CYBER S.H.I.E.L.D.

Smart Home Integrated Environment for Learning and Defense

Initial Divide and Conquer Document

EEL4914 - Senior Design I

Group 12

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Chapter 1: Project Description

1.1 Motivation & Background

From its development back in the early 1880s, the U.S. electric grid has been constantly growing and evolving. Now, more than ever, the grid is seeing changes that may have never been imagined. Many of these changes are inspired by the expansion of the electric power system to meet growing demands for energy. Other changes to the grid are motivated by the hope to achieve a net-zero future. In any case, the U.S. electric grid is being modernized to develop a smarter grid that allows for larger amounts of electricity generation and longer transmission distances. Two of the main forces driving this modernization include the expansion of renewables and a shift towards a connected and decentralized grid. The goal is to create an evolved grid that is flexible to integrate distributed energy resources (DER), accommodate the two-way flow of electricity and information for better power management, and provide protection against physical and cyber risks.

Unfortunately, with the changes towards grid modernization comes an increasing risk for cyber attacks. These attacks are able to disrupt the grid, damage costly equipment, and even threaten human life and safety. There are many methods of employing a cyber attack. For example, there are a growing amount of smart microgrids in the U.S. today. These microgrids are small-scale power supply networks that enable local power generation for local loads. They can be created by installing grid-edge technologies such as solar panels, energy storage systems, smart inverters, smart appliances, and electric vehicles charging stations. The increased interconnectedness between critical operational technology and these grid edge devices leads to a higher complexity and risk for cyber attacks unless proper security is built in. A hacker can employ a multitude of attacks in order to violate the confidentiality, integrity, or availability of the network. They can also exploit vulnerabilities of the network to gain access to private information of consumers or illegal access to nodes.

Due to this, it is crucial for engineers to develop a method to effectively detect cyber attacks for the U.S. to continue modernizing its grid. Once these algorithms are developed, they must be tested to ensure that they are able to function in real time scenarios. While one cannot test these algorithms on the physical grid itself, engineers are able to use real time simulators such as the OPAL-RT to model a grid. These simulators allow cyber attack detection and prevention algorithms to be effectively tested. Furthermore, through simulations such as the OPAL-RT, students can learn more about how the grid functions and the necessity of security in our power systems as they continue to be modernized. This project is set up to be a physical testbench of a cyber attack detection and prevention algorithm as well as an educational outlet for the complexity and evolution of the U.S. electric power system.

1.2 Review of Prior Related Work

In preparing for this project, we researched work online to have an understanding of how to complete our objectives. After in-depth research, we came across a great example of a solar metering project. This was found on the website "Open Green Energy" and the project was titled "DIY Solar Panel Monitoring System". This project detailed why one needs a solar panel monitoring system, the materials one needs to build the project, how it works, the schematic diagram, and setting up the circuit. From here it showed the process of measuring current and voltage from the solar panel. This prior work was extremely helpful in explaining how to create a metering PCB and how it works. We plan to use this open source schematic for our project.

In addition to this work, we were able to find a video discussing a project called "Smart Hybrid Energy Management System Using Arduino". In this, the creator of the video discussed a flowchart used to create the energy management system and its implementation into the project. This project made use of three sources: solar, battery, and the grid. It also classified loads into three separate categories: high priority, medium priority, and low priority. These loads would be on or off depending on the state of the battery or if it was during peak/off-peak hours. An arduino was used to implement the energy management system. Relays were controlled by the arduino to connect and disconnect the different sources and loads. The sources and loads could be selected manually or were automatically selected by the energy management system depending on the constraints. High, medium, and low priority loads were represented by three light bulbs. Overall, this project perfectly demonstrated a project that implemented an energy management system to select energy sources and loads. We plan to use ideas from this project to apply on our own.

Lastly, we reviewed a Senior Design project from a few years ago that created a project with a few similar characteristics. This project was titled "Power Systems Knowledge Hub". For example, this Senior Design project made use of a solar panel to supply energy to a load. Measurements were collected from the panel and loads and sent to be displayed on a touch screen. In addition to this, the measurements were sent to the OPAL-RT simulator in the Siemens Digital Grid Lab. Reviewing this past work allowed us to get a better understanding of what communication protocols could be used to connect the devices together. This project also gave us a baseline on what Raspberry Pi would be good to use and how to connect it to the metering hardware. Overall, this project gave us a good baseline to go off of for our project.

1.3 Overview of Project Goals

As the U.S. electric grid continues to evolve, there are new challenges arising for the protection of its resilience and reliability. Increased use of grid-edge devices, such as solar panels, inverters, and batteries, has caused the distribution system to become more complex to manage. The UCF Digital Grid Laboratory is currently working on researching this complexity and how to ensure that our power systems are protected from cyber threats. For this reason, this project focuses on the development of a model smart home that functions as a high fidelity testbench for an attack detection and prevention algorithm developed in the UCF Digital Grid Laboratory.

Shown in Table 1 on the following page are the three levels of goals for this project. Our team plans to conclude this project by providing a functioning cybersecurity testbed for the UCF Digital Grid Laboratory. This testbed should serve as an educational experience for students wanting to learn more about the modernization of power and energy as well as the functioning of a smart home with a hybrid-solar system.

Table 1: Project Goals Overview

Goal Type	Description
Basic	Create a model smart home with a functioning Energy Management System. A touch screen used to interact with the model. This serves as an educational experience to demonstrate knowledge on power systems.
Advanced	Model smart home implemented and updated to account for a hybrid solar system. Simulated cyber attacks are employed on the model smart home and attack detection and mitigation algorithms are tested.
Stretch	Model smart home completed with hybrid solar system and educational touch screen. Loads are categorized into three levels of priority: low, medium, high.

1.4 Objectives

In order to more accurately test the algorithm, the model smart home must function using a hybrid solar system. A solar panel will be used to provide energy to the loads within the model smart home. There will be a battery used for energy storage. This battery can be used in the case where the solar panel is not generating energy. In the model, multiple loads will demonstrate that the system is functioning correctly. The more accurately the model smart home resembles an actual smart home, the more accurate the test results. Data collected from meters on the model will be sent to the OPAL-RT simulation in the Digital Grid Lab. This data will be used to employ multiple forms of cyber attacks. If an attack is detected, then the appropriate measures should be taken for the event to be isolated. For example, the power supplying the loads could be disconnected to ensure the safety of the smart home.

The model smart home will have a functioning energy management system (EMS) in order to appropriately distribute and store energy. The EMS must be able to account for instances in which there is not enough power being generated by the solar panels and efficiently switch to an alternative power source, such as a DC battery or AC power source. If there is more power being generated than absorbed by the loads, then the EMS must allow the charging of the DC battery. A digital touch screen will be utilized to encourage interaction with the project. Users will be able to select areas of the model to see the voltage, current, state of charge (SoC), and power absorption or supply.

1.5 Project Features and Functionalities

This project will be made up of several key features. To begin, the project involves having a physical model of a home made out of wood. The front of the model will be opened so that the user can see inside to monitor the function of the DC and AC loads. Mounted on the roof of the model will be solar panels. The solar panels will be connected to a charge controller that is connected to a battery. The DC load port on the charge controller will pull from the battery. In addition to this, the battery will be connected to a DC/AC inverter. The DC/AC inverter will be connected to an AC load. In a scenario where there is not enough sunlight or battery charge, there will be a wall outlet connection to represent a “grid tied” system. At the battery, solar panel, and outlet connection there will be meters to collect voltage, current, and state of charge measurements. There will also be metering at the loads to collect voltage and current measurements. The model will be able to intelligently select what source and load is appropriate for the conditions at the time using a programmed energy management system. To allow the selection of the source and load, relays will be utilized. A touch screen will be used to show all of the measurements and allow for manual selection of the source and load by the user. Measurements will be sent to the OPAL-RT simulator to be used in the RT-Lab model for testing of the UCF Digital Grid Lab’s cyber attack detection algorithm.

The research group working with the UCF Digital Grid Lab has listed the required functionalities of the model. As expressed previously, the model must allow for the accurate collection of voltage, current, and state of charge measurements. In addition to this, the measurements collected must be communicated with the OPAL-RT simulator to ensure appropriate testing of the cyber attack detection algorithm. Beyond this, we saw there was a need in the market for an educational smart home model. This would allow students to get a better understanding on how smart homes function and the cyber risks associated with grid modernization.

1.6 Requirement Specifications

The requirements of this project address two main areas of focus:
1) Creating an educational environment for students to learn more about the technologies used in grid modernization (such as microgrids, smart homes, and security resilience)
2) Building a cyber-physical system (CPS) testbench in order to test the cyber attack detection algorithm developed in the Siemens Digital Grid Lab at UCF

In order to accomplish the requirements and specifications for these two areas of focus, the team must design a functioning model smart home with a realistic energy management system. This EMS should function the way that it would in a realistic smart home. The user should also be able to select what source (DC or AC) is supplying the load. In addition to this, the user should be able to select what load is on (DC and/or AC). Each source and load should be metered. The measurements collected should be stored for use in the EMS and the OPAL-RT Simulation. The specific engineering requirements and specifications for this project were detailed by the Siemens Digital Grid Laboratory. These requirement specifications can be found in Table 2.

Table 2: Requirement Specifications

Touch Screen & Touch Screen Platform			
Parameter	**Specification**	**Engineering Requirement**	**Marketing Requirement**
Dimension	34.06” x 56” x 34.75”	The touch screen platform must be the appropriate size for the weight, length, and width of the screen	11, 12

Weight	At Most 100 lbs	The weight of the touch screen must be suitable for transportation	11, 12
Touch Screen Response Time	At Most 5 Seconds	Once a setting has been selected on the touchscreen, the model must reflect that selection of a source or load within five seconds	7
Number of Touch Points	At Least 2	The touchscreen should be multi touch capable and the total number of touch points should be at least 2	7
Number of Available Measurements	At Least 7	Must display V, I, P, and SoC measurements of sources on the touch screen	1
Communication with Model	Wired Communication with USB	The model must be able to accurately communicate source measurements to be displayed on the touch screen	5
User Interface Capability	Allows Selection of AC and DC Loads, AC and DC Sources	UI Will Allow Selection of DC and AC loads depending on PV panel and battery SoC; UI Will Allow Selection of Sources (DC or AC)	8, 7
Response to Cyber Attack Detection	Shows Warning on Touch Screen	Following the launch of a cyber attack on the OPAL-RT, the touch screen should send an alert and indicate if attack was detected	2
Communication Accuracy of Metered Data	100% Accurate	The information sent by a single board computer must match the information received by the UI application, verifying that data remains consistent after communication	5
Smart Home Model			
Parameter	**Specification**	**Engineering Requirement**	**Marketing Requirement**
Dimension	34” x 34.5” x 83”	The smart home model must be the appropriate size to support the weight, length, and width of the PV Panel, Battery, and Inverter	11, 12

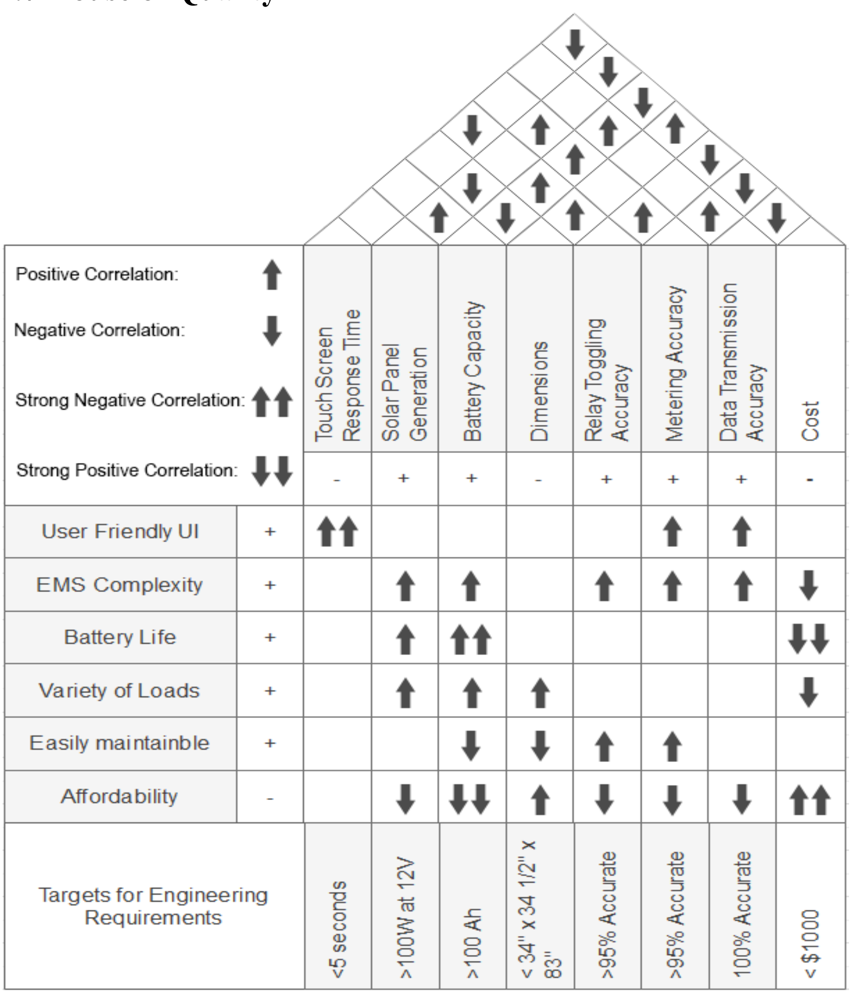
Weight	Up to 300 lbs	The weight of the model must be suitable for transportation	11, 12
Battery Voltage	12V	Battery must meet the voltage requirements of the PV panel and be used to supply the loads when PV panel is not producing power	9
Battery Capacity	100Ah	Battery must meet the current requirements of the PV panel	9
Battery Lifespan	At Least 5 Years	Battery must function successfully for at least five years	9
PV Panel Voltage	12V	PV panel must meet the voltage requirements of the system and provide power to AC and DC loads	9
PV Panel Power	100W	PV panel must meet the power requirements of the system and provide power to AC and DC loads	9
Relay Module Operating Voltage	12V	Relays must meet the voltage requirements of the system and enable connection or disconnection of sources/loads	3
Relay Module Maximum Current	10A	Relays must meet the current requirements of the system and enable connection or disconnection of sources/loads	3
Relay Toggling Accuracy	Equivalent or Above 95% Accurate	Relays must function with over 95% accuracy to switch on and off; Selection of sources and loads	3, 8
Inverter Voltage	12V	Inverter must meet voltage requirements of the system and convert DC/AC	3, 6
Inverter Output Power	At Least 100W	Inverter must meet the power requirements of the system and convert DC/AC	3, 6
Charge Controller Voltage	12V	Charge controller must meet the voltage requirements of the system and allow safe connection from the PV panel to the battery	3, 9

Charge Controller Current	10A	Charge controller must meet the current requirements of the system and allow for connection from the PV panel to the battery	3, 9
Source Types	DC and AC	DC (solar, battery), AC (wall outlet connection, inverter output from battery)	8
Load Types	DC and AC	There must be both DC and AC loads (each having low, medium, and high priority)	6, 8
Load Power Consumption	100W	The system must meet load power consumption requirements to function properly	9
MPU	Capable of Connecting to Touch Screen and OPAL-RT	MPU Must Receive Data from meters and Communicate with OPAL-RT/Touchscreen	4, 5
Energy Management System	Allow for Appropriate Selection DC, AC Source	EMS must intelligently select the appropriate source and loads for the state of the system	3
Communication with OPAL-RT	Voltage, Current Measurements Sent to OPAL-RT	Measurements collected in the model must be communicated with the OPAL-RT	4, 5
Source Measurements	Voltage, Current, SoC Measurements	There must be a collection of V, I, and SoC measurements from solar, battery, AC connection and this is sent to MPU	5
Load Measurements	Voltage, Current Measurements	There must be a collection of V and I measurements from DC loads and AC loads and this is send to MPU	5
Metering Accuracy	Equivalent or Above 95% Accurate	Sources and loads measurements must be accurate to reflect real time system conditions	4
Cells Highlighted in Yellow Will Be Shown in the Demo			

Marketing Requirements

1. The system should function as an educational tool for students to learn more about the technologies used in grid modernization
2. The system should serve as a testbench to test the cyber attack detection algorithm developed in the Siemens Digital Grid Lab
3. An EMS should be designed to intelligently toggle sources and loads depending on the system state
4. System should communicate metering information to the OPAL-RT simulator
5. Data should be processed and transmitted between devices quickly
6. The model smart home should have a variety of loads to simulate a real smart home.
7. The system's UI should be user friendly
8. Users should be able to choose sources of power and loads
9. The system should be able to meet load requirements using appropriate energy source
10. The system should minimize cost
11. The system should be designed to ensure maintenance is efficient and straightforward
12. The system should be easily transported

1.7 House of Quality



Chapter 2: Project Block Diagram

Shown in the figure below is the hardware block diagram for the project. The sources and the loads will all be metered and the information will be used to intelligently select sources and loads to power based on the state of the system.

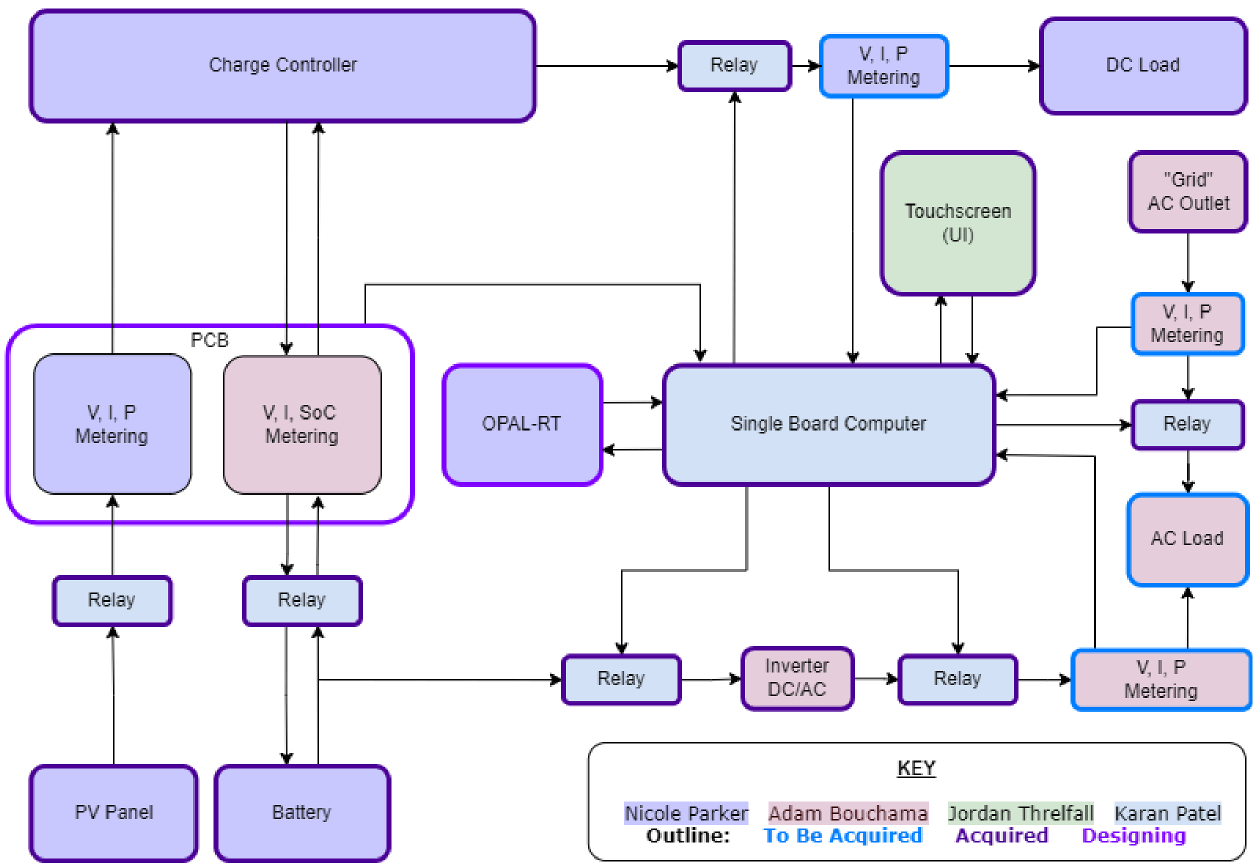


Figure 1: Hardware Block Diagram for Project

Chapter 3: Flow Charts

The diagram on the following page demonstrates the flow of communication between the application on the touch screen and the microprocessor. Starting with the Raspberry Pi 4 Model B, we transmit the data collected from the Smart Home System Metrics as a JSON into the Touch Screen's to be able to be interacted to the user. Afterwards, we give the user the ability to manually select system requirements through the touch screen onto the Raspberry Pi 4. Then after the software requests, the Raspberry Pi will change the state of the relays to reflect the changes requested. Then the information changes will occur again and repeat the system.

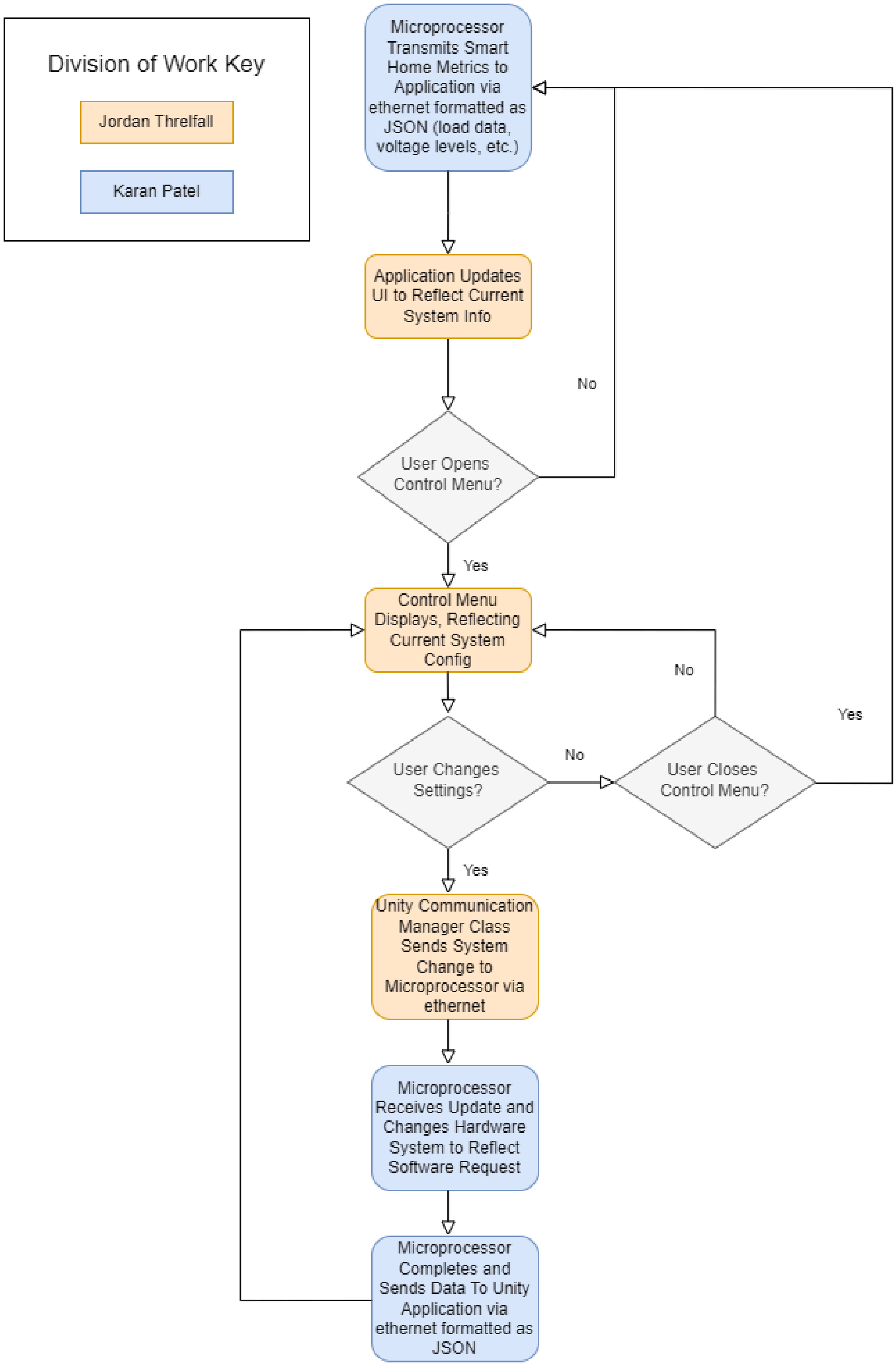


Figure 2: Flow of Communication Between Application and Microprocessor

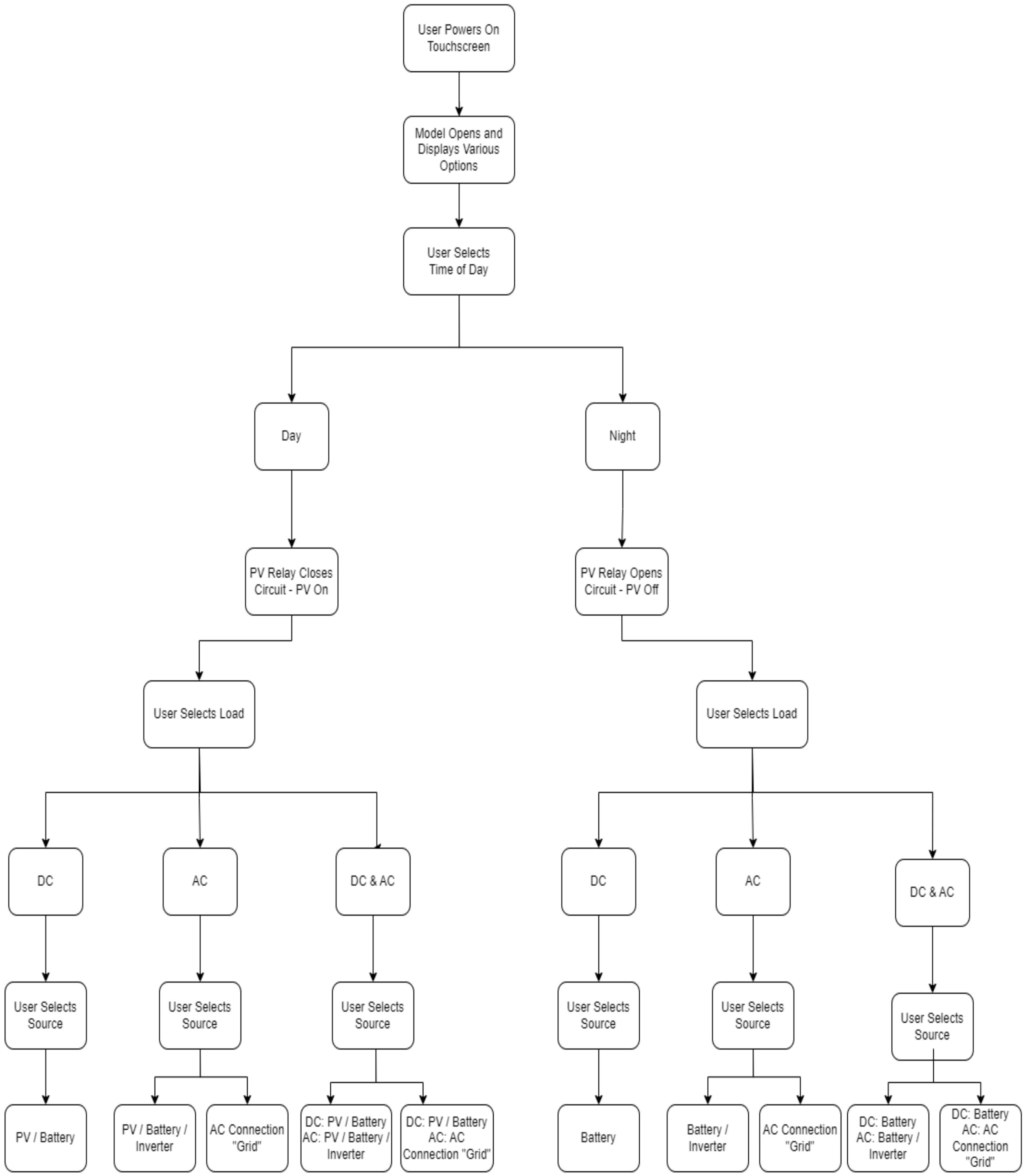


Figure 3: Touch Screen & User Interface

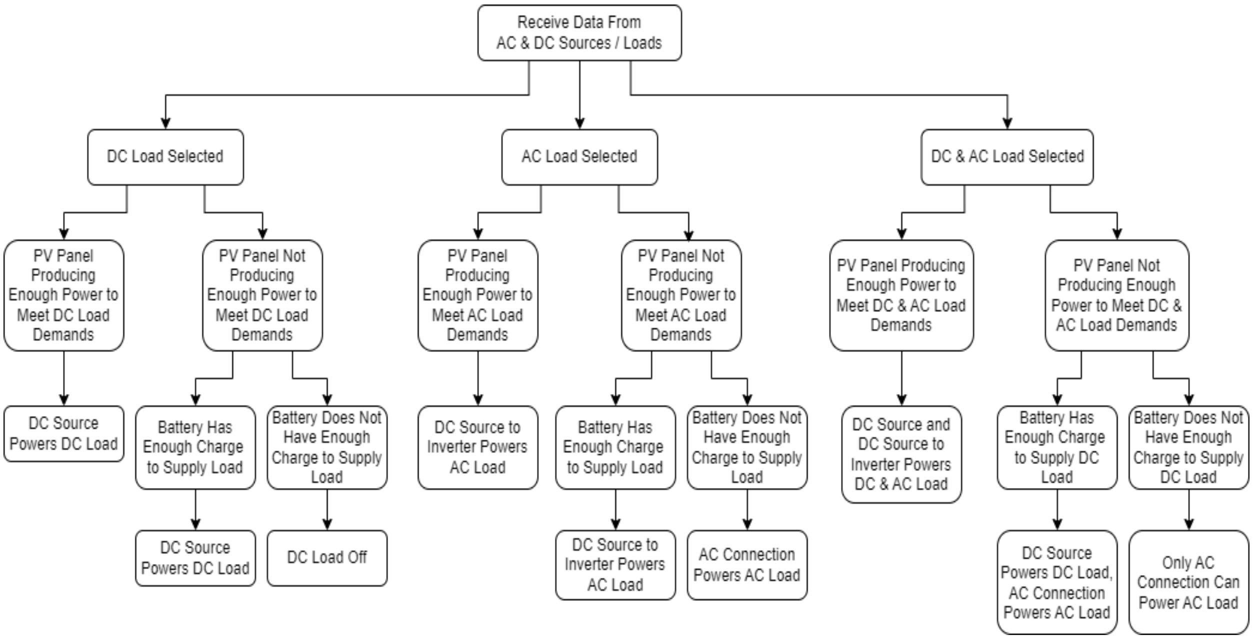


Figure 4: Energy Management System

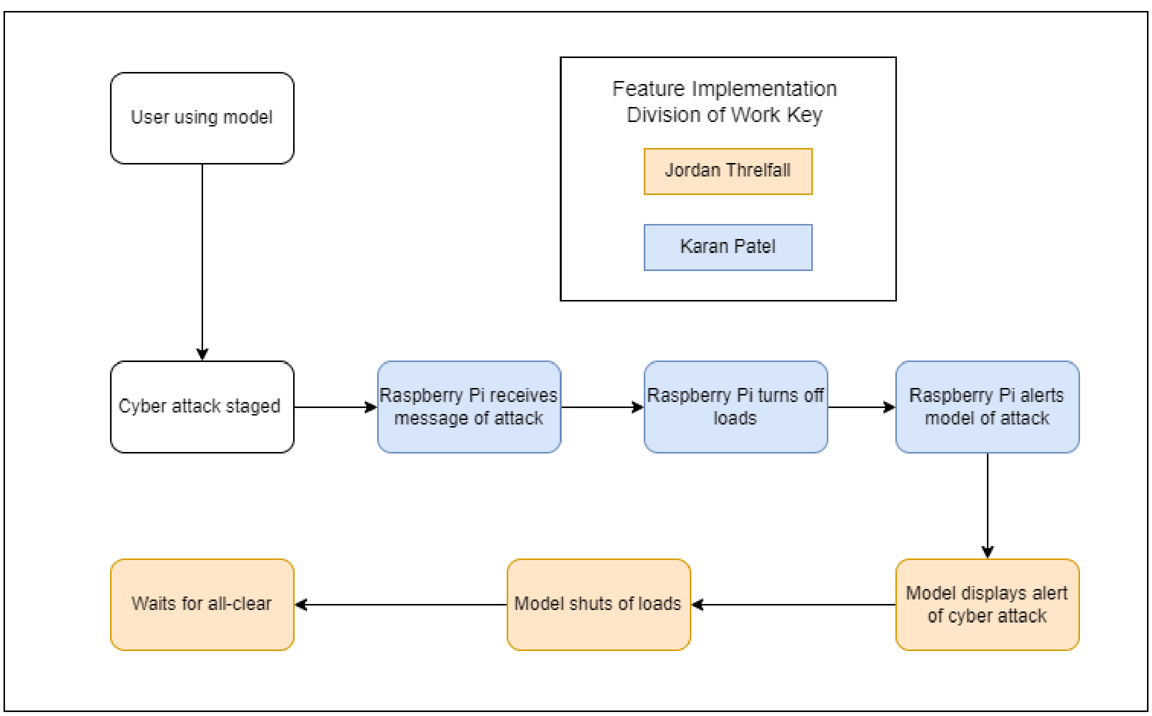


Figure 5: Cyber Attack Response

Chapter 4: Budget and Financing

An itemized list of the materials required for the project, their costs, and the quantity needed is shown in Table 3. The costs of these materials were sponsored by the UCF Digital Grid Laboratory. The exact price of the PCB will be priced once it is completely designed.

Table 3: First Draft Budget

Item	Price	Qty	Total Cost	Details
Solar Panel & Controller	$129.99	1	$129.99	Power Source
Battery	$159.99	1	$159.99	Power Source
Smart Relay Module	$11.29	1	$11.29	EMS Control
Touch Screen	$1,678.00	1	$1,678.00	User Interface
Inverter	$199.99	1	$199.99	DC/AC Conversion
Meter (V, I, P)	$14.99	2	$30.00	Metering for AC Source/Load
Meter (V, I, P)	$14.99	3	$45.00	Metering for DC Load
DC Fan	$15.99	1	$15.99	DC Load
AC Lamp	$9.99	1	$9.99	AC Load
Raspberry Pi 4 Model B	$61.79	1	$61.79	EMS and Communication with OPAL-RT / Application
Printed Circuit Board	TBD	1	TBD	Used for Metering

Chapter 5: Initial Project Milestones

In order to stay on track, the team made a table of project milestones with what tasks need to be accomplished at what time. This table details anticipated time frames for each part of the project and what team member will be working on that milestone. It shows dates for the entire project spanning over the course of two semesters. Creating a list of milestones is important in order to ensure that the team stays on track. We wanted to ensure that the project objectives were being accomplished in a timely manner as to prevent issues with tight time constraints.

Project milestones can be found in Table 4.

Table 4: Project Milestones

Senior Design I - Summer 2024			
Task	**Time Period**	**Dates**	**Responsibility**
Project Selection	2 Weeks	5/13 - 5/17	All
D&C Documentation	1 Week	5/17 - 5/31	All
D&C Meeting With Advisors	30 Minutes	6/7	All
Research Energy Monitoring	2 Weeks	6/3 - 6/17	Nicole, Adam
Research Designing EMS	2 Weeks	6/3 - 6/17	Nicole, Adam
Research Connection of Raspberry Pi 4 Model B to Relays	2 Weeks	6/3 - 6/17	Karan
Research User Interface	2 Weeks	6/3 - 6/17	Jordan
Research Wired Connection to OPAL-RT to Send Data	2 Weeks	6/3 - 6/17	Karan
Research How to Control Smart Relays to Direct Flow of Power	1 Week	6/17 - 6/24	Nicole/Karan
Start Building UI for Touch Screen	4 Weeks	6/24 - 7/22	Jordan
Research Communication Between Relays, Meters, EMS, and UI	2 Weeks	6/24 - 7/8	All
Start PCB Design	3 Weeks	6/24 - 7/15	Nicole, Adam
Final Decision on PCB Design	1 Week	7/15 - 7/22	Nicole, Adam
Order PCB and Other Materials	1 Week	7/22 - 7/29	All
Start Project Prototype	2 Weeks	7/22 - 8/2	All
60 Page Draft	2 Weeks	7/1 - 7/15	All
Final Documentation	6 Weeks	6/21 - 8/2	All

Senior Design II - Fall 2024			
Task	**Number of Weeks**	**Dates**	**Responsibility**
Model Building	4 Weeks	8/19 - 9/9	All
Complete UI	4 Weeks	8/19 - 9/9	Jordan
Connect the MPU and Touch Screen	4 Weeks	8/19 - 9/9	Jordan, Karan
Construct Energy Management System	4 Weeks	8/19 - 9/9	Nicole, Adam
Connect the Energy Management System to the Raspberry Pi 4	4 Weeks	9/9 - 10/7	Nicole, Adam, Karan
Connect Raspberry Pi 4 to the Touch Screen	4 Weeks	9/9 - 10/7	Karan, Jordan
Connect Raspberry Pi 4 to OPAL-RT	2 Weeks	9/23 - 10/7	Nicole, Adam, Karan
Construct The Final Communication Channels	4 Weeks	10/7 - 11/4	All
Connect The PCB to the Raspberry Pi 4 and the Energy Management System	4 Weeks	10/7 - 11/4	All
Final Adjustments	4 Weeks	11/4 - 12/6	All
Final Presentation	1 Hour	12/6	All

Appendices

[1] Advancing Cybersecurity to Strengthen the Modern Grid, www.energy.gov/sites/default/files/2021/01/f82/OTT-Spotlight-on-Cybersecurity-final-01-21.pdf.

[2] Communications with the Grid Edge, www.energy.gov/sites/default/files/2023-07/Communications with the Grid Edge - Unlocking Options for Power System Coordination and Reliability_0.pdf.

[3] "How Has the Electric Grid Changed over Time?" EnergySage, www.energysage.com/electricity/how-has-electric-grid-changed/#grid-modernization.

[4] Khoei, Tala Talaei, et al. "Cyber-Security of Smart Grids Attacks, Detection, Countermeasure Techniques, and Future Directions." SCIRP, Scientific Research Publishing, 2022, www.scirp.org/journal/paperinformation?paperid=121421#:~:text=In%20smart%20grids%2C%20an%20attacker,illegal%20access%20to%20the%20nodes.

[5] "Smart Hybrid Energy Management System Using Arduino || Code & Circuit." YouTube, YouTube, 10 June 2023, www.youtube.com/watch?app=desktop&v=A9fEb-v0cCw.

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[9] "Raspberry Pi or Arduino – When to Choose Which?" Leo Rover Blog, www.leorover.tech/post/raspberry-pi-or-arduino-when-to-choose-which. Accessed 29 May 2024.