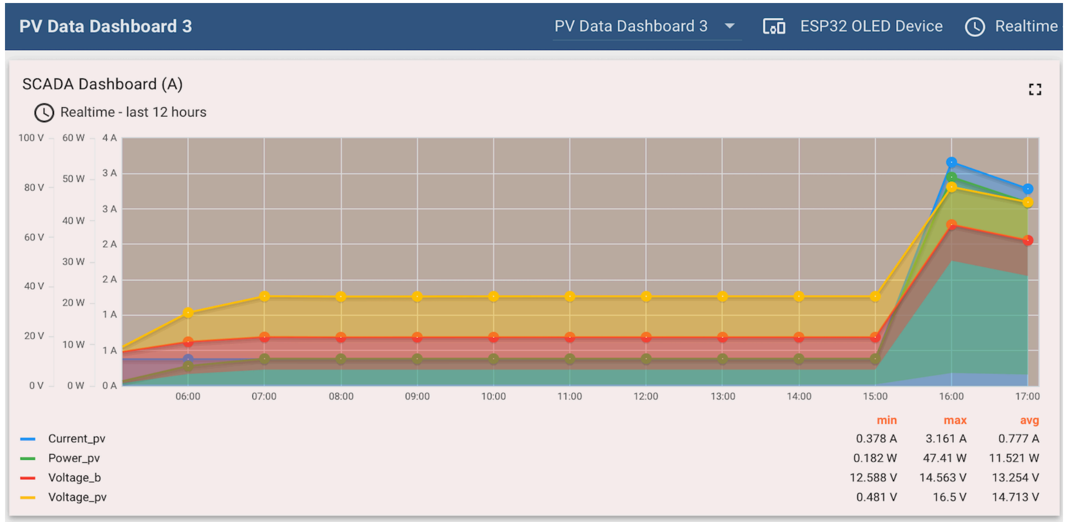
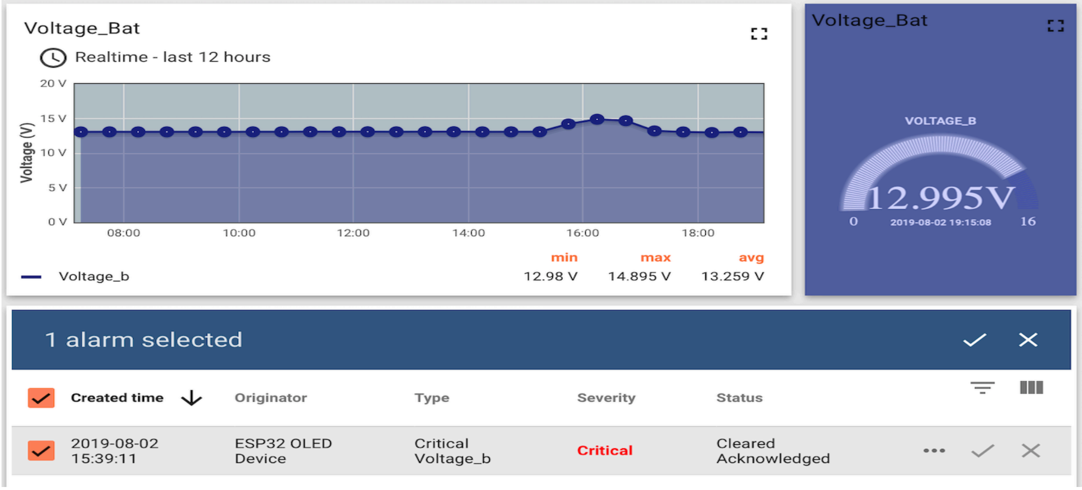
Dashboards:

Dashboards:



Alarm:



Conclusions: Some Key Features of SCADA 3:

- IoT-based, Secure, Reliable, Low-cost, Low-Power, & Open Source
- Reporting, Remote Data Monitoring & Supervisory Control, Data Acquisition, Historic Data Storage & Trending, etc.
- Local Operator Data Monitoring Interface

Table 5.1: Bill of Materials.

S/N	COMPONENT	QTY	PRICE (CAD)
1	ThingsBoard IoT Server	1	00.00
2	PostgreSQL.	1	00.00
3	Raspberry Pi 2 B	1	45.95
4	TTGO LoRa32 ESP32 OLED	1	17.49
5	16GB Memory Card	1	19.99
6	Voltage Sensor	2	11.98
7	Current Sensor	1	5.25
8	D-Link D1-524 Wireless Router	1	98.51
9	Miscellaneous (Boxes, Breadboard, Resistors, Wires, etc.)	1	80.00
	Grand Total:		**$ 279.17 CAD**

Table 5.2: Power Consumption of Hardware Components.

S/N	HARDWARE	POWER(W)
1	Raspberry Pi 2 B	1.8
2	ESP32 OLED (alone)	0.9
3	D-Link D1-524 Wireless Router	4.2
4	Breadboard (with ESP32 OLED, Sensors, Resistors, etc. connected)	3.3
	Overall System Power Consumption (less ESP32 OLED alone):	**9.3 W**

Conclusions:

- Designed and Simulated a Hybrid Power System with a Small Renewable Power Generation System & ESS.
- Designed & Implemented 3 different Low-cost, Low-Power, Secure, Reliable, IoT-based Open Source SCADA Systems
- The designed Open Source SCADA systems used for a Small Renewable Power Generation System

Table 6.1: Comparison Between The Three IoT-Based Open Source SCADA Systems.

IoT-Based Open Source SCADA Systems			
Key Properties	Emoncms-based SCADA (SCADA 1)	Thinger.IO-based SCADA (SCADA 2)	ThingsBoard-based SCADA (SCADA 3)
IoT Server (MTU)	Emoncms	Thinger.IO	ThingsBoard
RTU	Arduino Uno/Raspberry Pi	ESP32 Thing	ESP32 with OLED
Communication Channel	Node-RED/Ethernet	Wi-Fi/SPI	MQTT/Wi-Fi
FIDs	Sensors	Sensors	Sensors
Security Measure	Local/Self-hosted main data server	Local/Self-hosted main data server	Local/Self-hosted main data server
Reliable from Testing?	Yes	Yes	Yes
Alarm & Notifications	Yes	Yes	Yes
Ease of Use	Yes	Yes	Yes
Internet	Yes	Yes	Yes
Offline Option	No	Yes	Yes
Local Operator Interface	No	No	Yes
Cost	$404.84 CAD	$291.87 CAD	$279.17 CAD
Power Consumption	5.1 W	9.4 W	9.3 W

Key Contributions:

- A house in Nigeria chosen for the HPS Design; House Energy Assessments; Optimum Renewable Generation System Sizing.
- Implementation of SCADA System security strategies on each system.
- Selection & Testing of each SCADA Element for overall system design goals, e.g. Low-power, low-cost, reliability, etc.

List of Publications:

Refereed Journal Articles:

1. Lawrence O. Aghenta and M. Tariq Iqbal, "Design and implementation of a low- cost, open source IoT-based SCADA system using ESP32 with OLED, ThingsBoard and MQTT protocol," Submitted with *AIMS Electronics and Electrical Engineering*, October 2019 . (*Under Review*) .
2. Lawrence Oriaghe Aghenta and Mohammad Tariq Iqbal, Low-Cost, "Open Source IoT-Based SCADA System Design Using Thinger.IO and ESP32 Thing," *Electronics 2019, 8(8), 822*; https://doi.org/10.3390/electronics8080822.
3. Lawrence O. Aghenta and M. Tariq Iqbal, "Design and Dynamic Modelling of a Hybrid Power System for a House in Nigeria," *International Journal of Photoenergy, Volume 2019*, Article ID 6501785, 13 pages; https://doi.org/10.1155/2019/6501785.

Refereed Conference Publication:

1. Lawrence O. Aghenta and M. Tariq Iqbal, "Development of an IoT-Based Open Source SCADA System for PV System Monitoring," Presented at *CCECE 2019*, Edmonton, AB, Canada. May 5 - 8, 2019; doi: 10.1109/CCECE.2019.8861827

Regional Conference Publications:

1. Lawrence O. Aghenta and M. Tariq Iqbal, "A Low-Cost, Open Source IoT-Based SCADA System Design, and Implementation for Photovoltaics," Accepted for presentation at the 28th IEEE NECEC 2019, St. John's, NL, Canada. November 19, 2019.
2. Lawrence O. Aghenta and M. Tariq Iqbal, "Thermal Modelling and Analysis of a House in Nigeria and PV System Design to meet its Energy needs," Presented at the 27th IEEE NECEC 2019, St. John's, NL, Canada. November 13, 2018.

Poster Presentation:

1. Lawrence O. Aghenta and M. Tariq Iqbal, "Internet of Things (IoT) based Reliable Open Source SCADA System for Remote Battery Energy Storage Systems," Presented during the poster session at the NESTNet 2nd Annual Technical Conference, Ryerson University, Toronto, ON, Canada. June 18 - 20, 2018.

Future Recommendations:

- Detailed Reliability Calculations & Analysis of each of the Open Source SCADA Systems for Reliability Comparison.
- Inclusion of Data Encryption on each SCADA Communication Channel for greater security.
- Emoncms installed on a more recent Linux machine, while using ESP32 Thing as the RTU, and MQTT protocol for data transfer from the RTU to the MTU to improve on SCADA 1 & reduce cost.
- Configuring the Raspberry Pis in SCADA 2 & 3 as a Wireless Access Point to provide the needed Wi-Fi connections, thereby eliminating the Wi-Fi Router in each case to further reduce power consumption.
- Developing new Open Source SCADA Systems using CoAP API and HTTP API of the ThingsBoard platform for data transfer so as to compare their performance with the MQTT API used in SCADA 3 option.

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Contributions & Questions???

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