# EEL4914 Senior Design I - Divide and Conquer

# Thermal Dune Energy Storage


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## Group 9

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| | | |
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# Chapter 2: Project Description

## 2.0 Project Background and Motivation

The thermal sand battery is intended to electrically heat a home while saving money by utilizing off-peak electric rates. This battery uses a thermally insulated core made of sand to store heat until it is needed later. The inspiration for this project came from exploring alternative energy storage methods for excess solar power. As the power grid transitions to renewable energy sources, there is an increasing focus on the issue of renewable energy intermittency. Although solar and wind energy are significantly cheaper than fossil fuels (even when controlled for industry subsidies), the question of what happens when the wind doesn't blow, and the sun doesn't shine is crucial. The answer is 'energy storage,' but the debate centers on the best form of energy storage.

Currently, lithium-ion batteries are the favored solution. While they are capable and efficient, they have drawbacks that our Thermal Sand Battery can address. Renewable energy intermittency is often discussed alongside 'load shifting.' Solar panels can produce excess power during the day, which is often dumped into the grid. This overproduction can cause net grid demand to drop drastically (and sometimes go negative), jeopardizing grid stability. Solar production causes a significant drop in net grid demand during the day, followed by a sharp increase at sunset when people return home, creating a 'duck curve' in overall grid demand.

This situation has led to the popularity of 'time of use rates' for residential electric users, where electric rates vary depending on projected grid demand. Users pay higher rates during 'peak grid use' (6pm-9pm) and lower rates during 'off-peak grid use' (12pm-6am). This approach encourages 'load shifting,' where users perform energy-intensive tasks during off-peak hours. This strategy promotes a more even distribution of power demand, reducing extreme swings in grid demand. Users with solar battery packs often charge their batteries during off-peak hours if their solar array didn't fully charge the battery during the day or if they lack enough storage to last through the night.

The Thermal Sand Battery aims to provide a form of energy storage comparable in density to lithium batteries, convenient home/room heating, and significantly cheaper energy storage. According to the US Energy Information Administration, 42% of energy usage in the average American home is for space heating, increasing to 45% in single-family homes. While it is possible to run a heater on a lithium-ion battery, the cost is prohibitive. Commercially accessible lithium-ion batteries, including those for residential solar arrays, cost about $300 per kWh. This makes the upfront cost of saving money through load shifting significantly higher. On the other hand, a gallon of fine-grain sand can store roughly 500Wh of power considering a specific heat of 830 J/kg. Given the low cost of sand and its lack of performance degradation over ten years (compared to a 10% capacity decline every five years for lithium batteries), we believe we can build a battery that is several times cheaper than a lithium-ion battery both short and long term.

The Thermal Sand Battery allows consumers to charge and store heat energy during off-peak hours and discharge it when needed, ensuring maximum comfort. Additionally, it avoids the risks associated with storing highly combustible lithium-ion cells and thermal runaway, offering greater stability. Our project aims to adhere to the saying, "if you want to make a dirt-cheap battery, you have to make it out of dirt."

Lastly, ease of installation is a significant consideration. The $300 price tag for 1 kWh of lithium battery storage covers just the battery. Lithium batteries and their DC power require an inverter with proper fusing and wire sizing. For non-DIY consumers, power stations cost far more than $300 per kWh, and professional installation adds significantly to the break-even cost. Our sand battery is designed to be a no-frills solution, running off a simple 120V outlet, requiring no permitting, DIY knowledge, or concerns about lithium cell fires.

## 2.1 Project Goals and Objectives

After meeting with professor Chan and Professor Wei, this project can be built so as to be able to meet the requirements for senior design. The requirements presented to us were to have a custom PCB board with an integrated MCU, a custom power supply to power this MCU, and to have our custom PCB interface with an array of external sensors. The design of this project aesthetically will be an object that can actually be placed within a room, think along the lines of a coffee table. In terms of the engineering components, this is where it may get a little more difficult. This project will include a main PCB board, this PCB will interface with an LCD with an interactive GUI that will allow the user to change various settings from the thermal battery. The GUI will allow the user to set a specified charge time, set a specified room heating time, set an ideal room temperature to heat the room up to, and to be able to override the room heating schedule and instead start immediately heating the room. The GUI will be controlled by the MCU on our custom PCB board, the average internal battery temperature will be calculated by two thermometers in the MCU and displayed on the LCD for the user to see, the average external room temperature would also be calculated by two outward facing temperature sensors.

**Goals:**

1. The battery must be capable of releasing thermal energy to heat a room to a specified temperature
2. The battery must use a heating element that can fully heat our battery within a reasonable amount of time
3. The battery will be enclosed in an insulated box to prevent heat loss and injury to the user
4. The battery must know when to stop heating and charging

5. The MCU must communicate with temperature sensors to process that information back to the LCD display
6. The LCD must have an interface that will let the user control heat settings and charging settings
7. The user must be able to charge the battery on a specified schedule

**Stretch Goals:**
1. The custom-made PCB can communicate via Bluetooth to outer sensors for a more accurate reading of the external room temperature
2. The MCU can store energy usage data and history onto a cloud-based server
3. Create a mobile application to communicate with GUI

**Objectives:**
1. Determine the best insulator materials required for the battery enclosure
2. Determine a sufficient heating element that is energy efficient
3. Determine a microcontroller (MCU) capable of scheduling and task handling
4. Identify the optimal design for implementing the AC-DC converter
5. Determine which sensors are compatible with selected MCU
6. Determine the power requirements for the heating element and components
7. Determine communication protocols required between peripherals and MCU
8. Determine the best approach for implementing a user-friendly interface
9. Identify components required to realize custom made PCB
10. Identify the best PCB layout design for EMC considerations

## 2.2 Project Description of Features and Functionalities
Because thermal sand batteries are new to adoption as a form of energy storage the consumer/utility sector hasn't quite reached the point of widespread adoption as we've seen with something like flooded lead acid batteries, and lithium-ion batteries. Our research has brought two notable theoretically similar - in that we are utilizing energy storage in the form of heat as opposed to a chemical process- instances of a thermal sand battery.

The first instance of this project comes from a company called 'polar night energy' based in Finland. Their sand battery is a grid scale heating store, their battery is roughly the side of a medium sized corn silo which was connected to their district heating system and was able to deliver a 100kW quantity of heat to the local Kankaanpaa municipality and a boasts a storage of 8mWh. Finland has a high degree of renewable energy adoption in the form of wind energy and polar night energy has been able to utilize low energy rates during peak wind production to be able to charge their thermal sand battery. This gives them a market advantage over on demand heating sources like regular electric heaters or fossil fuel sources. It has been estimated that because of this system the battery will allow the municipality to reduce carbon dioxide emissions from district heating by as much as 70%.

The second market implementation comes from a company called ‘batsand’. Conceptually it is a similar idea, using sand to store and distribute heat and controlling it with a thermostat. The implementation of their battery is one of the largest drawbacks, however. The basic specs of their system are a rated power of 14kW of heating and a claimed battery capacity of 12,000 kWh, but the system is a geothermal installation type system. Meaning the sand battery component is a massive installation process which gives the flexibility of being able to store lots of power and be ‘out of sight out of mind’ but lacks in terms of affordability. The cost of the system along is already setting back the consumer around $8000, we then need consider the installation and permitting process of digging a massive hole in the back yard to then be able to run the proper piping into the house to connect to the home radiator and thermostat. This sets their system apart from our project as we intend on making the battery affordable for anyone that wants to heat their home, and easy to install for those that may not even be in a position to dig a massive hole in their backyard.

## 2.3 Engineering Specifications

Table 2.4.1 below shows the important specifications for this project, and we intend to demonstrate 3 of the specifications highlighted in blue.
The external temperature display indicates the current temperature outside of the thermal sand battery system. This information is important because it allows users to understand the environmental conditions and how they may affect the system’s performance.

The internal temperature display shows the temperature of the sand inside the thermal battery. This is critical for monitoring the system’s performance and safety, ensuring it operates within the specified temperature range of 0°C to 395°C.

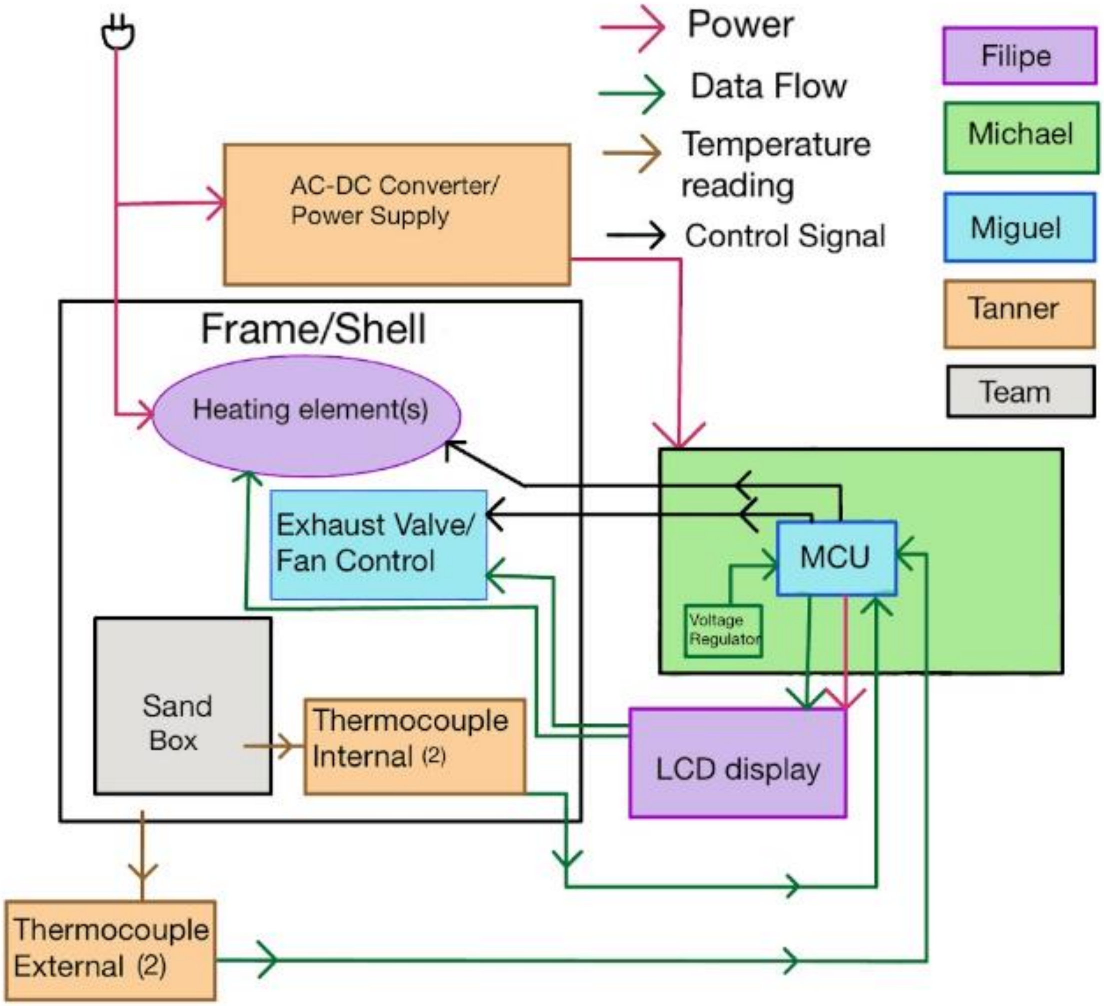
The user interface, which consists of an LCD 3.5 inch, facilitates users to set charging times and schedule heating periods, making the system accessible and simple to use. Its significance comes from the fact that it provides a user-friendly interface for customizing the system’s operation to meet individual requirements.

| Specification | Description | Range/number |
|---|---|---|
| Charging Time | The time during which the battery is charged is set by the user. | 3-10 hours |

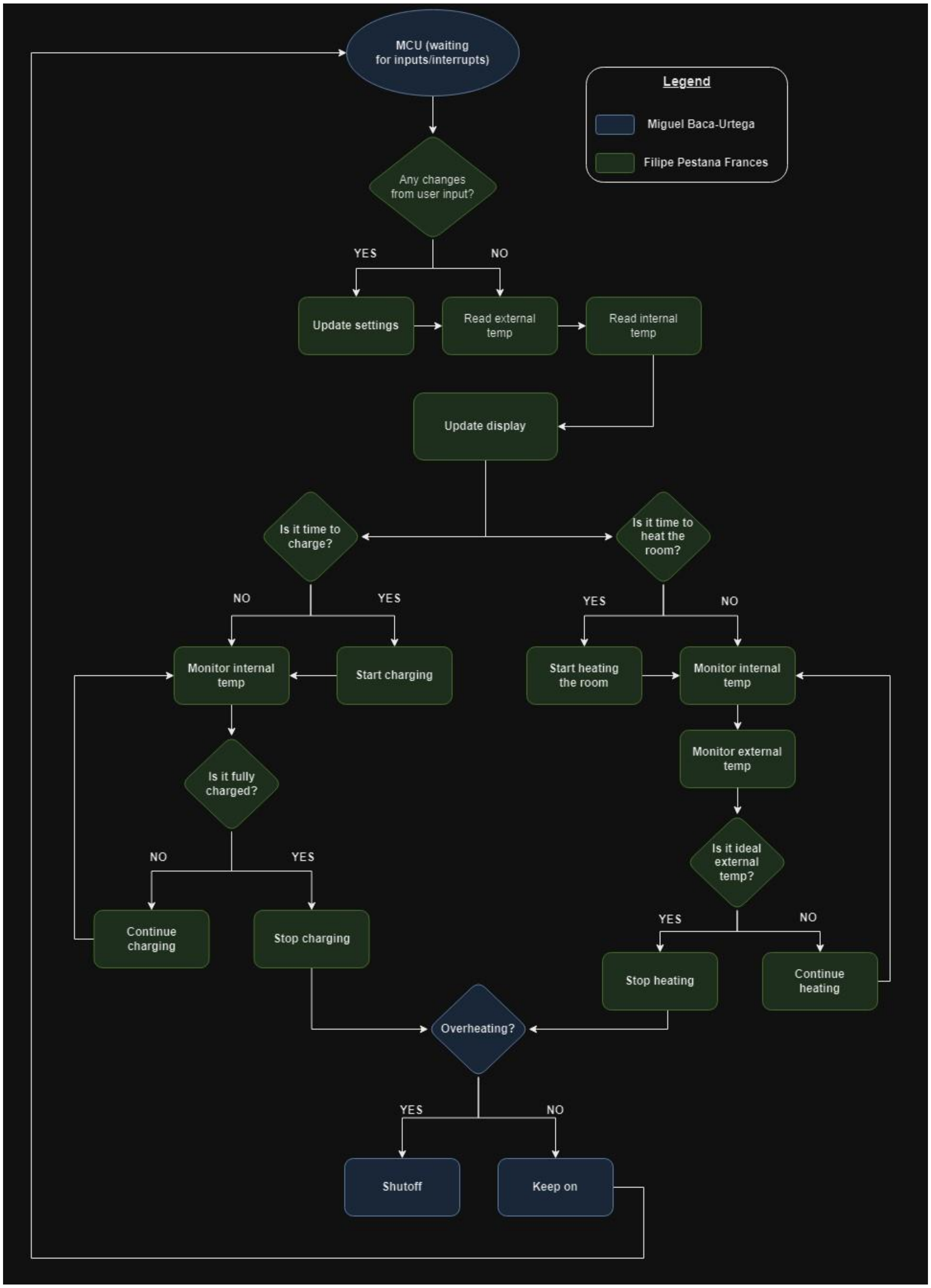
| | | |
|---|---|---|
| Discharge Duration | Duration for which the battery can maintain ambient warmth. | 4-12 hours |
| User Interface | Interface allowing the user to set charging and discharge times. | LCD 3.5” |
| Battery | Shows the percentage of the battery on the screen. | 0-100% |
| Turn on/off | User is able to turn on/off overriding the schedule time. | LCD on/off button |
| External Temperature Display | Display showing the current external temperature. | 0°C to 55°C |
| Internal Temperature Display | Display showing the current internal temperature of the sand. | 0°C to 395°C |
| Temperature Range (Internal) | Range of temperature the internal sand can reach. | ~0°C to 395°C |
| Energy Capacity | Amount of energy the battery can store. | 5KWh |
| Power Input | Power is required for charging the battery. | 120V, 60Hz |
| Power Output | Max current/power drawn | 12A, 500W - 1KW per hour |
| Efficiency | The efficiency of the battery in converting electrical energy to heat. | 80-90% |
| Heat Retention | The ability of the sand to retain heat over time. | Up to 24 hours (if fully charged) |
| Safety Features | Built-in safety mechanisms such as overheat protection. | Overheat shut off at 450°C (internal) |
| Dimensions | Maximum dimensions | 18” x 24” x 24” Excluding wheel height |

*Table 2.3.1: Engineering Specifications*

## 2.4 Block Diagrams




*Flowchart 2.4.1: Hardware Block Diagram*




*Flowchart 2.4.2: Software Diagram*

## Main loop

● User Input
**Purpose:** Determine whether the user has interacted with the system via the LCD.
**Actions:** If user input is detected, update the system settings (for example, change the charging time or heating time).

● Read External Temp
**Purpose:** Monitor the temperature of the external environment.
**Actions:** Record the current external temperature for display and decision purposes.

● Read Internal Temp
**Purpose:** Monitor the temperature of the sand inside the battery.
**Actions:** Record the current internal temperature to ensure that it falls within the desired range for charging and heating.

● Update Display
**Purpose:** Keep the user informed of the system's current status.
**Actions:** Display external and internal temperatures in real-time, as well as charging and heating status on the screen.

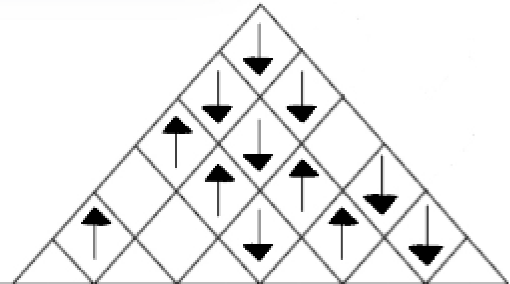
● Charging Time
**Purpose:** Determine whether it is time to begin the charging process based on the user-defined schedule and real-time clock.
**Actions:** Once the scheduled charging time is reached, begin the process. Continuously monitor the internal temperature while charging. When the desired Temperature or time limit is reached, the charging process comes to an end.

● Heating Time
**Purpose:** Determine whether it is time to begin the heating process based on the user-defined schedule and real-time clock.
**Actions:** Once the scheduled heating time is reached, begin the process.
Continuously monitor the internal and external temperature while heating. When the desired temperature or time limit is reached, turn off the heat.

● Overheat Protection
**Purpose:** To ensure the system's safety by preventing overheating.
**Actions:** Constantly monitor the interior temperature for indicators of overheating.
If overheating is detected: Shut down the system to avoid any harm or dangers.

● Loop Back
**Purpose:** Continuously repeat the look to monitor and regulate the system.
**Actions:** Return to the beginning of the main loop to perform the checks and updates.

## 2.5 House of Quality



| Weight / Importance | Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") | Power Output | Efficiency | Installation time | Dimensions | Weight | Cost |
|---|---|---|---|---|---|---|---|
| | Column # | 1 | 2 | 3 | 4 | 5 | 6 |
| | Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x) | ▲ | ▲ | ▼ | ▼ | ▼ | ▼ |
| ▲ | Battery Storage | ↑ | ↑ | | ↓ | ↓↓ | ↓↓ |
| ▼ | Installation difficulty | | | ↑↑ | ↓ | ↑ | ↓ |
| ▲ | Heat Output | ↑↑ | ↑↑ | | ↑ | | ↓ |
| ▼ | Power Consumption | ↑↑ | ↓ | | ↑ | ↑ | ↓ |
| ▲ | Asthetics | | | | ↑ | | ↓ |
| ▲ | Mobility | | | ↑ | ↑ | ↑ | |
| ▼ | Cost | ↓↓ | ↓↓ | | ↑ | ↓ | ↑↑ |
| | Specification target value | 500-1000W/hour | 80-90% | 5 minutes | 18" x 24" x 24" | 150 Lbs | $1000 |

*Table 2.5.1: House of Quality Diagram*

# Chapter 10: Administrative Content

## 10.1 Budget and Financing

The budget for this project will be limited to USD 800 and is set by our group members. This amount will help the group to stay true to one of our goals, which is to make this device affordable should it ever be mass-produced. We have allotted larger portions of the budget toward the transformer, thermistor sensors, microcontrollers, and the frame of the device.

| Systems | Budget |
|---|---|
| Frame/Sand Storage | $250 |
| Microcontrollers/Sensors | $150 |
| AC-DC Converter/Heater | $200 |
| Valves/Fans/Aesthetics | $200 |
| **TOTAL** | **$800** |

*Table 10.1.1: Initial Budget and Startup Costs*

## 10.2 Project Milestones

To ensure the timely completion of this project, we have established extensive milestones to track the team's progress and meet specified deadlines. Team formation and initial brainstorming for the project took place during Senior Design I (Documentation Phase), where we will research the feasibility of the project to confirm its viability. Most of the planning, research, and initial designs will occur over the summer, with the goal of having a working prototype ready before Senior Design II (Validation Phase). In the next phase, we will conduct extensive testing and validation before releasing the final design for inspection. Below is the tentative schedule for both Senior Design I and II.

| Task | Start Date | End Date | Description |
|---|---|---|---|
| Team Formation/Brainstorm | 5/13/24 | 5/17/24 | Teams will be formed, and the project is initially agreed upon. |
| Individual Research/ Feasibility determination | 5/17/24 | 5/22/24 | Roles and responsibilities are assigned to team members. Each team member breaks off and investigates the feasibility of their respective system. |
| Initial Divide and Conquer Report (Chapter 2 and Chapter 10) | 5/22/24 | 5/31/24 | Initial research, costs, specifications, and project descriptions are gathered and presented for approval. |
| 30 Page Milestone (Chapter 1 and Chapter 3) | 5/31/24 | 6/14/24 | A formal executive summary of the project and extensive engineering research is conducted, building upon initial research. |
| 60 Page Report Milestone (Chapter 4 and Chapter 5) | 6/14/24 | 6/28/24 | Using gathered research, design constraints are constructed for each system of this project. Standards are formally written and implemented. |
| 90 Page Milestone (Chapter 6 and Chapter 7) | 6/14/24 | 7/5/24 | System schematics are refined utilizing block diagrams. The architecture of each system will be thoroughly evaluated. The software team will implement the user interface architecture |

| | | | |
|---|---|---|---|
| | | | and communication protocols. |
| 120 Page Milestone (Chapter 8 and Chapter 9) | 7/5/24 | 7/23/24 | PCB layout is finished utilizing ECAD (Fusion 360). System test procedures (STP) are created. Performance parameters are evaluated based on established standards. |

*Table 10.2.1: Project Report Milestones SD1*

| **Task** | **Start Date** | **End Date** | **Description** |
|---|---|---|---|
| Schematic Design | 6/10/24 | 6/26/24 | Begin the initial schematic design that will be used to designate individual component functions on the PC. |
| Begin building GUI Software Interface | 6/10/24 | 6/26/24 | Software team will begin coding the GUI. |
| Parts Order | 5/31/24 | 6/21/24 | Order the necessary parts required for SMT and breadboard prototyping. |
| Begin PCB Layout Design | 6/15/24 | 7/12/24 | Once the schematic is complete, translate into PCB layout. Focusing on EMC and Layers considerations. |
| Breadboard/Dev board Prototyping | 6/21/24 | 7/12/24 | Prototyping the designs using a breadboard and a dev board to catch potential points of failure and redesigns. |

| | | | |
|---|---|---|---|
| Initial System Testing and Function Validation | 7/12/24 | 7/19/24 | Systems are initially tested and validated to meet engineering specifications and standards. |
| Finish PCB layout Design | 7/19/24 | 7/23/24 | PCB layout is completed and Ready for fabrication. |

*Table 10.2.2: Project Design Milestones SD1*

| **Task** | **Start Date** | **End Date** | **Description** |
|---|---|---|---|
| PCB manufacturing and fabrication | 7/23/24 | 8/6/24 | The PCB will be fabricated and SMT components will be placed. |
| PCB validation and testing | 8/6/24 | 9/06/24 | PCB is rigorously put through the same validation and testing from SD1 to ensure functionality. |
| GUI testing and validation | 8/6/24 | 9/06/24 | GUI is tested to ensure user friendliness and no bugs are missed. |
| System Integration and Testing | 9/06/24 | 10/07/24 | All systems are assembled, connected, and tested to ensure specifications are met. |
| Practice Demo Initiated | 10/07/24 | 10/28/24 | The finished battery system is demoed. Ensuring all goals are met and objectives were completed. |
| Refine Final Documentations | 10/28/24 | 11/22/24 | All documentation is edited and refined to account for last minute findings. |

| | | | |
|---|---|---|---|
| Final Presentation | TBD | TBD | Finished product is presented to review committee for approval. |

*Table 10.2.3: Project Design Milestones SD2*

## 10.3 Workload Distribution

| Student | Student Major | Responsibility |
|---|---|---|
| **Michael Hernandez** | **Electrical Engineering** | PCB design/layout |
| | | PCB-Sensor communication protocols |
| **Miguel Baca-Urteaga** | **Computer Engineering** | MCU-Hardware communication |
| | | MCU/embedded system programming |
| | | Hardware Implementation |
| **Filipe Pestana Frances** | **Computer Engineering** | LCD-MCU communication |
| | | MCU user interface programming |
| **Tanner Cyr** | **Electrical Engineering** | AC-DC converter design |
| | | Thermocouple and Hardware implementation |
| | | PCB-Hardware considerations |

*Table 10.3.1: Workload Distribution Table*

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