4.2 Design Exploration

4.2.1 Design Decisions

4.2.1.1 Transmission (Substation) Team

One of the key design decisions is selecting the right battery storage system, such as lithium-ion or flow batteries. This choice is essential because the battery will help manage energy from renewable sources like wind and solar, ensuring the substation can operate efficiently. The right battery will improve performance, cost, and lifespan, while the wrong choice could lead to inefficiency or higher costs. Another critical decision is determining the appropriate transformer size for the 69kV–13.2kV system. The transformer plays a key role in adjusting the voltage between the transmission and distribution systems, and selecting the right size is crucial for stable operations. A transformer that's too small may not handle the power load, while one that's too large could increase costs unnecessarily.

Finally, choosing the right modeling and simulation software is vital for designing and testing the substation, especially for integrating battery storage and renewable energy sources. Tools like PSCAD and AutoCAD will help simulate how the substation interacts with the grid, storage, and renewable energy, allowing the team to identify and fix issues early in the design process. These decisions directly impact the project's cost, performance, and safety, ensuring the substation meets energy needs and is built effectively.

4.2.1.2 Distribution Team

The first choice made was how to develop the campus load profile. Coming into the project, the team was unsure how much power the campus consumed, as this was not information typically shared in class or publicly. In order to figure this out, the client suggested a manual walk around the campus to gauge each building based on size and devices present to estimate the power consumption (in kilowatts). However, we were able to discover a public website that helped show the 12 month power consumption from all buildings on the microgrid, which then helped us define the profile.

Based on the load data available, another subsequent choice that was made was what information would be approximated, and what other data we would attempt to collect from the contacts we had found at the ISU utility from either web searches or our advisor. Information like the voltage rating of the distribution system and the power factor at which buildings on campus were being operated at are crucial to the design of the model and any subsequent improvements. As a team, we decided that we would attempt to obtain as much information as possible from our contacts and ask as many questions necessary, and wherever they declined to share this information or were unable to give us a direct answer we would work with the client to fill in these gaps based on industry standards or recommended operation levels.

The final design choice that was important for the project was the selection of a distribution modeling software. Different softwares will all have the same capabilities in terms of voltage drop calculations, but they will also provide different areas of ease for things like geographic modeling and equipment specifications. This decision will have instant impacts on the different aspects of the microgrid we can look at past the modeling phase.

4.2.2 Ideation

4.2.2.1 Transmission (Substation) Team

For selecting the appropriate battery storage system, we will be using brainstorming to explore various options based on factors like cost, efficiency, lifespan, and scalability. We are currently considering five potential options: lithium-ion batteries, known for their high energy density and efficiency; flow batteries, which offer longer energy storage durations and better scalability; lead-acid batteries, which are cost-effective but have a shorter lifespan and lower energy density; sodium-ion batteries, an emerging technology with similar efficiency to lithium-ion but using more abundant materials; and nickel-cobalt-manganese (NCM) batteries, which offer higher performance but are more expensive. After evaluating the pros and cons of each option, we will be able to choose the best fit for the greenfield substation project, balancing performance and cost while supporting the integration of renewable energy sources and battery storage.

4.2.2.2 Distribution Team

For the selection of a modeling software, our team came up with 5 common industry standard softwares that could all be used for distribution network modeling. The 5 softwares we settled on are: CYME, ETAP, OpenDSS, PSS/E, and SKM. These are softwares that we had heard about from the client (CYME and ETAP), software used by our advisor for his research (OpenDSS), and other industry softwares that have been mentioned in class or briefly other places (PSS/E and SKM). With each of these, there are tradeoffs that come in the forms of familiarity of team members, advisor and the client, as economical considerations such as cost on our budget. There were also considerations on how easy the modeling software is to use, and if it can use a geographic information system (GIS) to help make the layout more accurate.

4.2.3 Decision-Making and Trade-Off

4.2.3.1 Transmission (Substation) Team

For the substation design, we focused on choosing a battery type that would balance cost, efficiency, and long-term reliability, considering the unique needs of the project. The most commonly used batteries in substations are **vented/flooded lead acid, sealed maintenance-free lead acid (VRLA), nickel-cadmium (Ni-Cd), and lithium-ion**. We used a weighted decision matrix to assess each option against the factors most important to the project: **cost, energy efficiency, lifespan, maintenance needs, and environmental impact**. We also considered the specific substation design, which involves integrating battery storage with a renewable energy solution and ensuring that the system can operate efficiently over the long term.

Option	Cost (Weight: 30%)	Energy Efficiency (Weight: 30%)	Lifespan (Weight: 20%)	Maintenance (Weight: 10%)	Environmental Impact Weight: 10%)	Total Score
Vented/Flooded Lead Acid	4	2	5	3	3	3.7
Sealed Maintenance-Free (VRLA)	5	3	4	4	3	4.3

Nickel-Cadmium (Ni-Cd)	3	4	5	3	4	4.0
Lithium-Ion	2	5	4	4	5	4.0

Based on the matrix, **sealed maintenance-free lead acid (VRLA)** batteries scored the highest with a total of 4.3. These batteries offer a good balance of cost-effectiveness, compact size, and lower maintenance needs compared to other lead-acid types, making them ideal for the space-constrained environment of the substation. Nickel-cadmium (Ni-Cd) batteries scored similarly with a total of 4.0, excelling in lifespan and performance in extreme temperatures, but they were more expensive. Lithium-ion batteries, despite their high energy efficiency and environmental benefits, scored lower due to their high initial cost and safety concerns, making them less ideal for this particular substation project. Vented lead acid batteries, while durable and long-lasting, require more maintenance and are less efficient, making them a less favorable option for this design. Therefore, we chose VRLA batteries due to their lower maintenance needs, suitability for constrained space, and a reasonable balance of cost and performance for the substation's requirements.

4.2.3.2 Distribution Team

For the distribution design, the most important consideration was with what platform was being used to build a model. The three options below were the main options that had been both used by our advisor and client, and also industry standard sites for distribution planning. Software like PSS/E could also have been used, but instead our team chose to focus on packages that had primary use for distribution systems rather than those that just happened to also provide that service. The weighted matrix helped balance the pros and cons of each system, considering both availability and the difficulty of use for a rather short-term project as opposed to use for research or client work where time wasn't as limited as a resource.

Option	**Cost (40%)**	**Previous Knowledge (30%)**	**Ease of Use (20%)**	**GIS (10%)**	**Total Score**
CYME	2	5	4	5	3.6
ETAP	3	4	3	0	3.0
OpenDSS	5	3	3	4	3.9
PSS/E	4	1	3	3	3.0
SKM	1	1	4	0	1.5

Based on the results of the matrix, OpenDSS will be the software used for the design. It scored similar on average with CYME (the software our client prefers), but the main constraint that contributed to this choice ended up being cost limitations and the lack of funding available to cover the $2500 license ended up being a binding constraint.

4.3 Proposed Design

4.3.1 Overview

4.3.1.1 Transmission (Distribution) Team

Our substation design integrates both renewable energy sources and traditional power sources to ensure a reliable and sustainable electricity supply. The key components of the system include:

1. **Transformer**: This steps down high-voltage electricity from the grid (69kV) to a lower voltage (13.2kV) for safe use in homes and businesses.
2. **Battery Storage System**: The battery stores excess energy generated from renewable sources (solar and wind) when supply exceeds demand. This stored energy can then be used later when the renewable sources aren't producing enough power (such as during cloudy days or at night).
3. **Renewable Energy Sources (Wind/Solar)**: The renewable energy systems, such as wind and solar farms, feed electricity into the substation when available. They help reduce reliance on fossil fuels, lowering the environmental impact of the electrical grid.
4. **Power Plant/Grid**: When renewable sources are not generating enough power (for example, when the wind isn't blowing or it's nighttime for solar), the substation can rely on electricity from the power plant to meet the demand. The grid serves as the backup to ensure continuous and stable electricity supply.
5. **Distribution Feeders**: These are the power lines that carry electricity from the substation to homes and businesses. They ensure that the electrical system is capable of delivering power from all sources efficiently and safely.

In this design, the battery system works in conjunction with both renewable energy sources and the traditional grid, ensuring that the community always has a reliable source of power, regardless of fluctuations in renewable energy generation. The system supports sustainability and resilience by integrating different energy sources to create a more stable and environmentally friendly power grid.

Basic Block Diagram:

- **Power Plant/Grid/Renewable Energy (Solar/Wind) → Transformer → Battery Storage→ Distribution Feeders → Consumers**

4.3.1.2 Distribution Team

The main distribution model will approximate the current campus distribution layout, providing an opportunity to improve on the previous solution and increase reliability. The proposed plan will have the following key components:

1. **ISU Campus Data Load profile:** The load profile of the campus will be formed based on a mesh of requested data and a publicly available website that provides the energy consumption on campus. This website shows data in a 12-month range, and will be converted into an average daily power consumption. Using other information such as peak usage times and power factor, a four season model and daily load shapes will be developed.
2. **Modeled ISU Microgrid Power Supply:** This step of the process will take the load profile developed previously and place the loads into OpenDSS, a distribution modeling software.

This model will break the campus into multiple circuits and provide guidance for the impedance in the lines and how power flow may be affected.

3. **Contingency and Jumpering Plans**: These plans will serve as n-1 and n-1-1 plans, which are plans to use when power is lost on accident or intentionally. The n-1 plan looks at moving a single circuit's load to another circuit, and the n-1-1 plan will look at the shutdown of an entire transformer, which will house 2-3 circuits.
4. **Potential Equipment Upgrades:** We are looking at adding reclosers or trip savers for the potential equipment upgrades. These will help stop the fault current from reaching the substation or power plant. We will also be looking at adding in capacitor banks to help with reactive power in the circuit to help with the distribution of real power.

4.3.2 Detailed Design and Visual(s)

4.3.2.1 Transmission (Substation) Team

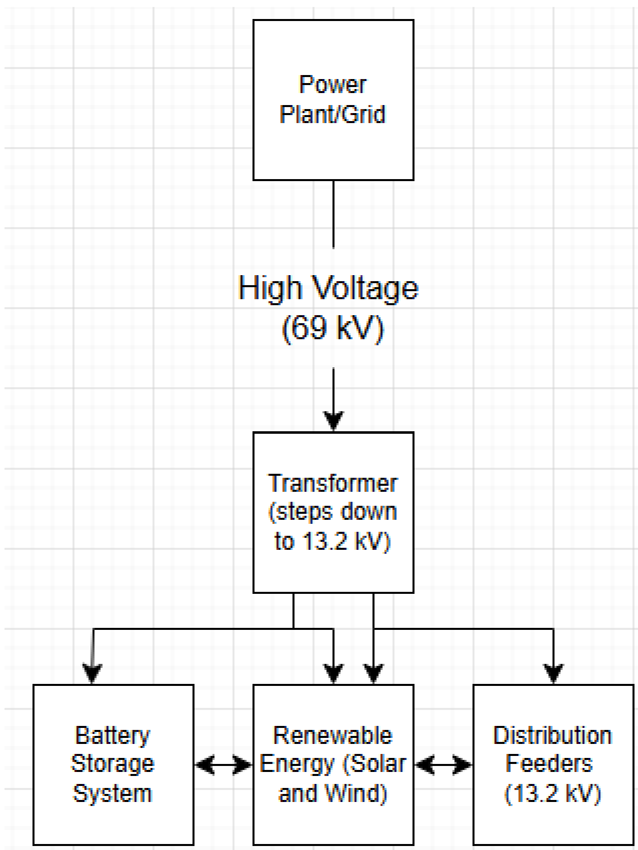

Fig. 1: Simple Block Diagram of Substation Components and Subsystems

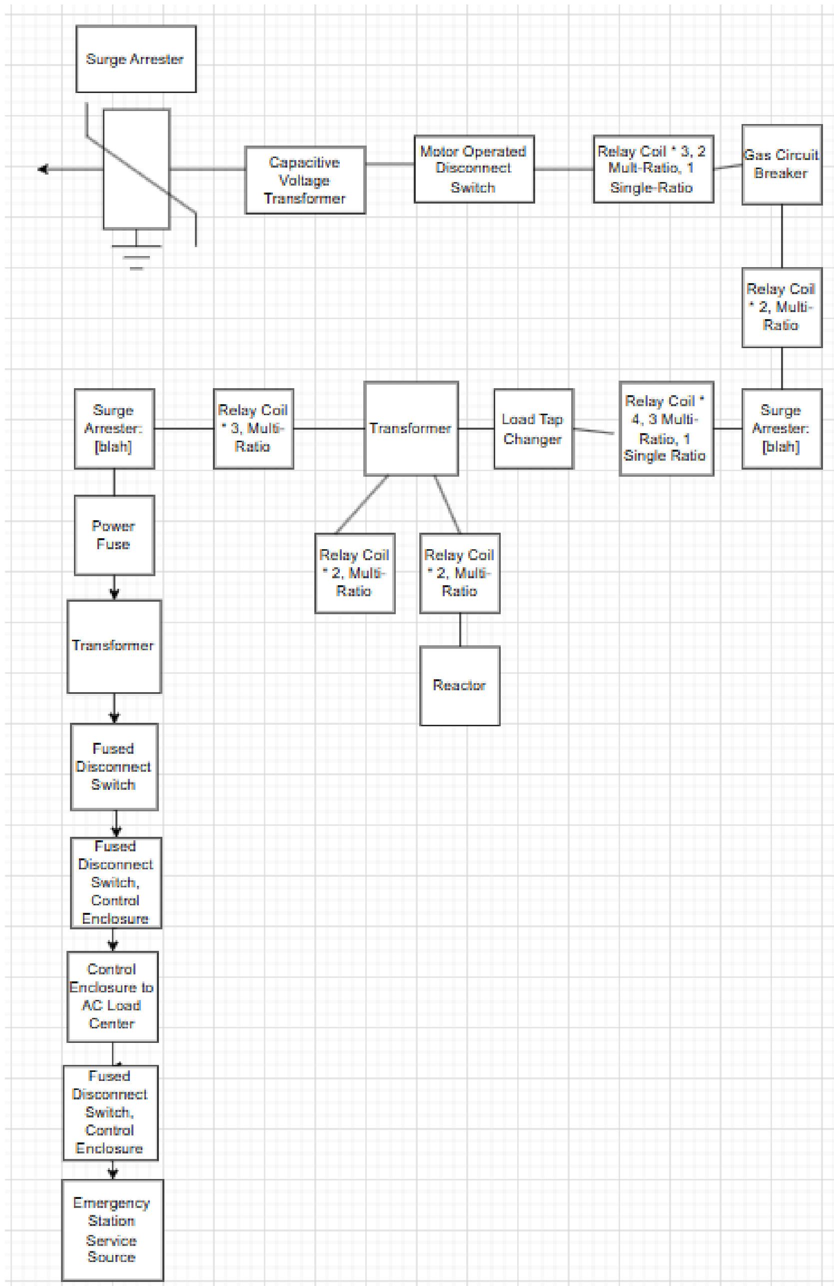

Fig. 2: Simple Block Diagram of Part of the Substation Components

The proposed substation design integrates renewable energy sources, battery storage, and traditional grid power to ensure reliable, sustainable electricity distribution. Key components include a transformer to step down the voltage from 69kV to 13.2kV, renewable energy sources (solar and wind) to provide clean power, and a battery storage system to store excess energy for later use. The battery system helps balance the intermittency of renewables by storing energy during periods of high generation and discharging when demand exceeds supply. The power grid interface ensures continuous power when renewable generation and battery storage are insufficient.

These systems work together to provide stable and efficient energy to the local distribution feeders. The renewable energy sources feed electricity into the substation through inverters, while the battery storage charges and discharges based on demand. The power plant/grid interface ensures reliability by supplying power when necessary. This design provides a flexible, scalable solution for power distribution, combining energy efficiency, sustainability, and grid resilience to meet modern energy demands.

4.3.2.2 Distribution Team

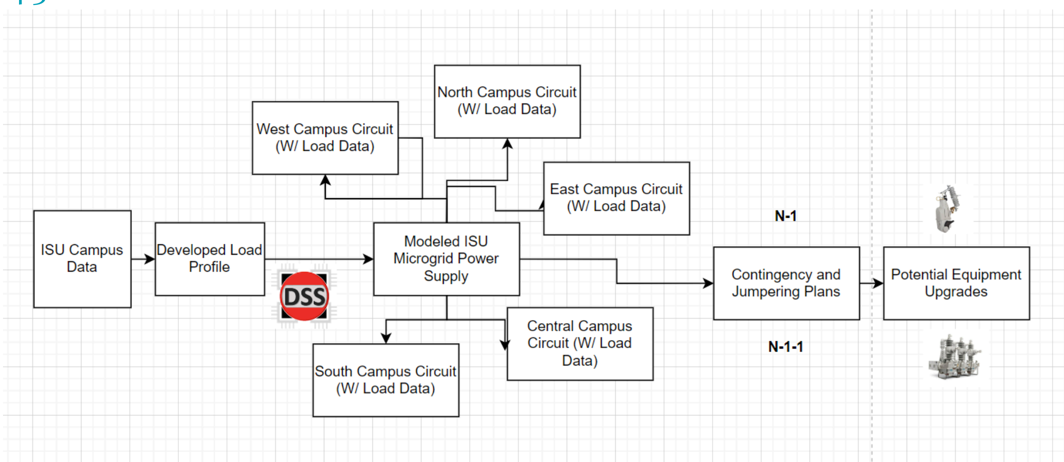

Figure 3: Simple Block Diagram of the Distribution Components

The proposed distribution system design implements the real-world campus load data to create a model of the day-to-day power used by the buildings at Iowa State University. From this detailed data, a model will be created to show these loads in relation to the power supply and each other. This model will show the different sectors of campus, and from there will allow for the contingency and jumpering plans to be created.

After the plans showing the movement of the load for loss of power are created, further equipment upgrades can be justified using the model. Devices like reclosers or trip savers can be added, helping stop fault current in the system. We can also advocate for or argue against the additions of solar and battery storage on campus based on the load demand and current power being supplied.

4.3.3 Functionality

4.3.3.1 Transmission (Substation) Team

In its real-world context, the substation design is intended to operate autonomously while being monitored and controlled by system operators. The primary user would be a utility operator or a technician, who oversees the performance of the substation, ensuring its safe operation and efficiency.

When the system is running, renewable energy sources like solar panels and wind turbines generate power, which is fed into the substation. The user can monitor the energy production and demand through a control system interface. If renewable generation exceeds demand, excess energy is stored in the battery storage system. If demand increases beyond renewable production, the battery discharges to meet the demand, while the grid connection provides additional power as necessary to ensure stability.

The user may also intervene in cases where maintenance is required, or if there is a need to adjust parameters for optimal operation (e.g., when a new battery set is added). In case of an issue, such as battery discharge failure or a fault in the renewable generation, the control system would automatically alert the user and possibly redirect power flow from the grid. The system is designed to balance reliability and sustainability, automatically adjusting the generation mix while providing flexibility for manual adjustments.

4.3.3.2 Distribution Team

In a real-world context, the OpenDSS model we are creating from scratch will be used as the base for performing analysis on the Iowa State campus microgrid. The OpenDSS model is an overview of the whole system and will allow us to see power flow throughout the campus distribution system. A utility operator would use the program to analyze how the campus distribution system operates and how the proposed changes affect the grid.

In proposing jumpering plans or installing renewable generation facilities, th eOpenDSS model allows users to analyze how each upgrade affects the system. Using OpenDSS to model new solar facilities or a battery storage dice expelling power back to the grid can help users understand the power flow throughout the campus and determine whether the upgrade will assist in reducing the amount of power needed. The user will use the open DSS model to determine whether different circuits can handle the extra load from the proposed jumpering plans.

Users can also use the OpenDSS model to plan for future growth and increases in load at specific locations. we can use the model to see areas for current system upgrades such as increasing conductor size and installing larger kVA transformers. It will also allow user to visualize the protective scheme of the distribution system.

4.3.4 Areas of Concern and Development

4.3.4.1 Transmission (Substation) Team

The current design is well-positioned to meet the core requirements of the substation project, particularly in terms of integrating renewable energy sources, battery storage, and the existing distribution network. The system is designed to manage energy flow efficiently, store excess renewable energy, and provide reliable power to the grid during periods of high demand. The substation's modular and scalable nature ensures that it can adapt to various user needs, including the integration of additional renewable sources or battery storage as required by the utility.

However, there are a few concerns that need to be addressed to ensure the design fully meets user and client expectations. One primary concern is ensuring that the battery storage system has enough capacity to handle fluctuations in renewable energy production and grid demand. Another concern is the integration of renewable energy sources like wind and solar with the existing infrastructure while maintaining grid stability. Additionally, understanding the exact requirements and constraints of the client's distribution network and making sure the system complies with industry standards for safety and reliability are crucial.

To address these concerns, immediate steps include conducting detailed simulations of energy flow to test the system's response under various load conditions, which our Distribution Team is doing. We also plan to refine the battery sizing calculations and optimize renewable generation integration for peak efficiency. We will engage with clients and TAs to ensure that we are meeting all safety and operational standards, and we plan to have regular check-ins with our advisors to validate our approach. Some key questions for the client would be: What are the specific performance and reliability expectations for the substation? Are there any constraints or preferences related to battery storage size or renewable generation integration? What are the long-term plans for expanding the grid or integrating additional renewable energy sources?

4.3.4.2 Distribution Team

The current design currency meets the needs of the recruitment and users. The majority of the distribution circuit is fed through an underground circuit. This provides fewer faults on the circuit due to tree branches or animals on the power lines.

Where the system is currently lacking in future load growth. As seen in the 2023 power plant fire, the grid is susceptible to overloading. As the university continues to grow in student population and Iowa State continues to grow, this begs the question of if the grid is capable of handling these changes.

Based on our current design, the main concern is making sure that we are working with accurate and up-to-date data. While Iowa State Utilities provides a website with live tracking of the energy usage on campus, it is difficult to access historical data. Additionally, with the distribution circuits being underground circuits, it is difficult to know how the university has the power lines laid out. This makes it to where we are walking campus to make our best judgments on how we believe the circuit planning was completed.

To address these concerns, we have been asking as many questions to Iowa State Utilities and others who have studied the microgrid. We want to ensure that we build an accurate model to study, and the best way we have found to do this is to learn from others. We have also been working very closely with our clients. At every major checkpoint, we are setting up meetings with Adam to have him review our work. This was, we can ensure that we are collecting useful data and making progressive steps.

4.4 Technology Considerations

The design incorporates key technologies, including **battery storage systems**, **renewable energy integration** (wind and solar), and a **distribution management system**. For energy storage, we are considering **sealed maintenance-free lead-acid batteries** due to their compact size and low maintenance, making them suitable for space-constrained substation environments. However, they have a shorter lifespan and lower efficiency in high temperatures compared to alternatives like lithium-ion batteries. To mitigate this, we could integrate temperature controls or explore **Nickel-Cadmium (Ni-Cd)** batteries, which perform better in extreme conditions but come at a higher cost. For renewable energy, the design integrates wind and solar power, utilizing inverters and energy management systems to convert and distribute energy. While renewable energy is clean and sustainable, its intermittency is a challenge. Increasing battery storage capacity or employing predictive modeling to better manage energy flow could help ensure a reliable energy supply.

The **distribution management system** ensures efficient energy distribution from renewable sources and stored energy to meet grid demand. The main trade-off here is between cost and system complexity—an **automated control system** would provide real-time adjustments but at a higher cost, while a **semi-automated system** would be more affordable but require more human oversight. The key challenges in this design are balancing system costs with performance and addressing renewable energy variability. Alternative approaches, like **demand-side management** or **smart grid technologies**, could improve grid stability and enhance the overall system's efficiency. Ultimately, the chosen technologies meet the project's sustainability goals, but further exploration and optimization will help address trade-offs and ensure long-term success.

4.5 Design Analysis

4.5.1 Transmission (Substation) Team

So far, we have made progress in the early stages of implementing the updated scope of the project. We've conducted research into potential locations for the new substation, focusing on the old coal lot near Fredrickson Court and Haber Round. This location has been selected due to its proximity to the existing distribution infrastructure and its suitability for accommodating the substation's footprint. Additionally, we have identified the type of battery storage we intend to use, specifically **sealed maintenance-free lead-acid batteries**, which offer a good balance between reliability, cost, and maintenance requirements for this application. We've also started selecting the software tools necessary for the design and simulation of the substation, evaluating options like **PSCAD** and **AutoCAD** for their ability to handle the integration of renewable energy sources and battery storage.

At this point, the proposed design is still in the conceptual phase, so we have not yet implemented or tested the full system. We have encountered challenges with finalizing some technical aspects, particularly in creating the one-line diagram for the substation with battery integration. While the initial research and selection of components have gone according to plan, the main issues lie in the design phase. Our next steps will focus on refining the one-line diagram to properly incorporate the battery storage system and renewable energy sources, ensuring the system's functionality and integration. We also plan to continue refining the location selection and start gathering more detailed data for the substation's power and environmental requirements.

4.5.2 Distribution Team

So far, most of the work of the distribution team has been determining and updating the scope of our project and determining the available resources. The first steps include researching and deciding which distribution system modeling software to use and obtaining the university's load data. In our research to figure out the best software to use for modeling, we ended up choosing to use OpenDSS. In the end, it was the one we could most afford since it was free, and it also helped that one of our faculty advisors used the program to perform research in his field. Our next steps will be to continue refining and obtaining load information.

At this point in time, our design is still mostly conceptual. While we have created the OpenDSS model, building a fully functioning distribution mode will take time and more information. We have encountered some challenges, mostly involving the resources available to us. We depend on the information that campus utilities can provide us; sometimes, it can take up to a week or two before they can get back to us with the information we need. We are still refining the information regarding the load and location of facilities. Once we have those resources we can begin to build our base model of the campus distribution grid that we can use to propose our upgrades.