THE ANALYSIS AND STUDY OF POWER SYSTEM DESIGNS FOR SAME POLYTECHNIC COLLEGE IN TANZANIA

A Thesis

presented to

the Faculty of California Polytechnic State University,

San Luis Obispo

In Partial Fulfillment

of the Requirement for the Degree

Master of Science in Electrical Engineering

by

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June 2018

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ABSTRACT

The Analysis and Study of Power System Designs for Same Polytechnic College in Tanzania

Kevin Lum Hua

The Mbesese Initiative for Sustainable Development (MISD) is a group aiming to help eliminate extreme poverty in Africa by creating educational opportunity. One project that the group is currently doing is to build Same Polytechnic College (SPC) in Tanzania. As part of the project, this thesis aims to study and analyze the electrical power system and distribution for the college. Based on the projected load profile of the college and high potential for solar generation in Tanzania, several different power systems utilizing local utility AC electricity and/or photovoltaic (PV) DC electricity are explored and simulated for their feasibility and performance. Analysis of each design is presented and compared to determine the most viable system based on reliability, costs, and space. Results of the study indicate that over designing the DC system may generate wasteful energy while under designing the DC system may cause the overall system to rely heavily on the AC power grid. Ultimately, this thesis demonstrates that integrating a 58.9% DC system mixed with AC system offers the highest payback while efficiently utilizing the PV system, the battery system, and provided land.

Keywords: power system design, Tanzania, load profile, photovoltaic, ETAP

ACKNOWLEDGMENTS

I would like to thank my thesis advisor, Dr. Taufik, for his support and guidance throughout the entirety of the thesis process. His hard work and dedication to help students is inspirational and recognized by many. His background and experiences helped format and structure my base of my thesis, ultimately providing a pathway to the success of my thesis. It was an honor and privilege working with Taufik.

I would also like to thank Professor Kevin Dong, David Lambert, and MISD for providing the opportunity and funding to work on this project. MISD is the non-profit in which Kevin and David works through to provide designs for The Same Polytechnic College Master Plan. It was a humbling experience to travel to Tanzania and learn about their cultures, traditions, and lifestyles. Thank you for letting me be part of this significant and impactful project.

I would also like to thank Professor Thomas Fowler and Dr. Ahmad Nafisi for their knowledge and support throughout the process. Each with their own expertise, allowed me to see different aspects of the project and gave me insight to several considerations addressed in the thesis.

I would also like to thank my friends and colleagues for their continual support and encouragement, especially those in the EE Graduate Resource Lab: Matt Guevara, Calin Bukur, Alex Marette, Eric Osborn, Grace Larson, Elliott Winicki, John Jackson, and David Maulick. It was stressful, yet fun working in the graduate lab together.

Finally, I would like to thank my family – especially my parents. Their support and encouragement is unmatched. They gave me to tools necessary to pursue a higher education that will lead into any future successes I may have. I am forever grateful.

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Chapter 1 : Introduction

Poverty is defined as "the state or condition of having little or no money, goods, or means of support; deficiency of necessary ingredients; insufficiency" [1]. In 2013, 10.7 percent of the world's population or 767 million people, lived on less than 1.9 US dollars a day [2]. The World Bank aims to eliminate the world of extreme poverty by the year 2030. Extreme poverty has been decreasing year by year over the past couple decades in all regions, but at an uneven rate. Between the years 2012 and 2013, extreme poverty was reduced by 1.7 percent, or 122 million people. Out of those 122 million people, 4 million were from Sub-Saharan Africa, 37 million from South Asia, and 71 million from East Asia and the Pacific. Half of the extreme poor, 389 million people, live in Sub-Saharan Africa. A 4 million reduction adds up to a belittling 1.02 percent reduction in Africa that year [2].

Poverty and education are thought to be directly linked, as education is the main reason for the cycle of poverty [3]. The cycle of poverty happens when the poor have to discontinue their education to work, which stunts their literary and numerical growth that can help them further different or more profitable career. Their children will then likely fall into the same cycle and repeat itself. In third world rural areas, discontinuing school for work typically means working in agriculture to provide food and money for sustenance. A good education can teach the people about newer and better agriculture and farming techniques, which will teach them how to grow and maintain healthy crops. These additional crops can be used to make nutritious meals while providing more income. A good education is necessary to take a step out of extreme poverty.

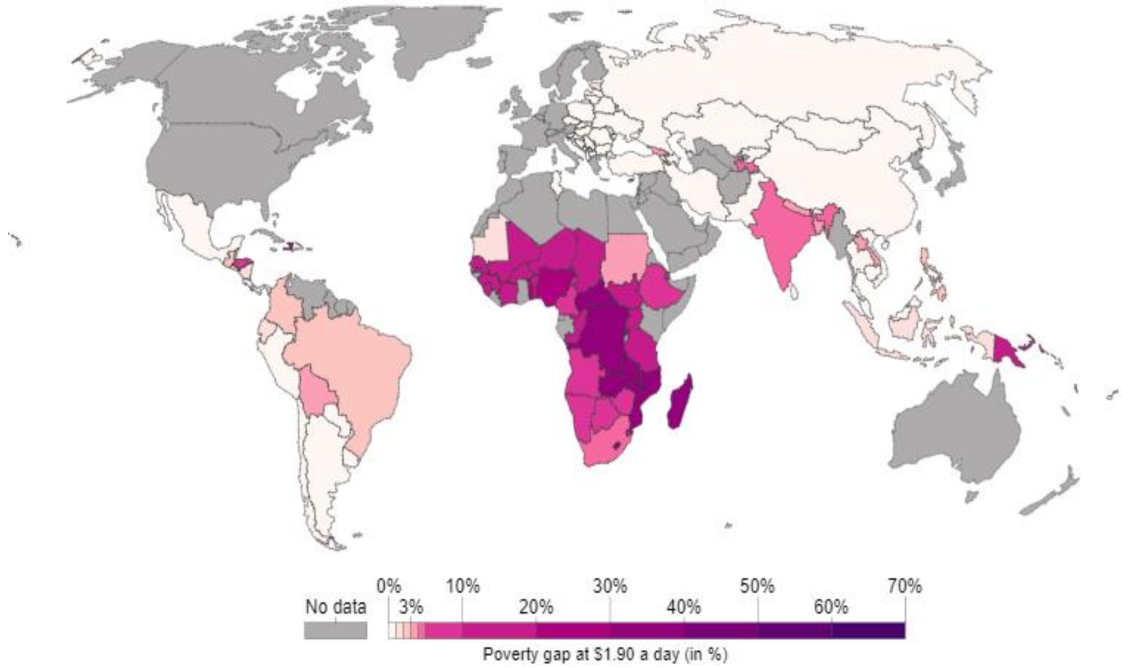

Figure 1-1: Poverty Gap Index at 1.9 int-$ per day, 2013 [4]

Poverty tends to exist in rural areas. Figure 1-1 shows the distribution of people living in extreme poverty on a world map, showing a high concentration of the extreme poor living in Sub-Saharan Africa - where good education, healthcare, electricity, and safe drinking water are not easily available. The educational system in Africa, namely Tanzania for example, is split into 3 strata: primary, secondary, and vocational or tertiary education. Primary education is split into pre-primary and primary level, in which students begin education from the age of 5 to the age of 13. At the end of primary school, children must pass an exam for a primary school certificate. Students then enter secondary school, which is split into a lower and upper level. The lower level is where students get their middle education. Middle education classes are taught in English, include taking a Swahili language class, and takes up to 4 years [5]. Students then take a test in order to advance to the second level of secondary school. Here, only about 15 to 20 percent of students pass and continue to secondary school. Once secondary school is complete, about 15 percent of those students go on to vocational or tertiary education. A lack of higher education exists in Tanzania due to early pregnancies, unvalued recognition for a higher education, and costs for tuition and school materials. Many families fall into the cycle of poverty with little motivation to escape due to these circumstances.

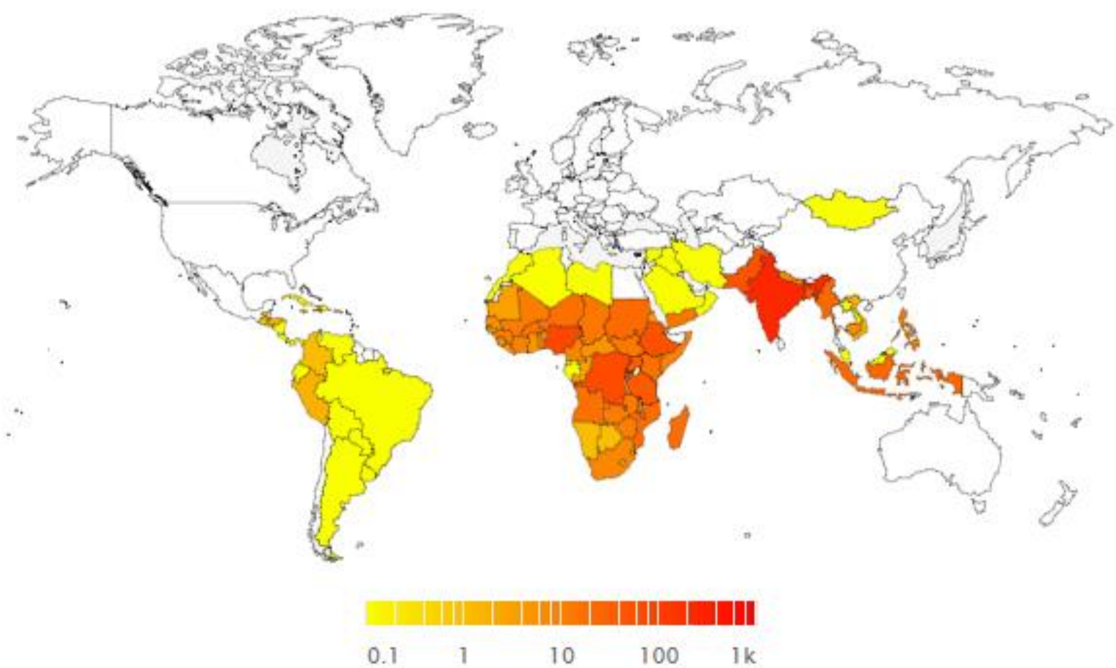

Figure 1-2: Population without Access to Electricity, 2016 (millions) [6]

Furthermore, higher education in Tanzania typically exists in cities of high population, where some type of electrical infrastructure has already been established. Access to electricity is also necessary for a good and engaged higher education. It will allow teachers to run labs that require electricity, students to have access to computers and the internet, chefs to cook without the need to obtain solid biomass, and schools to pump and filter water for safe drinking. It is estimated that 1.1 billion people live without access to electricity, with close to 80 percent of them living in rural areas in Sub-Saharan Africa and developing Asia [6]. Figure 1-2 shows the distribution of people living without access to electricity.

A correlation exists between poverty and accessibility to electricity when comparing the distribution of poverty around the world to the distribution of people without access to electricity. Areas with high concentration of poverty tends to also be areas without access to electricity. Figure 1-2 shows that Africa has a higher concentration of people without electricity in the center of the continent. Figure 1-3 provides a map of the existing major electrical transmission lines and infrastructure in Africa, showing the main concentrations of the infrastructures along the boundaries of Africa.

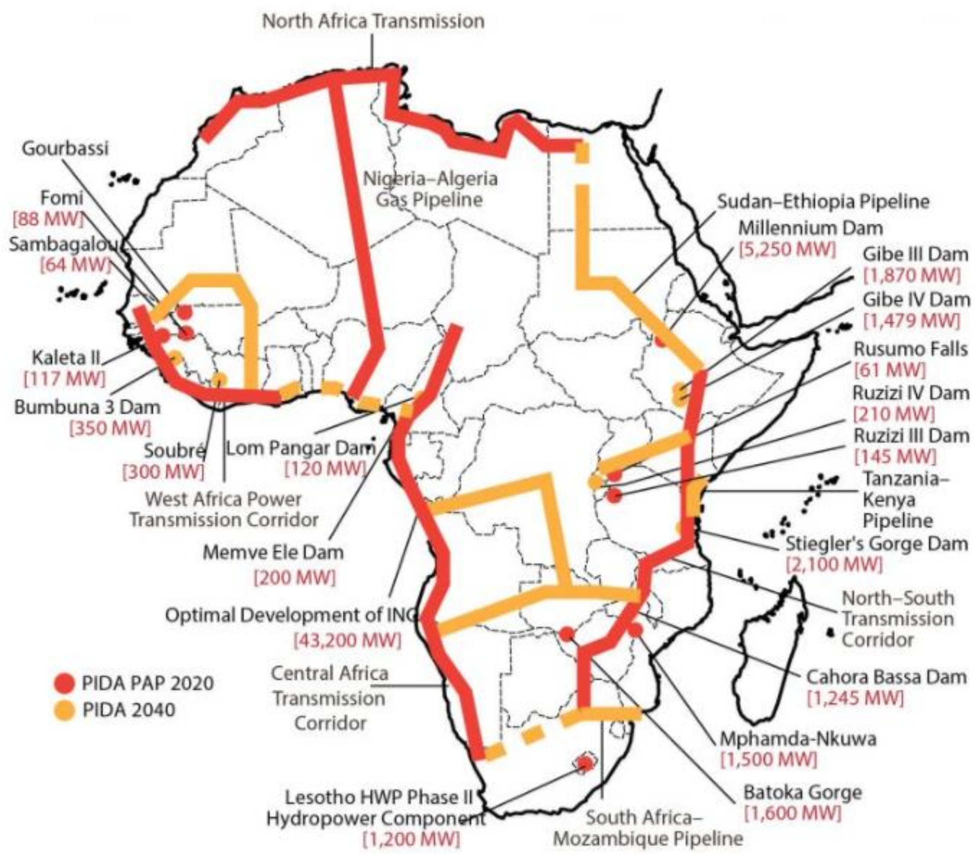

Figure 1-3: Program for Infrastructure Development in Africa

High concentrations of the extreme poor do not have access to electricity because of the lack of infrastructure in those regions. The costs of building enough connecting infrastructure throughout Africa would cost too much and take too much time. Options in these areas would be to utilize off-grid power systems that rely on renewable power generation such as solar photovoltaic, wind, hydroelectric, geothermal, biomass, and biofuel. Africa has an abundance in renewable resources, especially in hydroelectric, solar, and geo-thermal energy [7].

The technologies used in many parts of Africa are several years behind. In rural areas, electronics have little to no use because of the lack of electricity. Building off-grid power system in these areas would initially be minuscule; enough to cover the use of water heating, cooking, and cooling. For a college campus, an off-grid system needs to be large enough to provide power to broader functions such as the use of electronics like laptops and phones, water pumping and heating, electric ovens and stoves, refrigeration for the preservation of food, and operation of instructional labs. These loads may require the power system to utilize multiple renewable energy sources and possibly paired with the grid if available. Having multiple sources allows for improved reliability due to redundancy in case a single source is not able to provide enough electricity. Batteries may also be implemented as another feature to improve system reliability. This in essence demonstrates the unique challenges in planning the power system for a school to ensure the continuous supply of energy to support teaching and learning activities.

Chapter 2 : Background

This project is a multi-disciplinary and collaborative project that focuses on improving poverty levels in third world countries. The Mbesese Initiative for Sustainable Development (MISD) is a group aiming to help eliminate the world from extreme poverty. “Deriving our name (Mbesese) from the Northern Tanzanian Pare tribe’s word for ‘the sparks that ignite a fire’, we are a multidisciplinary collaborative of industry professionals, students, academics and humanitarians pioneering a broader, integrated approach to end poverty” [8]. MISD began as a collaboration between Cal Poly’s college of architecture and environmental design, Tanzania’s Father Mansuetus Setonga [9], and ARUP - an engineering consultant firm. The group’s involvement has extended to KFA Architects & Planning Inc. and several other engineering departments at Cal Poly, including electrical engineering. MISD hopes to further its involvement with Cal Poly’s agriculture and business department and continue their collaborative work with KFA.

MISD’s project, *The Same Polytechnic College Master Plan*, focuses on designing a college in Same, Tanzania - making higher education more accessible in the Same district. The goal of the project is to help improve the poverty level in this region by empowering the people with higher education. Countries in East Africa with lower gross national tertiary enrollment rates tend to have higher national extreme poverty rates, as shown the 2010 human development report illustrated in Figure 2-1 [10]. Tanzania is the focus of MISD’s project because it has the highest national poverty rate and the lowest national tertiary enrollment rate in East Africa. A 2016 human development report shows that Tanzania’s tertiary enrollment rate is up to 4% from 1.5% and its nation poverty rate is down to 66.4% from 87% [11]. Within six years, Tanzania has improved its enrollment and poverty rates, but is still amongst the poorest East African countries with the lowest tertiary enrollment rates. Comparing Tanzania's 2016 standings to the 2010 chart shows that Tanzania is still several years behind bordering countries.

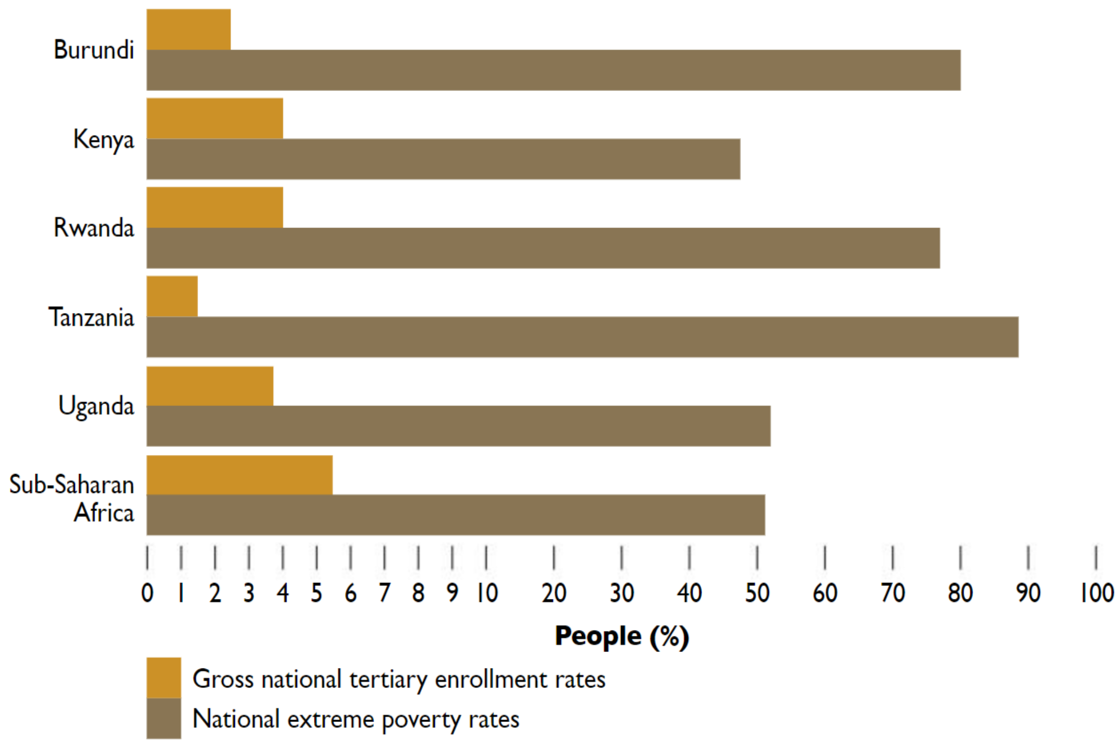

Figure 2-1: Enrollment and Poverty Rates by Region in 2010 [10]

A well-developed education is necessary to improve the state of poverty. In any field of work, a well-developed education allows people to work effectively, hence efficiently. Higher education allows people to envelope in their field of study and progress their careers further. The extreme poor of Tanzania are typically agriculture-based families that require extensive amount of time and labor in areas with little to no access to electricity. The Same district encompasses an area of 6,221 square kilometers with a predicted 2016 population of 289,000 people [12]. Though the Same district is large and well populated, electricity from the grid only runs along the major road as shown in Figure 2-2 [13]. The North-Eastern part of the district that borders Kenya is primarily a national park formed to preserve the indigenous animals. The center of Same, known as Same town, utilizes this access to electricity to run gas stations, provide lighting, and charge electronics. Some businesses require air conditioning and water heating, but is uncommon for local usage. Same is a thriving town, but still in need for a place of higher education.

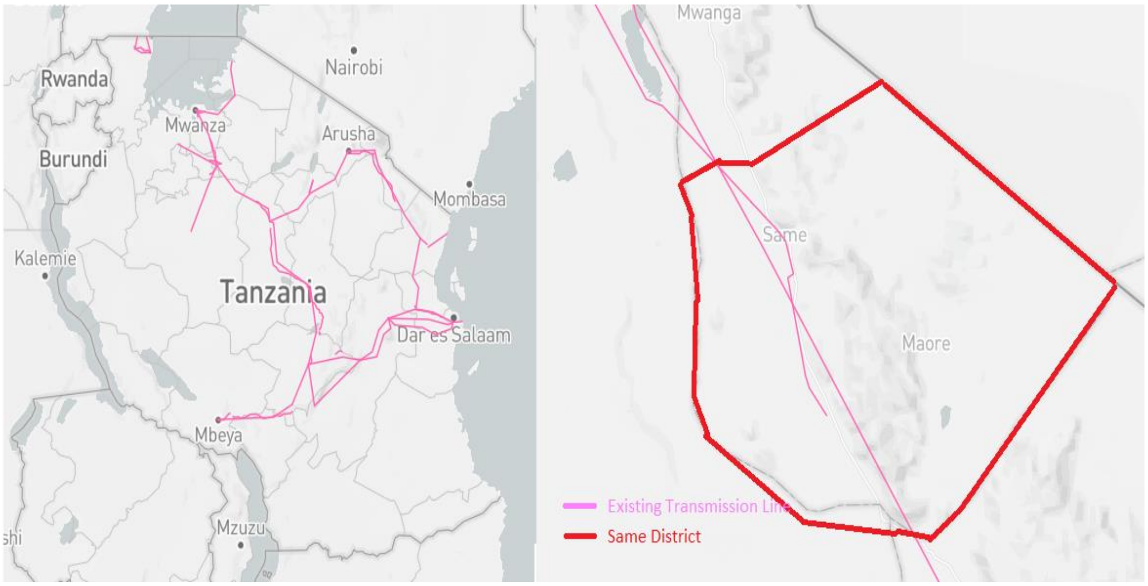

Figure 2-2: Existing Transmission Line In Same, Tanzania (2016) [13]

To build a robust technical college, access to electricity is a necessity. Same town is an ideal place to build a college for the following reasons: it has access to the grid, has a high potential for solar power, has a high population in its district, runs along the major road in Tanzania, and in need for a place of higher education – closest college or university is in Moshi, about 2 hours and 15 minutes away. The next closest university is in Tanga, Tanzania, about 3 hours and 45 minutes away. Same Polytechnic College can serve as a middle ground for those in between Moshi and Tanga with an upside of being near the major road – a high traffic area.

According to the African Development Bank Group (AFDB), “Tanzania is endowed with diverse renewable energy resources, ranging from biomass and hydropower to geothermal, solar and wind. Much of this potential has not been fully exploited. If properly utilized, such renewable resources would contribute significantly to Tanzania’s energy supply” [14]. The country’s main source of energy comes from burning fossil fuels and running large hydro plants. In 2010, fossil fuels made up 658 MW of the 1,219 MW system capacity that existed. Meanwhile, hydropower produced 561 MW of the 1,219 MW capacity, accounting for about 46% of the total generation [10]. In recent years, droughts have made overdeveloped hydro plants costly – load shedding supported by burning expensive fossil fuel as an emergency backup to the electrical demand.

Burning fossil fuels is not sustainable when electrical demands increase and hydropower output decreases. Utilizing Tanzania’s renewable energy sources is a must. These sources can be hydropower plants, geothermal sites, wind farms, solar farms, and biomass. According to the AFDB, biomass is currently unsustainably harvested, wind energy is viable only in certain regions, large hydropower plants is outputting only 35% of its potential, and geothermal energy is underused [14]. To utilize these sources properly, wind energy should be used only where viable, solar farms should be used everywhere off- and on-grid, biomass needs to be harvested sustainably, and the geothermal should be utilized to heat water and possibly produce energy converted from steam.

This thesis aims to update sections of *The Same Polytechnic College Master Plan* developed by MISD. The thesis primarily focuses on the power system design for the school, with a smaller emphasis on load profiling. The master plan was developed in 2010 and details the history of planning for the college, the vision for the college, the planning principles and context for the college, the site plan, and building design guidelines. The master plan shows that wind energy may not be viable because wind speeds must be at an average of 8 meters per second to start producing electricity. Data for that area shows speeds of only 4.5 meters per second, making wind turbines unsuitable as a renewable energy source. The master plan has a load profile study that details the daily electricity usage shown in Figure 2-3. The total electricity usage for the campus is estimated to be 1,900 MWh per year. To achieve a zero-net energy usage for the school, the photovoltaic (PV) system is estimated to be about 18,000 square meters.

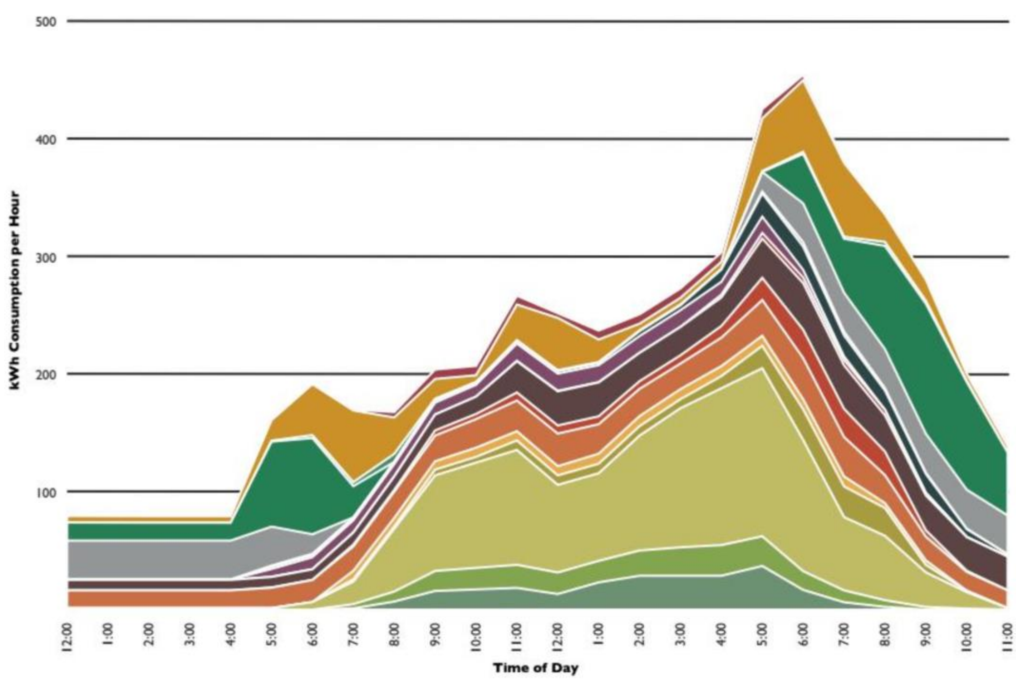

Figure 2-3: Same Polytechnic College Load Profile [10]

The history of the site planning has changed over the years. Within the past six years, the location of the planned site changed to four different location. In the summer of 2017, a fourth location was finalized with an agreement between MISD, the district of Same, and the land owner. To further confirm the action, a team of Cal Poly students, staff, MISD representatives, and locals built a masonry wall and sign to mark the land. The promised land is between 95 to 100 acres. Currently, students in the college of architecture and environmental designs are working on a new master plan for the building design. The placement of the buildings is based on an older version of the site that happens to be roughly the same size and shape as the finalized site – shown in Figure 2-4.

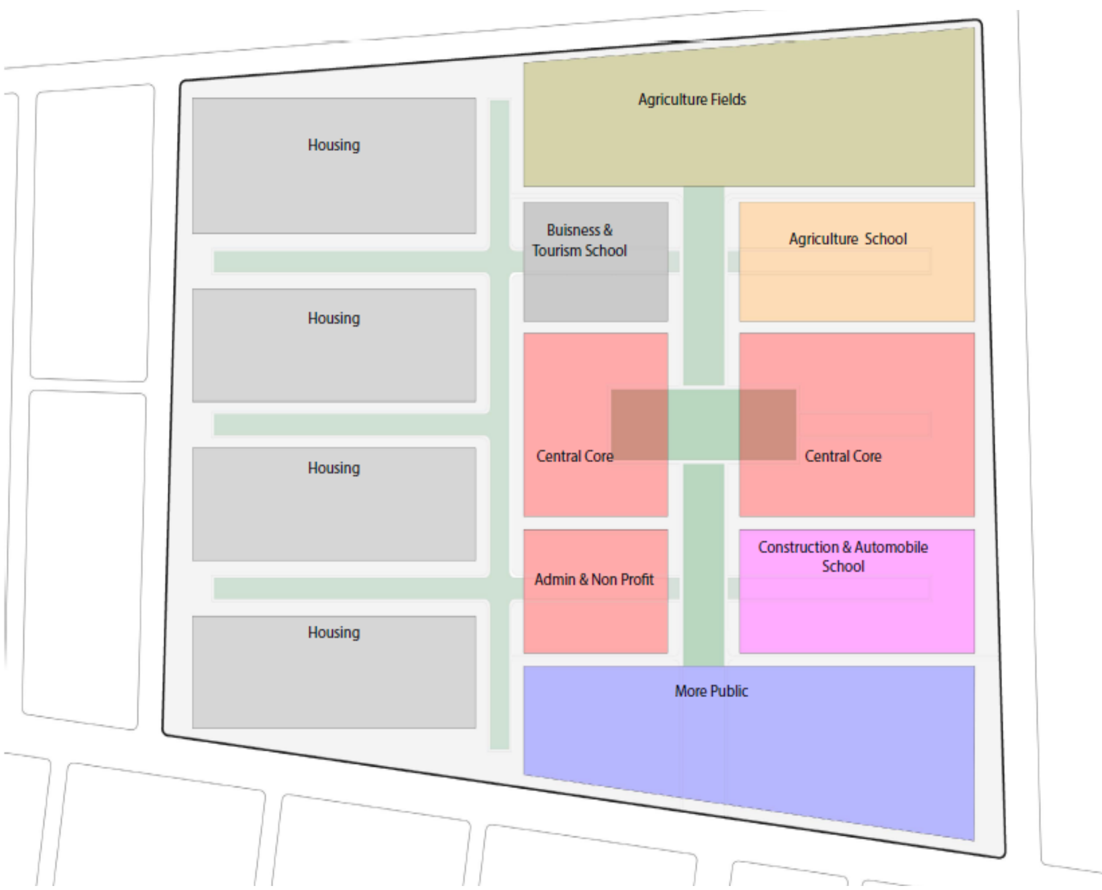

Figure 2-4: Same Polytechnic College Site Plan [15]

The objective of this thesis is to investigate and design an optimal power system distribution for the Same Polytechnic College (SPC). The critical functions of this investigation focus on the tradeoff between the cost, land area, and energy storage occupied by the power system. As seen in proposed site plan in Figure 2-4, no plot of land is dedicated to the power system itself – originally planning to mount solar panels on roofs. With these three critical functions serving as the basis of the design, the use of AC and DC power can be optimized. This thesis will assume the following: an appropriate power load for the college and a centralized system design. The cost, area, and energy storage analysis will include all major equipment from power generation to distribution. By the end of the thesis, an optimal power system distribution architecture will be presented with specific system designs and cost analysis.

The assumptions made above are in consideration for the tight time constraint of the project. The scope of the project becomes too wide when including a detailed analysis of the power load, decentralized space planning, and equipment after distribution. In the master plan of the Same Polytechnic College, a zero-net-energy (ZNE) design was also considered and discussed. This thesis therefore will also investigate the possibility of designing a ZNE system using 100% renewables, in comparison to systems with different mixes of AC and DC power. The study will include consideration of major equipment from power generation to distribution which includes transformers, cables, solar panels, inverters, etc. However, due to time constraint the controls and materials beyond the power distribution system will not be considered in this thesis.

Chapter 3 : Design Requirements

3.1 Design Requirement Overview

This chapter outlines the design requirements of the thesis. The thesis is split up into three main sections: load profile, system design architecture, and cost analysis. The load profile reviews the strategies and assumptions made to formulate an appropriate daily energy profile for the campus. The system design architecture reviews the viable energy sources available in area and its approach for continuous and reliable energy for campus operations. The cost analysis reviews the cost from infrastructure to equipment in comparison to the amount of land and energy storage needed for the system design. The concluding section for this chapter will include a table with parameters and its corresponding specifications.

3.2 Load Profile

A load profile is important to this thesis as the system design cannot begin without it. In the master plan for the college, strategies, and assumptions were formulated to help yield the final energy profile. The strategies listed by the master plan are to "minimize energy usage in building and at the site, deploy efficient building and campus energy systems, and maximize on-campus renewable energy generation" [10]. The following assumptions were made to help building the energy profile: campus population, occupancy schedule, campus equipment, and miscellaneous usage of lighting and pumping outside of classes.

With the assumptions made above, charts for the total site breakdown by space type and the classroom operational schedule were generated as shown in Figure 3-1 and Figure 3-2. These breakdowns can be used to formulate the Same Polytechnic College load profile as seen in Figure 3-2. A load profile will be generated using the master plan's strategies and assumptions in comparison to a researched, personal, and generalized strategies and assumptions. These two new load profiles will be compared to the master plan's load profile that was generated in 2012. The final load profile will be chosen in reflection of the lowest energy consumption – made after consultation with contributing members of the Mbesese Initiative for Sustainable Development (MISD).

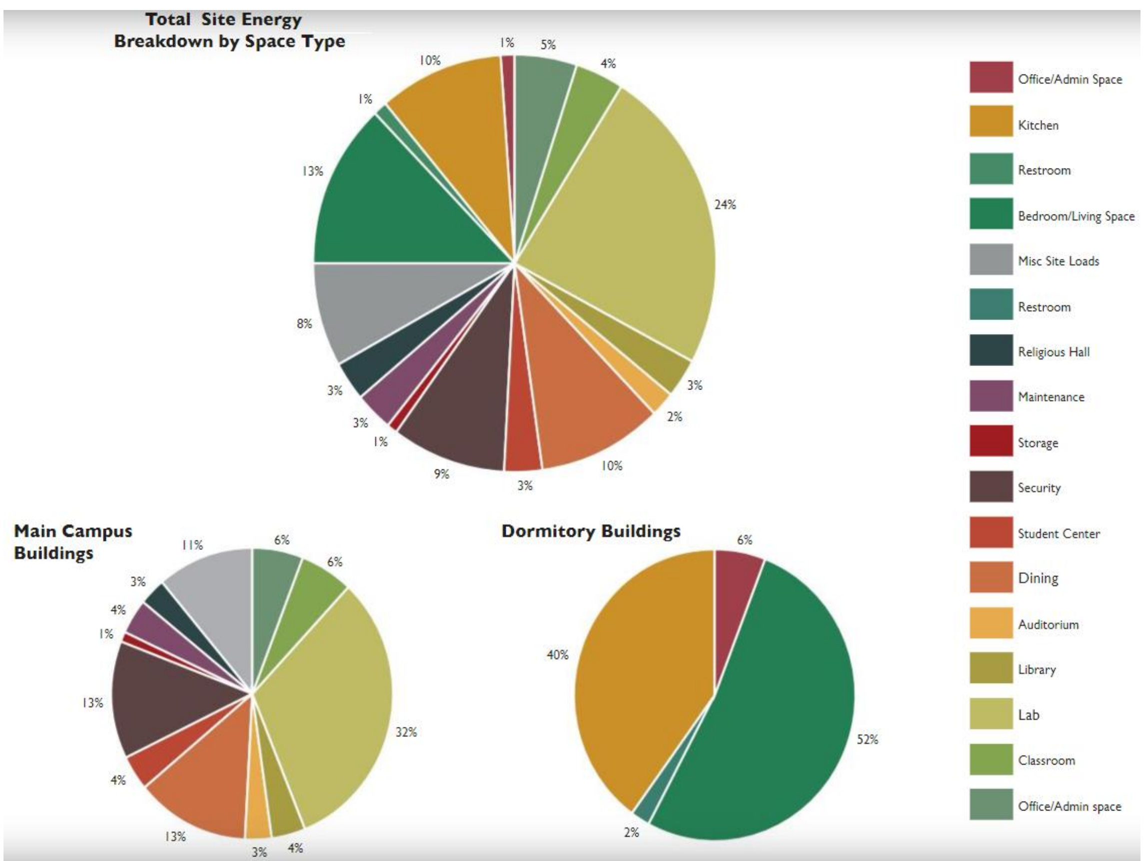

Figure 3-1: Original Total Site Energy Breakdown [10]

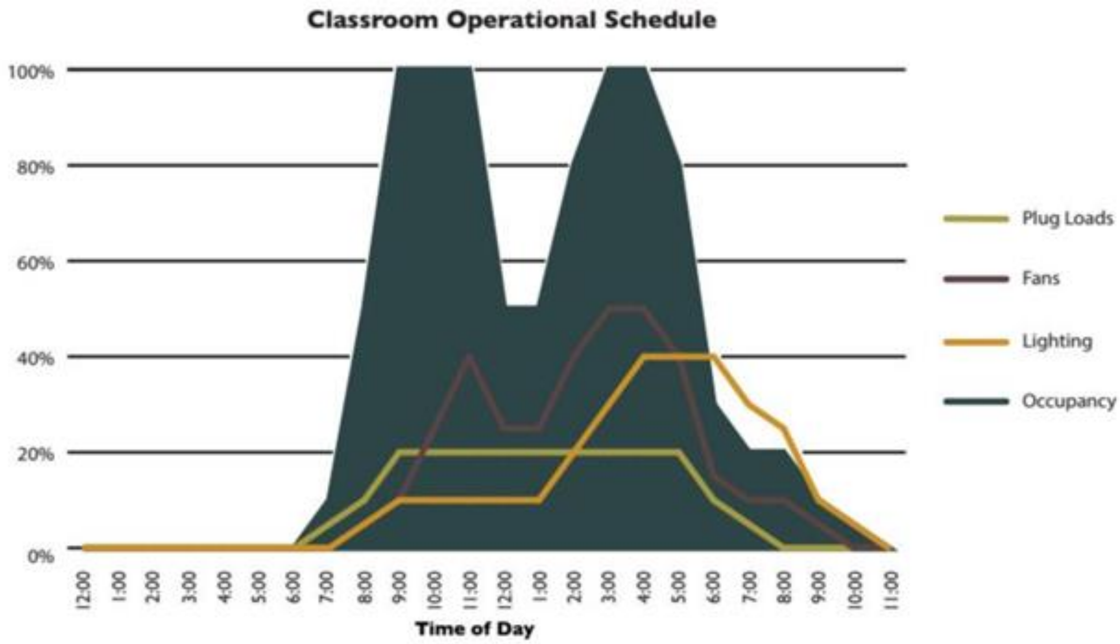

Figure 3-2: Original Classroom Operation Schedule [10]

3.3 System Design Architecture

The system design architecture will be based on the available energy sources in Same and driven by the master plan's aspirational target: "Implement carbon-positive energy systems and provide renewable standby energy to enable continuation of campus operations in case of power outage" [10]. From a power system generation standpoint, the only viable energy sources for the college is using solar energy and tying to the major grid that runs along Same. As mentioned before, wind power is not viable as wind speeds are insufficient. Hydropower plants are not reliable due to drought and unsuitable for a school. Geothermal is a possibility, but costs too much for its infrastructure. Biofuel generators are plausible as a backup source, but not a main source due to its high carbon emission. Solar thermal can be used to replace natural gas, electricity, and biomass, but only in places that have a high demand for hot water – uncommon for local usage. Thus, the power system will be made up of photovoltaic power generation and AC grid generation while using batteries or fuel generators as backup, as shown in the block diagrams in Figure 3-3 and Figure 3-4.

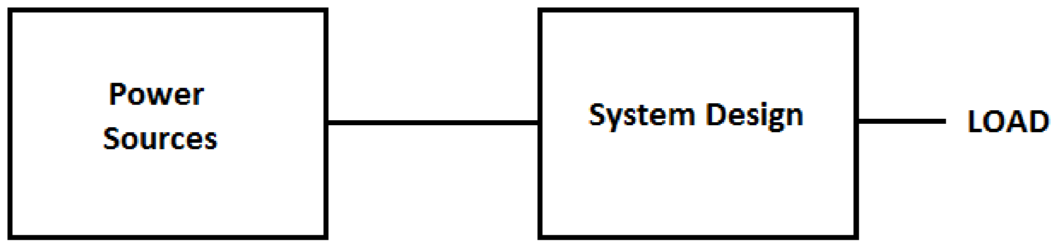

Figure 3-3: Level 0 System Block Diagram

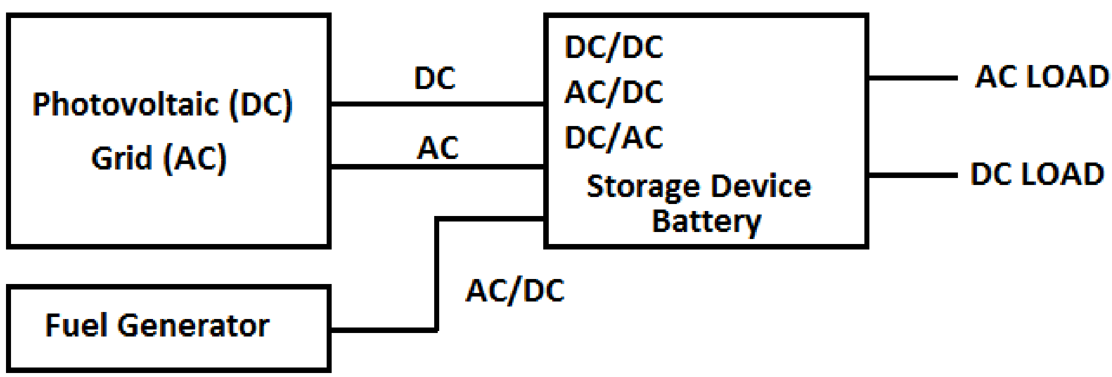

Figure 3-4: Level 1 System Block Diagram

The power system utilizes solar panels that are only operational during the day. When the solar panels are overproducing energy, the excess energy can be stored in the battery, later to be used in case of a blackout from the grid during the night. Alternatively, the battery can be charged during the day and used during the night while the grid acts as a backup. In the case of a grid blackout and total usage of the battery, a fuel generator can be added for redundancy. These decision will be based on the base criteria: cost, land usage, and storage device.

3.4 System Design Analysis

The system design will be modelled in the software ETAP - electrical transient and analysis program. Their base package is embedded with core tools for basic measurements, analysis modules for running power flow and several types of short circuit fault analysis, and engineering libraries to build single line diagrams with ease. The tool allows to assemble three phase and single phase AC and DC networks one line diagrams quickly with unlimited amount of busses and elements. This includes instrumentation and grounding components. ETAP's upgraded packages allow for real-time analysis, integrated protection schemes, microgrid controllability, distribution management, transmission grid, and data exchange [16].

The system design will be made for 11 different iterations of AC and DC generations. Beginning with 100% AC and 0% DC to 0% AC and 100% DC generation in steps of a 10% increments. The design will be different in each iteration as the size of the transformers, batteries, motors, generators, protection schemes, cables, and busbars may change. ETAP will be used to evaluate the load flow, perform a short circuit analysis, and possibly design its protection coordination. The initial stability analysis may be added to test basic operations during faults, loss of distribution generators, and islanding. These tests will show us variations in power flow, frequency, and voltage depending on the fault location.

3.5 Cost Analysis

The cost analysis will include a detailed report of how much each system design costs – from generation (sources), to distribution (transformer and cables), to storage device (battery), and finally to converters or inverters used. The cost will vary for each iteration due to the changing sizes of components in the power system. The cost analysis will include a report of advantages and disadvantages of each system design. It will take into account the limited amount of land allotted to the campus for the system and energy storage.

3.6 Summary of Design Requirements

According to the load profile generated in the original master plan, the total electricity usage for the campus is estimated to be 1,900 MWh per year, totaling to a PV area of about 18,000 square meters to achieve zero-net-energy. This is equivalent to about 4.45 acres. The key performance indicator define in the master plans are as follows: energy measured in watts per meters square, renewables in percentage of total consumption, utility cost in dollars per meters squared, and floor area ratio (FAR) measured by system floor area to campus total area.

Table 3-1: Design Requirement Parameters and Specifications

Design Requirements	
Parameter	**Specification**
Energy Profile	≤ 1,900 MWh per year
System Design	Details for design decision
PV system Efficiency	> 15%
Power Flow	Proper operation during load flow
System Cost	Detailed cost of components per design
Cost Consideration	Long-term payback

Chapter 4 : Load Profile and System Sizing

4.1 Load Profile Overview

A load profile is necessary in any power system design. It allows the designer to calculate the estimated amount of energy used per day as well as the amount of energy used each year. It provides details to size the battery, photovoltaic DC system, and essential AC system equipment in order to maintain operation at the college throughout the year. The SPC master plan, published in 2012, generated a load profile as shown in Figure 2-3. The load profile estimates about 1,900,000 kWh of energy per year, equaling to 5,200 kWh per day [10].

This chapter uses the master plan's building layout [15] to generate the load used in each building - ultimately creating an updated load profile. The chapter will have sections detailing the amount of energy used by the building based on the equipment that will be used in that particular building. These building types include a dining space, the library, computer room, auditorium, admin building, student center, and several types of lab workshops. Lighting for walkways, streets, and security lighting will be isolated from the load calculations due to the vast amount of standalone solar technology that is already commonly used for these purposes. Classrooms will operate during the day, when natural lighting and ventilation takes care of the lighting and cooling that may be needed. Roof- mounted solar can be used for these classrooms if necessary. Two different load profiles will be generated: one using personal, generalized, and researched strategies; and another using similar strategies and assumptions as in the SPC master plan. With technology becoming more efficient over the past six years and the elimination of more buildings from the updated master plan's layout, the energy usage is predicted to decrease.

4.2 Lighting and Cooling

The amount of lighting for a room is determined by the size and type of the room. According to Maxim Lighting, the amount of foot-candles or lumens can be calculated by multiplying the size of the room in square feet to the foot-candles per square feet for that specific room type [17]. Given the area of each building type provided by the master plan's building layout, the amount of lumens and wattage can be calculated automatically through the Charlston Lights website [18]. This website calculates the amount of lighting and wattage needed for the specific room type and size. To build the load profile, Charlston Lights was used to determine the amount of wattage necessary for each building.

In Tanzania, the main form of cooling is to use fans as it is uncommon for locals to own air conditioners. The size of a ceiling fan is determined by the size of the room or space needed. Typical ceiling fans by blade size in inches are 36, 48, and 55 consuming 55, 75, and 100 watts respectively [19]. According to Lowe's ceiling fan guide, 36 inches can provide coverage up to 75 square feet, 42 inches to 144 square feet, 44 inches to 225 square feet, and 54 inches to 400 square feet [20]. Using this data, a graph and trend line was generated in excel to see how much coverage a 48 and 55 inch fan will provide as shown in Figure 4-1. A 48 inch fan will provide 285 square feet of coverage while a 55 inch fan will cover 415 square feet. Most of the areas given in the building layout document include outside space that does not need to be cool. To reduce the time needed for exact measurements, assume a 55 inch blade that uses 100 watts will be estimated to provide coverage for 600 square feet. This will be the standard for all building types in the building layout document.

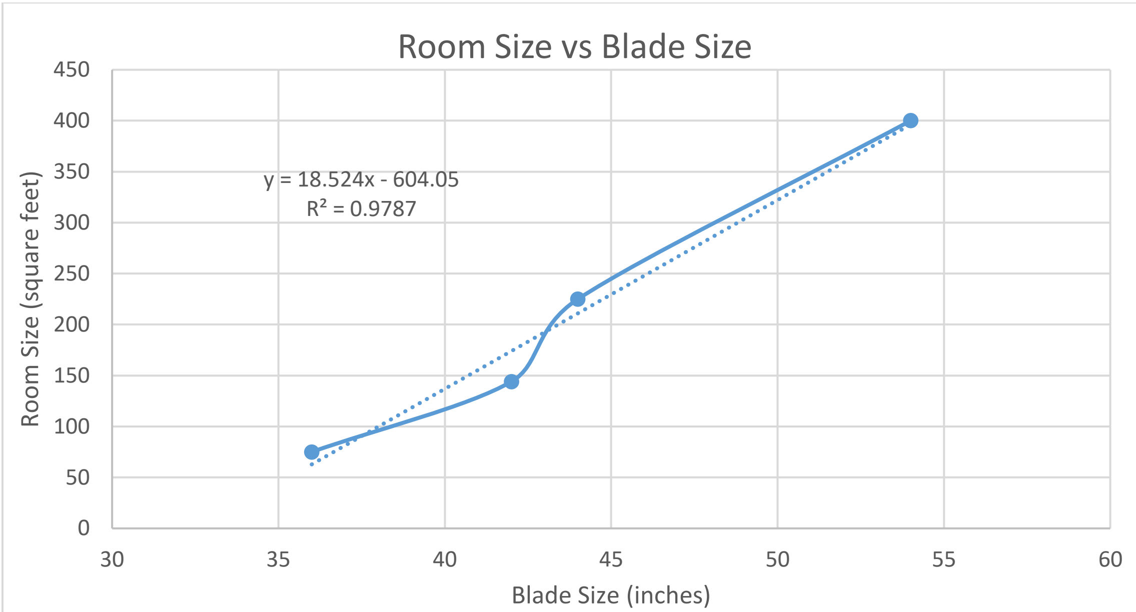

Figure 4-1: Room Size to Fan Size Trend

4.3 Dining

In Tanzania, groceries are typically bought on a daily to weekly basis. Most locals do not have the luxury of a large household refrigerator. With an anticipated 576 student body, two industrial refrigerators and two industrial freezers will be used for the dining area, each running at 1 HP with a duty cycle of about 50%. There will also be two blenders with a peak output power of 1000 watts. Assuming 1 drink is made every 5 minutes and it takes 1.5 minutes to make a drink, the power consumption calculates to 300 watts per machine. Figure 4-2 is used to calculate the amount of energy needed for lighting and cooling needed for the area.

Table 4-1 tabulates the dining energy usage.

Table 4-1: Energy Usage for Dining Area

Building Type	Power Consumers	Quantity	Power Consumption (W)	Hours	Energy/day (Wh)	Ref #
Dining	Industrial Fridge	2	746	12	17904	[21]
	Industrial Freezer	2	746	12	17904	[22]
	Blender	2	300	12	7200	[23]
	Fans	30	100	8	24000	[20]
	Lighting	1	3102	6	18612	[18]

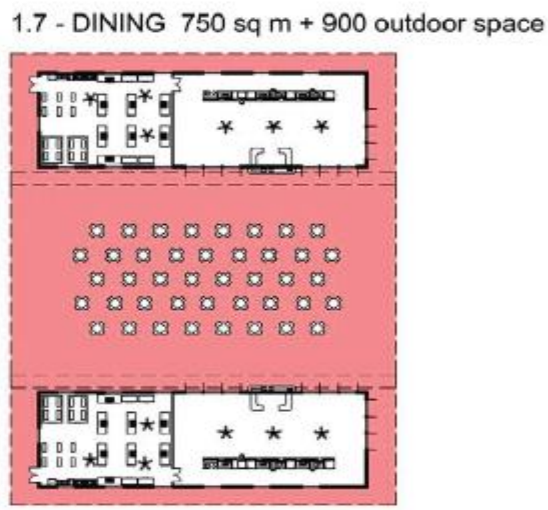

Figure 4-2: Master Plan Building Layout – Dining

4.4 Library and Computer Room

The library consists of eight computers that run on 100 watt desktop paired with a 40 watt monitor. The charging stations can charge up to 8 devices running on 5 volts and 1 amp, hence 40 watts. For safety, the charging station is set to a 50 watt rating. The computer room is used to teach students how to use certain programs such as Microsoft word, excel, power point, and more. Students in this class are assumed to have their own laptops, but may use school laptops if available. Laptops are estimated to consume anywhere between 65 to 90 watts. The room also has two desktop computers that may be used. A projector and two medium LED screens are provided for teaching purposes. Figure 4-3 is used to calculate the amount of energy needed for lighting and cooling needed for the area. Table 4-2 tabulates the library computer room energy usage.

Table 4-2: Energy Usage for the Library and Computer Room

Building Type	Power Consumers	Quantity	Power Consumption (w)	Hours	Energy/day (Wh)	Ref #
Library	Computers	8	140	14	15680	[24]
	Charging Stations	8	50	14	5600	-
	Fans	37	100	9	33300	[20]
	Lighting	1	5856	6	35136	[18]
Computer Room	Laptops	24	90	8	17280	[25]
	Computers	2	140	14	3920	[24]
	Projector	1	300	9	2700	[26]
	LED Screen (MED)	2	100	9	1800	[27]
	Fans	6	100	9	5400	[20]
	Lighting	1	835.5	6	5013	[18]

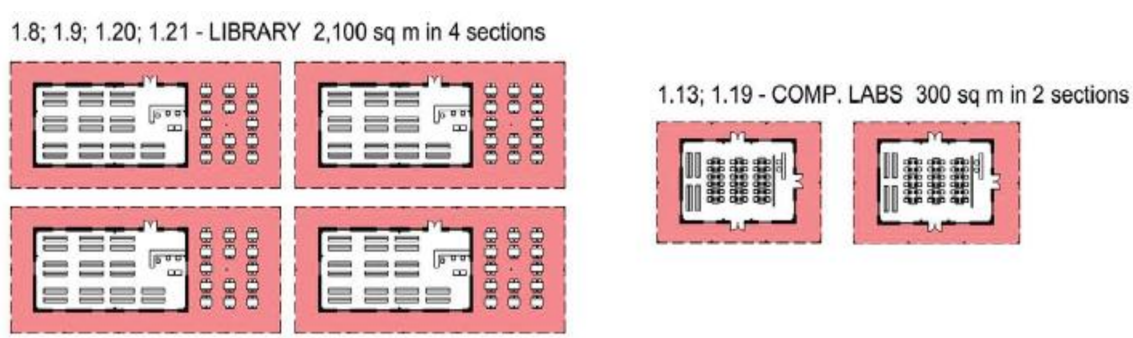

Figure 4-3: Master Plan Building Layout – Library and Computer Room

4.5 Auditorium

The auditorium consists of a speaker system consuming up to 500 watts. The speakers are a simple left and right large speaker. The speaker control station runs on 140 watts. The usage of the auditorium is to hold events that require a stage presence or an audience. A center stage light is also provided for the auditorium. Figure 4-4 is used to calculate the amount of energy needed for lighting and cooling needed for the area. Table 4-3 tabulates the auditorium energy usage.

Table 4-3: Energy Usage for the Auditorium

Building Type	Power Consumers	Quantity	Power Consumption (W)	Hours	Energy/day (Wh)	Ref #
Auditorium	Speakers (L,R)	1	500	4	2000	[28]
	Speaker Station	1	140	4	560	[28]
	Center Light	1	52	4	208	[29]
	Fans	9	100	7	6300	[20]
	Lighting	1	2295	5	11475	[18]

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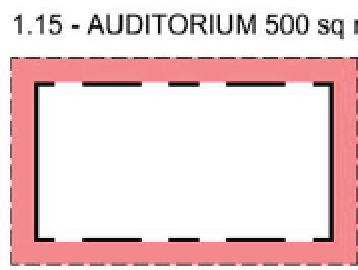

Figure 4-4: Master Plan Building Layout – Auditorium

4.6 Admin Building, Student Center, and Community Center

The admin building is designed to be much like Cal Poly’s building 20A EE lobby with a more open concept approach. Instead of offices, the admin offices will have dividers much like business offices. The admin building has two LED monitors used for announcements and desk lamps for each desk. The student center is a room for student to work and study together. LED screens are provided for group projects. The community center, much like the student center, has two medium LED screens for student usage.

Figure 4-5 is used to calculate the amount of energy needed for lighting and cooling needed for the area. Table 4-4 tabulates the admin building, student center, and community center energy usage.

Table 4-4: Energy Usage for the Admin Building, Student Center, and Community Center

Building Type	**Power Consumers**	**Quantity**	**Power Consumption (w)**	**Hours**	**Energy/day (Wh)**	**Ref #**
Admin Building	LED Screen (LRG)	1	240	8	1920	[27]
	LED Screen (MED)	1	100	8	800	[27]
	Desk Lamp	20	4	3	240	[30]
	Fans	2	100	7	1400	[20]
	Lighting	1	345	3	1035	[18]
Student center	LED Screen (LRG)	1	240	9	2160	[27]
	LED Screen (MED)	2	100	9	1800	[27]
	Fans	16	100	7	11200	[20]
	Lighting	1	1800	2	3600	[18]
Community Center	LED Screen (MED)	2	100	9	1800	[27]
	Fans	8	100	8	6400	[20]
	Lighting	1	829.5	6	4977	[18]

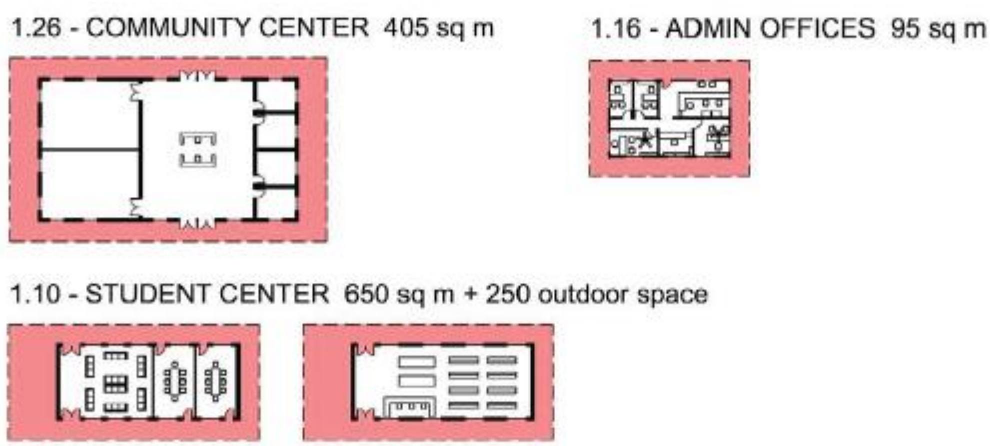

Figure 4-5: Master Plan Building Layout – Admin Building, Student Center, and Community Center

4.7 Masonry Shop, Timber Mill, Timber Carpentry Shop

These specialized classes use a lot of heavy duty machineries. The machineries were chosen by its affordability and commonality. The Masonry saw has a peak power of 1500 watts with a duty cycle of about 50%. Thus the average output power is equal to 750 watts. The table saw, miter saw, and jointer also have 50% duty cycle, while the planer has a duty cycle of about 75%. These duty cycles are taken from data with interviews from past workshop teachers. Because the duty cycles varied from 25% to 50% depending on the activity for the day, the higher percentage was chosen as a buffer for the load profile. Figure 4-6 is used to calculate the amount of energy needed for lighting and cooling needed for the area. Table 4-5 tabulates the masonry shop, timber mill, and timber carpentry shop energy usage.

Table 4-5: Energy Usage for the masonry shop, timber mill, and timber carpentry shop

Building Type	**Power Consumers**	**Quantity**	**Power Consumption (w)**	**Hours**	**Energy/day (Wh)**	**Ref #**
Masonry Shop	Masonry Saw	1	750	9	6750	[31]
	Fans	7	100	7	4900	[20]
	Lighting	1	375	10	3750	[18]
Timber Mill	Planer	1	567	9	5103	[32]
	Jointer	2	373	9	6714	[33]
	Table Saw	2	1119	9	20142	[34]
	Miter Saw	2	550	9	9900	[35]
	Fans	7	100	7	4900	[20]
	Lighting	1	375	10	3750	[18]
Timber Carpentry Shop	Planer	1	567	9	5103	[32]
	Jointer	1	373	9	3357	[33]
	Table Saw	1	1119	9	10071	[34]
	Miter Saw	1	550	9	4950	[35]
	Fans	7	100	7	4900	[20]
	Lighting	1	375	10	3750	[18]

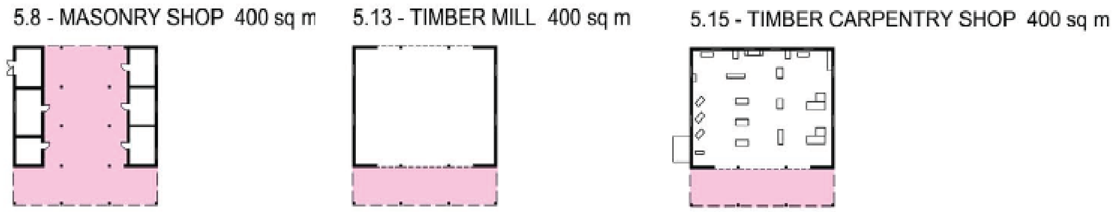

Figure 4-6: Master Plan Building Layout – Masonry Shop, Timber Mill, and Timber Carpentry Shop

4.8 Concrete, Plumbing, Electric, Steel, and Timber Framing Shops

In the concrete shop, the concrete mixer is the primary power consumer. Concrete for every local usage is typically mixed in a wheel barrel. The plumbing, electric, and steel shops all have welders. Welders can vary in output from 2 kilowatts to 22 kilowatts. It was agreed upon to use the welding machines that students from Cal Poly use. The welding machine has a maximum output of 1655 watts, in which the duty cycle is about 12 minutes per hour – 20%. Thus the average output power is 333 watts. The machine also specifies that it can operate at 650 watts at 100% duty cycle. In this case, we take the average of 333 watts based on how classes are typically ran. The soldering irons are also taken from standard soldering irons used at Cal Poly. The steel shop's grinder has a relatively high duty cycle as it may take several minutes to sharpen or grind a tool. At 75% duty cycle, the average output power is estimated to be 2629.5 watts. Lastly, the timber framing shop uses four nail guns at 300 watts each. Figure 4-7 is used to calculate the amount of energy needed for lighting and cooling needed for the area. Table 4-6 tabulates the concrete, plumbing, electric, steel, and timber Framing Shops energy usage.

Table 4-6: Energy Usage for the Concrete, Plumbing, Electric, Steel, and Timber Framing Shops

Building Type	Power Consumers	Quantity	Power Consumption (w)	Hours	Energy/day (Wh)	Ref #
Concrete Shop	Concrete Mixer	1	560	9	5040	[36]
	Fans	3	100	7	2100	[20]
	Lighting	1	375	10	3750	[18]
Plumbing Shop	Welders	3	331	9	8937	[37]
	Fans	5	100	7	3500	[20]
	Lighting	1	375	10	3750	[18]
Electric Shop	Soldering Irons	4	60	9	2160	[38]
	Welders	4	331	9	11916	[37]
	Fans	5	100	7	3500	[20]
	Lighting	1	375	10	3750	[18]
Steel Shop	Welders	4	331	9	11916	[37]
	Grinder	1	2629.5	9	23665.5	[39]
	Fans	7	100	7	4900	[20]
	Lighting	1	375	10	3750	[18]
Timber Framing Shop	Nail Gun	4	300	9	10800	[40]
	Fans	7	100	7	4900	[20]
	Lighting	1	375	10	3750	[18]

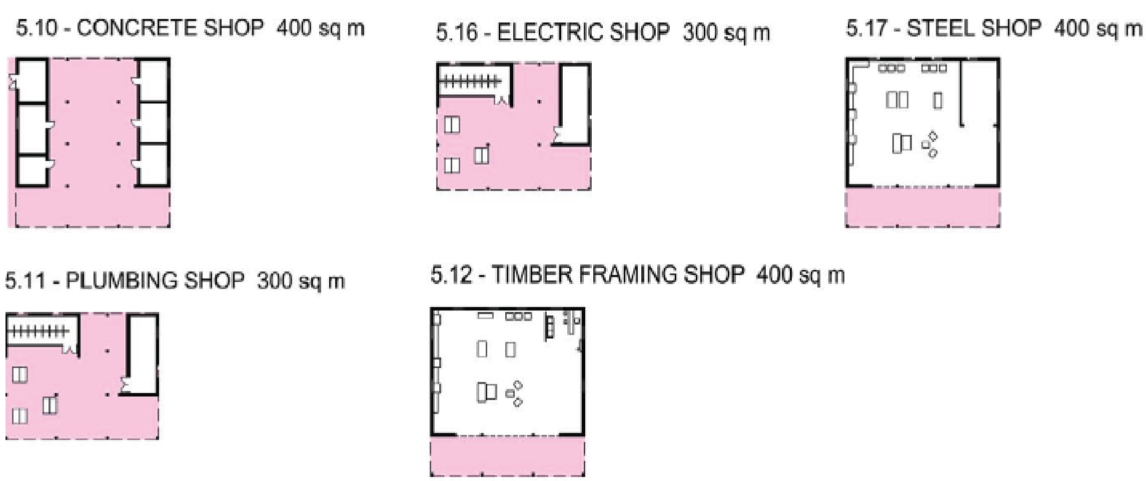

Figure 4-7: Master Plan Building Layout – Concrete, Plumbing, Electric, Steel, and Timber Framing Shops

4.9 Dining Service Workshop, Housekeeping Workshop, and Laundry Services

The dining service workshop is a class where students learn how to waiter for restaurants as tourism and hospitality is a common field of interest in Tanzania. The housekeeping workshop is much like the dining service workshop in which students learn how to upkeep motels/hotels for the tourism and hospitality. The laundry service is mainly used for the upkeep for the school. This includes washing large table cloths and towels for the dining area. Laundry is typically done by hand in Same, Tanzania. The laundry service will provide irons for student usage. It has a peak power of 1100 watts, and a duty cycle of about 50%. Figure 4-8 is used to calculate the amount of energy needed for lighting and cooling needed for the area. Table 4-7 tabulates the concrete, plumbing, electric, steel, and timber Framing Shops energy usage.

Table 4-7: Energy Usage for the Laundry Services, Dining Services and Housekeeping Workshop

Building Type	**Power Consumers**	**Quantity**	**Power Consumption (w)**	**Hours**	**Energy/day (Wh)**	**Ref #**
Dining Service Workshop	Lighting	1	582	10	5820	[18]
Housekeeping Workshop	Lighting	1	436.5	10	4365	[18]
Laundry Services	Iron	2	550	8	8800	[41]
	Washing Machine	1	700	12	8400	[42]
	Fans	3	100	7	2100	[20]
	Lighting	1	372	10	3720	[18]

Figure 4-8: Master Plan Building Layout – Laundry Service, Dining Service and Housekeeping Workshop

4.10 Culinary Arts Lab

This lab is for students who plan to pursue a profession in the culinary arts. Much like the dining space, a refrigerator and freezer are used to preserve food for the class. Blenders are also provided for its usage. Stoves and ovens are gas powered. Figure 4-9 is used to calculate the amount of energy needed for lighting and cooling needed for the area. Table 4-8 tabulates the culinary arts lab energy usage.

Table 4-8: Energy Usage for the Culinary Arts Lab

Building Type	Power Consumers	Quantity	Power Consumption (w)	Hours	Energy/day (Wh)	Ref #
Culinary Arts Lab	Blender	4	300	8	9600	[23]
	Large Fridge	1	373	10	3730	[43]
	Large Freezer	1	373	10	3730	[44]
	Fans	6	100	7	4200	[20]
	Lighting	1	582	10	5820	[18]

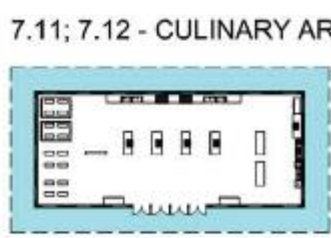

Figure 4-9: Master Plan Building Layout – Culinary Arts

4.11 Agricultural Building Types

The agricultural building types include the greenhouse, irrigation water management, livestock caretaker office, the sheep unit, dairy cattle unit, poultry, and composting. In the green house, the fans are assumed to be at half load for the plants to have circulating air without disruption. The pumps are typically operating at 300 watts, but may need stronger pumps for the irrigation water management. The animal units need a pump for water and cleaning. The need for fans is unnecessary in the animal units as well. Figure 4-10 is used to calculate the amount of energy needed for lighting and cooling needed for the area. Table 4-9 tabulates the culinary arts lab energy usage.

Table 4-9: Energy Usage for the Agricultural Building Types

Building Type	Power Consumers	Quantity	Power Consumption (w)	Hours	Energy/day (Wh)	Ref #
Greenhouses	Pump	4	300	2	2400	[45]
	Fans	16	50	10	8000	20]
Irrigation Water Management	Welders	2	277	9	4986	[37]
	Pump	2	600	4	4800	[45]
Livestock Caretaker Office	General Light	1	75	9	675	[18]
	Computers	2	140	9	2520	[24]
	Fans	1	100	7	700	[20]
Sheep Unit	Pump	1	300	2	600	[45]
Dairy Cattle Unit	Pump	1	300	2	600	[45]
Poultry	Pump	1	300	2	600	[45]
Composting	Pump	1	300	2	600	[45]

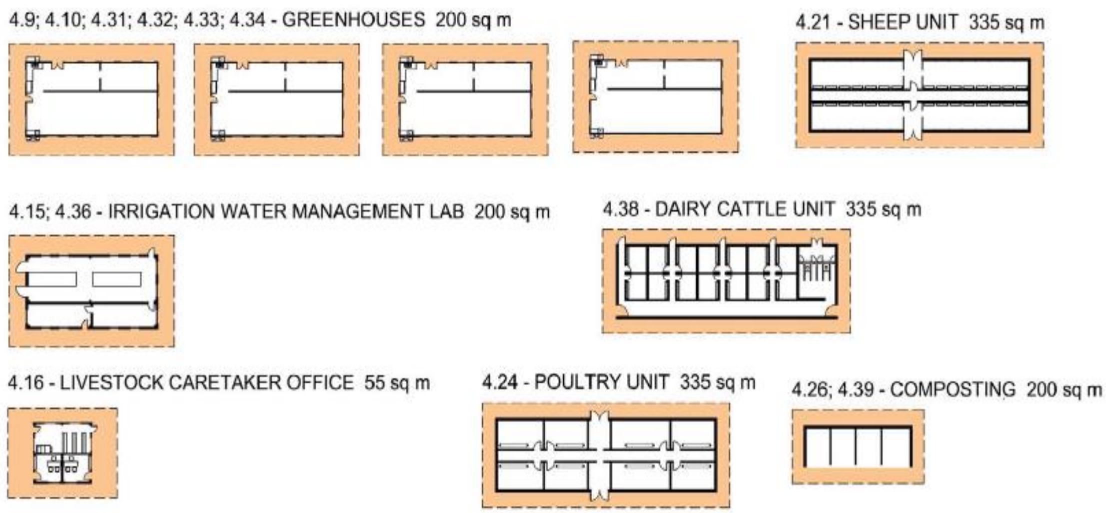

Figure 4-10: Master Plan Building Layout – Agricultural Building types

4.12 Repair Shops

The repair shops consist of an agriculture (AG) machinery lab, an AG equipment repair shop, a generator repair shop, a truck/lorry/tractor repair shop, and an auto body repair shop. The AG machinery lab consists of a charging station used to charge power drills. The portable welding machine is smaller than that in the welding shop. The AG equipment repair shop is like the AG machinery lab, but has a diagnostic machine for student to learn how to use on vehicles. The generator, truck, and auto body repair shops have similar equipment. It is common for students to take a vocational interest in repairs as maintenance is not commonly done in Tanzania. According to a local of the region, the word maintenance did not exist in the Swahili language as it was a not a common practice. The hope of the polytechnic college is to teach students vocational skills that can apply to their everyday life. The goal is to make life easier by developing problem solving skills. Figure 4-11 is used to calculate the amount of energy needed for lighting and cooling needed for the area. Table 4-10 tabulates the repair shops energy usage.

Table 4-10: Energy Usage for the Repair Shops

Building Type	Power Consumers	Quantity	Power Consumption (w)	Hours	Energy/day (Wh)	Ref #
AG Machinery Lab	Charging Station	8	54	9	3888	[46]
	Portable Welder	1	277	9	2493	[37]
	Fans	3	100	7	2100	[20]
	Lighting	1	414	10	4140	[18]
AG Equipment Repair Shop	Charging Station	8	54	9	3888	[46]
	Portable Welder	1	277	9	2493	[37]
	Diagnostic Machine	2	10	9	180	[47]
	Fans	6	100	7	4200	[20]
	Lighting	1	789	10	7890	[18]
Generator Repair Shop	Charging Station	4	54	9	1944	[46]
	Fans	7	100	7	4900	[20]
	Lighting	1	889.5	10	8895	[18]
Truck/Lorry/Tractor Repair Shop	Diagnostic Machine	2	10	9	180	[47]
	Fans	7	100	7	4900	[20]
	Lighting	1	889.5	10	8895	[18]
Auto Body Repair Shop	Diagnostic Machine	3	10	9	270	[47]
	Fans	7	100	7	4900	[20]
	Lighting	1	687	10	6870	[18]

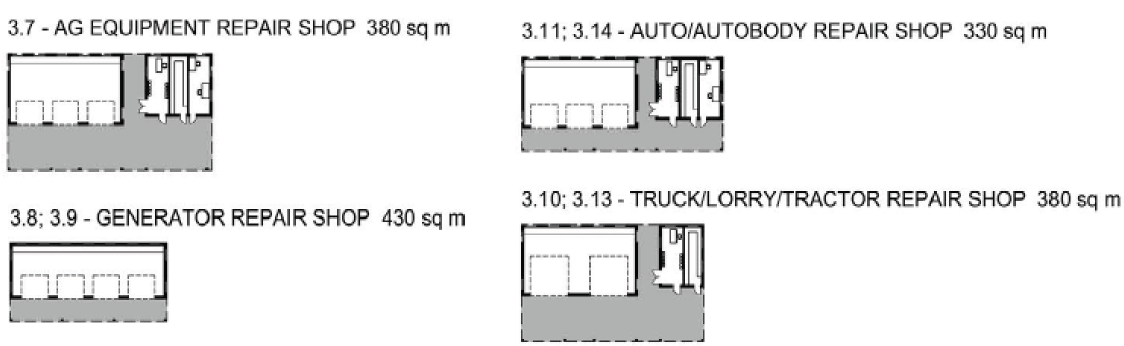

Figure 4-11: Master Plan Building Layout – Repair Shops

4.13 Dormitories

The dormitories are designed to accommodate up to 576 students, a 20 percent round up from the original 480 students. The design of the room is made to be modular, therefore easily repeatable. The architectural engineering students at Cal Poly have made an update to the master plan with rooms accommodating two or four students to a room, as shown in Figure 4-12 [53]. For load considerations, students are anticipated to have their own phones and laptops; desk lamps are provided for each desk in the room; and the room lighting and fan sizing are determined by the size of the room. The smaller room is 18 feet by 20 feet while the larger room is18 feet by 40 feet room. Table 4-11 tabulates the dorms power usage and

Table 4-12 tabulates the dorms energy usage.

Figure 4-12: Housing Module for Same Polytechnic College

Table 4-11: Power Consumption for Dormitories

Clusters of Dorms Calculation (Load)				
	Value	**Ratings (W)**	**Total Power (W)**	**Units**
Number of Students	4	-	-	-
Number of Desk Lamps	4	4	16	W
Number of Laptops	4	90	360	W
Number of Phones	4	5	20	W
Lighting (1 or 2 bulbs)	2	46	92	W
Ceiling Fan (S, M, L)	L	55, 75, 100	100	W
Number of Repeated Rooms	96			Each
Total Power Consumption / Type			56448	W
	Value	**Ratings (W)**	**Total Power (W)**	**Units**
Number of Students	2	-	-	-
Number of Desk Lamps	2	4	8	W
Number of Laptops	2	90	180	W
Number of Phones	2	5	10	W
Lighting (1 or 2 bulbs)	1	46	46	W
Ceiling Fan (S, M, L)	M	55, 75, 100	75	W
Number of Repeated Rooms	96			Each
Total Power Consumption / Type			30624	W
Total Power Consumption for Dorms			87072	

Table 4-12: Energy Usage for Dormitories

Building Type	**Power Consumers**	**Quantity**	**Power Consumption (w)**	**Hours**	**Energy/day (Wh)**	**Ref #**
Dorms	Desk Lamp	1	2304	6	13824	[30]
	Laptops	1	51840	4	207360	[25]
	Phones	1	2880	3	8640	-
	Lighting	1	13248	8	105984	[18]
	Fans	1	16800	12	201600	[20]

4.14 Miscellaneous Loads and Assumptions

In this analysis, assumptions were made for the campus population, the occupancy schedule of the dorms and classes, and the type equipment in each building. The campus population was predicted to be 480 students in 2012. A new estimation made by members of the non-profit in charge of the project shows a 20 percent markup to 576 students. The class schedule follows a typical university schedule with the exception that classes end at dusk, utilizing the architectural design's natural and diffused lighting as possible. Classes and labs are assumed to begin at 8 a.m. and end at 6 p.m. The occupancy of the dorms varies depending on the student's schedule, thus it is assumed to operate during most times outside of class time. The equipment are assumed to be the basic and affordable models of its kind.

In the SPC master plan, miscellaneous site loads were made to compensate for extra site lighting or pumping that may be present. For the generalized load profile, the miscellaneous site load will account of any loads that have not already been accounted for. It will also account for rooms where the lights or fans may be accidently been left on. To gage this load, the percentage of the miscellaneous load compared to the entire load profile from the original load profiled developed in the SPC master plan will be used as a scale.

4.15 Load Profile One: Personal, Generalized, and Researched strategies

Load Profile One follows the assumption made in Section 14 of this chapter. When the miscellaneous loads are not included, the energy profile shows a peak power of 125 kilowatts. The miscellaneous loads are estimated to be 25 kilowatt, about 20 percent of the peak power. Although equipment are not always running at full load, the machinery and equipment are assumed to be operating at full load during the times of operation in order to generalize the build of the load profile and to ensure the power system can support the school when operating at full load. Table 4-13 tabulates the times in which the equipment in certain building types are operating. Figure 4-13 illustrates the energy load profile using the personal, generalized, and researched strategies.

Table 4-13: Specific Operating Time per Equipment (Generalized Strategies)

Building Type	Power Consumers	Time of Operation	Building Type	Power Consumers	Time of Operation
Dining	Industrial Fridge	8am-8pm	Steel Shop	Welders	8am-5pm
	Industrial Freezer	8am-8pm		Grinder	8am-5pm
	Blender (1000 W Peak)	9am-9pm		Fans	10am-5pm
	Fans (55")	10am-6pm		Lighting	8am-6pm
	Lighting (Restaurant)	8am-9am , 5pm-10pm	Timber Framing Shop	Nail Gun	8am-5pm
Library	Computers	8am-10pm		Fans	10am-5pm
	Charging Stations	8am-10pm		Lighting	8am-6pm
	Fans (55")	10am-7pm	Dining Service Workshop	Lighting	8am-6pm
	Lighting	8am-9pm , 5pm-10pm	Housekeeping Workshop	Lighting	8am-6pm
Computer Room	Support for 24 students LPTP	8am-11am , 1pm-6pm	Laundry Services	Iron	9am-5pm
	Computers	8am-10pm		Washing Machine	8am-8pm
	Projector	9am-6pm		Fans	10am-5pm
	LED Screen (MED)	9am-6pm		Lighting	8am-6pm
	Fans	10am-7pm	Culinary Arts Lab	Blender	9am-5pm
	Lighting	8am-9pm , 5pm-10pm		Large Fridge	9am-7pm
Auditoriun	Speakers (L,R)	11am-1pm , 6pm-8pm		Large Freezer	9am-7pm
	Speaker Station	11am-1pm , 6pm-8pm		Fans	10am-5pm
	Center Light	11am-1pm , 6pm-8pm		Lighting	8am-6pm
	Fans	11am-6pm	Greenhouses	Pump for Water	8am-9am , 5pm-6pm
	Lighting	8am-10am , 5pm-8pm		Fans	8am-6pm
Admin Building	LED Screen (LRG)	9am-5pm	Irrigation Water Management	Welders	8am-5pm
	LED Screen (MED)	9am-5pm		Pumps	8am-10am , 5pm-7pm
	Desk Lamp	8am-10am , 5pm-6pm	Livestock Caretaker Office	General Light	8am-5pm
	Fans	10am-5pm		Computers	8am-5pm
	Lighting	8am-10am , 5pm-6pm		Fans	10am-5pm
Student center	LED Screen (LRG)	9am-6pm	Sheep Unit	Pump	8am-9am , 5pm-6pm
	LED Screen (MED)	9am-6pm	Dairy Cattle Unit	Pump	8am-9am , 5pm-6pm
	Fans	10am-5pm	Poultry	Pump	8am-9am , 5pm-6pm
	Lighting	8am-9am , 4pm-5pm	Composting	Pump?	8am-9am , 5pm-6pm
Community Center	LED Screen (MED)	9am-6pm	AG Machinery Lab	Charging Station	8am-5pm
	Fans	10am-6pm		Portable Welding Machine	8am-5pm
	Lighting	8am-9pm , 5pm-10pm		Fans	10am-5pm
Masonary Shop	Masonary Saw	8am-5pm		Lighting	8am-6pm
	Fans	10am-5pm	AG Equipment Repair Shop	Charging Station	8am-5pm
	Lighting	8am-6pm		Portable Welding Machine	8am-5pm
Timber Mill	Planer	8am-5pm		Diagnostic Machine	8am-5pm
& Timber Carpentry Shop	Jointer	8am-5pm		Fans	10am-5pm
	Table Saw	8am-5pm		Lighting	8am-6pm
	Miter Saw	8am-5pm	Generator Repair Shop	Charging Station	8am-5pm
	Fans	10am-5pm		Fans	10am-5pm
	Lighting	8am-6pm		Lighting	8am-6pm
Concrete Shop	Concrete Mixer	8am-5pm	Truck/Lorry/Tractor Repair Shop	Diagnostic Machine	8am-5pm
	Fans	10am-5pm		Fans	10am-5pm
	Lighting	8am-6pm		Lighting	8am-6pm
Plumbing Shop	Welders	8am-5pm	Autobody Repair Shop	Diagnostic Machine	8am-5pm
	Fans	10am-5pm		Fans	10am-5pm
	Lighting	8am-6pm		Lighting	8am-6pm
Electric Shop	Soldering Irons	8am-5pm	Dorms	Desk Lamp	6pm-12am
	Welders	8am-5pm		Laptops	5pm-9pm
	Fans	10am-5pm		Phones	9pm-12am
	Lighting	8am-6pm		Lighting	6am-9am , 6pm-11pm
Miscellaneous Load	Miscellaneous Load	12am-12am		Fans	9am-9pm

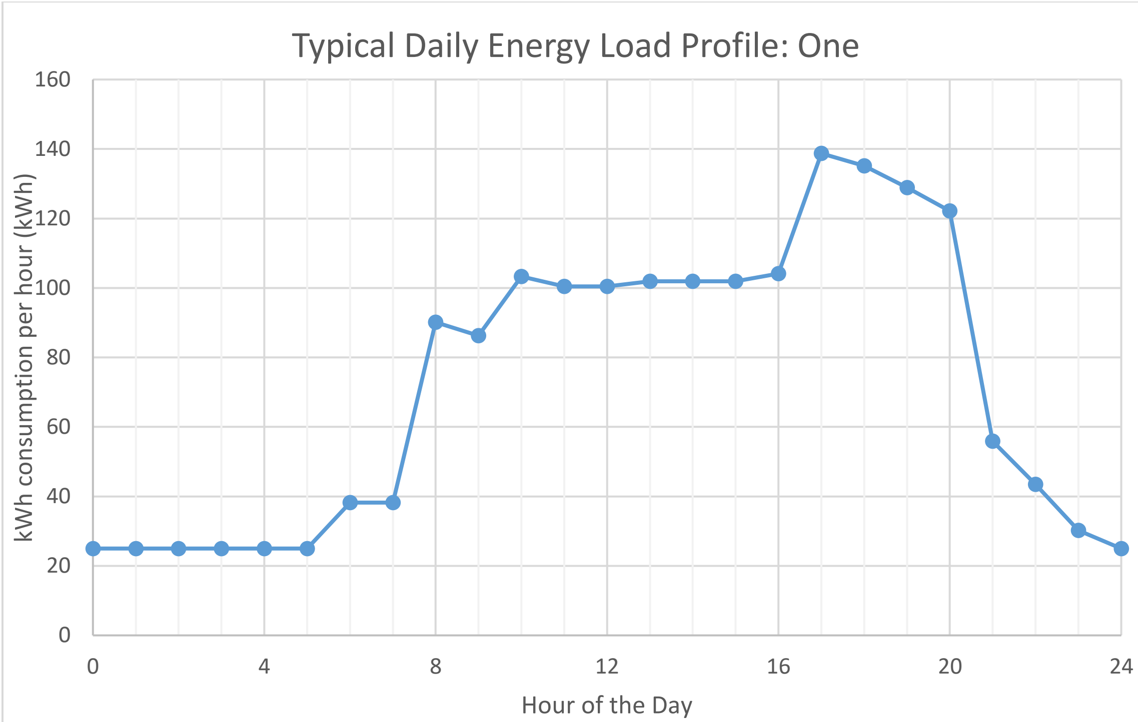

Figure 4-13: Typical Daily Energy Load Profile (Personal, Generalized, and Research Strategies)

In this energy load profile, the daily energy consumption adds up to 1,771.55 kWh per day, equaling to about 646,616 kWh per year. The annual energy consumption from this load profile is about 34 percent of the annual energy consumption that was calculated in the 2012 master plan. The shape of the load profile is comparable to the shape of the load profile that was generated in the master plan, shown in Figure 2-3. In both profiles, the day typically begin at about 5 in the morning and increases throughout the day until it hits a peak sometime in the evening. In this case, the peak time is at 5 p.m. while the peak usage of the original load profile is at 6 p.m. Figure 4-14 shows a load profile for a typical college building in California, in which it peaks at about 2 in the afternoon, but does not account for the residential or dormitory usage. A typical residential would have electrical usage in the morning when people are getting ready to go to school or work and in the evening when families come home from school and work. The higher peak is in the evening when people are turning on the television, air conditioners, charging electronics, and cooking dinner. Figure 4-13 fits a typical daily energy load profile of an entire college campus when combining a typical college building energy usage and the residential energy usage.

4.16 Load Profile Two: Same Polytechnic College Master Plan Strategies

Load Profile Two have similar assumptions made in the original master plan. Assumptions of the campus population remains the same as that of the first load profile. The campus occupancy schedule is adjusted to fit the same schedule shown in the original load profile, shown in Figure 2-3. In their profile, classes begin at 7 in the morning and end at 7 in the evening. Table 4-14 tabulates the adjusted times in which the equipment in certain building types are operating. The miscellaneous loads are estimated to be 32 kilowatt, maintaining 20 percent of the peak power. Equipment are assumed to be operating at full loads during times of operation. Figure 4-14 illustrates the energy load profile using the SPC master plan's strategies.

Table 4-14: Specific Operating Time per Equipment (SPC Strategies)

Building Type	Power Consumers	Time of Operation	Building Type	Power Consumers	Time of Operation
Dining	Industrial Fridge	5am-10pm	Steel Shop	Welders	7am-7pm
	Industrial Freezer	5am-10pm		Grinder	7am-7pm
	Blender (1000 W Peak)	5am-10pm		Fans	7am-7pm
	Fans (55")	5am-10pm		Lighting	7am-7pm
	Lighting (Restaurant)	5am-10pm	Timber Framing Shop	Nail Gun	7am-7pm
Library	Computers	8am-10pm		Fans	7am-7pm
	Charging Stations	8am-10pm		Lighting	7am-7pm
	Fans (55")	8am-10pm	Dining Service Workshop	Lighting	7am-7pm
	Lighting	8am-10pm	Housekeeping Workshop	Lighting	7am-7pm
Computer Room	Support for 24 students LPTP	8am-10pm	Laundry Services	Iron	7am-7pm
	Computers	8am-10pm		Washing Machine	7am-7pm
	Projector	8am-10pm		Fans	7am-7pm
	LED Screen (MED)	8am-10pm		Lighting	7am-7pm
	Fans	8am-10pm	Culinary Arts Lab	Blender	7am-7pm
	Lighting	8am-10pm		Large Fridge	7am-7pm
Auditoriun	Speakers (L,R)	7am-8pm		Large Freezer	7am-7pm
	Speaker Station	7am-8pm		Fans	7am-7pm
	Center Light	7am-8pm		Lighting	7am-7pm
	Fans	7am-8pm	Greenhouses	Pump for Water	7am-7pm
	Lighting	7am-8pm		Fans	7am-7pm
Admin Building	LED Screen (LRG)	7am-6pm	Irrigation Water Management	Welders	7am-7pm
	LED Screen (MED)	7am-6pm		Pumps	7am-7pm
	Desk Lamp	7am-6pm	Livestock Caretaker Office	General Light	7am-7pm
	Fans	7am-6pm		Computers	7am-7pm
	Lighting	7am-6pm		Fans	7am-7pm
Student center	LED Screen (LRG)	9am-9pm	Sheep Unit	Pump	7am-7pm
	LED Screen (MED)	9am-9pm	Dairy Cattle Unit	Pump	7am-7pm
	Fans	9am-9pm	Poultry	Pump	7am-7pm
	Lighting	9am-9pm	Composting	Pump?	7am-7pm
Community Center	LED Screen (MED)	9am-9pm	AG Machinery Lab	Charging Station	7am-7pm
	Fans	9am-9pm		Portable Welding Machine	7am-7pm
	Lighting	9am-9pm		Fans	7am-7pm
Masonary Shop	Masonary Saw	7am-7pm		Lighting	7am-7pm
	Fans	7am-7pm	AG Equipment Repair Shop	Charging Station	7am-7pm
	Lighting	7am-7pm		Portable Welding Machine	7am-7pm
Timber Mill	Planer	7am-7pm		Diagnostic Machine	7am-7pm
& Timber Carpentry Shop	Jointer	7am-7pm		Fans	7am-7pm
	Table Saw	7am-7pm		Lighting	7am-7pm
	Miter Saw	7am-7pm	Generator Repair Shop	Charging Station	7am-7pm
	Fans	7am-7pm		Fans	7am-7pm
	Lighting	7am-7pm		Lighting	7am-7pm
Concrete Shop	Concrete Mixer	7am-7pm	Truck/Lorry/Tractor Repair Shop	Diagnostic Machine	7am-7pm
	Fans	7am-7pm		Fans	7am-7pm
	Lighting	7am-7pm		Lighting	7am-7pm
Plumbing Shop	Welders	7am-7pm	Autobody Repair Shop	Diagnostic Machine	7am-7pm
	Fans	7am-7pm		Fans	7am-7pm
	Lighting	7am-7pm		Lighting	7am-7pm
Electric Shop	Soldering Irons	7am-7pm	Dorms	Desk Lamp	6pm-12am
	Welders	7am-7pm		Laptops	5pm-9pm
	Fans	7am-7pm		Phones	9pm-12am
	Lighting	7am-7pm		Lighting	6pm-11pm
Miscellaneous Load	Miscellaneous Load	12am-12am		Fans	9am-9pm

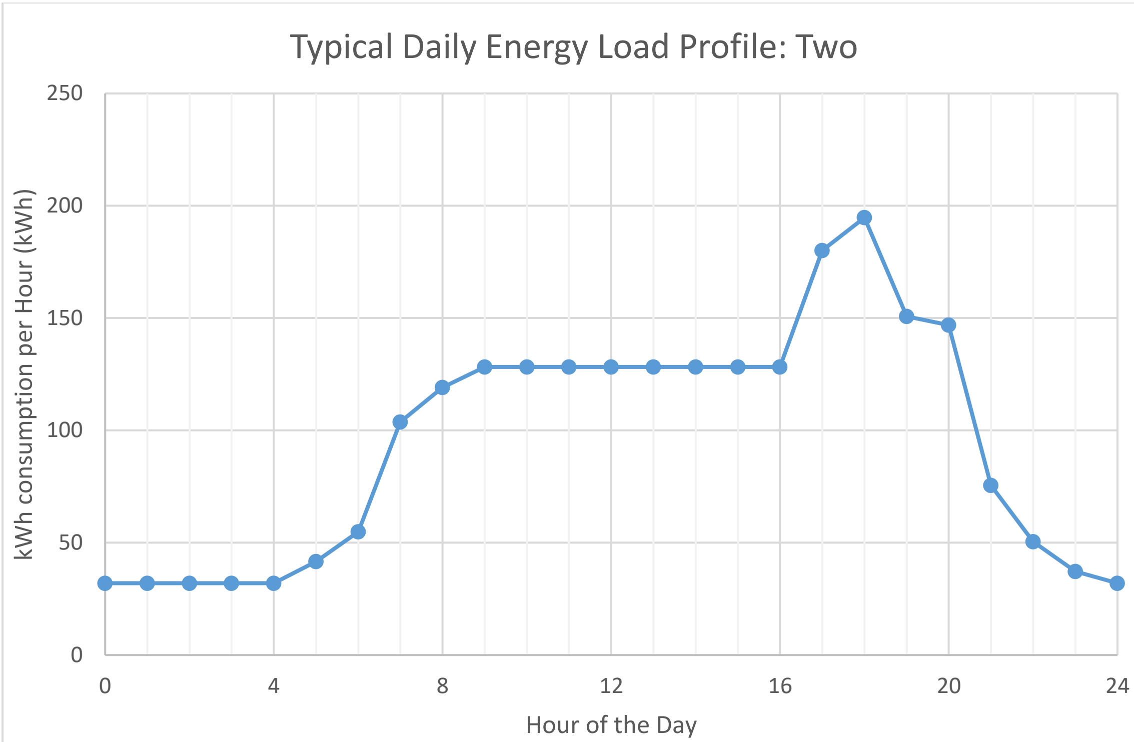

Figure 4-14: Typical Daily Energy Load Profile (SPC Strategies)

In this energy load profile, the daily energy consumption adds up to 2,341.34 kWh per day, equaling to about 854,589 kWh per year. The annual energy consumption from this load profile is about 45 percent of the annual energy consumption that was calculated in the 2012 master plan. This load profile is significantly greater than the load profile generated using the generalized strategies – about 32.1 percent greater. The shape of the load profile is again comparable to the shape of the load profile that was generated in the master plan, shown in Figure 2-3. In this energy load profile, the peak usage is at 6 p.m., in which classes are ending and dining halls, dorms, student centers, and community centers are beginning to be utilized.

Although the shape of the first and second profile are similar, a 32.1 percent difference exist in the total energy used per day. A major contribution to this discrepancy comes from the assumed occupancy times. In the master plan, many buildings begin to operate at earlier times and end at later times. If the miscellaneous load from the second profile was assumed to be 25 kilowatts like the first load, the energy contributed from the time changes alone calculates to a plus 22.6 percent change. Adjusting the miscellaneous load to fit the 20 percent criteria adds an additional plus 9.5 percent change. For some buildings, the time change in relation to the equipment load can be justified. For example, beginning class earlier and ending later would result in an increase of lighting and fanning. Other changes are harder to justify. For example, the dining service begins its operation at 5 a.m. and ends at 10 p.m. according to the master plan. Realistically, the refrigerators and freezers will not be operating during the full time.

4.17 Load Profile Choice

In the design requirements from Chapter 3, the energy profile to be chosen should have an annual energy consumption of less than 1,900 MWh. Load Profile One, generated using personal, generalized, and researched strategies, has a conservative approach to the load profile – consuming 646 MWh per year. Load Profile Two has modifications to the times that may be justified for some building types, but not all of the buildings. These modifications resulted in a 32.1 percent energy increase – consuming 854 MWh per year. Both load profiles meet the load requirement. There are pros and cons in choosing Load Profile One over Load Profile Two.

The benefit of choosing Load Profile One is that the system design overall will cost less. The reduction in energy usage means a reduction in the amount of equipment needed for the power system, space needed for the equipment, and type of equipment – as higher loads call for larger wires and circuit breakers. The disadvantage of choosing Load Profile One is in its conservative approach. The energy consumption calculated from this approach may be at borderline of its actual energy usage. If the energy usage is greater than calculated, the power system will not provide enough electricity and energy for continual operation.

The benefit of choosing Load Profile Two is in its approach. The energy consumption is about 32 percent higher than the first profile. The over estimating approach will allow the power system to provide enough energy to the college for continuous usage. It will be less likely for the power system to be under-designed. The disadvantage of choosing Load Profile Two is in its cost. Since the load is larger, the equipment must be suited to handle the loads. A major cost also comes from the energy storage in batteries. The higher the daily energy consumption, the more storage capacity the batteries will have to handle. Another disadvantage may also be in its approach. If the real annual energy consumption is significantly less than the predicted consumption, than the cost of over-designing a power system goes to waste.

For this thesis, Load Profile Two will be the chosen load profile used throughout the sizing and design of the power system. The pros and cons of the second profile outweighs the pros and cons of the first profile. Under-designing a power system risks discontinuous operation for the school. In most cases, especially in America, power systems should be able to provide continuous electricity to its customers. If power goes out while a student or teacher is working on a desktop, they risk losing all their data. Under-designing can also mean that the power system cannot support the load, thus failing. Although choosing Load Profile Two increases the costs of the system and the amount of land used, its energy consumption is still much less than the load profile generated from the original master plan – 45 percent of the original calculation. The safer and more realistic choice would therefore be the Load Profile Two as its model load profile.

4.18 Photovoltaic (PV) System Size

Typical steps in choosing a PV system size includes the following [48]: calculate the average daily energy usage in kilowatt hours, determine the average insolation based on location and using available databases [49], and sizing the PV system based on these values while including losses. This process is automated with greater accuracy through the use of the PVWatts Calculator developed by the National Renewable Energy Laboratory (NREL) [50]. The free online resource is commonly used for students studying PV systems – specifically at Cal Poly. PVWatts gathers weather data using online resources, allows users to adjust the system parameters, and calculates monthly solar radiation and AC energy results.

Same, Tanzania is a small rural town located at about 4.133° S and 37.808° E. PVWatts prompts the user to enter a location and generates a map with pinpoint locations that have weather resource data in the area. Figure 4-15 shows the surrounding weather data that can be chosen. Two weather data options are available: one in Voi, Kenya and another in Mombasa, Kenya. Mombasa is eliminated as a possible option to substitute Same's weather data because the region resides too close to the ocean, which can greatly affect the weather patterns. Voi is the better option as it is closer to Same and located next to a national park like Same. The geographical location of Voi, Kenya is 3.400° S and 38.570° E, about 115 kilometers away from Same, Tanzania.

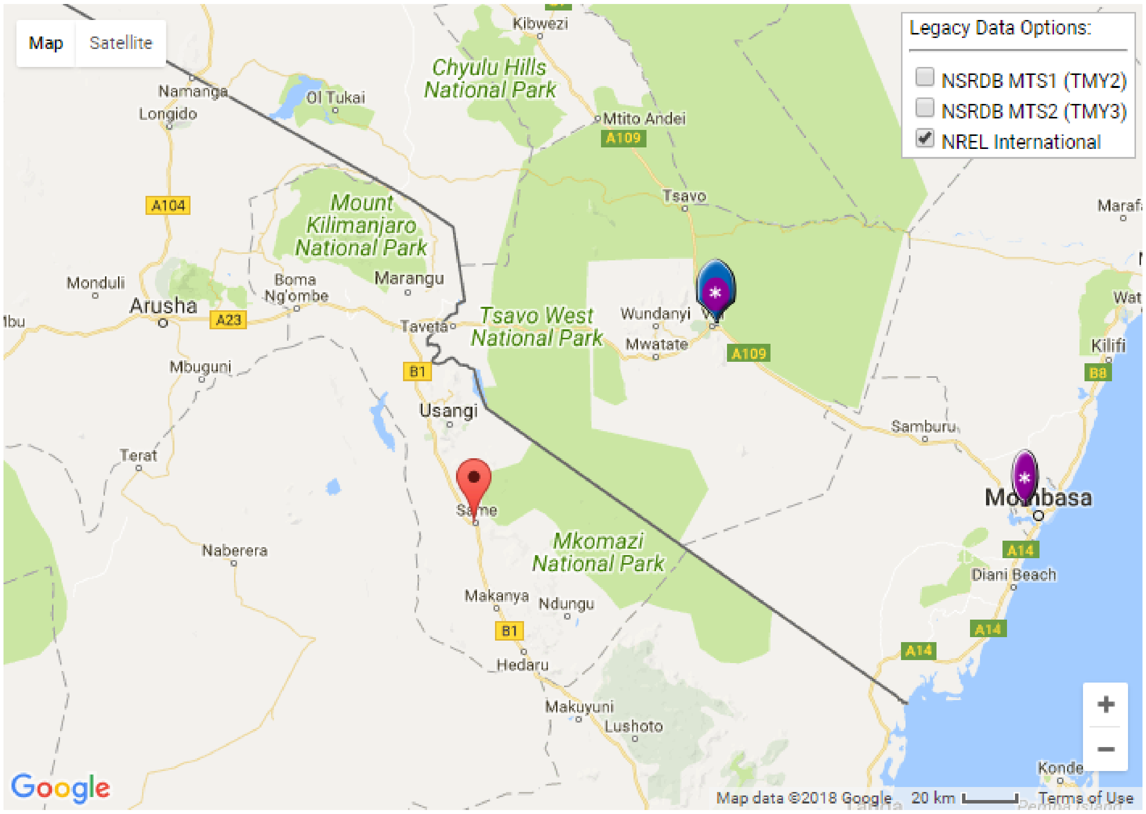

Figure 4-15: Resource Data Map for Same, Tanzania

Once the resource data is chosen, the next step is to adjust the system info. The DC system size is adjusted to 1 kilowatt in order to find the annual specific yield. The module type is set to standard, assuming the solar panels are either donated or cheaply acquired. The array type is set to a fixed, open rack array as this thesis assumes a centralized PV system. The system loss is estimated to be 14 percent, using PVWatts documentation as a guide shown in Table 4-15. An extra 2 percent is added on to account for the dust that may accumulate on solar panels. The tilt angle and azimuth is adjusted to the location of Same - tilt degree of 4.133 and an azimuth of 0 (north facing). The advanced parameters remain to their default values; a 1.1 DC to AC size ration, a 96 percent interview efficiency, and a ground coverage ratio of 0.4. The retail electricity rate can be ignored for this section.

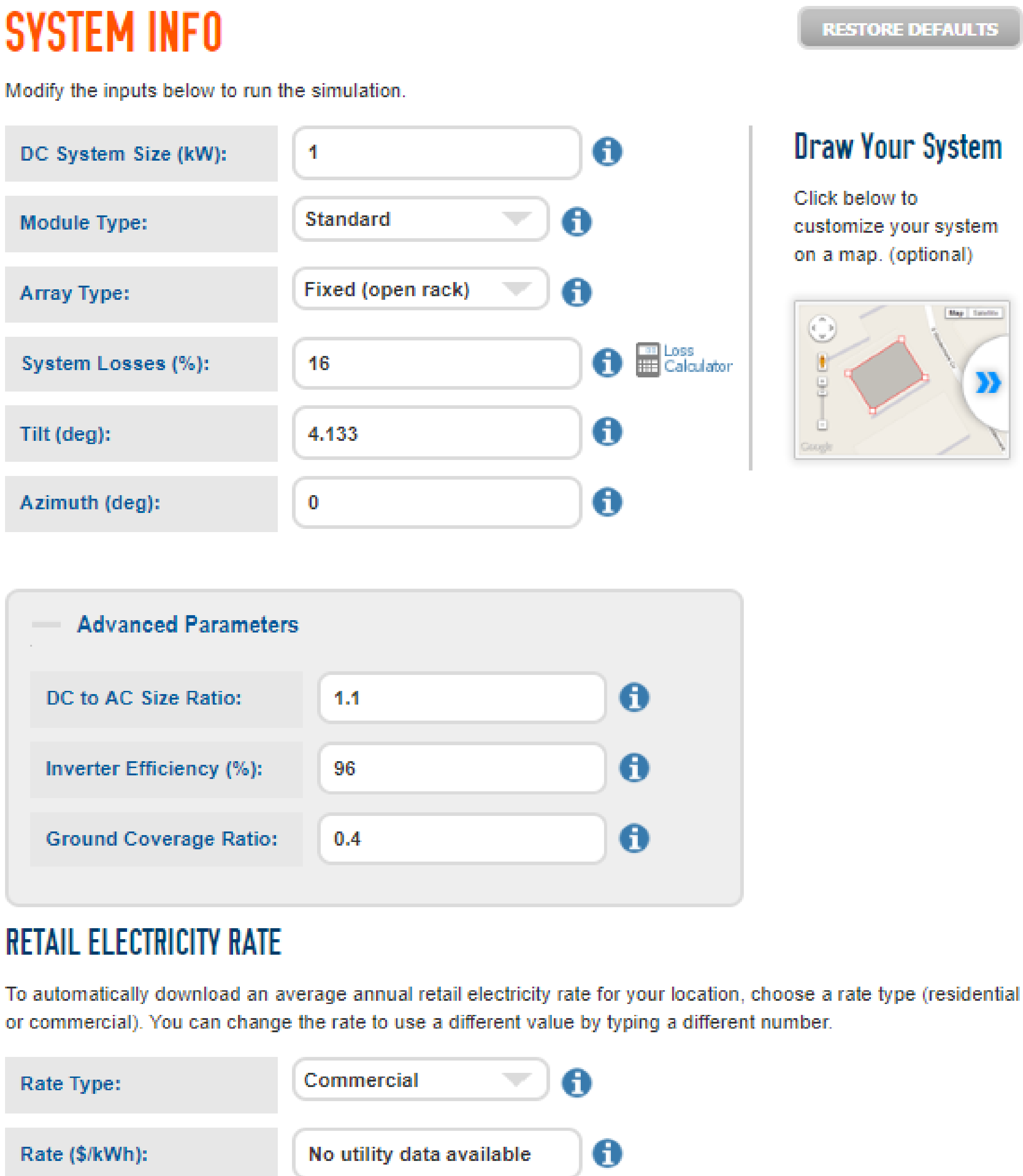

Figure 4-16: System Information and Parameters – 1 kW DC system

Table 4-15: Default Values for the System Loss Categories

Category	Default Value (%)
Soiling	2
Shading	3
Snow	0
Mismatch	2
Wiring	2
Connections	0.5
Light-Induced Degradation	1.5
Nameplate Rating	1
Age	0
Availability	3

Once the system information is completely filled, the calculator shows the annual yield of the system along with the solar radiation and AC energy per month as seen in Figure 4-17. From this data, the annual specific yield of is set to 1,401 kilowatt hour per year per 1 kilowatt DC. The actual size of the system can be calculated using the specific yield as shown in Equation 4-1. The actual DC system size calculates to about 610 kilowatts. The results of this adjustment can be seen in Figure 4-18.

Equation 4-1

$$\text{DC system size} = \text{Annual Energy Consumption} / \text{Specific Yield}$$

RESULTS

Print Results

1,401 kWh/Year*

Month	Solar Radiation (kWh / m² / day)	AC Energy (kWh)	Value ($)
January	5.43	124	N/A
February	5.85	118	N/A
March	5.66	127	N/A
April	5.27	116	N/A
May	4.83	111	N/A
June	4.81	107	N/A
July	4.77	111	N/A
August	5.05	117	N/A
September	5.43	121	N/A
October	5.56	126	N/A
November	5.11	112	N/A
December	4.86	111	N/A
Annual	5.22	1,401	0

Figure 4-17: PVWatts Calculator Simulated Results – 1 kW DC system

RESULTS

Print Results

854,690 kWh/Year*

Month	Solar Radiation (kWh / m² / day)	AC Energy (kWh)	Value ($)
January	5.43	75,443	N/A
February	5.85	72,076	N/A
March	5.66	77,374	N/A
April	5.27	70,805	N/A
May	4.83	67,577	N/A
June	4.81	65,498	N/A
July	4.77	67,617	N/A
August	5.05	71,400	N/A
September	5.43	73,790	N/A
October	5.56	77,017	N/A
November	5.11	68,304	N/A
December	4.86	67,789	N/A
Annual	5.22	854,690	0

Figure 4-18: PVWatts Calculator Simulated Results – 610 kW DC system

Adjusting the DC system size to 610 kilowatts yields an annual 854,690 kWh of energy, enough to sustain the annual 854 MWh energy usage for the college. The common problem associated with this result is that the solar radiation varies each month. This system will be able to yield enough energy for months that have sufficient solar radiation. During months with insufficient solar radiation, this system will not be able to power the college for the full day. If the school runs on a pure DC design that relies solely on PVs, the system has to be adjusted in order to be able to provide reliable and continuous power to the school. To make this adjustment, calculate the new annual specific yield by taking the smallest monthly AC energy yield from Figure 4-17 and multiply by 12 months. The new annual specific yield calculates to 1,284 kilowatts, resulting in a 665 kilowatts DC system design. The results are shown in Figure 4-19.

RESULTS

Print Results

931,752 kWh/Year*

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	5.43	82,245	N/A
February	5.85	78,574	N/A
March	5.66	84,350	N/A
April	5.27	77,189	N/A
May	4.83	73,670	N/A
June	4.81	71,404	N/A
July	4.77	73,714	N/A
August	5.05	77,837	N/A
September	5.43	80,443	N/A
October	5.56	83,962	N/A
November	5.11	74,463	N/A
December	4.86	73,901	N/A
Annual	5.22	931,752	0

Figure 4-19: PVWatts Calculator Simulated Results – 665 kW DC system

The energy yield from the 665 kilowatt system can provide continuous and reliable energy for the school throughout the year. This system produces an additional 9.02 percent of energy of the expected annual load. This excess energy can either be wasteful or utilized as backup energy, requiring an extra battery from the main battery system.

The amount of space to contain the 665 kilowatt system can be calculated. According to Brightstar Solar, a common solar panel size for commercial applications is 77 inches by 39 inches [51]. For this project, a specific solar panel model has not been chosen as panels may be donated or sponsored. Arbitrarily choosing a 340 watts solar panel as a model for determining the system size [52], the system will need 1,956 solar panels to make up for the 665 kilowatt system. The area of each solar panel calculates to 1.99541 square meters, equaling to a total system size of 3,903 square meters. The original master plan estimated the need of 18,000 square meters of solar panels to provide 1,900 MWh of energy. Using the master plan's estimation, 8,100 square meters of solar panels is needed to provide enough energy for the 854 MWh load. The significant difference in size may be contributed from calculation using old technology. Over the past six to seven years, the solar market and technology has been rapidly expanding and improving. These improvements have increased the amount of energy yield per square meter of solar panels. Another contribution for the difference is from spacing requirements. The original master plan does not specify the layout and build of the PV system, but the layout can be a major contribution in size if requirements for walking space and shadowing is considered.

4.19 Battery Bank Sizing

There are many considerations to take when sizing the battery bank for a large power system. The first consideration is dependent on the layout of the PV system - a centralized or decentralized system [10]. Land is required and dedicated for a PV farm in a centralized system. The PV farm will generate all the solar electricity at the site as DC power, an inverter and charge controller will invert the DC power into AC power in order to transfer the energy from the generation site to the campus, and the excess energy will charge the battery. The charge controller can direct the generated DC power straight into the battery bank if the battery bank is kept near the generation site. If the battery is kept near the campus and away from the generation site, the battery will require a rectifier to change the power back into DC for charging. When the load demands are greater than the supply of the solar panels, another inverter converts the battery's DC power for AC usage. In this case, it is best to keep the battery bank as close to the PV farm as possible to reduce the amount of power electronics needed to change the signals from AC to DC and vice versa. It will also reduce the amount of wiring needed for the entire system. In a decentralized system, each building utilizes rooftop solar panels that is dedicated to that individual building. These systems tend to have their own backup batteries per building. The PV array on these buildings will generate DC power, go into an inverter and charge controller device and provide AC power to the building. The excess power generation charges the battery bank. In this case, the batteries are much smaller than the centralized battery bank since they are isolated, but requires a battery per building. This method is preferable when there is not an already existing micro-grid between the buildings. For this thesis, a centralized system is assumed to avoid bidirectional power flow.

The second consideration is voltage of the battery. If the DC power has to travel a long distance, it is more efficient to convert the power from DC to AC first. It is more efficient to operate at a higher voltage point for a large power system, but comes at an increased cost. Another effect on the battery voltage is the PV system voltage. The voltage of the PV panels is directly related to the amount of panels in series per module. The load capabilities of the PV panels is directly related to the amount of modules in parallel.

The third consideration is to account for the amount of days of autonomy, days in which there are no power generation from the PV site due to clouding and rains [53]. The size of the battery varies significantly for a 100 percent solar design as compared to a 50/50 percent design. In a full PV system design, the only source of generation comes from the solar panels. The battery will regularly charge during the day, and discharge during the night. The size of the battery bank needs to be able to support the amount of days of autonomy times the daily energy usage. Using Load Profile Two for this calculation and assuming a maximum three days of autonomy, the battery will have to hold up to 7,019 kWh. In a 50/50 design, half of the load is ideally supported by an AC grid. The number of autonomy days is reduced to half, but the battery size does not have to follow the same set of rules as the 100 percent PV design, as the AC grid can take over and support the load during the days of autonomy. In this case, the battery may only have to be sized to support the AC load during peak hours while acting as a backup supply when the grid is down.

The last consideration is the amount of batteries to have in parallel and series. Much like the solar panels, increasing the amount of batteries in series increases the operating voltage. Increasing the amount of batteries in parallel increases the amount of current or load it can support. Batteries are commonly rated by amp-hours, and the amount of energy can be calculated by multiplying the amp-hours rating to its operating voltage. Other considerations include ambient temperature effects and seasonal factors. The ambient temperature difference in Tanzania will have little effect as the temperature is consistently warm being near the equator. The batteries will also be in a concealed vented room. The seasonal factor in which different times of the year produces different amounts of power will be offset by the living style. The sun produces less energy during the cold season, but less energy is consumed at this time as demand for cooling is less and the demand for heating is unnecessary. Heating air is uncommon for this region in which the weather is consistently warm. The college does not provide heating because of Tanzanian's thermal comfort in this weather.

Commonly used off-grid storage batteries include the following: flooded lead acid, sealed lead acid, and lithium batteries [54]. The flooded lead acid batteries have the lowest upfront cost, but require maintenance and ventilation. Sealed lead acid batteries are more expensive and need ventilation, but they require no maintenance. Lithium batteries are very expensive, but do not require any ventilation or maintenance. They also have the highest efficiency, fastest changing, and longest life span of three. According to a cost analysis done by PowerTech System, lithium-ion batteries have better overall cost as shown in Table 4-16 [55]. Lithium-Ion battery prices have been decreasing as its technology have been expanding over the past decade with the increase popularity of electric cars. According to New Energy Finance (BNEF), based on a survey of more than 50 companies, "Lithium-ion battery packs are selling at an average price of $209 a kilowatt-hour, down 24 percent from a year ago and about a fifth of what it was in 2010… The rate has further to fall — reaching below $100 a kilowatt-hour by 2025" [56]. Lithium-ion battery cost is predicted to be further reduced, as seen on the BNEF chart in Figure 4-20.

Table 4-16: Lithium-Ion versus Lead-Acid Cost Analysis

	Lead-Acid AGM	Lithium-Ion
Installed capacity	100 KWh	50 KWh
Usable capacity	50 KWh	50 KWh
Lifespan	500 cycles at 50% DOD	2000 cycles at 100% DOD
Battery cost	15 000€ (150€/KWh) (x 4)	35 000€ (700€/KWh) (one shot)
Installation cost	1K€ (x 4)	1K€ (one shot)
Transportation cost	28€ per KWh (x 4)	10€ per KWh (one shot)
TOTAL COST	**76 200€**	**36 500€**
Cost per KWh per cycle	**0.76€ / kWh / cycle (+95% vs Li-Ion)**	**0.39€ / kWh / cycle**

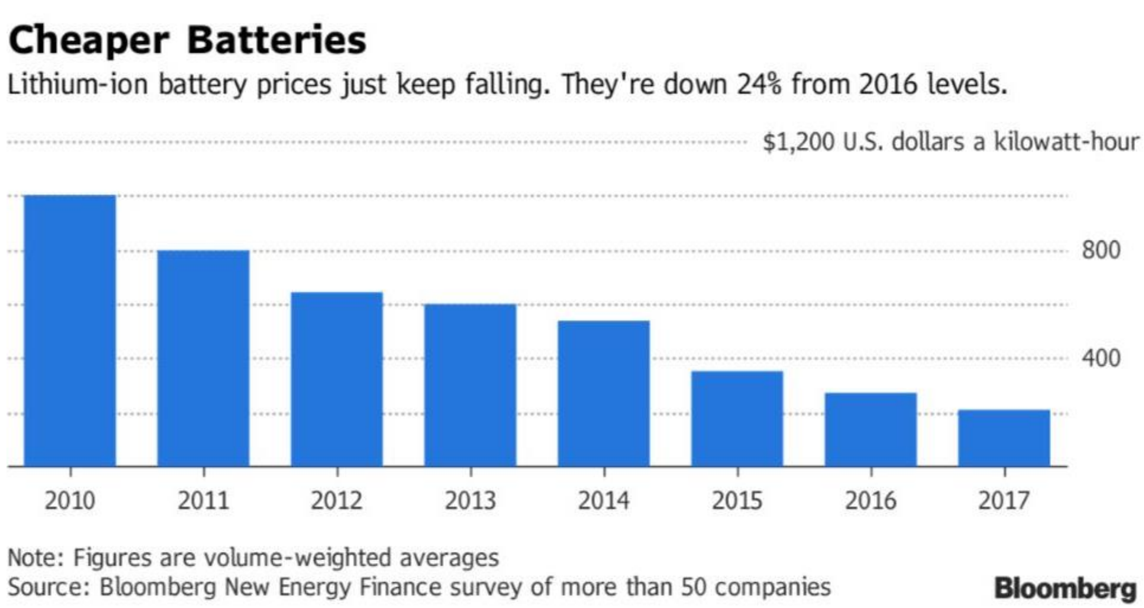

Figure 4-20: Lithium-ion Battery Cost Recent Cost (BNEF) [56]

4.20 Inverter, Transformer, and Transmission Line Sizing

An inverter is an electronic device that converts DC power to AC power. Almost all PV projects require an inverter because most electronics are made to operate with an AC input – usually with its own rectifier to change the AC power back to DC power for usage. For this thesis, all loads are assumed to be AC loads that operates with their own rectifier. The peak power and typical or continuous power ratings of the system are needed in order to size the inverter [57]. Peak power is the maximum power that a system can produce from current surges, seen mainly when starting motors. The typical power is the power at which the machinery operates at steady state. The main source of surge power comes from the refrigerators, freezers, blenders, various lab equipment, and fans. It is typical to rate the surge watts 1.5 to 2 times the continuous watts [58]. The continuous power ratings for this system is equal to the PV system size, and the inverter power ratings must match the PV system size. The 665 kW PV system requires multiple inverters in parallel or a custom inverter than can handle that much power. The input voltage of the inverter must match the output voltage of the solar panel's charge controller and the battery input voltage rating. A typical household battery bank operates from 12 to 48 volts, but an inverter input voltage can rate as high as a 1,000 volts. The operating input voltage is set to 1,000 volts as off the shelf inverters and solar panels can operate at that level. An important quality of the inverter to keep in mind is the maximum point power tracking (MPPT). The MPPT tracks the point in which the most amount of power can be extracted from the PV system. The MPPT changes the load resistance accordingly in order to draw out the maximum potential of the system.

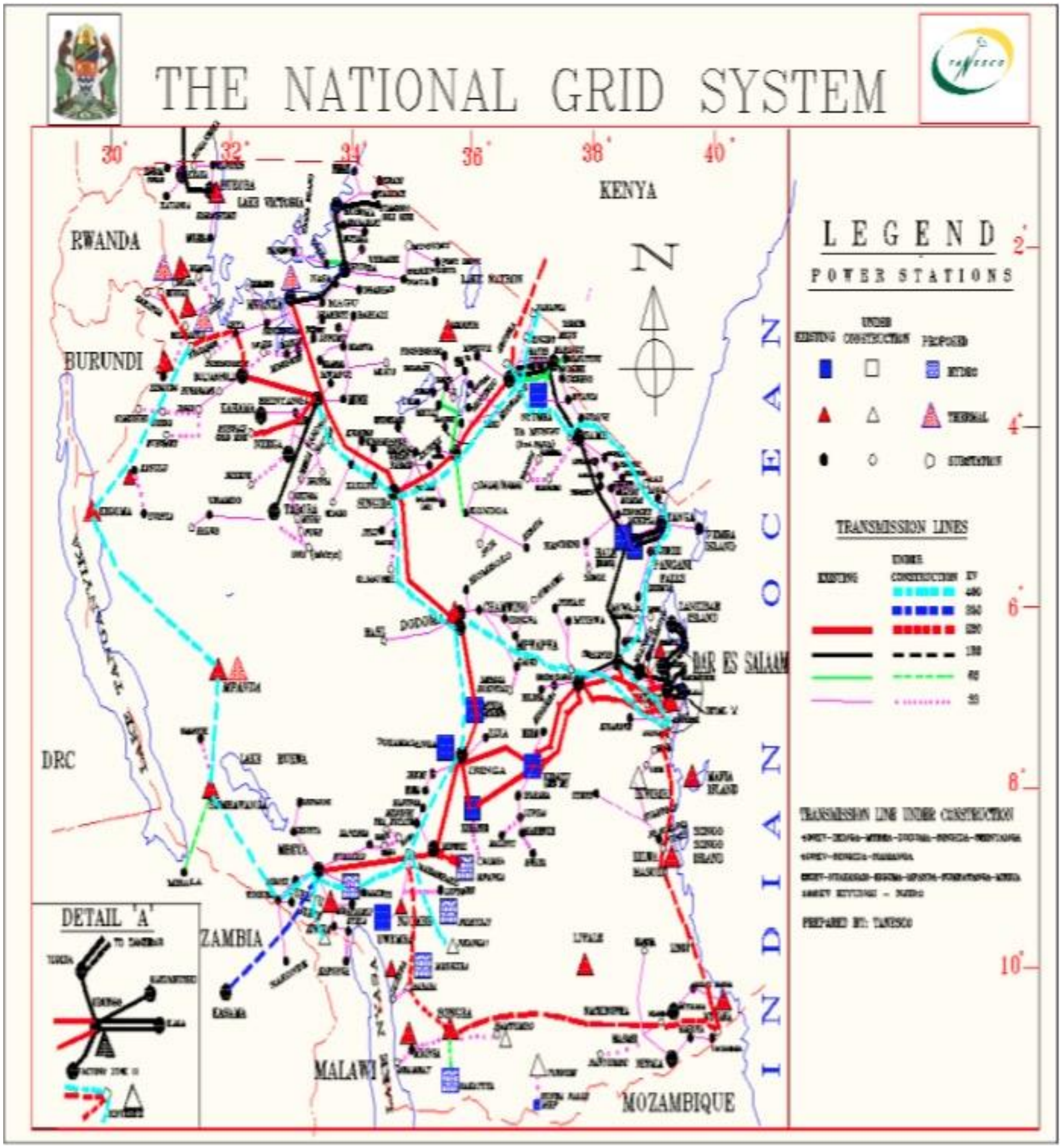

Figure 4-21: Tanzania's National Grid System

A transformer is an electrical device that transfers energy through electromagnetic induction. It is typically used to step-up or step-down voltages in power systems. The voltage is stepped-up during long distance transmission to reduce the amount of line loss from the transmission line – higher voltage results in reduced currents. The voltage is stepped-down for commercial and residential use. The operating voltage in Tanzania is 415 volts AC at 50 hertz for three-phase and 230 volts AC at 50 hertz for single-phase. According to a map shown by the Africa-EU Renewable Energy Cooperation Programme, the transmission line running across Same, Tanzania can either be 480, 132, or 33 kilo-volts (kV) as shown in Figure 4-21 [59]. The 480 kV line crosses through Same, but not at the actual campus site. The power lines run from north to south at the campus site and diverge from the power lines located parallel from the main traveling road. The power lines at the site branch off the 132 kV lines, operating at 33 kV. The transformer for the school should be sized to step down 33 kV to 415 volts three-phase. The power rating of the transformer in apparent power (kVA) is dependent on load line-to-line voltage and the maximum load phase current. For this project, the maximum worst-case power load operates at 198.6 kilowatts. The apparent power can be calculated by assuming a power factor. Contributions to a lower power factor typically comes from induction motors found in air conditioners and appliances like refrigerators. The college's only air conditioning comes from fans, which contribute little to the power factor reduction. For the load, we will assume a 0.85 power factor [60]. From this assumption, the rated kVA of the transformer calculates to 231.5 kVA for a pure AC power system design.

Transmission lines are used to transfer electricity from the source to the load. When traveling long distances, a transformer is used to step up the voltage in order to reduce the amount of line loss in the transmission line. Rating the transmission line is dependent on the ampacity - amount of current flowing through the line. The transmission line must also handle the surge current. In the worst case scenario, all loads would be operating at full load. From the data used to formulate the load profile, the worst case output power is

198.6 kilowatts at 231.5 kVA. The worst case peak current for the transmission line is seen during the peak operating hours. For a three phase circuit, the power equation used to calculate the current is shown in Equation 4-2. Using this equation, the transmission lines must be thick enough to handle 322 amperes at about 231.5 kVA. In this thesis, the load is assumed to be operating on single phases of the 415 volts three-phase network, splitting the amount of current to each phase as evenly as possible.

Equation 4-2

$$\text{Apparent Power (MVA)} = \frac{\sqrt{3} * kV * I}{1000}$$

4.21 System Design and Component Size

The component sizing in this chapter is based on Load Profile Two – generated in this chapter. Assumptions on the power factor were made to calculate the apparent power. The transformer and line current for the AC system was calculate using this apparent power. The DC system component sizes were based on available off-the-shelf panels and inverters. In Chapter 5, these component sizes may change depending on the available libraries on ETAP. For example, ETAP has a library of solar panels that are commonly used, typically in the range of 180 watts to 230 watts. The inverters may have to be manually inputted to account for the regional output voltage of 230/415 volts AC. The software carries a large library of transmission lines with varying impendences per length. Chapter 5 goes over the system design and any new assumption made for the component sizing. Chapter 5 also runs through the power flow and some short circuit analysis. Finally, the chapter goes over the system cost of each design.

Chapter 5 : System Design and Cost Analysis

5.1 Overview

This chapter simulates different system designs that is based on varying amounts of AC and DC power supply. The AC generation is supplied by Tanesco, the utility company for that region; while the DC generation is supplied through a PV system. The chapter begins with sections pertaining to the system design. These sections include what assumptions were made in the build of the system, why these assumptions were made, the load flow analysis, and the short circuit analysis of the system. Following these sections is the analysis for costs of these systems, with a final section overviewing which system design provides optimal usage and cost benefit.

5.2 System Design: 100 percent AC and 0 percent DC

In a full AC power system design, the primary source of power comes from the utility – Tanesco. The simplest one-line diagram that models the full AC power system includes a utility power grid connected to a transformer to step down the voltage, and distributed through a short transmission line to a bus that feeds the load. Figure 5-1 shows the one-line diagram used for this simulation. In this design, Load Profile Two sets simulation to operate during the peak load of 198 kilowatts – or 231.5 kilo-volt-amps (kVA) when assuming a 0.85 power factor. The voltage of the bus that connects to the load, Bus3, is set to 415 volts three-phase AC. In order to obtain the 230 volts typically used in the wall outlets in Tanzania, the load simply connects to a single-phase of the system. Equation 5-1 shows that 415 volts line-to-line converts to about 240 volts line-to-neutral.

The 240 volts is then assumed to drop anywhere between 5 to 10 volts due to the voltage drops in the wiring.

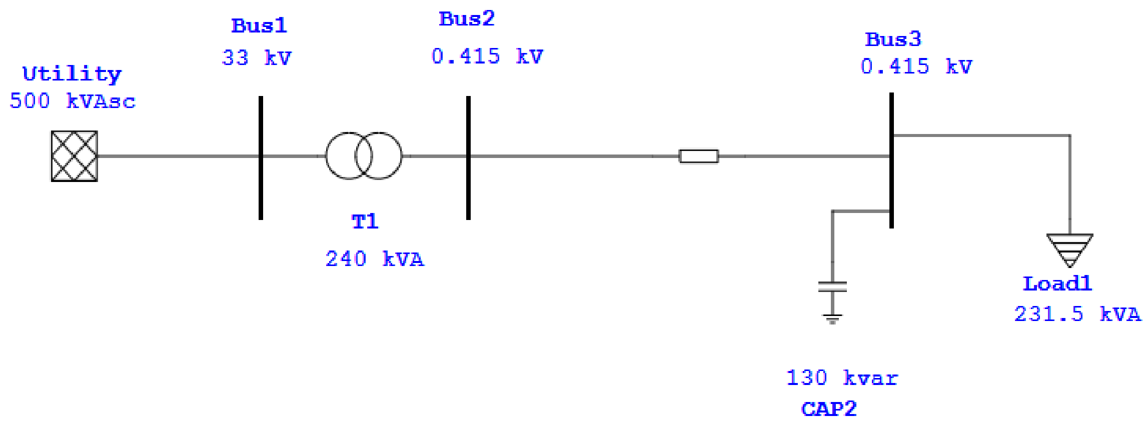

Figure 5-1: One-Line Diagram of 100% AC system

Equation 5-1

$$\text{Line Voltage} = \text{Phase Voltage} * \sqrt{3}$$

In order to model the transmission line that feeds into the school, the conductor has to be sized to handle the amount of current the system may see. As mentioned in Chapter 4 section 20, the transmission line sees a steady-state current of 322 amperes during peak operations. Much like the inverter, the transmission line must be able to handle surge currents between 1.5 to 2 times the normal operating current. Thus, the transmission line is sized to be able to handle 644 amperes. The Pirelli-AAAC-OXYGEN conductor is chosen from the ETAP library for the simulation as the ampacity shows the line can handle 748 amperes seen in Figure 5-2. An important setting for the transmission line is to set the phase height and spacing in the configuration tab. The height is set to 10 meters while the spacing between the phases are 1 to 2 meters as seen in Figure 5-3. Lastly, the length of the transmission line affects the amount of resistance in the wire, which has a proportional effect on the power loss in the wire – power loss equals the line resistance times the line current squared. In order to calculate the worst case length of the transmission line, an outline of the campus site is used in comparison to the land area given for the campus. The campus is given 100 acres of land, equivalent to 0.405 square kilometers. The distance between on side of campus to the other side of campus is 0.635 kilometers when assuming a perfect square. The campus itself is more rectangular with the utility transmission lines running parallel to the longer side of the rectangle. Figure 5-3 shows an outline of the campus in comparison to a square campus, and shows simple measurements that will help set the length of the transmission line. The length is set to 0.35 kilometers, traveling from the transformer location to the bus at the center of campus.

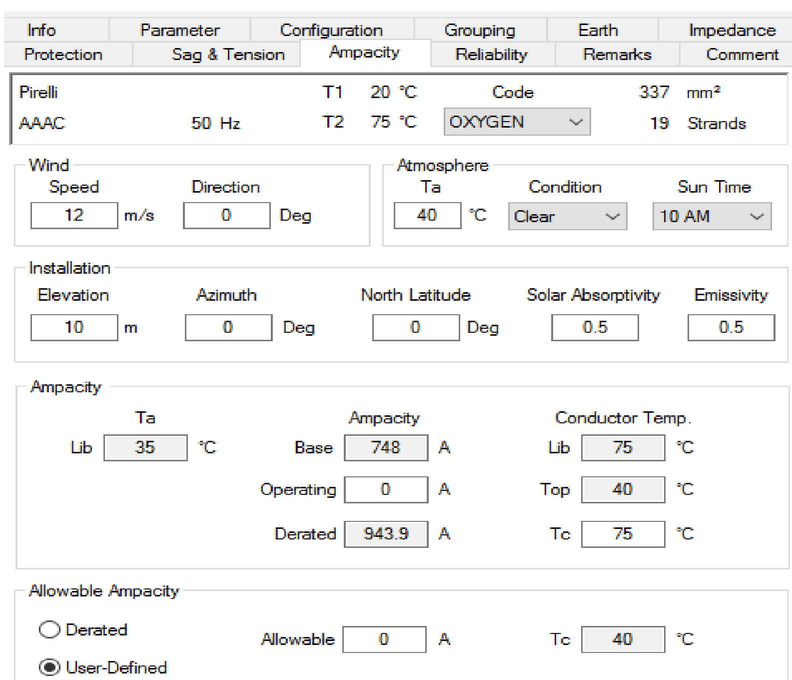

Figure 5-2: Transmission Line - Ampacity of OXYGEN cable

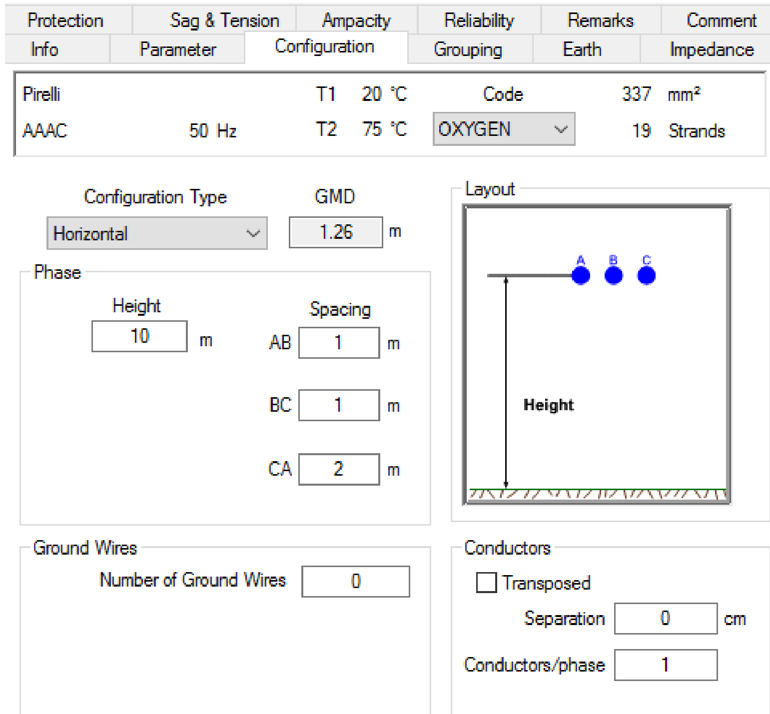

Figure 5-3: Transmission Line - Configuration of OXYGEN cable

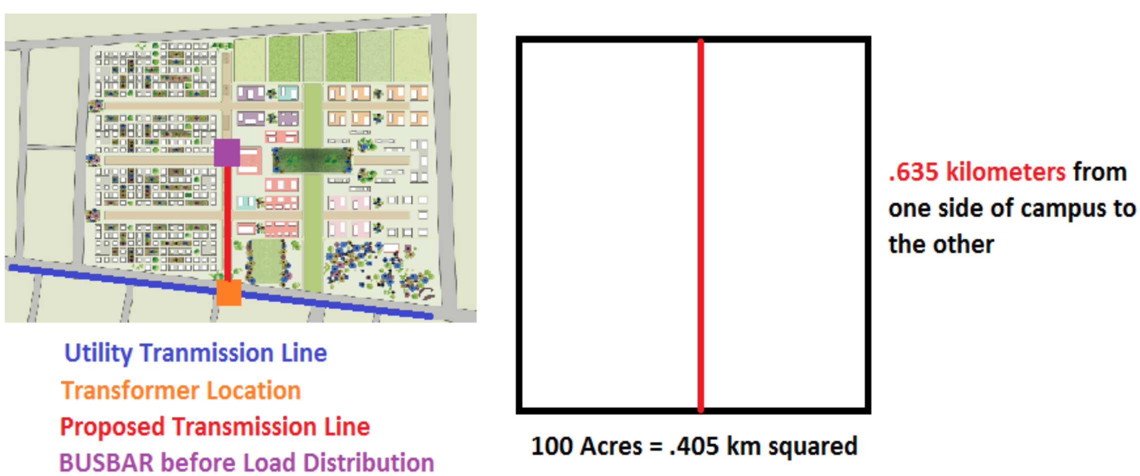

Figure 5-4: Campus Outline and Transmission Line Length Estimation [15]

After setting the transmission line length in the info tab, choosing the conductor from the parameter tab, and setting the spacing and height in the configuration tab, the impedance of the transmission line is automatically calculated. The transformer must be connected to busses, and not directly to the transmission line or power grid for the software to function properly. By labeling the bus voltages, the transformer steps down the voltage from 33 kilovolts to 415 volts on Bus1 to Bus2. The voltage rating in the transformer is automatically set if the connected bus ratings have already been set. The transformer power rating must be able to handle the power drawn from the load. The transformer power rating is set to 240 kVA in order to handle the 231.5 kVA load, as seen in Figure 5-5. The impedance of the transformer must be set in order to run the simulation. Typical values can be chosen by simply clicking on the "Typical Z & X/R" button provided in impedance tab in Figure 5-6. The transformer model is able to run once these values are set.

Figure 5-5: Transformer - Rating Tab

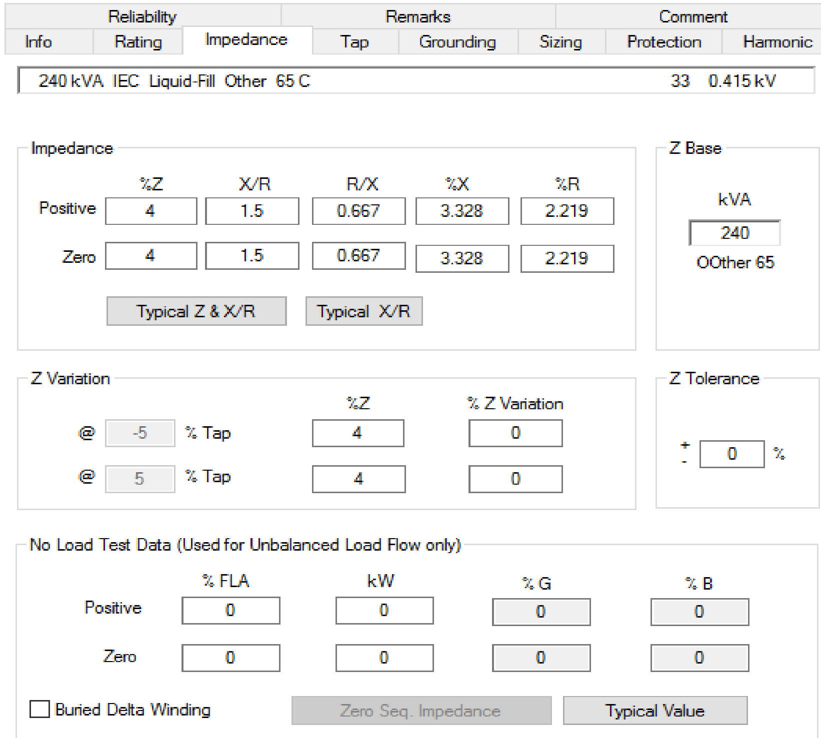

Figure 5-6: Transformer - Impedance Tab

The last component of the single line diagram needed to run the simulation is the power grid. This thesis assumes that the power grid as an infinite bus or power source. The power grid is set to a short circuit apparent power rating of 500 kVA, more than enough power to operate the load – about two times the power load. The grounding follows a Y-to ground and the power grid is set to a swing operation mode. Once these settings have been placed and the components have been connected, the software is ready to simulate to the design.

Running a load flow analysis on the full AC design yields the results shown in Figure 5-7. Plus or minus 5 percent is the acceptable range of the voltages in the busses for power systems. In the simulation, Bus 3 falls under this acceptable range by an additional 3.04 percent and is highlighted red in order to signify improper operation. When the bus is highlighted pink as shown in Bus 2, the software signifies that the bus is still in its acceptable range but needs to be monitored. In order to raise the bus voltage, a capacitor to ground is typically added at the bus that has a voltage drop. The voltage of Bus 3 significantly improves to 98.28 percent by adding a 100 kilo-volt-amp-reactive (kvar) capacitor as shown in Figure 5-8. Adding the capacitor also improves the voltage at Bus 2. However, adding capacitors have a drawback on the front end of the load flow. The reactive power at busses 1 and 2 change from a positive to negative in order to provide the reactive power the capacitor consumes. If these reactive powers are large, utilities typically charge their customers for the extra load current these customers consume. The reactive power is typically insignificant in households and homeowners do not have to pay for the little amount of reactive power they produce. In this case, the reactive power is still insignificant and the utility company will not charge extra for the reactive power.

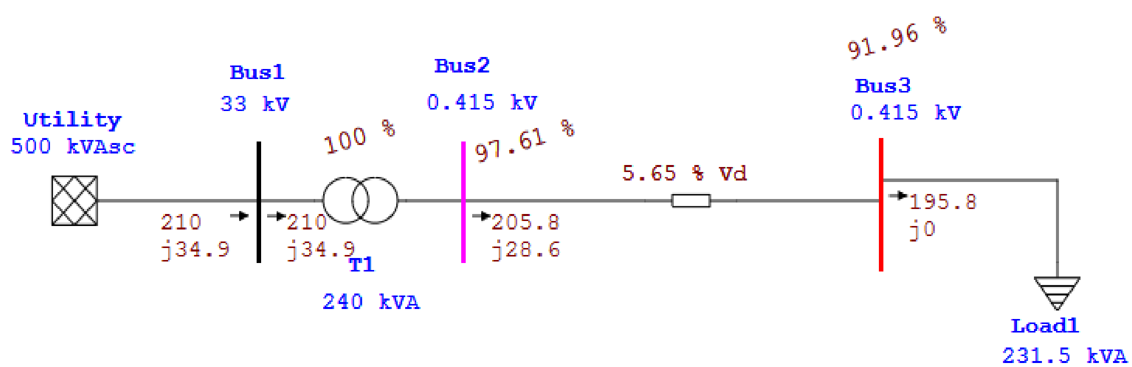

Figure 5-7: Load Flow Analysis on AC Design

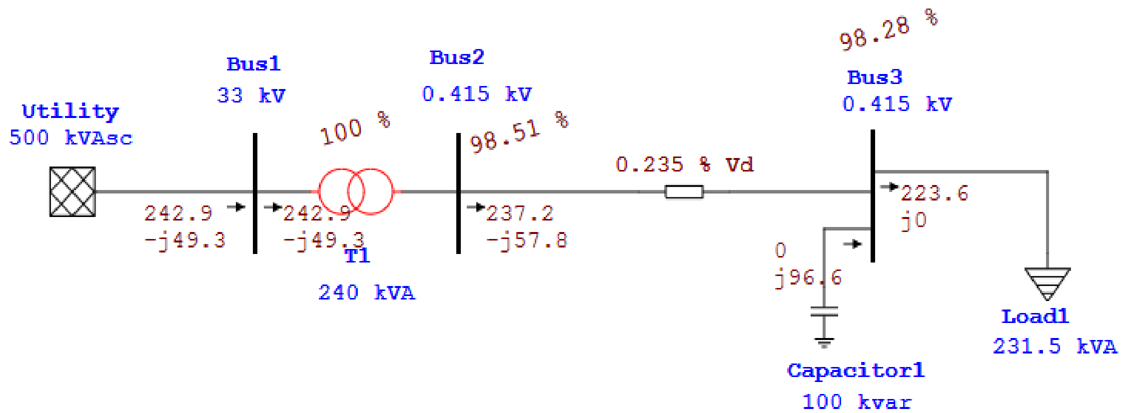

Figure 5-8: Load Flow Analysis on Capacitor Compensated AC design

The power flow from bus 3 to the load shows 223.6 kilowatts of real power and no reactive power. The expected real power of the load is about 200 kilowatts. Assuming a 0.85 power factor, the power flow expects about a 123.9 kvar – calculated using Equation 5-2. The loading tab of the load ratings allows users to enter the apparent power rating and the power factor, which automatically calculates the real power, reactive power, and load current shown in Figure 5-9. The results seen in Figure 5-10 shows that the voltage at Bus 3 is 3.12 percent lower than the acceptable range with the 100 kvar capacitor. Adding more capacitance mitigates the problem of the voltage drop as seen in Figure 5-11. Increasing the capacitance rating also bumps the real power from 166.2 kilowatts to 190.3 kilowatts and the reactive power from 103 kvar to about 118 kvar. This system design provides a sufficient AC power system model for the college.

Equation 5-2

$$\text{Reactive Power} = \text{Real Power} * \tan(\cos^{-1}(\text{power factor}))$$

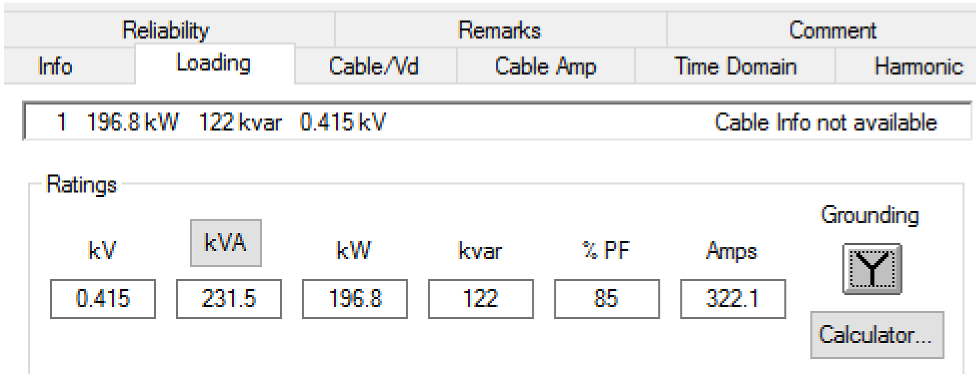

Figure 5-9: Load - Loading Tab

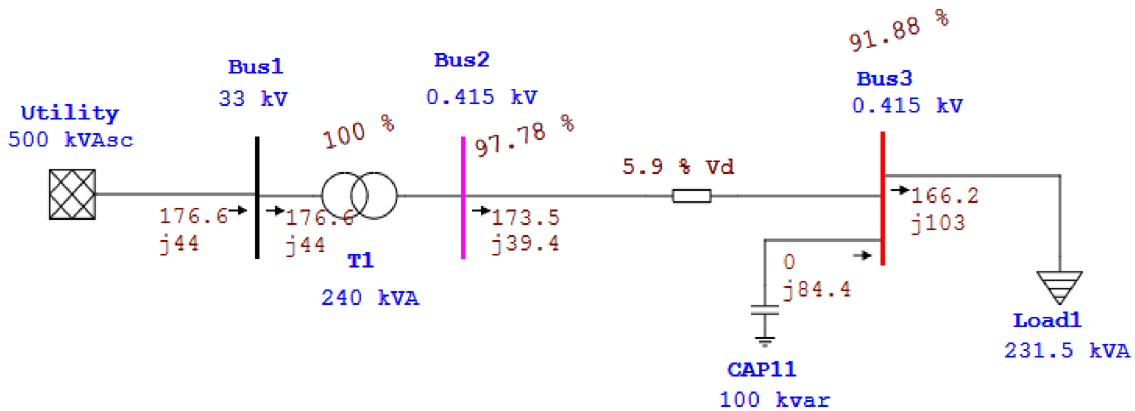

Figure 5-10: Load Flow Analysis on Load Corrected AC Design

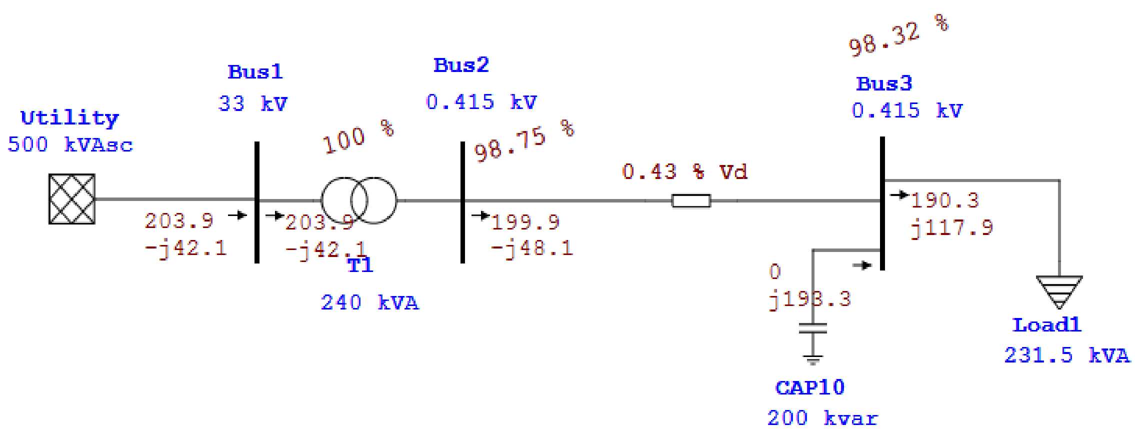

Figure 5-11: Load Flow Analysis on Load Corrected and Capacitor Compensated AC Design

The short circuit analysis in ETAP is used to determine the fault currents contributed by the power generators for different types of faults – single line to ground, line to line, double line to ground, and three-phase. The fault currents calculated from the simulation are typically used in order to set values and implement different protection schemes and coordination for the power system. The fault currents are also used to see if the electrical equipment is rated properly. The scope of this thesis does not include the protection scheme and coordination of the power system, but they will provided as future work. The short circuit test requires the user to define the utility grid reactance to resistance ration, the X/R ratio. According to the ANSI Standard C37.010, the X/R ratio of a utility source for long open-wire line ranges from 2 to 16 and the typical range is from 5 to 12 [61]. The X/R ratio is set to 10 in order to comply with the ranges given in the ANSI standard. The normal operating current load flow of the system is given in Figure 5-12 with the largest current at 316.7 amperes for the load. After running the short circuit analysis, the highest peak current comes from a double line to ground fault at Bus 2, running at 2.4 kilo-amperes. The short circuit analysis results are listed in Table 5-1

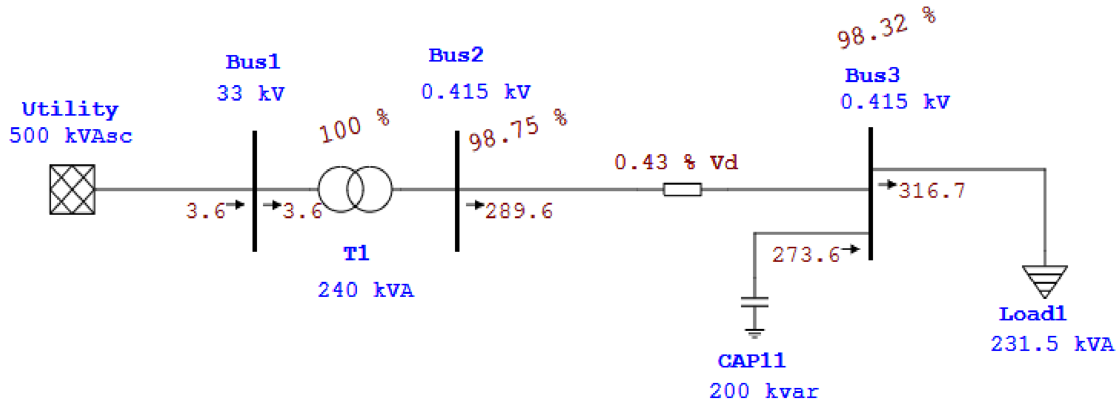

Figure 5-12: Current Flow Analysis on Load Corrected and Capacitor Compensated AC Design

Table 5-1: Short Circuit Analysis of AC Design

Bus Fault	Results		3-Phase	L-G	L-L	L-L-G
Bus 1	Initial Symmetrical Current (kA, rms)	:	0.009	0.012	0.008	0.012
	Peak Current (kA), Method C	:	0.022	0.030	0.019	0.031
	Breaking Current (kA, rms, symm)	:		0.012	0.008	0.012
	Steady State Current (kA, rms)	:	0.009	0.012	0.008	0.012
Bus 2	Initial Symmetrical Current (kA, rms)	:	0.623	0.906	0.539	1.014
	Peak Current (kA), Method C	:	1.478	2.149	1.280	2.405
	Breaking Current (kA, rms, symm)	:		0.906	0.539	1.014
	Steady State Current (kA, rms)	:	0.623	0.906	0.539	1.014
Bus 3	Initial Symmetrical Current (kA, rms)	:	0.486	0.468	0.421	0.478
	Peak Current (kA), Method C	:	1.095	1.054	0.948	1.077
	Breaking Current (kA, rms, symm)	:		0.468	0.421	0.478
	Steady State Current (kA, rms)	:	0.486	0.468	0.421	0.478

For most power systems, the double line to ground faults typically have the highest fault currents. Protection schemes that utilizes relays, circuit breakers, and fuses will use this information in order to protect the system from these large current spikes may damage the electrical equipment. The final AC system design is sufficient to run power to the college. Integrated protection schemes will help protect the system in case of faults. In cases where reliability takes precedence, the system design can be modified to account for distributed loads, in which the loads are divided per phase. Splitting the loads into equal sections will decrease the amount of current flowing through the load lines. The system can also be modified to account for maintenance in the transmission line or transformer by adding another transformer and transmission line in parallel to the already existing one. In this case, the transformers will operate at half load during peak hours and the power losses from the transmission lines decreases by a factor of 4 – where the current is half and the power loss is equal to I^2R. Operating at half the rated power promotes longevity of both the transformer and the transmission line.

The one-line diagram of having a system that pertains to these reliability modifications is shown in Figure 5-13. In this load flow, the power being transmitted through the transformer and transmission line is split in half for the real power at about 200 kilowatts to 100 kilowatts. The reactive power sees less of a drop due to the internal reactance of the transformers and power grid. The apparent power – the square root of real power squared plus reactive power squared – is also halved. The load is split into three equal sections of the campus, splitting the amount of power flow through the load lines by a factor of 3. The bus voltages approaches 100 percent since there are less losses in the transmission lines. When looking at the current flow shown in Figure 5-14, the currents for the load line, transmission line, and utility lines are all halved. This alternative design is more reliable, but also more costly in equipment and land usage.

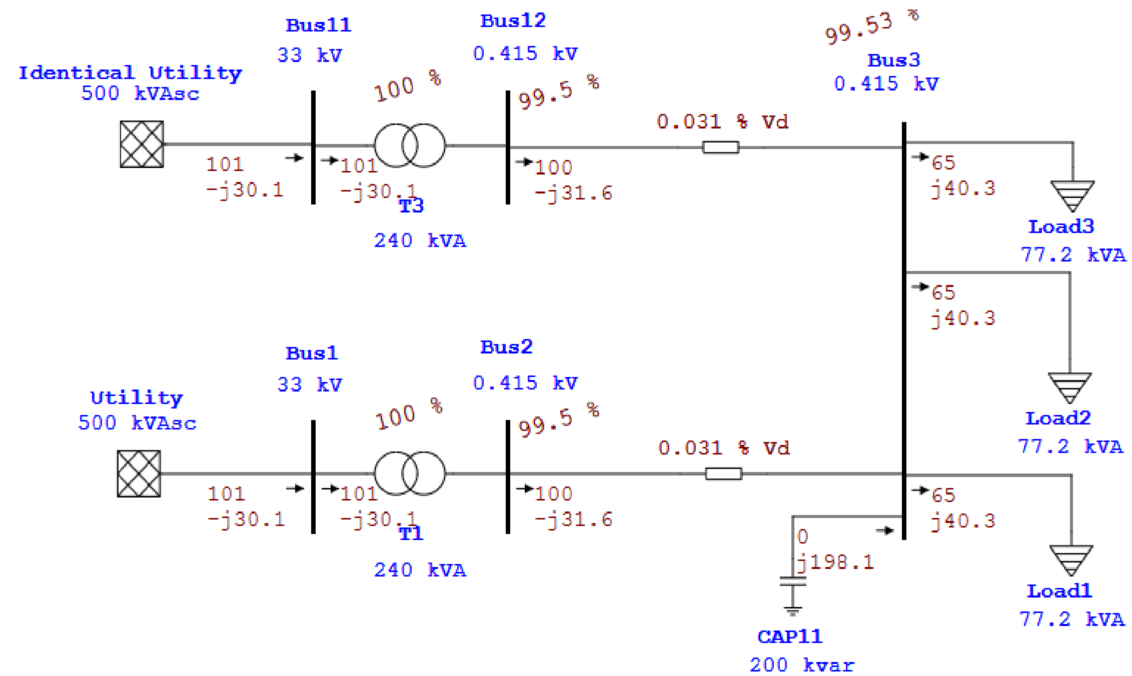

Figure 5-13: Load Flow Analysis of Reliability Modified AC design

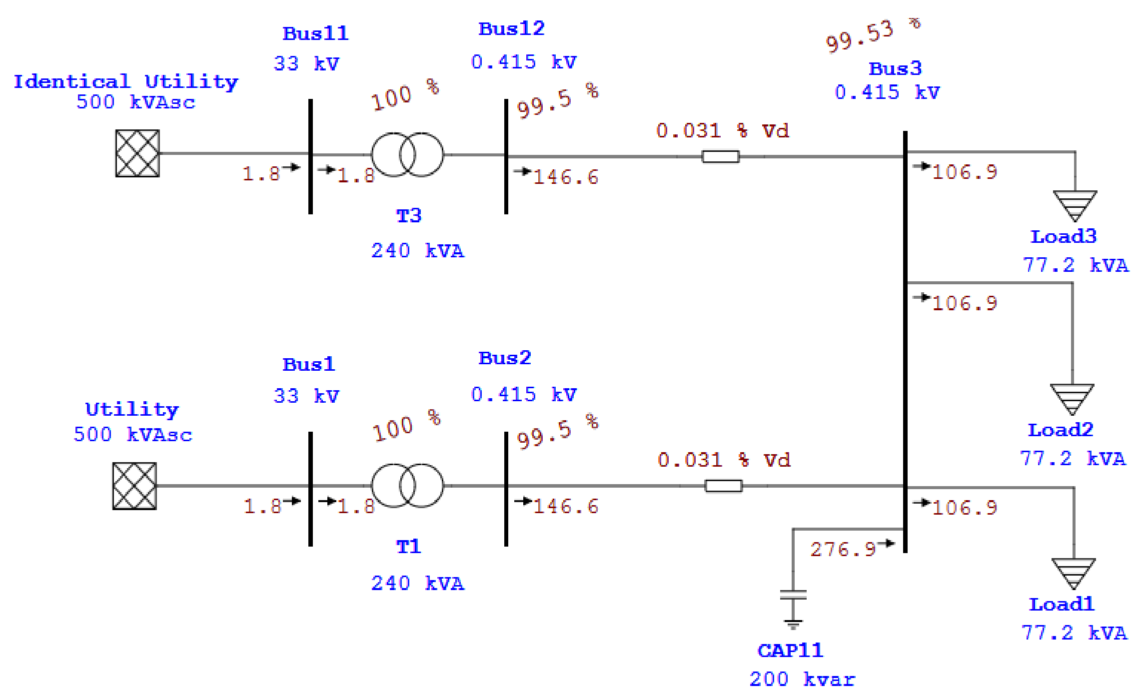

Figure 5-14: Current Flow Analysis of Reliability Modified AC design

For all mixed AC and DC system design, the AC system will integrate the DC solar panels and inverter into the AC design shown in Figure 5-11; with the exception that the load will be split into three equal loads – one per phase. When designing the mixed system, the AC design must be able to support the load during the peak hours – the worst case. The power grid, transformer, transmission line, and loads models will have remain the same in all mixed models in order to support the load during peak hours. The only way to decrease the peak during the peak hours is to shed the load from another source. The PV system has the capability to shed the load, but the peak hour is at 7 in the evening according to the load profile. The PV panels will not be able to produce any power by that time as location is close to the equator; in which the sun rises relatively consistently at 6 in the morning and falls at 6 in the evening. Integrating a battery in order to compensate for the time is one possible solution, but is not practical. The battery will charge with excess solar energy. Unpredictable weather patterns may cause the battery to discharge more than usual and risk being unreliable in the power system. The mixed systems should not be dependent on the battery to help curve the peak hour. The AC design of the mixed system must be able to handle the peak power in order to maintain reliability regardless of an additional DC power generation. The purpose of the solar DC power generation is provide renewable energy to the college, approaching a zero-net-energy model. These considerations and rules will be utilized in the mixed design starting at Section 5.4.

5.3 System Design: 0 percent AC and 100 percent DC

The 100 percent DC design in this thesis is simulated by emulating a solar farm that utilizes photovoltaic solar panels. The solar farm generates DC power and is inverted to three-phase AC power for campus usage. ETAP is equipped with a DC quick toolbar that helps designers build integrated DC power systems. Generally, a high level block diagram for a DC power system includes a PV array that feeds into a DC bus through a DC to DC converter that lowers the DC voltage at the bus. A charge controller at the DC bus controls whether or not to charge the external battery used for the system. Ideally, the battery charges when the supply of power is greater than the demand of the load. The DC bus is connected to an AC bus via an inverter. The loads consist of AC loads and dump loads. AC loads are used commonly in most electronics and appliances. Dump loads help relieve the over production of electricity by dumping the electricity through a large resistive load. The over production of electricity happens when the PV generation supply is too large and the battery is already full. The dump load is used to prevent the battery bank from overcharging. The high level block diagram is shown in Figure 5-15: High Level Block Diagram of DC systemFigure 5-15.

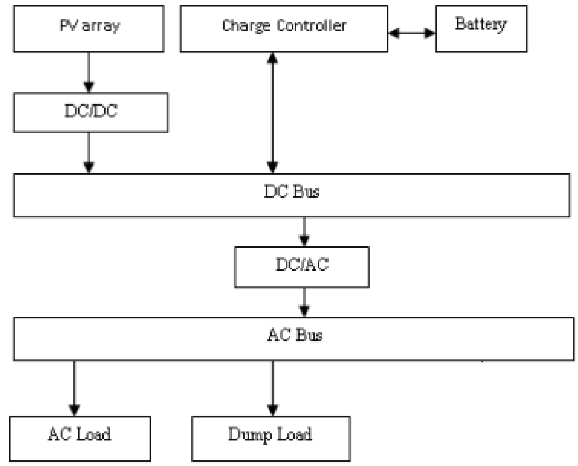

Figure 5-15: High Level Block Diagram of DC system

The first step to simulate a DC system on ETAP is to choose or create a model for the PV panels that will be used. Creating a model requires the user to enter information shown on the PV panel datasheet. Once all of the data have been entered, a P-V curve and I-V curve are generated and the model itself is ready to go. The curves that is generated from ETAP tends to be a rough estimation of the actual curves shown in the datasheet. For this reason, the PV panels used in this simulation will be chosen from the ETAP library. The Suniva ART245-60-3-1 model is chosen as the PV panel model because of its power capability. It is rated at 240 watts with an efficiency of 14.9 percent as shown in Figure 5-16. The other PV models in the library are rated at wattages and lower efficiencies. The chosen PV model also operates at 1 kilo-volt, compatible with the Sunny Tripower Core1 inverter that will be used as the inverter model in this simulation [62].

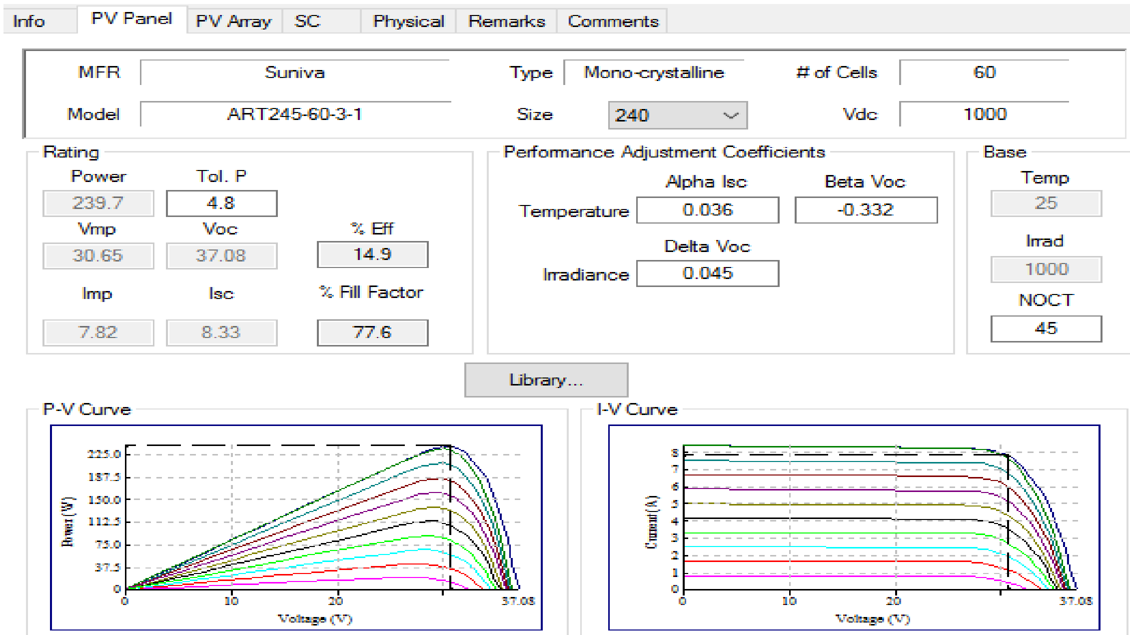

Figure 5-16: PV Array - PV Panel Tab

Designing the layout of the PV modules can be calculated to understand how many panels in series for a module and modules to have in parallel. Much like batteries, increasing the number of panels in series increases the voltage rating of the string. Increasing the number of string in parallel increases the amount of current the group of modules can provide. The amount of panels that can be in series is dependent on the open circuit voltage. The panels are rated to have a maximum system voltage of 1 kilo-volts DC. The open circuit voltage changes proportionally with temperature. The number of panels in series is equal to the maximum system voltage divided by the open circuit voltage. When the temperature is higher than the standard testing condition (STC) temperature of 25 degrees Celsius, the open circuit voltage decreases. The open circuit voltage increases when the temperature is colder than the STC temperature. According to the World Weather Online, the maximum temperature since 2010 is 34 degrees Celsius with the lowest temperature recorded at 13 degrees Celsius [63]. For the worst case calculation, the low temperature is assumed to be 10 degrees Celsius to add buffer for the calculation. The change in temperature is equal to the lowest temperature minus the nominal temperature. Beta is the percent open circuit voltage constant, rated at negative 0.332 percent [64]. Equation 5-3 is used to calculate the worst case open circuit voltage, equaling to 39.494 volts. Dividing 1 kilo-volt by the worst case open circuit voltage equals 25.32 panels. Each module will consist of 25 panels in series. The worst case open circuit voltage varies more drastically in areas with freezing temperatures.

Equation 5-3

$$V_{OC(worst\ case)} = V_{OC(nominal)} * [1 + (\Delta Temp * \beta)]$$

The number of string to have in parallel is dependent on the current ratings of the inverter. According to the datasheet of the Sunny Tripower Core1, the maximum operating input current per maximum point power tracker (MPPT) is equal to 20 amperes. The maximum current of the panel is equal to 7.82 amperes while the short circuit current is equal to 8.33 amperes. Thus, a maximum of two strings is allowed per MPPT. The inverter consists of 6 independent MPPT, and the array can be set to have 12 strings in parallel. The layout of the PV system is set accordingly as shown in Figure 5-17. After entering the numbers of panels in series and parallel, the software automatically calculates the amount of panels in the array, its nominal operating voltage, its DC power rating, and the total DC current rating.

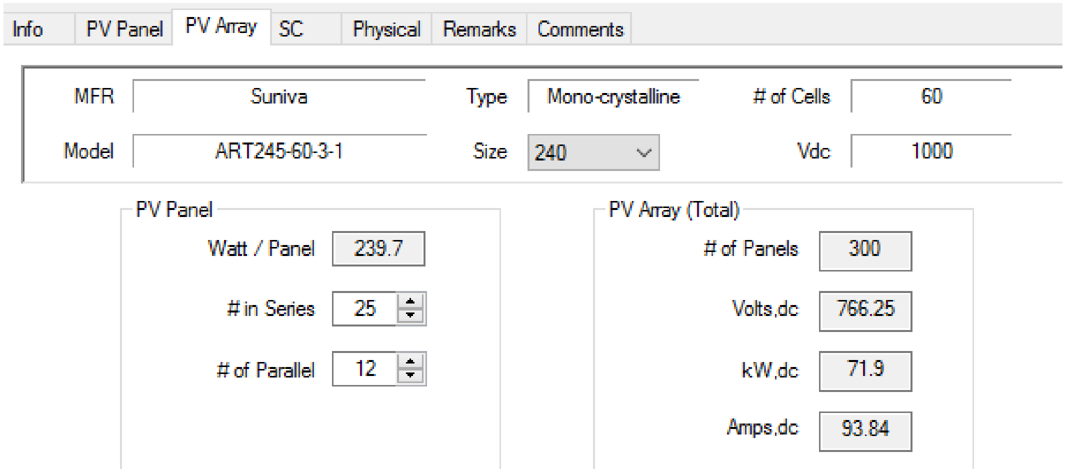

Figure 5-17: PV Array – PV Array Tab

The next step is to model the inverter. In the ratings tab, the parameters for the DC ratings, AC ratings, and the efficiency at different percent loads were entered as shown in Figure 5-18. In the inverter ratings, the AC apparent power is automatically calculated after entering in the DC rating information and the efficiency. The DC kilowatt rating of the inverter is set to 75 kilowatts. When changing the AC apparent power to 50 kVA, the DC power rating readjusts to 49 kilowatts. For this problem, the AC rating was ignored in the inverter rating tab and the DC rating was set to 75 kilowatts. The solar panels will not be able to supply maximum power throughout the entire day as the irradiance changes over time, reducing the amount of power generated from the panels. Sizing a 75 kilowatt DC system ensure the inverter can supply 50 kVA for a longer period of time, instead of operating at a critical point. The inverter is able to supply 50 kVA as long as the panels are able to produce 50 or more kilowatts DC. ETAP allows the user to simulate a DC load flow in order to see how much DC power the PV system is able to produce at varying irradiances. The irradiance setting can be calculated for different time zones at a specific geographical location in the PV array tab under the PV array settings.

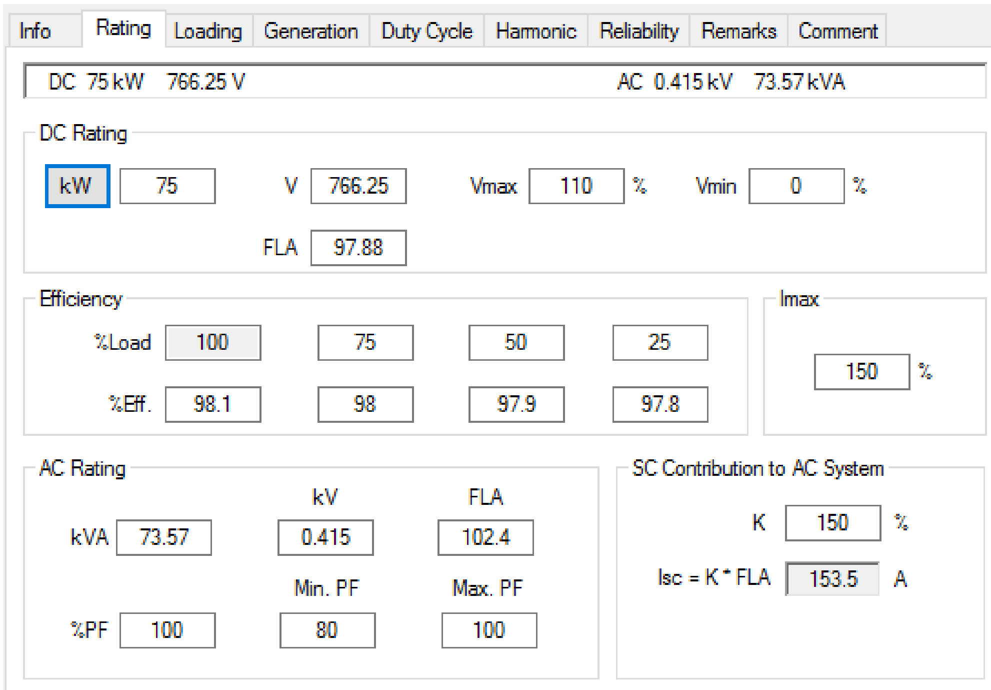

Figure 5-18: Inverter – Rating Tab

After entering the inverter specifications, the entire DC system model needs to be sized in order to produce enough energy for the school to run all year. In Chapter 4, the DC system is sized to a 665 kilowatts system. A single inverter is capable of providing up to 75 kilowatts on the DC side. In Figure 5-17, the inverter is assigned to support 25 solar panels in series with 12 of those strings in parallel – providing 71.9 kilowatts of DC power. The design will need to encompass 10 Sunny Tripower Core1 inverters, calculated by dividing the overall DC system size by 71.9 kilowatts. Running the 10 inverters at full capacity yields a DC system size of 719 kilowatts. To compensate for the extra size, one of the inverters will be running with 4 parallel strings of 25 panels – totaling to a 671.1 DC system size.

The last step before running the DC simulation is to connect the PV arrays to the inverters. In ETAP, the arrays and inverters are connected through a DC cable. The inverters are located at the end of the strings of PV panels to reduce the length of the cable. The cable length is set to 10 meters, under the info tab of the DC cable editor. The impedance of the cable is set to 10 ohms per 1 kilometer as shown in Figure 5-19, more resistance than expected for measuring worst case. Once the DC cables have been connected, the output of the inverters must be connected to an AC bus that connects to the load via transmission line. The final DC system model is shown in the DC power flow in Figure 5-20.

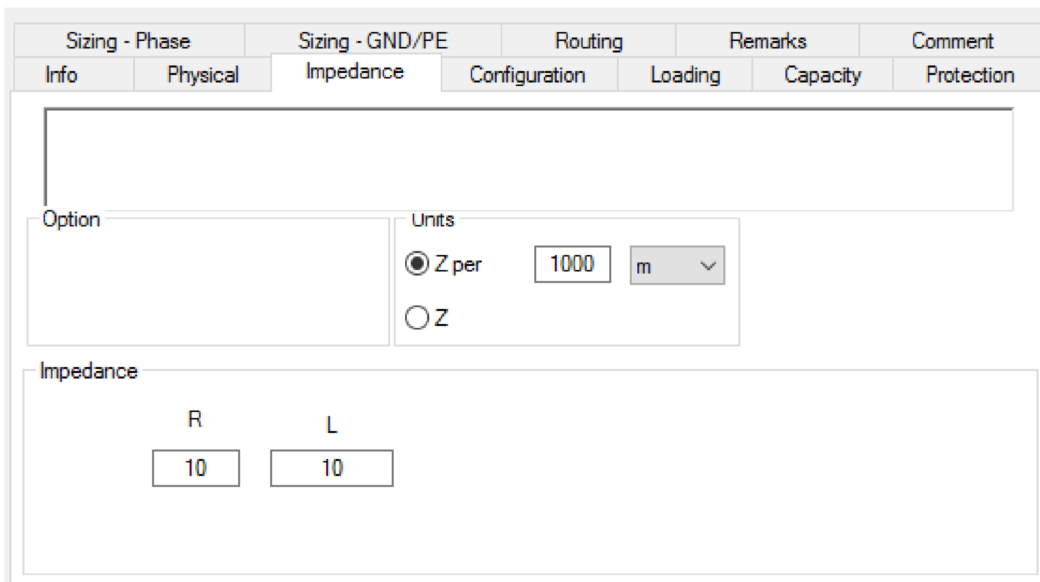

Figure 5-19: DC Cable – Impedance Tab

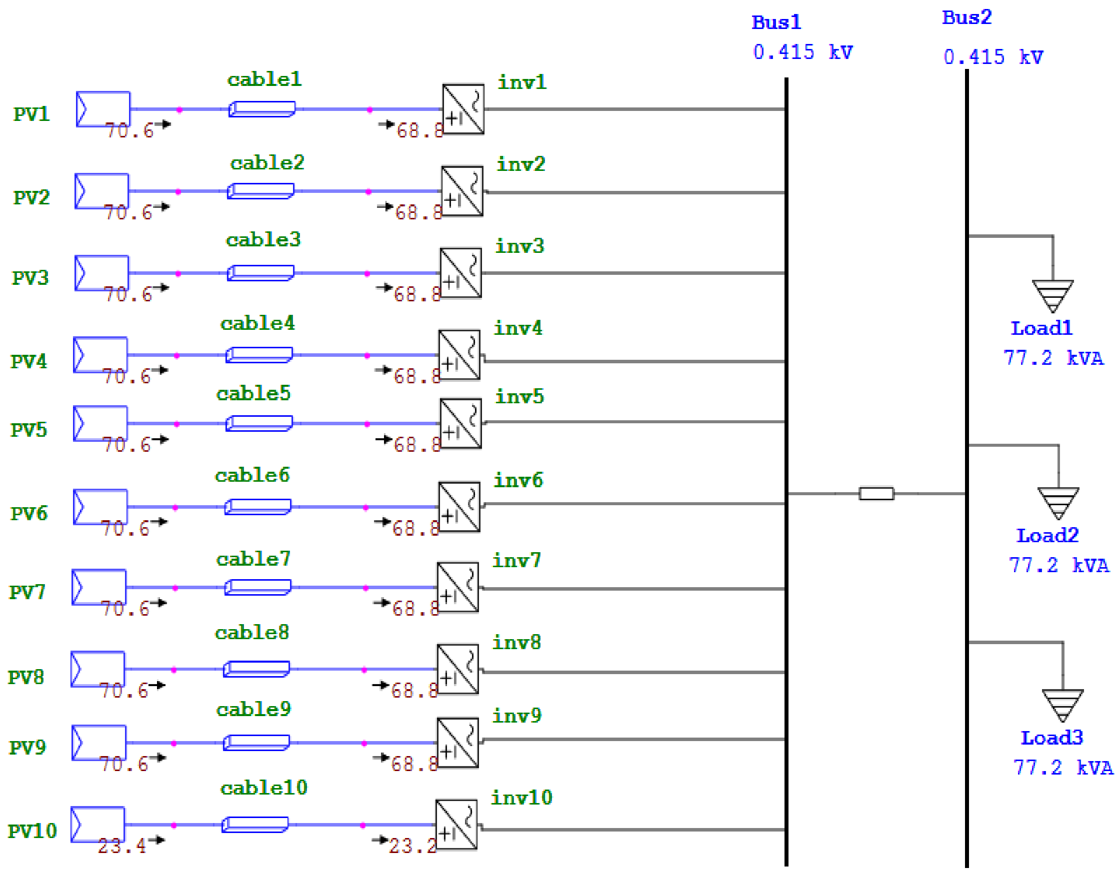

Figure 5-20: DC Load Flow Analysis on DC System

In the DC power flow simulation, each cable has a power loss of 1.8 kilowatts – 2.55 percent of the power generated. The cables are set to have much more resistance than expected. When changing the cables to an impedance that matches the transmission line, each cable burns 300 watts – about 0.43 percent of the power generated. The PV arrays are operating at the theoretical maximum irradiance of 1,000 watts per square meters (W/m^2). The output power of the panels are dependent on the available irradiance. The graph from Figure 5-21 shows the relationship between the generated AC and DC power in relation to the irradiance – detailed in

Table 5-2.

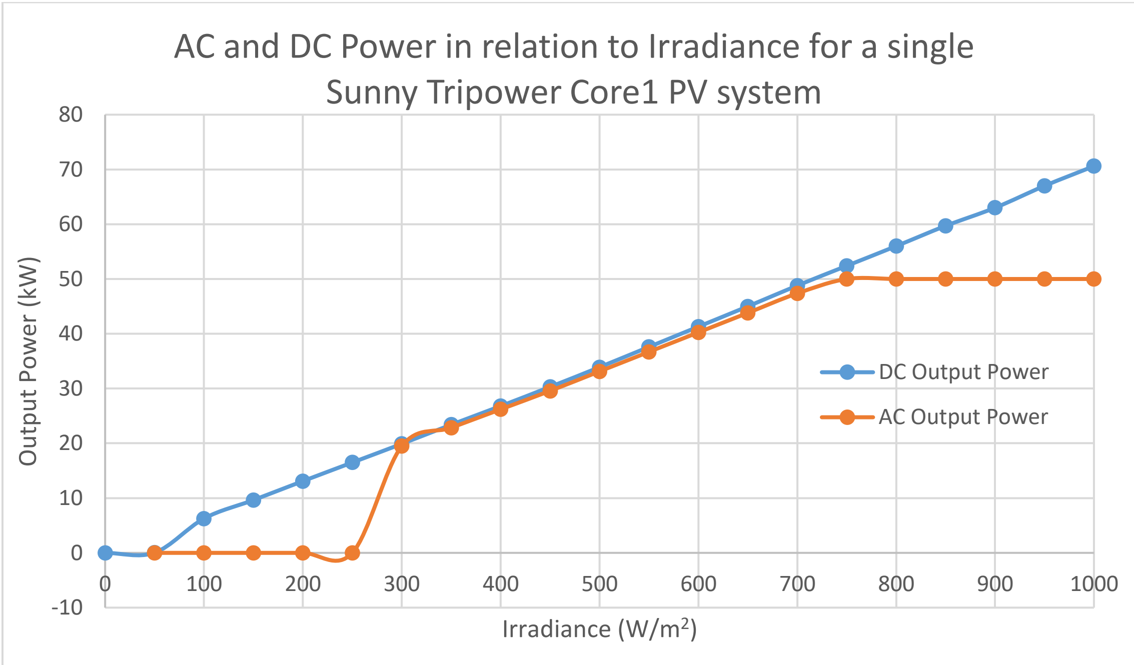

Figure 5-21: AC and DC power in relation to irradiance for single inverter and PV model

Table 5-2: AC and DC power in relation to irradiance for single inverter and PV model

Irradiance (W/m^2)	Array Power (kW)	DC power (kW)	% Power Loss	AC power (kW)
1000	70.6	68.8	2.55	50
950	67	65.3	2.54	50
900	63	61.9	1.75	50
850	59.7	58.4	2.18	50
800	56	54.9	1.96	50
750	52.4	51.4	1.91	50
700	48.8	47.9	1.84	47.4
650	45	44.3	1.56	43.8
600	41.3	40.7	1.45	40.3
550	37.6	37.1	1.33	36.7
500	33.9	33.5	1.18	33.1
450	30.3	29.9	1.32	29.6
400	26.8	26.5	1.12	26.2
350	23.4	23.1	1.28	22.8
300	19.9	19.7	1.01	19.5
250	16.5	16.4	0.61	0.0
200	13.1	13	0.76	0.0
150	9.64	9.6	0.41	0.0
100	6.27	6.25	0.32	0.0
50	0.029	0	100.00	0.0
0	0	0	-	0.0

In order to run an AC load flow in the DC system model, the simulation requires connection to a power grid. The power grid settings follow the settings made in the AC model – operating at a short circuit apparent power of 500 kVA and assumed X/R ratio of 10. The AC load flow analysis in Figure 5-22 shows that each inverter is able to produce 50 kilowatts to the system at the maximum irradiance, with the last inverter producing 23.1 kilowatts. The acceptable bus voltage must be within 5 percent of 100. In order to boost bus 2 into the acceptable voltage range, a 200 kVA capacitor is added to the load bus.

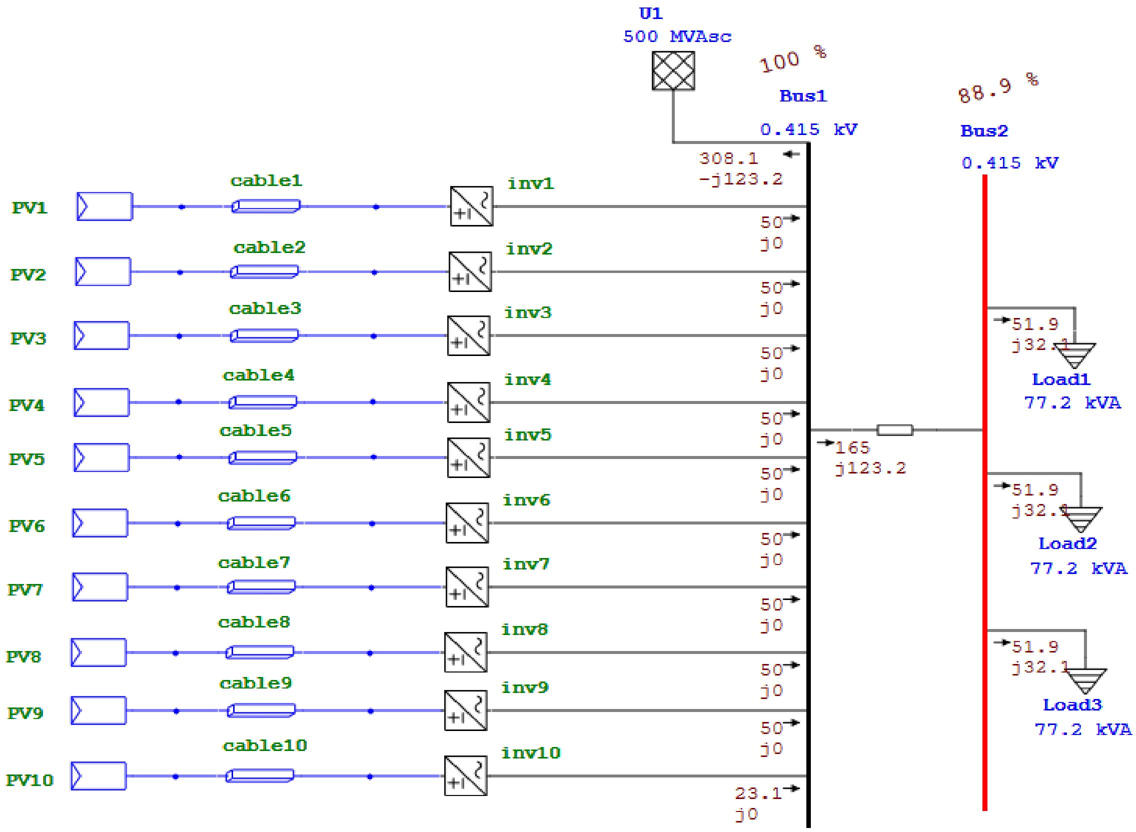

Figure 5-22: AC Load Flow Analysis on DC System

Adding the 200 kVA capacitor has many positive effects on the load flow. The bus voltage at bus 2 is boosted to 99.56 percent of its nominal voltage – shown in Figure 5-23. Each load receives sufficient power for operation, naturally decreasing the amount of power returning to the utility. The reactive power of the transmission line is also reduced to a negative 49.3 kvar. The utility grid will connect to a transformer before connecting to the bus in the mixed system designs. The DC design does not connect to the grid, but is necessary when running the AC simulation. The extra power produced during high supply and low demand will typically be used to charge batteries. In Figure 5-23, the utility receives returning power due to the excess power supply. Instead of returning to the grid, this power will be used to charge the batteries in the DC system.

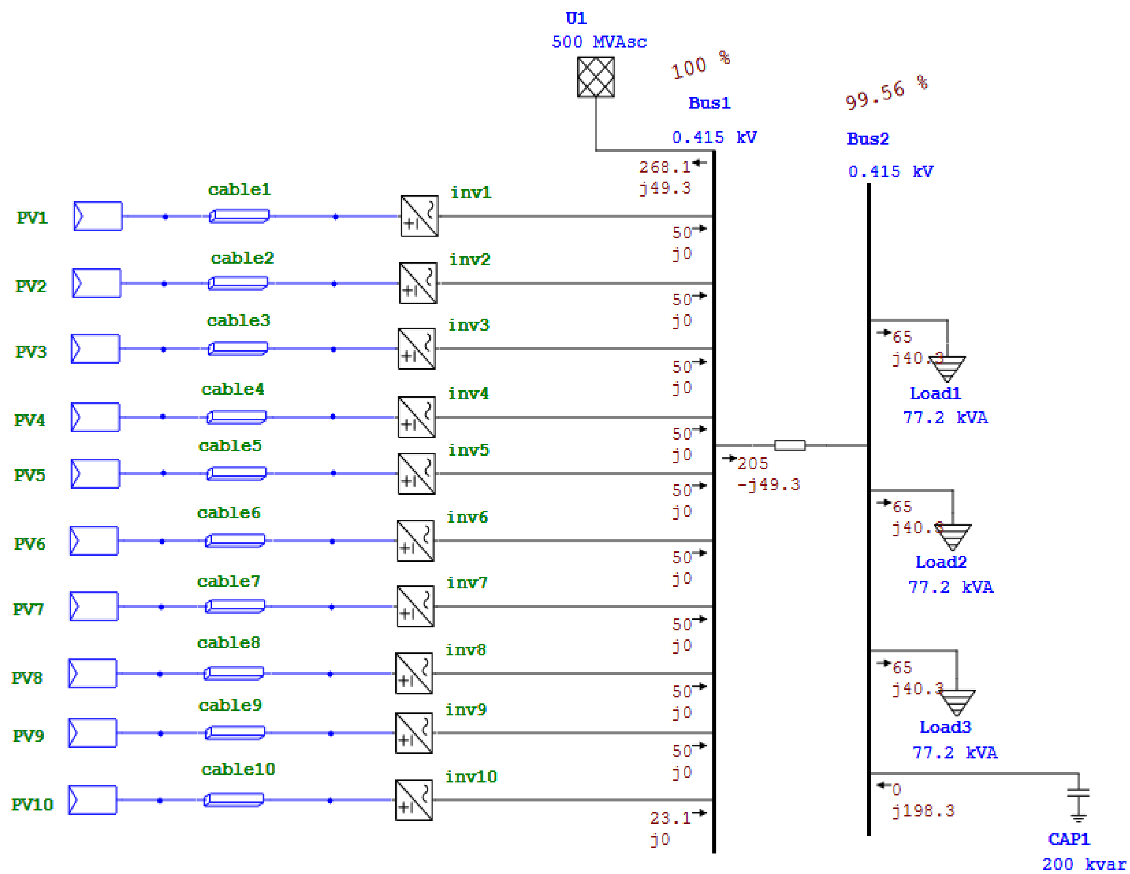

Figure 5-23: AC Load Flow Analysis on Capacitor Compensated DC system

Integrating the battery system on ETAP can prove to be a difficult task. A battery test simulation is performed before integrating the battery system into the DC design. The test simulation includes a single PV array connecting to an inverter with a DC cable. The output of inverter is tied to a 415 volt bus with a load. The battery is connected to the bus after the cable in order to centralize the battery system as much as possible. The battery is connected through a DC to DC converter as ETAP does not have a model for a charge controller. The DC to DC converter is important to step down the voltage in order to reduce that amount of batteries needed in series. Figure 5-24 details the one-line diagram of the battery test circuit. The chosen battery in the ETAP library is the EnerSys GC-M model.

Of all the batteries in the library, this battery provides the largest battery bank at 3550 amp-hours (Ah) – storing up to 170.4 kWh when operating at 48 volts. Increasing the number of cells in the rating tab of the battery increases the rated open circuit voltage. This voltage should be able to handle the voltage from the DC to DC converter. To create a rated open voltage close to 48 volts, the number of cells is set to 24 as shown in Figure 5-25. The DC to DC converter is set to convert an 800 input voltage to a 48 output voltage. Its power rating is set to 50 kilowatts and efficiency to 95 percent shown in Figure 5-26.

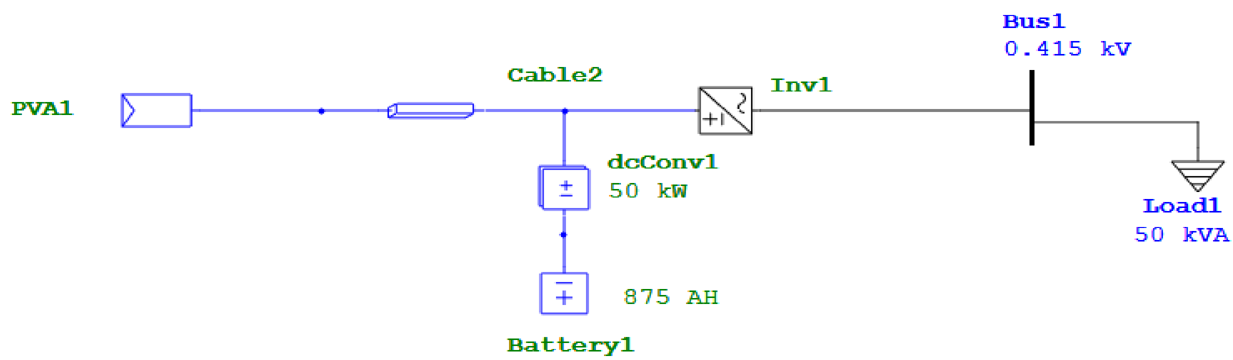

Figure 5-24: One-Line Diagram of Battery Test System

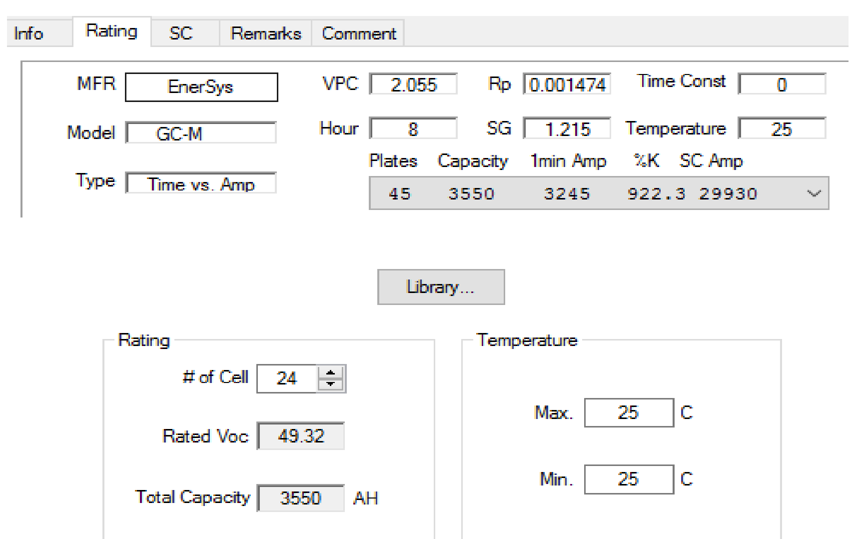

Figure 5-25: Battery – Rating Tab

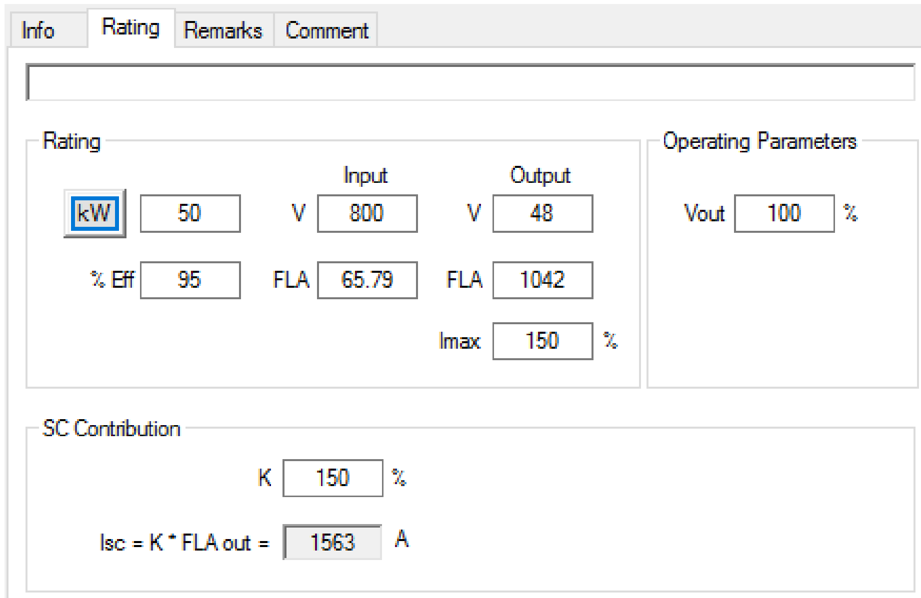

Figure 5-26: DC to DC Converter – Rating Tab

Upon running a DC load flow analysis, a calculation error appears stating that the PV arrays cannot be connected to a battery, a DC-DC converter, a grid-connected inverter and a charger, constant power load and a charger, and multiple grid-connected inverter as shown in Figure 5-27. For this reason, the battery has to connect to a battery charger from an AC bus. The only settings that has to be adjusted for a charger is the power ratings. The AC power ratings is adjusted to 10 kVA so that the PV array is able to provide power to both the load and battery without relying on the grid. Running a DC power load analysis shows that the battery does not receive any power flow as shown in Figure 5-28. Running an AC load flow analysis shows that the charger receives AC power, yet the battery does not receive any charge. When trying to run the battery sizing functionality given on ETAP, the program pops-up a message showing that the Cal Poly licensing does not support this battery modeling functionality. Because of these errors and complications, the battery will not be included in the simulations for the DC and mixed system designs. Instead, the sections will reflect on how to theoretically connect the batteries to the system and improvements that can be made.

Calculation Error

ETAP detected PV arrays being connected with one of the following elements
(a) Battery,
(b) DC-DC converter,
(c) Grid-connected inverter and a charger/UPS,
(d) Constant power load and a charger/UPS,
(e) Multiple grid-connected inverters.

These combinations are currently not supported. Please de-energize the unsupported elements to proceed.

Figure 5-27: Calculation Error of Battery Connection to PV array

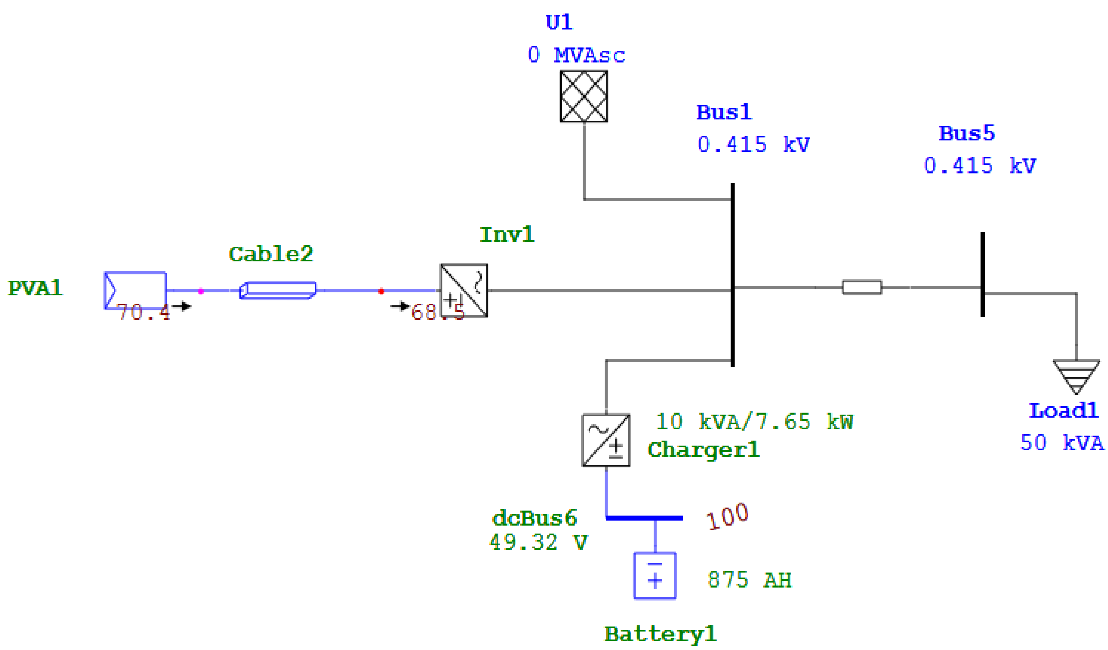

Figure 5-28: DC Load Flow Analysis on Adjusted Battery Model

In order to understand if the DC design is able to supply enough energy to the college, an irradiance graph is generated using ETAP's irradiance calculator. The irradiance at Same can be graphed by adjusting the longitude, latitude, date, and time. According to NASA's insolation data in Same, the month with the average daily irradiance is in June, while the highest average daily irradiance is in February. The sun rises anytime between 6:04 am to 6:38 am and falls anytime between 6:20 pm and 6:51 pm. The irradiance graph that is generated in Figure 5-29 uses a day that models the average yearly irradiance – April 24th. An energy production profile can be estimated using the Irradiance graph and the relationship between the output AC power and the irradiance generated in Figure 5-21.

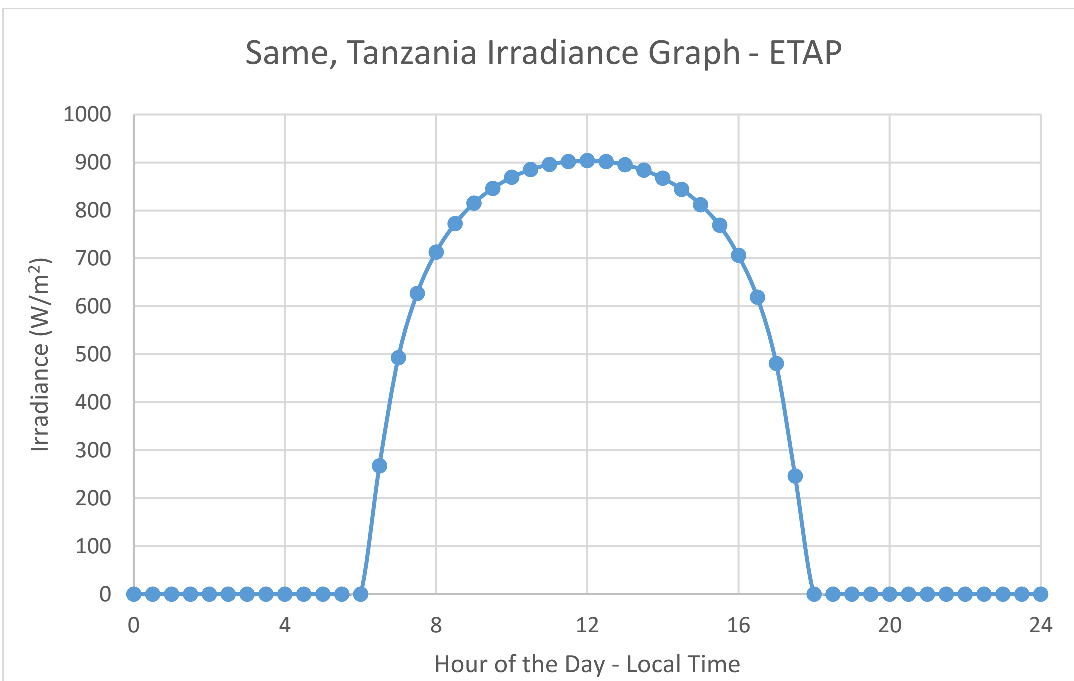

Figure 5-29: Same Irradiance Graph Generated through ETAP

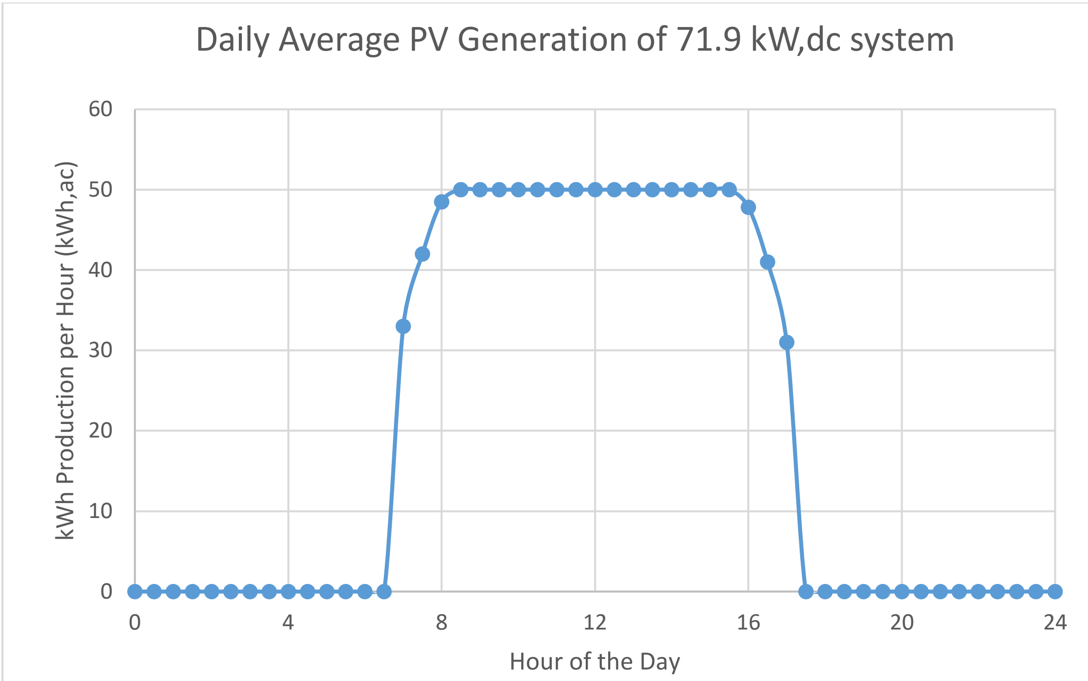

Figure 5-30: Average PV Generation of One Sunny Tripower Core1 PV System in Same, Tanzania

Using the energy production profile generated in Figure 5-30, a single Sunny Tripower Core1 PV system can produce 496.65 kWh daily. The 671.1 kilowatts DC system modeled in ETAP can produce 4,631 kWh of energy daily using the 71.9 kilowatts DC system energy profile as a template for calculations. According to PVWatts, the 665 kilowatts DC system is expected to produce an average of 2,552 kWh per day. According to the ETAP graphs, the 671.1 kilowatts DC system is producing about 80 percent more energy than expected. According to an ETAP tutorial video, the differences in the simulation and "real-time" measurements comes from degradation factors: utilizing averages, shading, surface dirt, temperature and more [65]. The NREL overall degradation factor is set at 0.75. Using the degradation factor, the amount of energy the 71.9 kilowatts DC system can produce equals to 1,200 kWh. Adjusting that to a 665 kilowatts DC system produces 11,098 kWh per day. Factoring in the 0.75 degradation factor, the 665 kilowatts DC system is expected to produce 2,774 kWh, much closer to the energy production predicted using PVWatts.

The energy production curve will be modified in order to adjust for the degradation factors. The modifications are made to the 71.9 kilowatts DC system in order to match the expected daily energy produced for a day. The 71.9 DC system is then scaled up to the designed 671.1 kilowatts DC system. The modified energy production profile shown in Figure 5-31 produces 2,781 kWh per day – 0.25 percent higher than the expected degraded energy production.

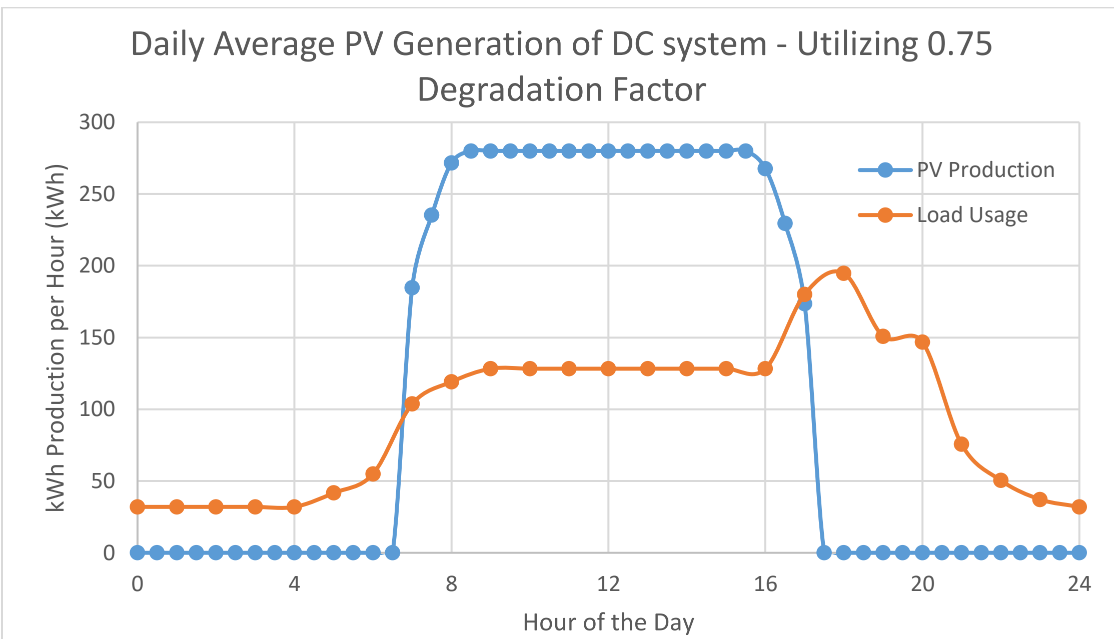

Figure 5-31: Average PV Generation of Entire DC system with Degradation Factor

Figure 5-31 overlays the daily energy production of the PV system over the load energy usage. Between 6:30 am and 5:30 pm, the PV system is able to support the load while also producing enough energy to charge the batteries. During the times when the PV system is not able to produce enough energy for the load, the charge controller will utilize the battery system as the power source. Taking the integral of these curves, the area under the curves, will show that the daily energy produced by the PV system is greater than the energy usage. It is important to make sure the energy production is greater than the usage for three reasons: so that the battery can charge to its maximum potential, the battery can support the daily night loads and hold enough charge in case of days of autonomy. The extra energy that the battery cannot store will be wasted in a dump load. This ensure that the batteries do not swell from overcharge, making the system safer.

The normal operating current load flow of the system is shown in Figure 5-32 with the largest current at 379.3 amperes returning to the utility. Once again, a full DC system will not include the power grid. An isolated PV system is not practical because of how large the battery bank has to be to accommodate consecutive cloudy days. The largest current will be 379.3 amperes going into a battery system instead of the power grid. After running the short circuit analysis, the highest peak current comes from a double line to ground fault at Bus 2, running at 7.0 kilo-amperes. The short circuit analysis results are listed in Table 5-3.

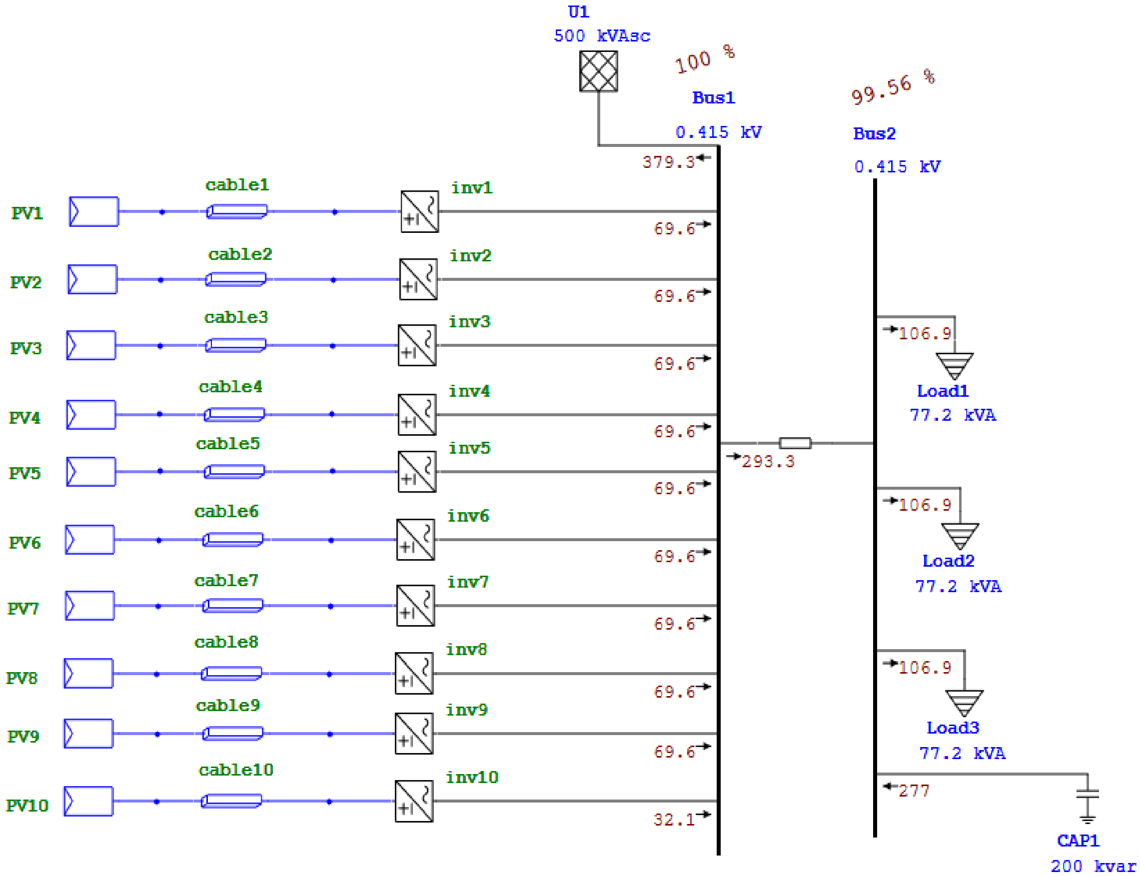

Figure 5-32: Current Flow Analysis of DC System

Table 5-3: Short Circuit Analysis of DC System

Bus Fault	Results		3-Phase	L-G	L-L	L-L-G
Bus 1	Initial Symmetrical Current (kA, rms)	:	1.818	2.726	1.575	3.150
	Peak Current (kA), Method C	:	4.043	6.061	3.501	7.004
	Breaking Current (kA, rms, symm)	:		2.726	1.575	3.150
	Steady State Current (kA, rms)	:	1.818	2.726	1.575	3.150
Bus 2			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	1.086	0.782	0.941	1.117
	Peak Current (kA), Method C	:	1.978	1.424	1.713	2.033
	Breaking Current (kA, rms, symm)	:		0.782	0.941	1.117
	Steady State Current (kA, rms)	:	1.086	0.782	0.941	1.117

One way to improve the DC system reliability is to properly size the battery system. A reliable battery system must account for days of autonomy, forcing the battery bank to be very large and costly. PV systems that are integrated in homes today typically have a battery life that can support the customer's nightly load. The battery does not have enough storage to support these customers during days of autonomy; in which the PV system does not generate power for multiple days. These customers are commonly connected to the utility grid and operate on the utility power when the PV system and batteries cannot support that load. Adding a fuel based generator to the DC system is one solution to reduce the size of the battery, but defeats the notion of zero-net-energy that the DC system strives to obtain. The last solution to improve the DC system reliability and reduce the battery bank size is to prioritize different sections of campus that have to be powered. During days of autonomy, sections of campus can be closed off in order to conservatively use the battery's stored energy.

5.4 System Design: Mixed AC and DC System Design

This section details the design and simulation of the iterative AC and DC system design. The AC contribution of the design follows the full AC system design shown in Figure 5-11. The DC contribution follows the full DC system design with modifications on the amount of PV arrays and inverters in order to size and scale the system correctly. Each iteration simulates the load flow, the current flow, and the short circuit analysis. The PV arrays, inverters, and compensating capacitor are the main changes between each successive mixed design.

It is important to understand how the PV system differs from a full DC design. As mentioned in Chapter 4, Load Profile Two is the governing energy profile for the system. The annual load usage is predicted to consume about 854 MWhs of energy. According to the PVWatts calculator, a 610 kilowatts DC system will be able to provide sufficient energy annually. The PV system is sized to 665 kilowatts in order to compensate for days of lower irradiance in the full DC system design. The AC portion of the mixed system design can compensate for the days of lower irradiance. Theoretically, a 610 kilowatts DC design can produce 100 percent of the energy needed in a mixed system design. For the mixed designs, the DC percentage will be taken from the base 610 kilowatts DC.

It is also important to understand how the battery bank differs from a full DC design. In the DC design, the only source of power comes from the PV arrays and its battery bank. The battery bank has to be sized for two conditions: to provide enough energy for the nightly loads and to provide enough storage to account for three days of autonomy. In the mixed design, the battery is setup to operate when the utility grid is down. The load of the school will be supported by the PV system during sun hours and supported by the grid once the load demand is greater than the PV supply. The battery backup will support the load in case of any power outages from the grid. Power outages in Same is common – blacking out about twice a week and lasting for three hours. The battery must be sized for the three worst-case load hours. Using Load Profile Two shown in Figure 4-14, the three worst case load hours are between 5 pm and 8 pm. The load is predicted to consume 525.6 kWh of energy during this time. The battery must be sized to store and support 525.6 kWh of energy for all of the mixed system designs.

5.5 Mixed System Design: 10 percent DC

The PV panel, array string, and inverter match the DC design in order to maintain consistency. In this mixed system design, the PV array is set with 11 strings of 25 panels – totaling to a 65.91 kilowatts DC design. Running 10 strings of 25 panels only produces 59.92 kilowatts DC. The output of the inverter is adjusted in order to conform to the degradation factor mentioned in Section 5.3. The DC load flow is assumed to operate at the average irradiance during sun hours. During most of the sun hours, the PV panels are able to produce more than enough power to output the maximum AC power as shown in Figure 5-30. By factoring in the degradation factor, the AC output of the inverter is assumed to be 30 kilowatts when loaded at with 12 strings of 25 solar panels – a 71.9 kilowatts DC system. The AC load flow in Figure 5-33 shows that the voltages and power flow meet the requirements to support the load. The PV array is able to reduce that amount of power drawn from the utility by a total of 27.5 kilowatts. Figure 5-34 shows the normal operating current with a high of 278.2 amperes at the capacitor. Table 5-4 lists the short circuit current at varying faults – highest fault current of 2.7 kilo-amperes at Bus 2. Figure

5-35 overlays the energy generated by the PV system with the energy used by the college. In this mixed design, the PV generation is not able to supply enough energy during the sun hours. This system relies heavily on the utility to operate throughout the entire day.

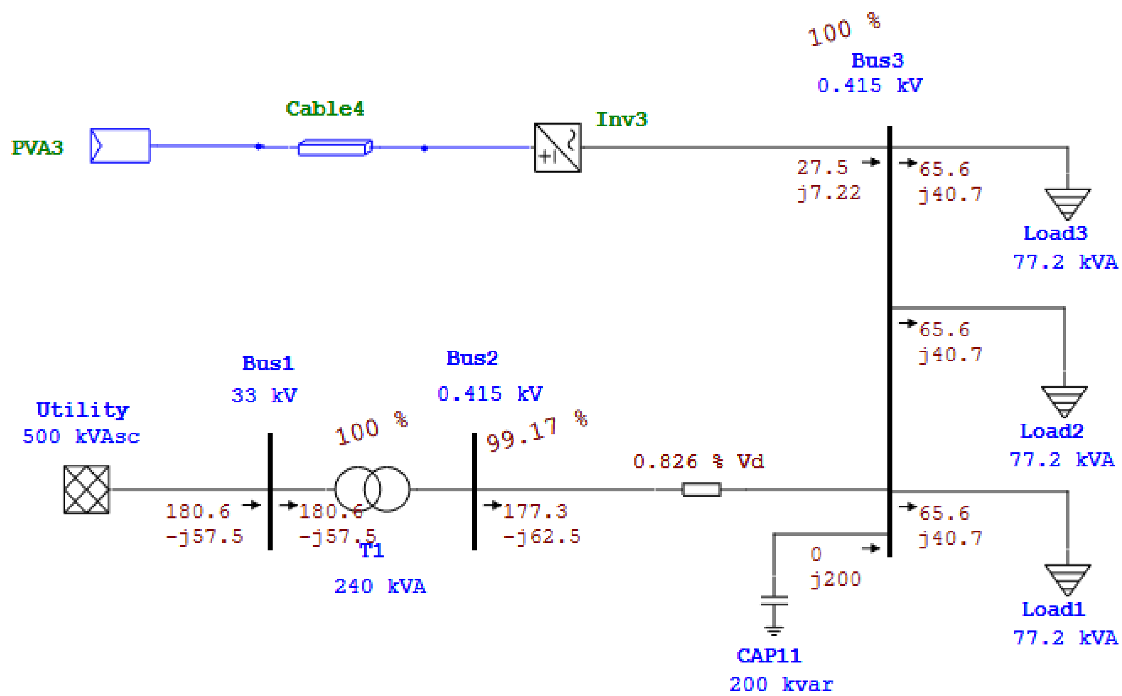

Figure 5-33: Load Flow Analysis of Mixed Design - 10% DC

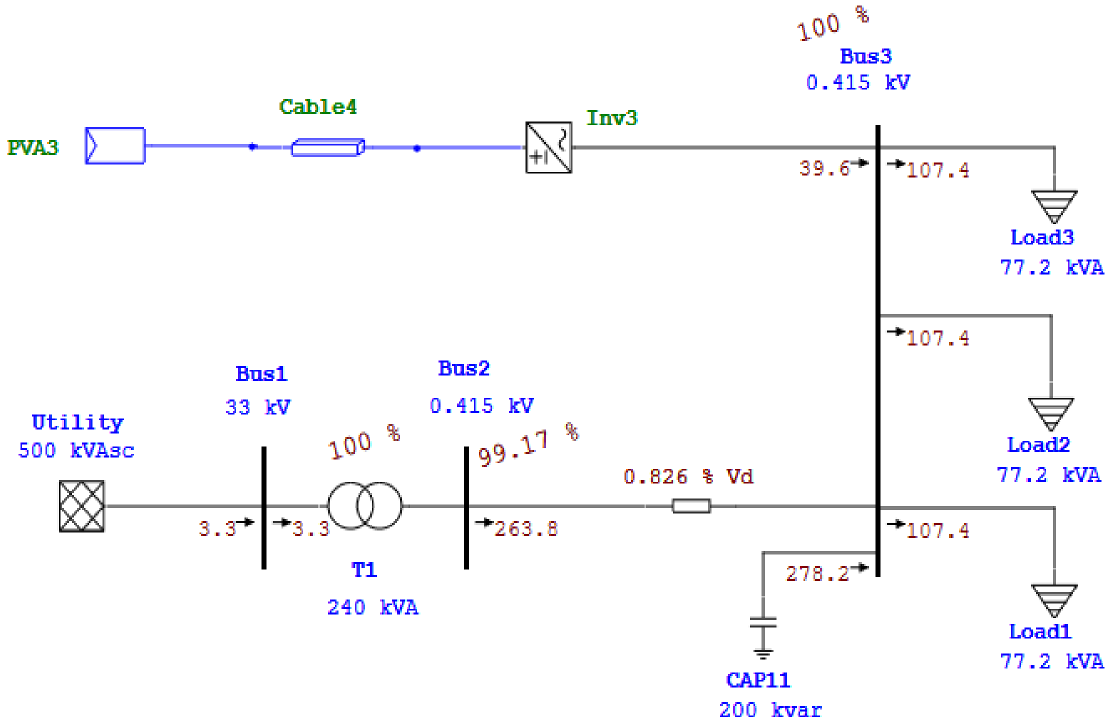

Figure 5-34: Current Flow Analysis of Mixed Design – 10% DC

Table 5-4: Short Circuit Analysis of Mixed Design – 10% DC

Bus Fault	**Results**					
Bus 1			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.009	0.013	0.008	0.014
	Peak Current (kA), Method C	:	0.025	0.034	0.021	0.036
	Breaking Current (kA, rms, symm)	:		0.013	0.008	0.014
	Steady State Current (kA, rms)	:	0.009	0.013	0.008	0.014
Bus 2			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.672	0.972	0.582	1.068
	Peak Current (kA), Method C	:	1.704	2.466	1.476	2.709
	Breaking Current (kA, rms, symm)	:		0.972	0.582	1.068
	Steady State Current (kA, rms)	:	0.672	0.972	0.582	1.068
Bus 3			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.539	0.504	0.467	0.564
	Peak Current (kA), Method C	:	1.328	1.243	1.150	1.391
	Breaking Current (kA, rms, symm)	:		0.504	0.467	0.564
	Steady State Current (kA, rms)	:	0.539	0.504	0.467	0.564

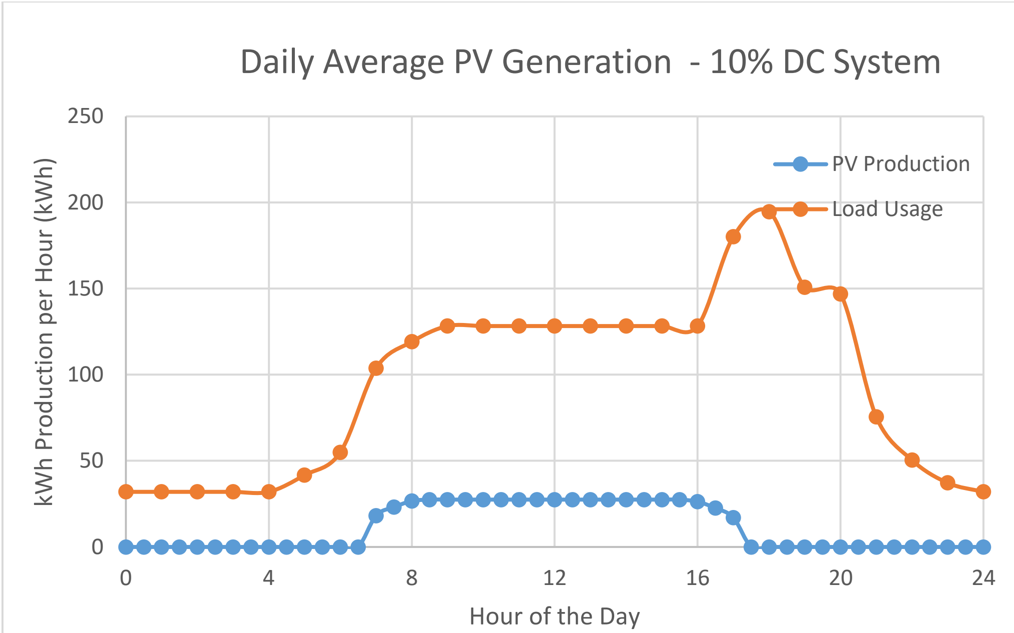

Figure 5-35: Daily Average PV Generation and Load Usage – 10% DC Mixed Design

5.6 Mixed System Design: 20 percent DC

In this mixed system design, one PV array is set with 11 strings of 25 panels and another at 10 strings of 25 panels – totaling to a 125.79 kilowatts DC design. The assumptions regarding the output of the inverter, the DC load flow, and the degradation factor remain. The AC load flow in Figure 5-36 shows that the voltages and power flow meet the requirements to support the load while reducing the capacitance to 180 kvar. The PV array is able to reduce the amount of power drawn from the utility by a total of 52.5 kilowatts. Figure 5-37 shows the normal operating current with a high of 250.4 amperes at the capacitor. Table 5-5 lists the short circuit current at varying faults – highest fault current of 2.56 kilo-amperes at Bus 2. Figure 5-38 overlays the energy generated by the PV system with the energy used by the college. In this mixed design, the

PV generation is not able to supply enough energy during the sun hours. This system relies heavily on the utility to operate throughout the entire day, much like the 10 percent DC mixed design.

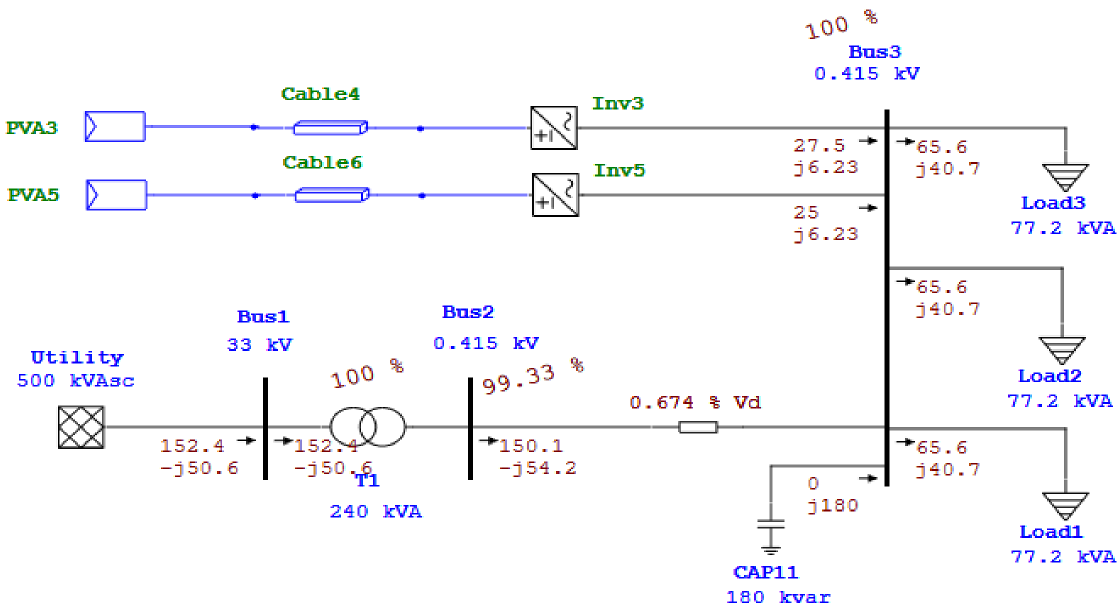

Figure 5-36: Load Flow Analysis of Mixed Design - 20% DC

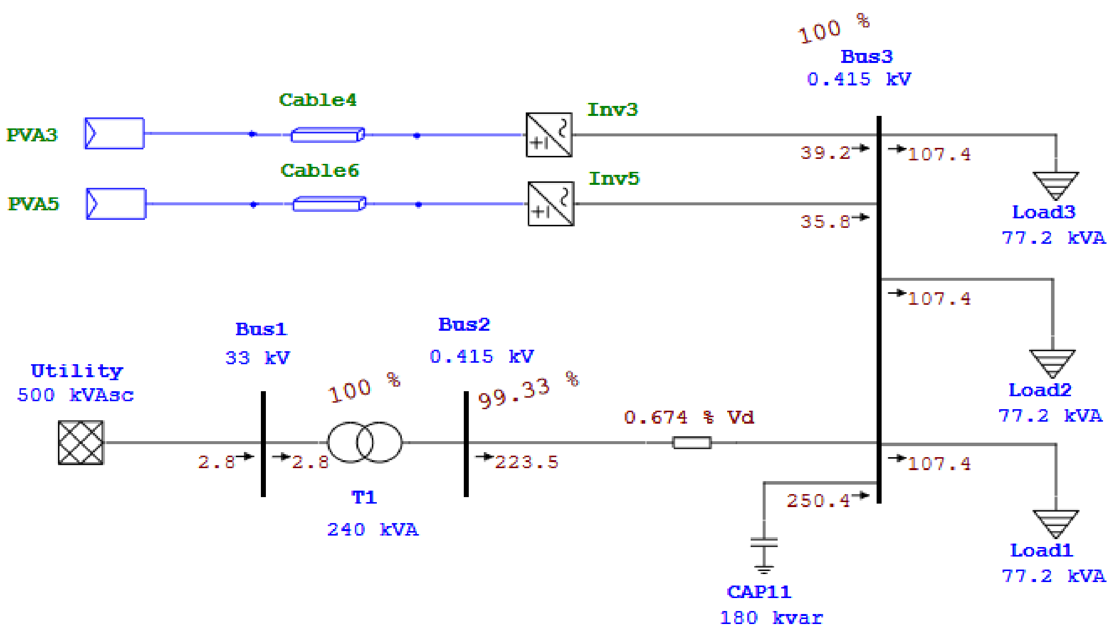

Figure 5-37: Current Flow Analysis of Mixed Design – 20% DC

Table 5-5: Short Circuit Analysis of Mixed Design – 20% DC

Bus Fault	Results					
Bus 1			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.010	0.014	0.009	0.015
	Peak Current (kA), Method C	:	0.024	0.032	0.021	0.035
	Breaking Current (kA, rms, symm)	:		0.014	0.009	0.015
	Steady State Current (kA, rms)	:	0.010	0.014	0.009	0.015
Bus 2			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.762	1.096	0.660	1.183
	Peak Current (kA), Method C	:	1.649	2.372	1.428	2.561
	Breaking Current (kA, rms, symm)	:		1.096	0.660	1.183
	Steady State Current (kA, rms)	:	0.762	1.096	0.660	1.183
Bus 3			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.629	0.567	0.545	0.680
	Peak Current (kA), Method C	:	1.560	1.405	1.351	1.687
	Breaking Current (kA, rms, symm)	:		0.567	0.545	0.680
	Steady State Current (kA, rms)	:	0.629	0.567	0.545	0.680

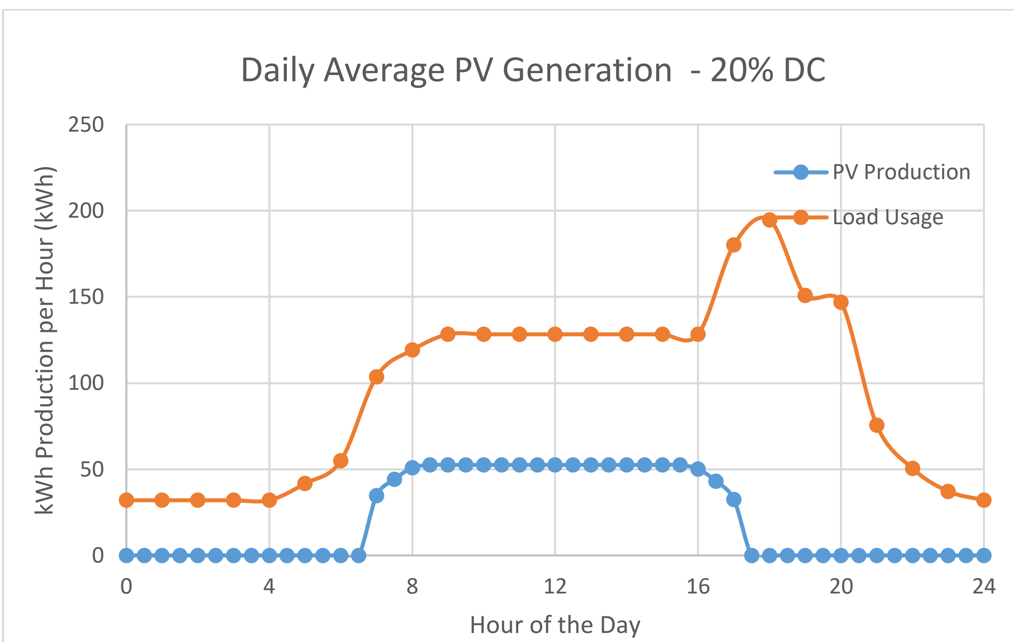

Figure 5-38: Daily Average PV Generation and Load Usage – 20% DC Mixed Design

5.7 Mixed System Design: 30 percent DC

In this mixed system design, one PV array is set with 11 strings of 25 panels and another two with 10 strings of 25 panels – totaling to a 185.69 kilowatts DC design. The assumptions regarding the output of the inverter, the DC load flow, and the degradation factor remain. The AC load flow in Figure 5-39 shows that the voltages and power flow meet the requirements to support the load. When the capacitor is set to 200 kvar, the bus voltage of Bus 3 operates at 101.5 percent, while reducing the capacitance to 180 kvar causes the bus voltage to operate at 100 percent. The PV array is able to reduce the amount of power drawn from the utility by a total of 77.5 kilowatts. Figure 5-40 shows the normal operating current with a high of 282.4 amperes at the capacitor. Table 5-6 lists the short circuit current at varying faults – highest fault current of 2.79 kilo-amperes at Bus 2. Figure 5-41 overlays the energy generated by the PV system with the energy used by the college. In this mixed design, the PV generation is not able to supply enough energy during the sun hours. This system relies heavily on the utility to operate throughout the entire day, much like the 10 and 20 percent DC mixed design.

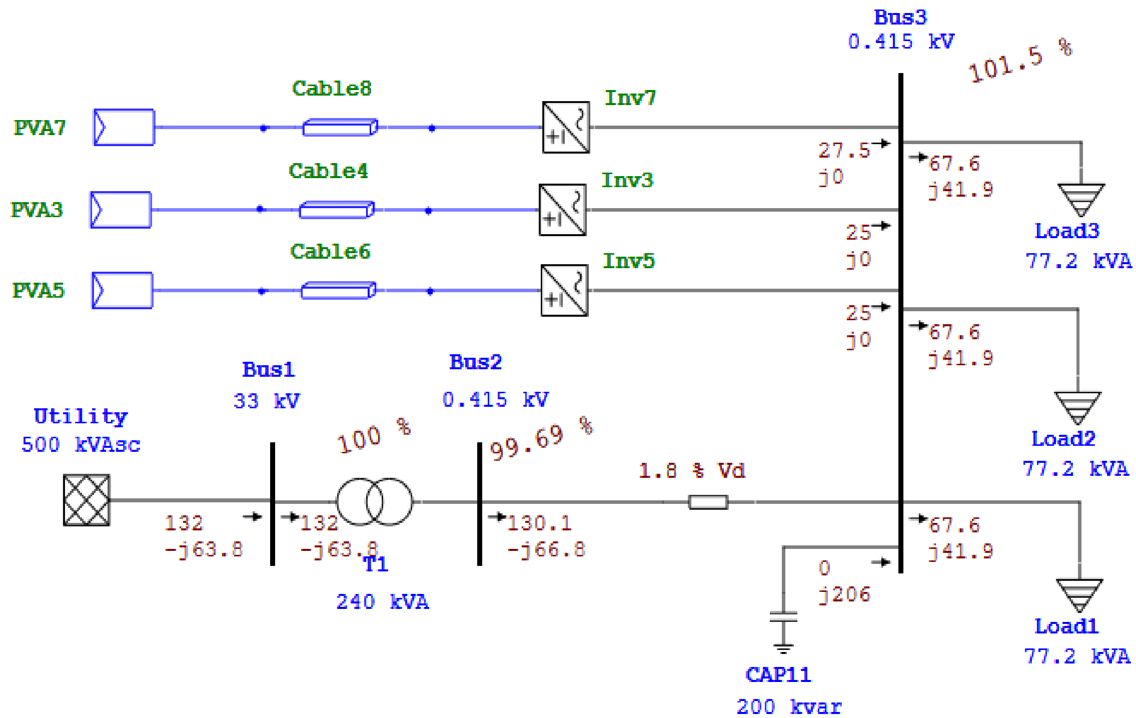

Figure 5-39: Load Flow Analysis of Mixed Design - 30% DC

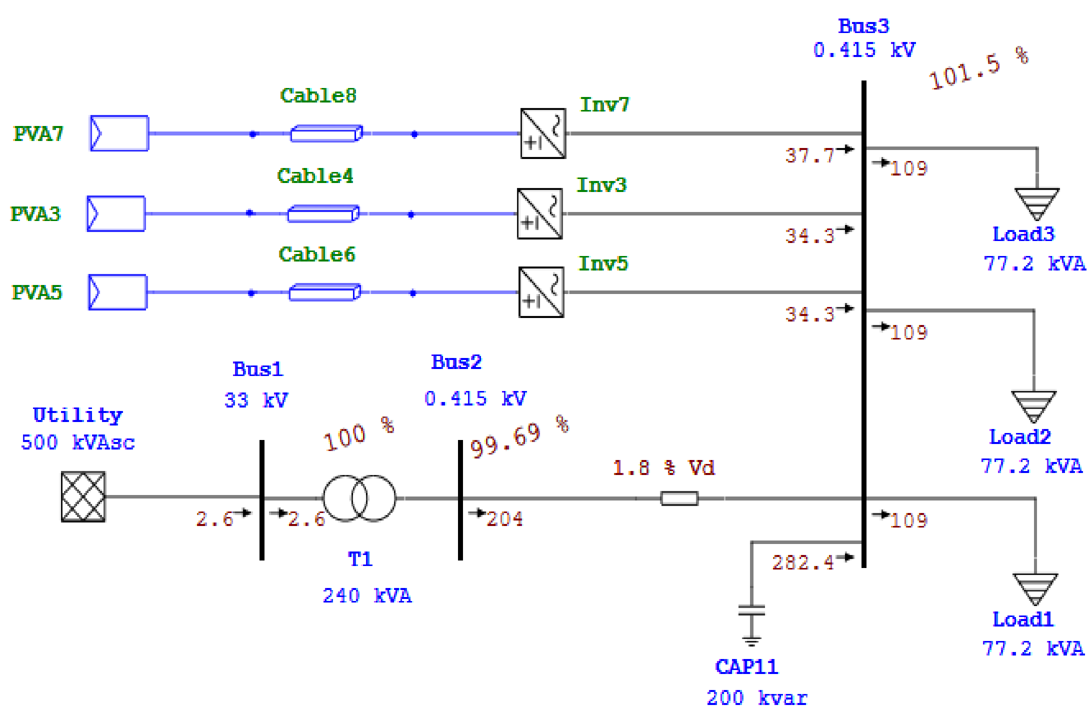

Figure 5-40: Current Flow Analysis of Mixed Design – 30% DC

Table 5-6: Short Circuit Analysis of Mixed Design – 30% DC

Bus Fault	Results					
Bus 1			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.012	0.016	0.010	0.017
	Peak Current (kA), Method C	:	0.026	0.035	0.022	0.038
	Breaking Current (kA, rms, symm)	:		0.016	0.010	0.017
	Steady State Current (kA, rms)	:	0.012	0.016	0.010	0.017
Bus 2			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.871	1.247	0.755	1.334
	Peak Current (kA), Method C	:	1.821	2.606	1.577	2.789
	Breaking Current (kA, rms, symm)	:		1.247	0.755	1.334
	Steady State Current (kA, rms)	:	0.871	1.247	0.755	1.334
Bus 3			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.744	0.639	0.644	0.812
	Peak Current (kA), Method C	:	1.793	1.540	1.552	1.956
	Breaking Current (kA, rms, symm)	:		0.639	0.644	0.812
	Steady State Current (kA, rms)	:	0.744	0.639	0.644	0.812

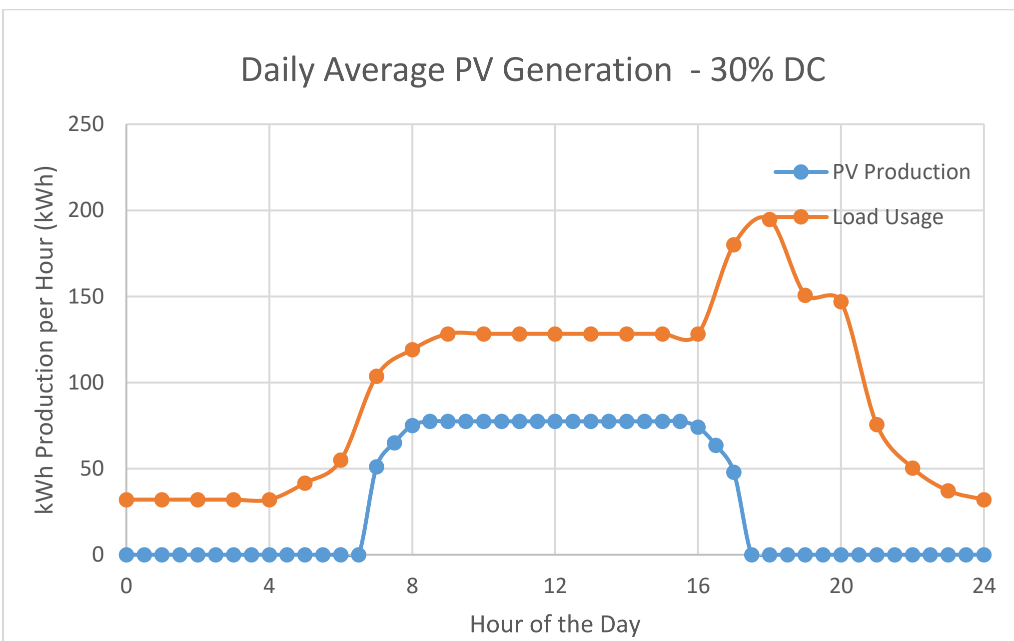

Figure 5-41: Daily Average PV Generation and Load Usage – 30% DC Mixed Design

5.8 Mixed System Design: 40 percent DC

In this mixed system design, one PV array is set with 11 strings of 25 panels and another three with 10 strings of 25 panels – totaling to a 245.59 kilowatts DC design. The assumptions regarding the output of the inverter, the DC load flow, and the degradation factor remain. The AC load flow in Figure 5-42 shows that the voltages and power flow meet the requirements to support the load. When the capacitor is set to 200 kvar, the bus voltage of Bus 3 operates at 102.4 percent, remaining within the acceptable 5 percent range. The PV array is able to reduce the amount of power drawn from the utility by a total of 102.5 kilowatts. Figure 5-43 shows the normal operating current with a high of 285.2 amperes at the capacitor. Table 5-7 lists the short circuit current at varying faults – highest fault current of 3.05 kilo-amperes at Bus 2. Figure 5-44 overlays the energy generated by the PV system with the energy used by the college. In this mixed design, the PV generation is not able to supply enough energy during the sun hours. This system relies on the utility to operate throughout the entire day, but not as heavily as the previous mixed designs.

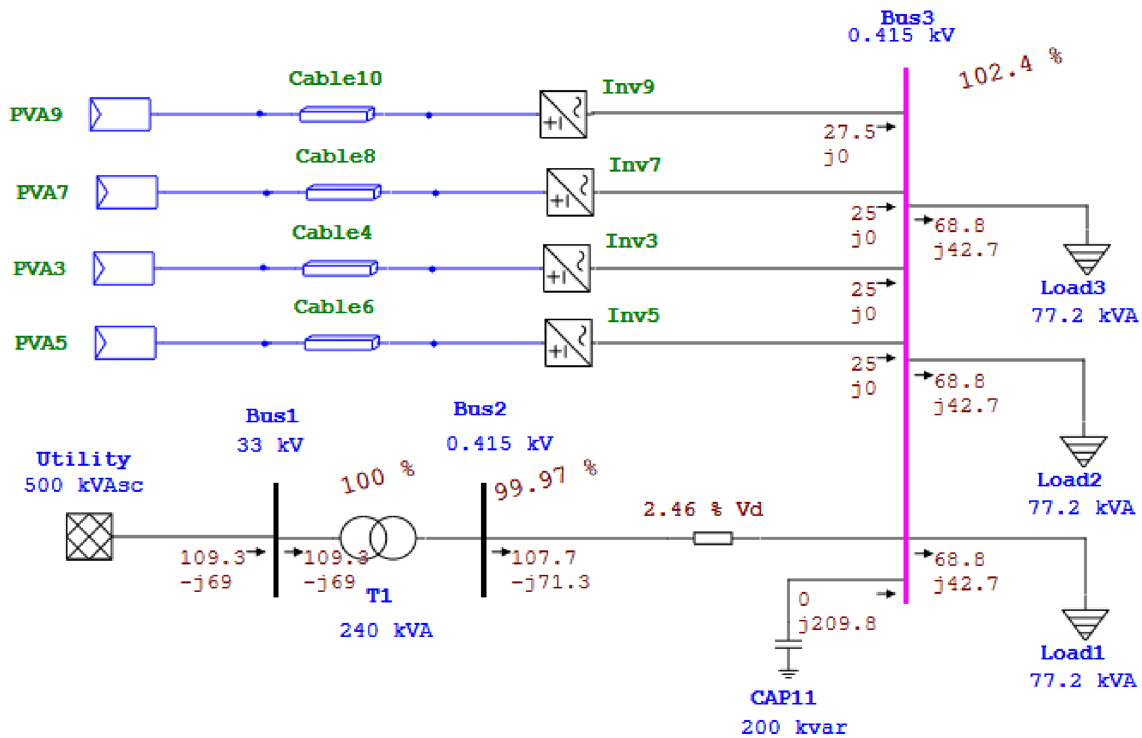

Figure 5-42: Load Flow Analysis of Mixed Design - 40% DC

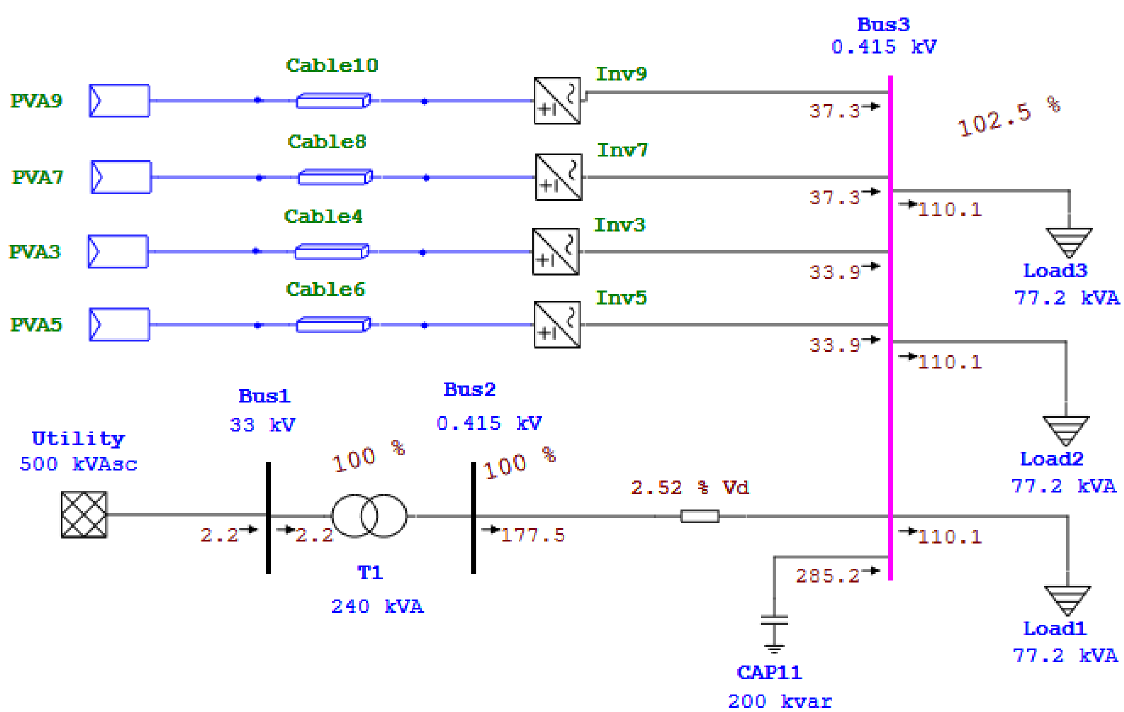

Figure 5-43: Current Flow Analysis of Mixed Design – 40% DC

Table 5-7: Short Circuit Analysis of Mixed Design – 40% DC

Bus Fault	Results		3-Phase	L-G	L-L	L-L-G
Bus 1	Initial Symmetrical Current (kA, rms)	:	0.013	0.018	0.011	0.019
	Peak Current (kA), Method C	:	0.028	0.038	0.024	0.041
	Breaking Current (kA, rms, symm)	:		0.018	0.011	0.019
	Steady State Current (kA, rms)	:	0.013	0.018	0.011	0.019
Bus 2	Initial Symmetrical Current (kA, rms)	:	0.988	1.405	0.855	1.500
	Peak Current (kA), Method C	:	2.006	2.853	1.737	3.046
	Breaking Current (kA, rms, symm)	:		1.405	0.855	1.500
	Steady State Current (kA, rms)	:	0.988	1.405	0.855	1.500
Bus 3	Initial Symmetrical Current (kA, rms)	:	0.874	0.712	0.757	0.950
	Peak Current (kA), Method C	:	2.025	1.650	1.754	2.202
	Breaking Current (kA, rms, symm)	:		0.712	0.757	0.950
	Steady State Current (kA, rms)	:	0.874	0.712	0.757	0.950

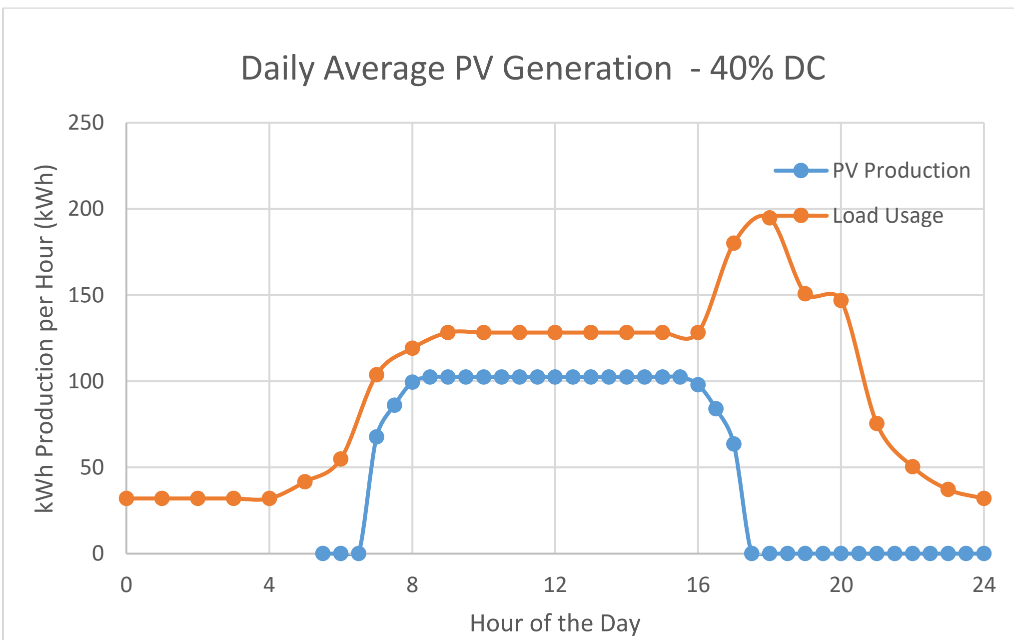

Figure 5-44: Daily Average PV Generation and Load Usage – 40% DC Mixed Design

5.9 Mixed System Design: 50 percent DC

In this mixed system design, one PV array is set with 11 strings of 25 panels and another four with 10 strings of 25 panels – totaling to a 305.49 kilowatts DC design. The assumptions regarding the output of the inverter, the DC load flow, and the degradation factor remain. The AC load flow in Figure 5-45 shows that the voltages and power flow meet the requirements to support the load. When the capacitor is set to 200 kvar, the bus voltage of Bus 3 operates at 103.3 percent, remaining within the acceptable 5 percent range. The PV array is able to reduce the amount of power drawn from the utility by a total of 127.5 kilowatts. Figure 5-46 shows the normal operating current with a high of 287.5 amperes at the capacitor. Table 5-8 lists the short circuit current at varying faults – highest fault current of 3.05 kilo-amperes at bus 2. Figure 5-47 overlays the energy generated by the PV system with the energy used by the college. In this mixed design, the PV generation can supply nearly enough energy to the load. Between 9 am and 4 pm, the load is predicted to operate at 128.3 kilowatts. The DC system is able to supply 127.5 kilowatts during that time. This system will have to rely on the utility to operate throughout the entire day, but draws only 0.8 kilowatts from the utility.

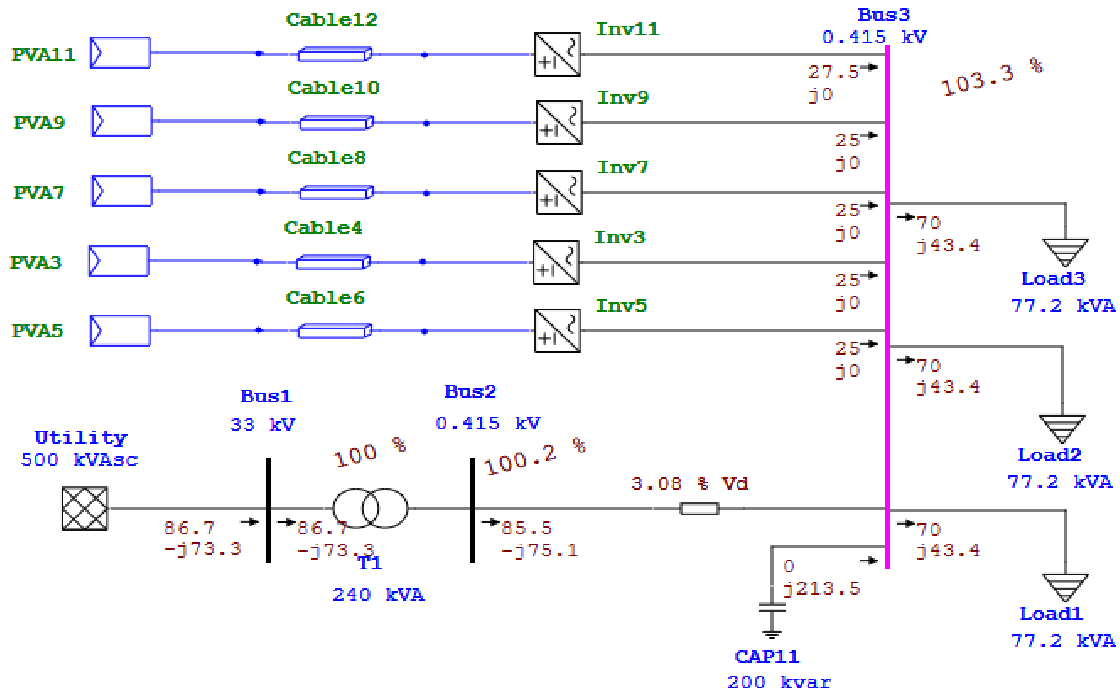

Figure 5-45: Load Flow Analysis of Mixed Design - 50% DC

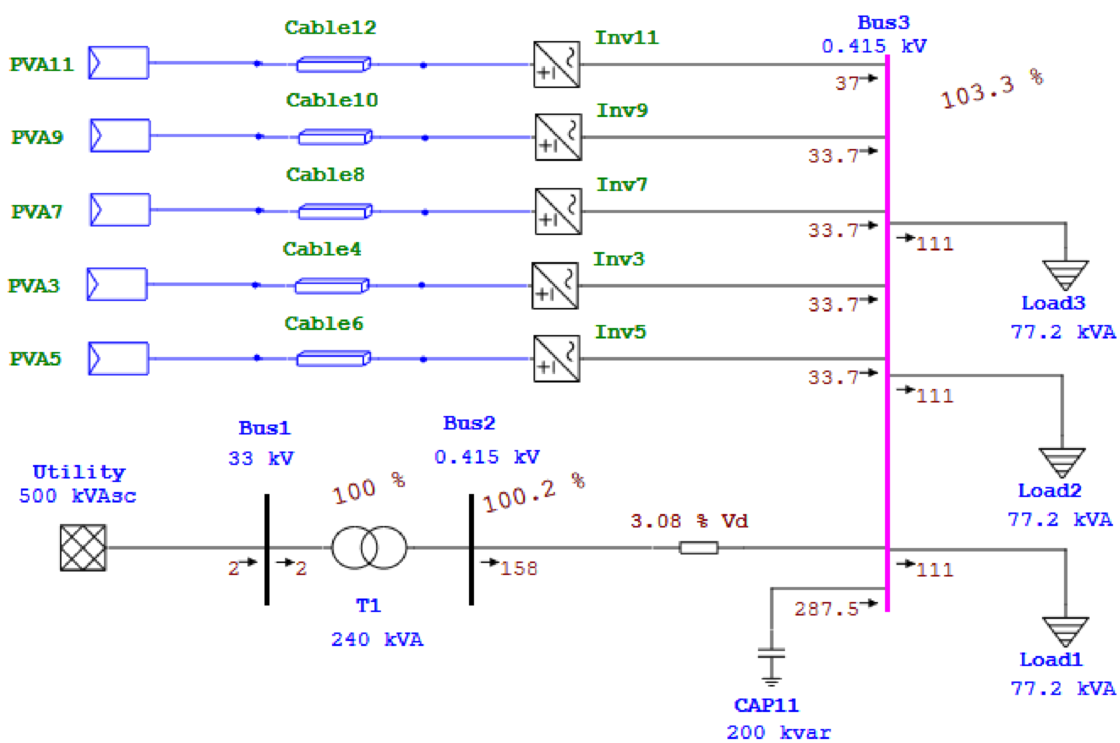

Figure 5-46: Current Flow Analysis of Mixed Design – 50% DC

Table 5-8: Short Circuit Analysis of Mixed Design – 50% DC

Bus Fault	Results					
Bus 1			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.015	0.020	0.013	0.021
	Peak Current (kA), Method C	:	0.030	0.041	0.026	0.044
	Breaking Current (kA, rms, symm)	:		0.020	0.013	0.021
	Steady State Current (kA, rms)	:	0.015	0.020	0.013	0.021
Bus 2			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.988	1.405	0.855	1.500
	Peak Current (kA), Method C	:	2.006	2.853	1.737	3.046
	Breaking Current (kA, rms, symm)	:		1.405	0.855	1.500
	Steady State Current (kA, rms)	:	0.988	1.405	0.855	1.500
Bus 3			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	1.012	0.779	0.877	1.091
	Peak Current (kA), Method C	:	2.258	1.737	1.955	2.433
	Breaking Current (kA, rms, symm)	:		0.779	0.877	1.091
	Steady State Current (kA, rms)	:	1.012	0.779	0.877	1.091

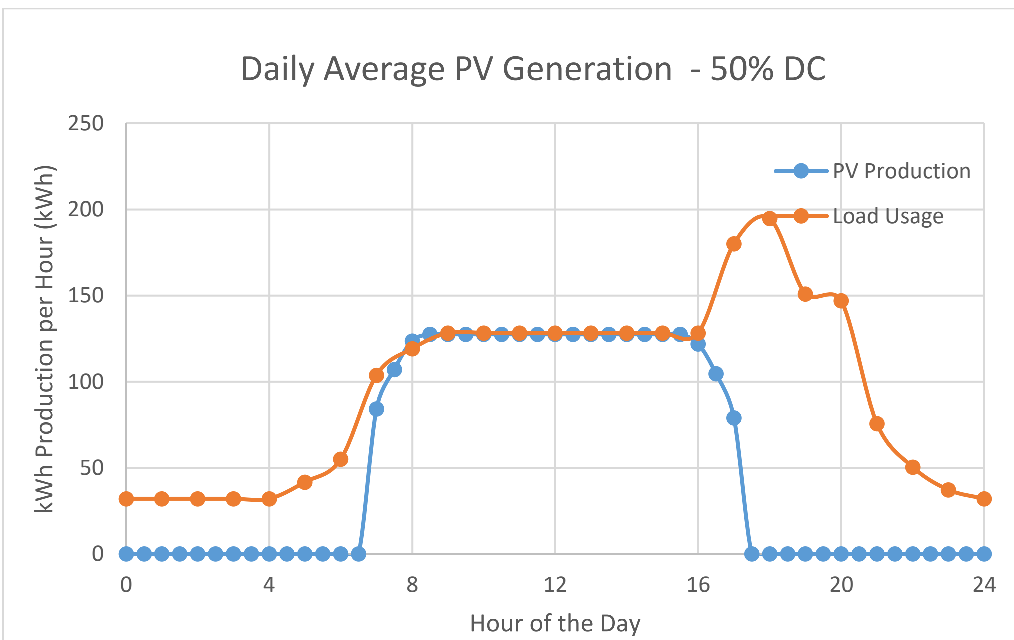

Figure 5-47: Daily Average PV Generation and Load Usage – 50% DC Mixed Design

5.10 Mixed System Design: 60 percent DC

In this mixed system design, two PV arrays are set with 11 strings of 25 panels and another four with 10 strings of 25 panels – totaling to a 371.38 kilowatts DC design. The assumptions regarding the output of the inverter, the DC load flow, and the degradation factor remain. The AC load flow in Figure 5-48 shows that the voltages and power flow meet the requirements to support the load. When the capacitor is set to 200 kvar, the bus voltage of Bus 3 operates at 104.2 percent, remaining within the acceptable 5 percent range. The PV array is able to reduce the amount of power drawn from the utility by a total of 155 kilowatts. Figure 5-49 shows the normal operating current with a high of 290.1 amperes at the capacitor. Table 5-9 lists the short circuit current at varying faults – highest fault current of 3.52 kilo-amperes at Bus 2. Figure 5-50 overlays the energy generated by the PV system with the energy used by the college. In this mixed design, the PV generation is able to supply enough energy to the load during the sun hours. The PV system is estimated to generate an extra 260 kWh of energy per day. The extra energy is used to charge up the battery. As mentioned in Section 5.4, the battery is sized to store up to 525.6 kWh of energy. The PV system can charge the battery within two days according to these estimations.

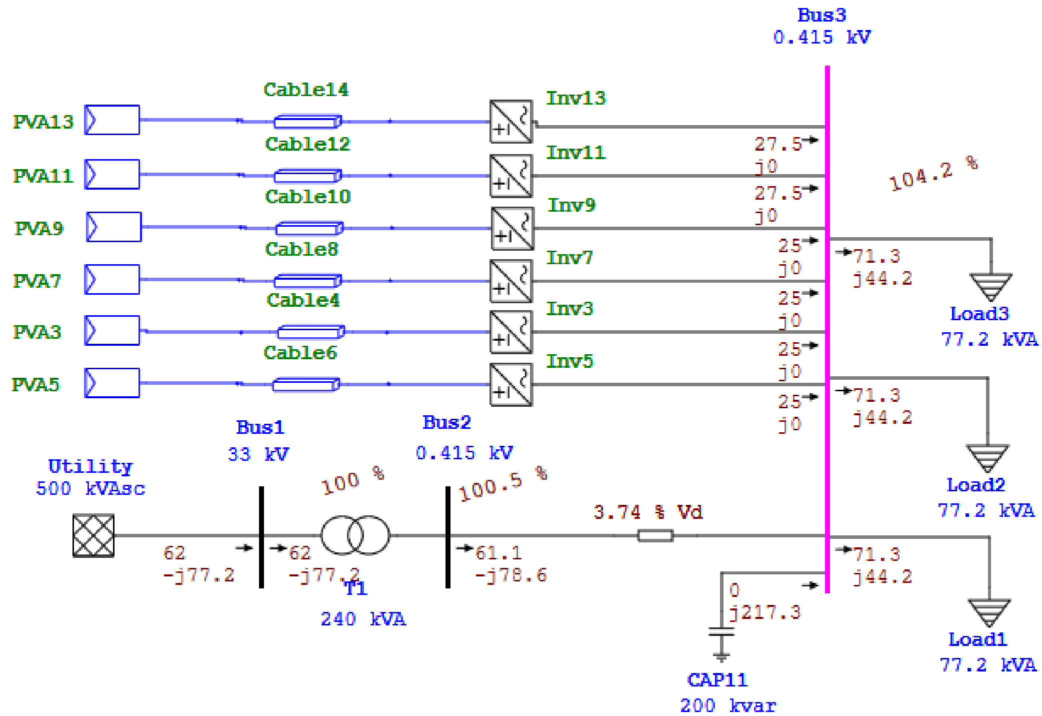

Figure 5-48: Load Flow Analysis of Mixed Design - 60% DC

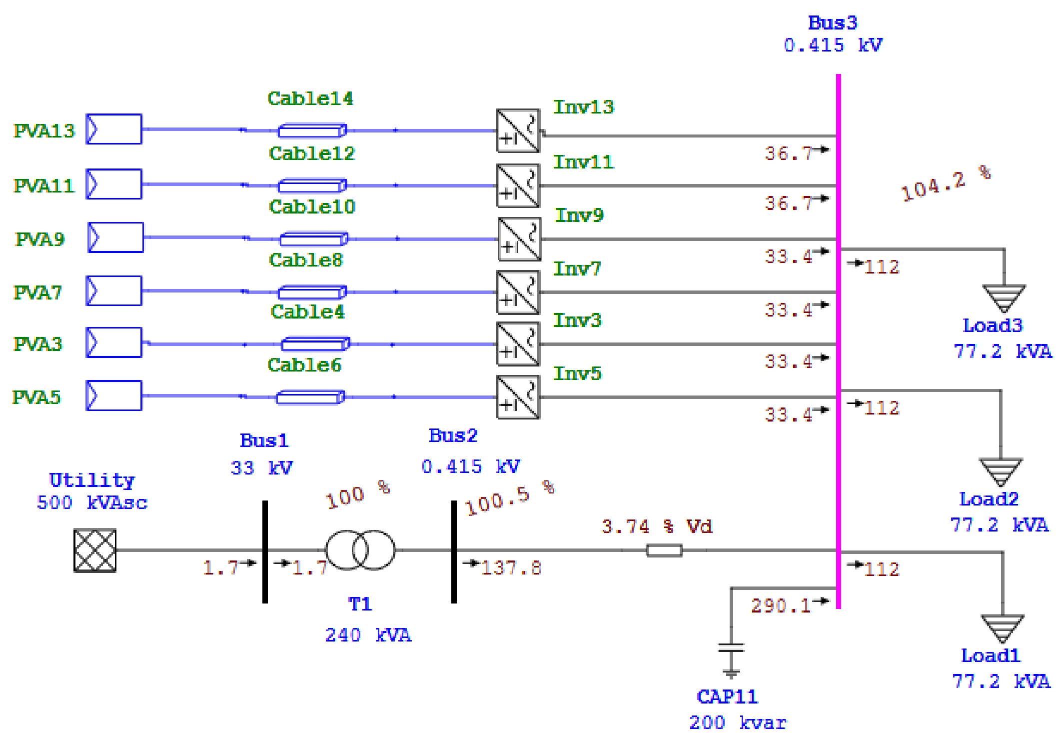

Figure 5-49: Current Flow Analysis of Mixed Design – 60% DC

Table 5-9: Short Circuit Analysis of Mixed Design – 60% DC

Bus Fault	Results					
Bus 1			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.016	0.021	0.014	0.023
	Peak Current (kA), Method C	:	0.033	0.043	0.028	0.047
	Breaking Current (kA, rms, symm)	:		0.021	0.014	0.023
	Steady State Current (kA, rms)	:	0.016	0.021	0.014	0.023
Bus 2			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	1.214	1.707	1.051	1.808
	Peak Current (kA), Method C	:	2.362	3.320	2.045	3.518
	Breaking Current (kA, rms, symm)	:		1.707	1.051	1.808
	Steady State Current (kA, rms)	:	1.214	1.707	1.051	1.808
Bus 3			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	1.157	0.839	1.002	1.232
	Peak Current (kA), Method C	:	2.490	1.805	2.157	2.653
	Breaking Current (kA, rms, symm)	:		0.839	1.002	1.232
	Steady State Current (kA, rms)	:	1.157	0.839	1.002	1.232

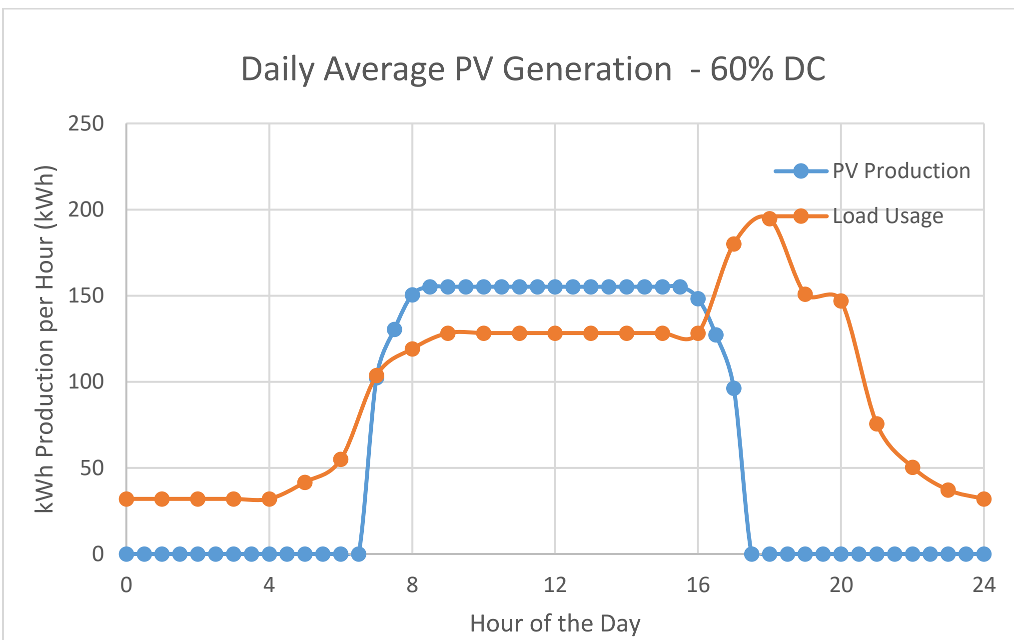

Figure 5-50: Daily Average PV Generation and Load Usage – 60% DC Mixed Design

5.11 Mixed System Design: 70 percent DC

In this mixed system design, six PV arrays are set with 12 strings of 25 panels – totaling to a 431.28 kilowatts DC design. The assumptions regarding the output of the inverter, the DC load flow, and the degradation factor remain. The AC load flow in Figure 5-51 shows that the voltage at Bus 3 falls outside of the acceptable 5 percent range, operating at 105.1 percent. In order to reduce the voltage level, the capacitor size has to be sized down. Reducing the compensating capacitor size has the greatest effect on the voltage level of the AC portion of the mixed design. In order to understand how the reduction affects the AC portion of the mixed system, Figure 5-52 simulates the load flow with the AC portion of the system isolated. The capacitor can only be reduced to 150 kvar before operating within the acceptable 5 percent range. The new mixed design load flow simulation incorporates the 150 kvar capacitor, reducing the voltage level to 101.5 percent - shown in Figure 5-53. The PV array is able to reduce the amount of power drawn from the utility by a total of 180 kilowatts. Figure 5-54 shows the normal operating current with a high of 211.7 amperes at the capacitor. Table 5-10 lists the short circuit current at varying faults – highest fault current of 3.52 kilo-amperes at Bus 2. Figure 5-55 overlays the energy generated by the PV system with the energy used by the college. In this mixed design, the PV generation is able to supply enough energy to the load during the sun hours. The PV system is estimated to generate an extra 510 kWh of energy per day. The extra energy is used to charge up the battery, charging the battery near its full capacity within a single day.

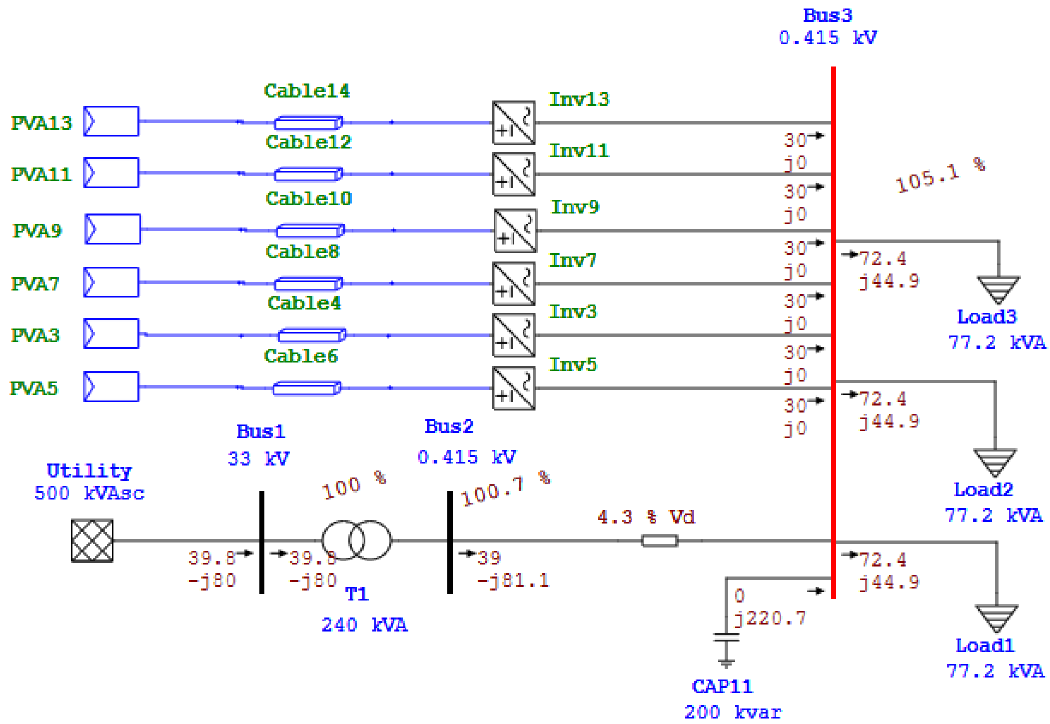

Figure 5-51: Load Flow Analysis of Mixed Design - 70% DC

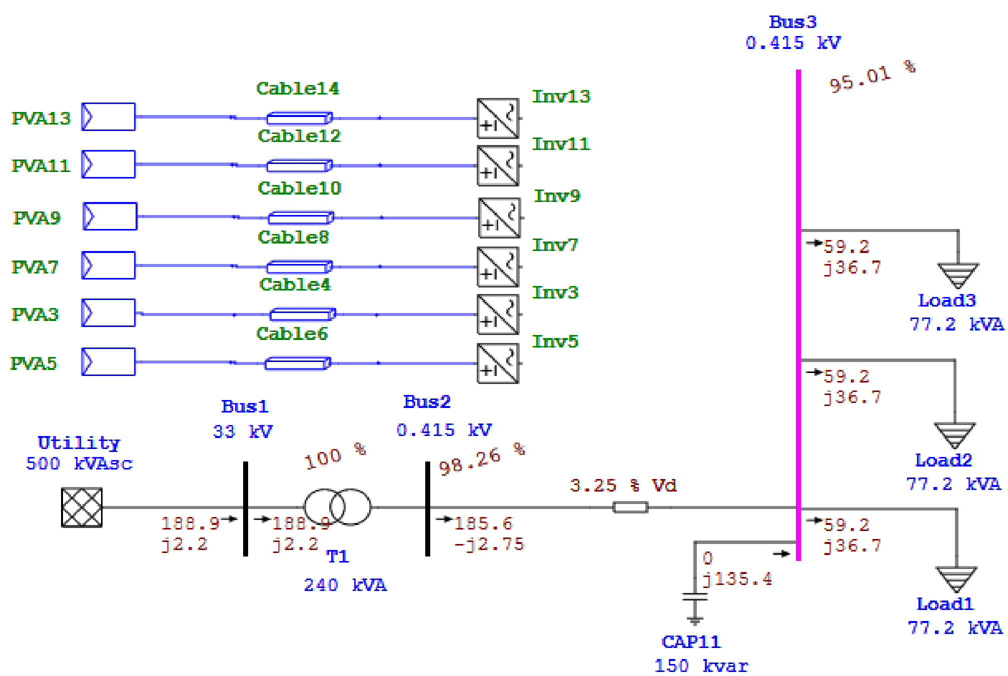

Figure 5-52: Load Flow Analysis of Isolated AC portion with Adjusted Capacitor – 70% DC

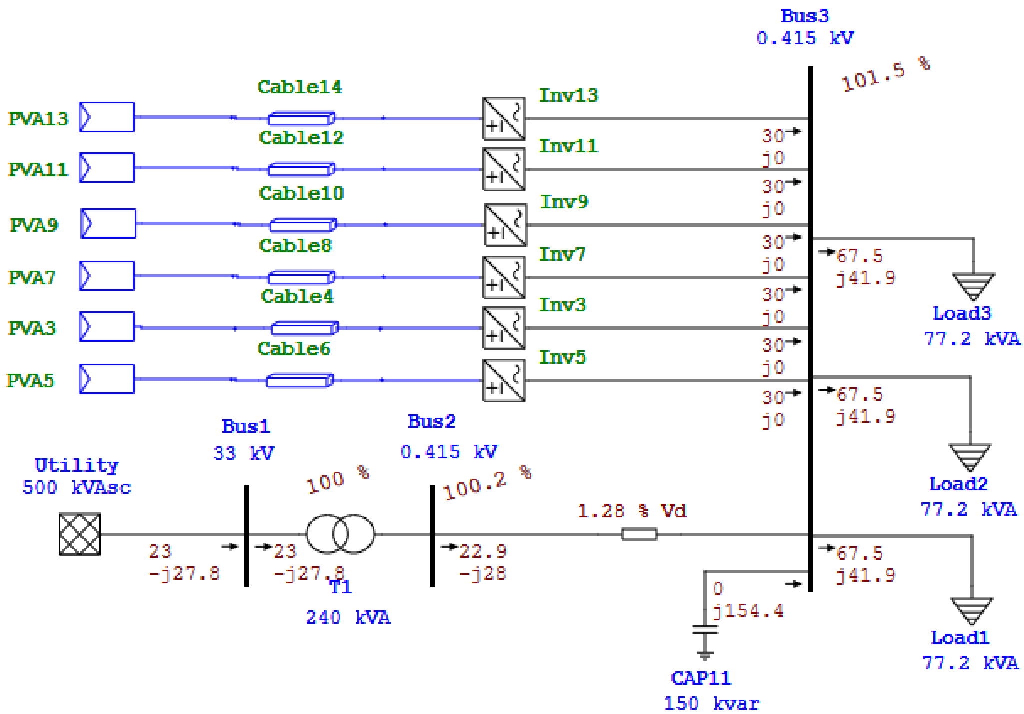

Figure 5-53: Load Flow Analysis of Mixed Design with Adjusted Capacitor – 70% DC

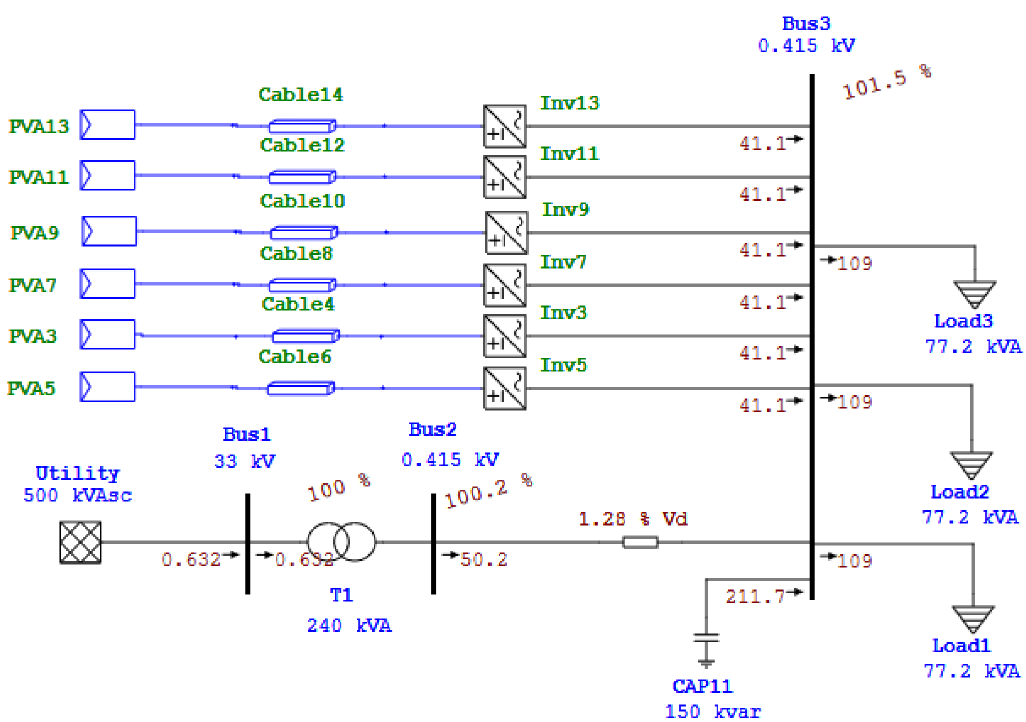

Figure 5-54: Current Flow Analysis of Mixed Design with Adjusted Capacitor – 70% DC

Table 5-10: Short Circuit Analysis of Mixed Design – 70% DC

Bus Fault	Results	3-Phase	L-G	L-L	L-L-G
Bus 1	Initial Symmetrical Current (kA, rms) :	0.016	0.021	0.014	0.023
	Peak Current (kA), Method C :	0.033	0.043	0.028	0.047
	Breaking Current (kA, rms, symm) :		0.021	0.014	0.023
	Steady State Current (kA, rms) :	0.016	0.021	0.014	0.023
Bus 2	Initial Symmetrical Current (kA, rms) :	1.214	1.707	1.051	1.808
	Peak Current (kA), Method C :	2.362	3.320	2.045	3.518
	Breaking Current (kA, rms, symm) :		1.707	1.051	1.808
	Steady State Current (kA, rms) :	1.214	1.707	1.051	1.808
Bus 3	Initial Symmetrical Current (kA, rms) :	1.157	0.839	1.002	1.232
	Peak Current (kA), Method C :	2.490	1.805	2.157	2.653
	Breaking Current (kA, rms, symm) :		0.839	1.002	1.232
	Steady State Current (kA, rms) :	1.157	0.839	1.002	1.232

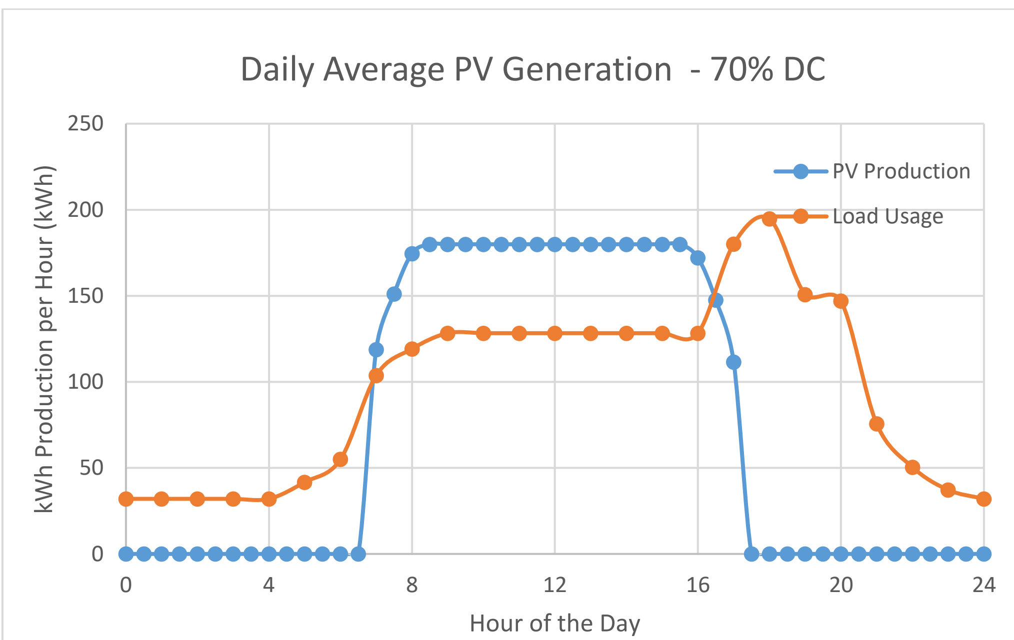

Figure 5-55: Daily Average PV Generation and Load Usage – 70% DC Mixed Design

5.12 Mixed System Design: 80 percent DC

In this mixed system design, six PV arrays are set with 12 strings of 25 panels with another set with 10 strings of 25 panels – totaling to a 491.18 kilowatts DC design. The assumptions regarding the output of the inverter, the DC load flow, and the degradation factor remain. The AC load flow in Figure 5-56 shows that the voltage and power flow meet the requirements to support the load. With the capacitor set to 150 kvar, the bus voltage of Bus 3 operates at 102.2 percent, remaining within the acceptable 5 percent range. Figure 5-57 shows the normal operating current with a high of 290.1 amperes at the capacitor. Table 5-11: Short Circuit Analysis of Mixed Design – 80% DCTable 5-11 lists the short circuit current at varying faults – highest fault current of 3.52 kilo-amperes at Bus 2. Figure 5-58 overlays the energy generated by the PV system with the energy used by the college. The PV array is able to produce 205 kilowatts of power, 7 kilowatts more than the maximum peak load. The maximum peak load during the sun hours operate at about 128 kW. The extra energy produced by the PV system will be used to charge the battery. The PV system is estimated to generate an extra 760 kWh of energy per day. The system can charge the battery within eight sun hours. The surplus 235 kWh of energy will be wasted in the dump load every day. This mixed system design is wasteful and should not be considered for the power system.

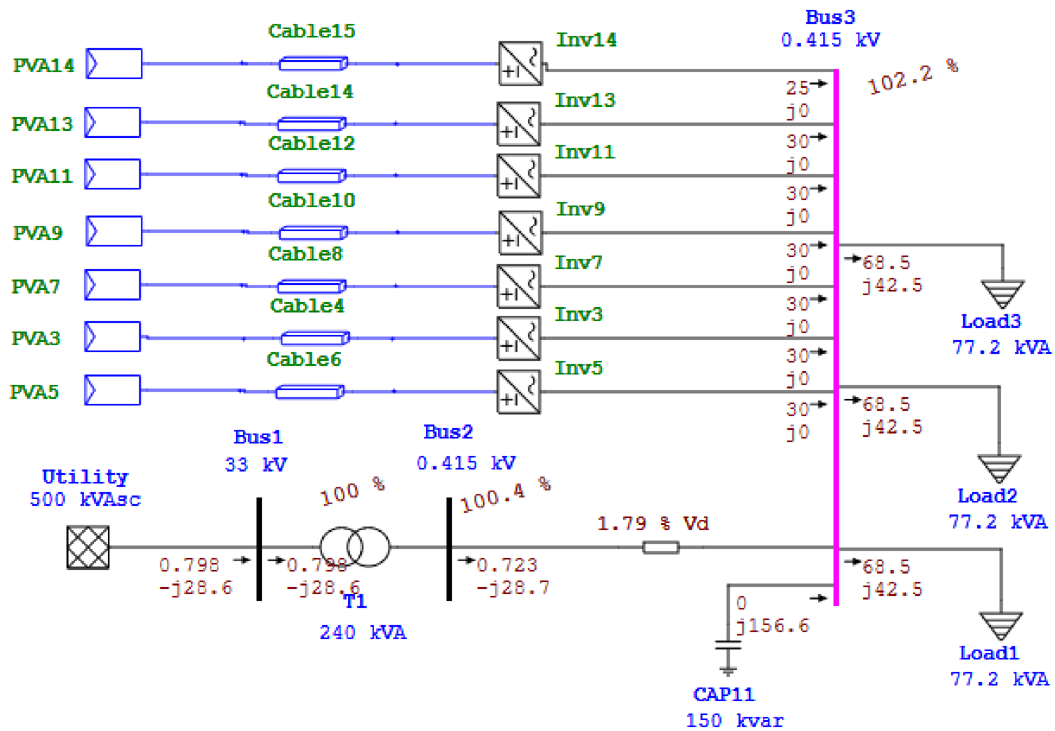

Figure 5-56: Load Flow Analysis of Mixed Design - 80% DC

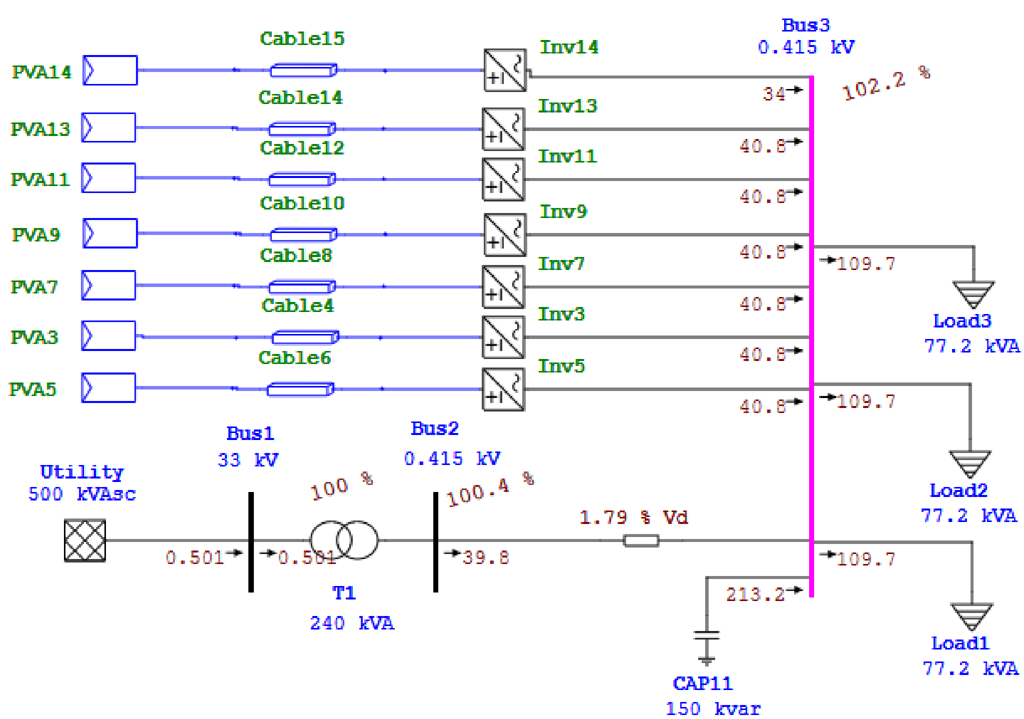

Figure 5-57: Current Flow Analysis of Mixed Design – 80% DC

Table 5-11: Short Circuit Analysis of Mixed Design – 80% DC

Bus Fault	**Results**				
Bus 1		3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms) :	0.017	0.022	0.015	0.024
	Peak Current (kA), Method C :	0.034	0.045	0.030	0.049
	Breaking Current (kA, rms, symm) :		0.022	0.015	0.024
	Steady State Current (kA, rms) :	0.017	0.022	0.015	0.024
Bus 2		3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms) :	1.318	1.843	1.141	1.944
	Peak Current (kA), Method C :	2.524	3.529	2.186	3.723
	Breaking Current (kA, rms, symm) :		1.843	1.141	1.944
	Steady State Current (kA, rms) :	1.318	1.843	1.141	1.944
Bus 3		3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms) :	1.305	0.891	1.131	1.374
	Peak Current (kA), Method C :	2.723	1.858	2.358	2.865
	Breaking Current (kA, rms, symm) :		0.891	1.131	1.374
	Steady State Current (kA, rms) :	1.305	0.891	1.131	1.374

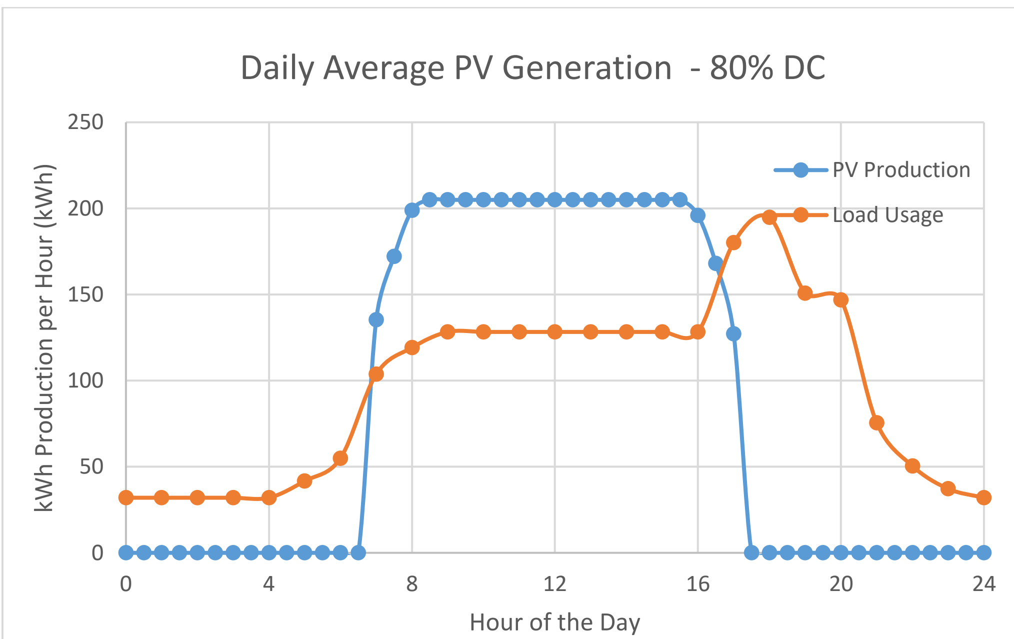

Figure 5-58: Daily Average PV Generation and Load Usage – 80% DC Mixed Design

5.13 Mixed System Design: 90 percent DC

In this mixed system design, six PV arrays are set with 12 strings of 25 panels with another two arrays set with 10 strings of 25 panels – totaling to a 551.08 kilowatts DC design. The assumptions regarding the output of the inverter, the DC load flow, and the degradation factor remain. The AC load flow in Figure 5-59 shows that the voltage and power flow meet the requirements to support the load. With the capacitor set to 150 kvar, the bus voltage of Bus 3 operates at 102.9 percent, remaining within the acceptable 5 percent range. Figure 5-60 shows the normal operating current with a high of 214.7 amperes at the capacitor. Table 5-12 lists the short circuit current at varying faults – highest fault current of 3.91 kilo-amperes at Bus 2. Figure 5-61 overlays the energy generated by the PV system with the energy used by the college. The PV array is able to produce 230 kilowatts of power, 32 kilowatts more than the maximum peak load. The maximum peak load during the sun hours operate at about 128 kW. The extra energy produced by the PV system will be used to charge the battery. The PV system is estimated to generate an extra 1,010 kWh of energy per day. The system can charge the battery within 5 sun hours. The surplus 485 kWh of energy will be wasted in the dump load every day. This mixed system design is wasteful and should not be considered for the chosen power system.

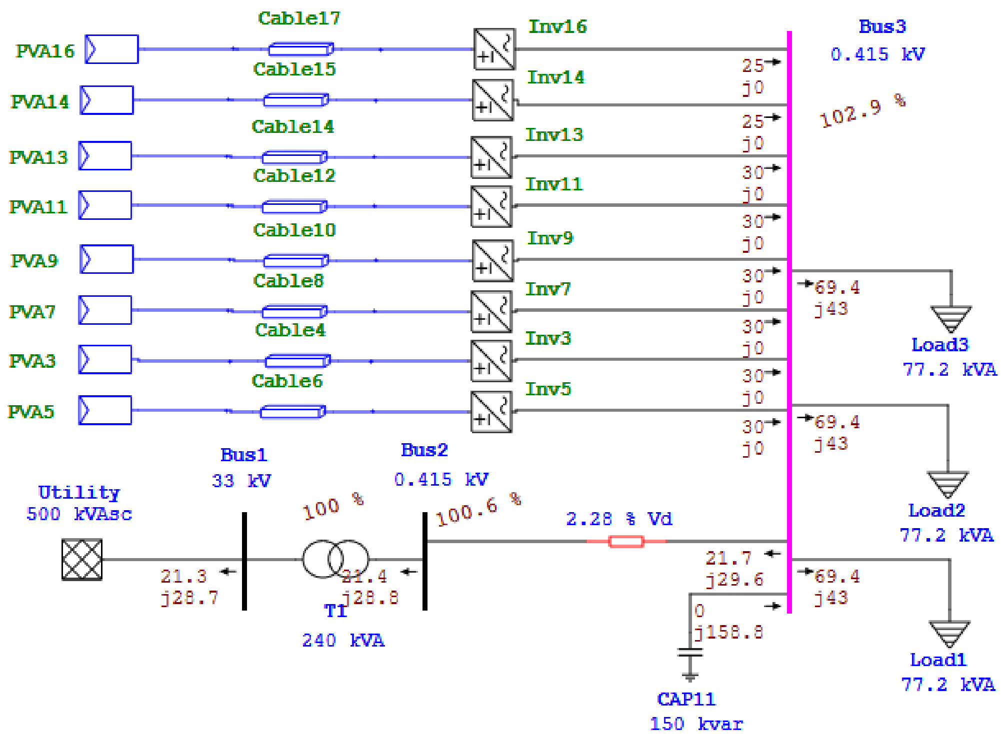

Figure 5-59: Load Flow Analysis of Mixed Design - 90% DC

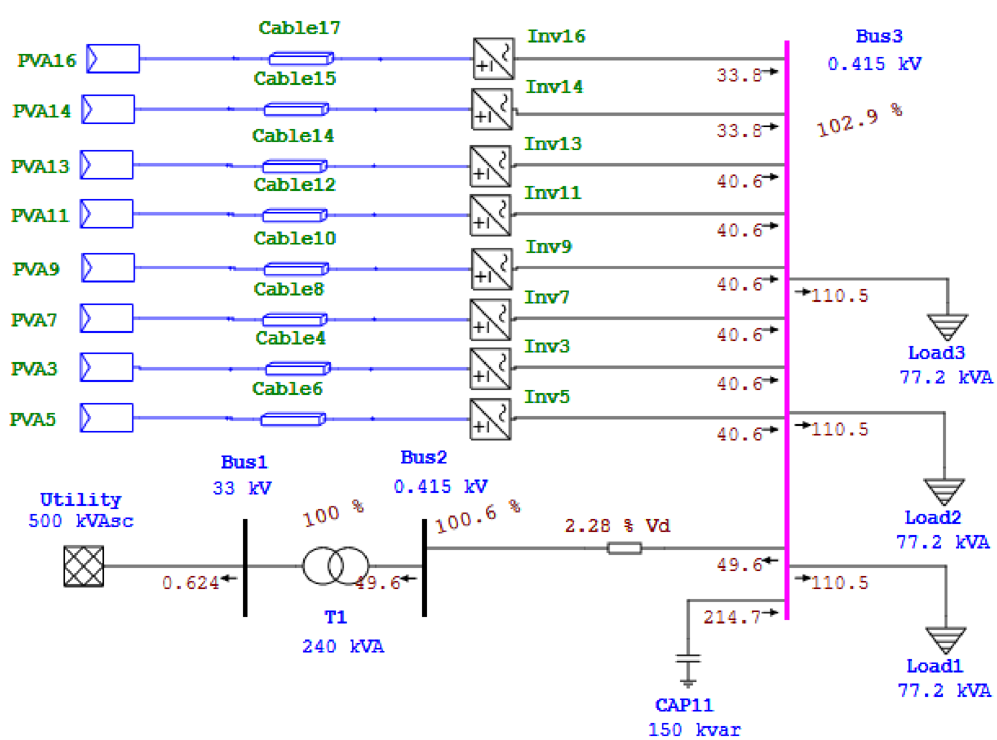

Figure 5-60: Current Flow Analysis of Mixed Design – 90% DC

Table 5-12: Short Circuit Analysis of Mixed Design – 90% DC

Bus Fault	Results					
Bus 1			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	0.018	0.024	0.016	0.025
	Peak Current (kA), Method C	:	0.036	0.047	0.031	0.051
	Breaking Current (kA, rms, symm)	:		0.024	0.016	0.025
	Steady State Current (kA, rms)	:	0.018	0.024	0.016	0.025
Bus 2			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	1.414	1.968	1.225	2.066
	Peak Current (kA), Method C	:	2.674	3.721	2.316	3.907
	Breaking Current (kA, rms, symm)	:		1.968	1.225	2.066
	Steady State Current (kA, rms)	:	1.414	1.968	1.225	2.066
Bus 3			3-Phase	L-G	L-L	L-L-G
	Initial Symmetrical Current (kA, rms)	:	1.457	0.936	1.261	1.515
	Peak Current (kA), Method C	:	2.955	1.899	2.559	3.074
	Breaking Current (kA, rms, symm)	:		0.936	1.261	1.515
	Steady State Current (kA, rms)	:	1.457	0.936	1.261	1.515

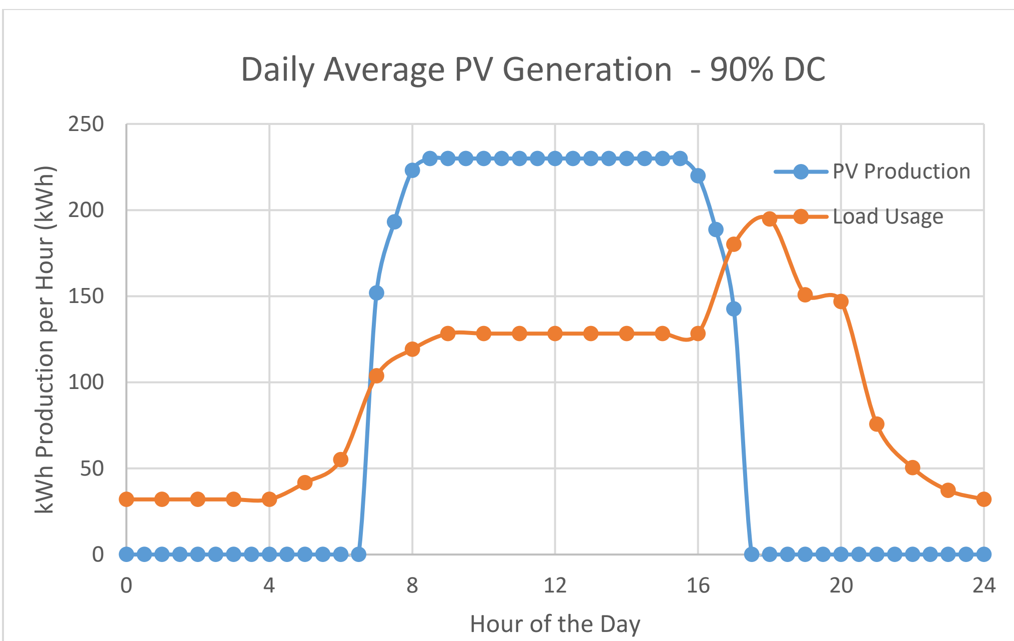

Figure 5-61: Daily Average PV Generation and Load Usage – 90% DC Mixed Design

5.14 Cost Analysis

The cost of each system design varies as the amount of panels, inverters, batteries, transformer, and transmission line length may be different in each design. The AC portion in each mixed design is identical to the full AC design. The initial cost of the full AC design provides the lowest capital cost, while the full DC design likely provides the highest capital cost. The difference between the costs in the design, aside from the size of the PV design, is the amount of payback for each system. Although a DC system may have a higher upfront cost, it is able to generate energy that the consumers do not have to buy from the utility. The DC system has the potential of paying for itself over time. Same in Tanzania has great potential for solar generation as it is close to the equator and receives plenty of solar irradiance annually. Oversizing the DC portion may lead to the waste of energy. For this reason, the implementation of the optimal amount of PVs integrated to the grid is critical for both the capital and the power flow design. In this analysis, a cost table is generated for each component in order to create another table with the total costs of each design.

The design on ETAP uses the Suniva ART245-60-3 solar panels. These panels are listed at 360 dollar per panel, but are obsolete in today's market. A quick search on Google's shopping tab lists 240 watt panels from $124 to 146$. Integrating the costs of connectors and cables for the panels, each panel will be estimated to cost $150. One way to reduce the size of the PV system is to use higher power rating solar panels, but this will increase the cost. According to SEP stored energy products, a single panel costs $131 – alternatively costing $116 when bought in a bulk of 50 [66]. The costs of the panels, connectors, and cables will be estimated at $135 per panel with a $47 maintenance cost per kW per year [67]. Although solar panels have a 25 year warranty, they typically have a life expectancy of about 20 years.

The design on ETAP uses the Sunny Tripower Core1 inverter, estimated at $6,232 per inverter. The inverter has a 10 year warranty. Most inverters come with a life-expectancy of 10 years, but may last for up to 20 years if maintained regularly [68]. The inverter's performance is subject to high ambient temperatures and low power grid quality. The inverters should be inspected regularly for any damages and the fans cleaned for proper air flow. The costs of each inverter will be estimated at $6,750 to account for any additional costs. The inverter also has a baseline maintenance fee of $0.77 per kW per year.

The cost of batteries are typically rated by its energy storage, kilo-watt-hours (kWh). The cost of lithium-ion batteries are at an all-time low, costing $209 per kWh. Lead-acid batteries are estimated to cost about $125 per kWh, but have a shorter battery life of 5 years. Lithium-ion batteries come with a life-expectancy of about 10 years and requires little maintenance compared to lead-acid batteries. The original master plan assumes the use of lead-acid batteries due to its availability and popularity at the time. Battery technology has advanced over the years with the increase popularity of electric vehicles. The cost of batteries will be estimated at $230 per kWh to account for the connectors and tax upon purchasing the units. The batteries also have a maintenance cost of $15 per kWh per year.

The cost of the transformer varies on the power capability and the step ratio. Online shopping sources are used to find an estimation of a transformer that can handle 240 kVA and provide the winding ratio of 33 kV to 415 volt. According to the global trading and selling website Alibaba, a three phase 630 kVA transformer with a 33kV to 415 volt transformer costs about $9,000 [69]. This value will be used for the cost analysis of the inverter. The transformer comes with a life-expectancy of about 20 years according to ANSI and IEEE standards. The maintenance cost is estimated to match the inverter maintenance cost.

The cost of transmission lines varies on the number and size of the lines. The conductor size of the transmission lines are relatively large in order to handle the expected current of the lines. Transmitting at 415 volts results in more current flowing, requiring wires with higher ampacity. Overhead transmission lines have a life expectancy of more than 80 years. Juho Yli-Hannuksela's thesis calculates the parts of total cost for a transmission line design in

Figure 5-62; relating the materials, commissioning, engineering, civil, and installation cost of the transmission lines [70]. The material costs includes the cost of towers, conductors, ground wire, spacers, and insulator strings. Data on the Perilli OXYGEN transmission line is unavailable. An equivalent cable is the ACSR Hawk cable. The size of the cable is 477 mm^2 and its ampacity at 659 amperes. The wire is estimated to cost $1.44 per feet. The design uses a total of 4 transmission lines, 3 for the phases and 1 for the neutral wire. The design estimates a length of 0.35 kilometers per line, or 1,148 feet. The total transmission line length equals 4,822 feet when allowing an additional 5 percent to account for sag – totaling to $6,847. The towers are assumed to be made of wood instead of steel, costing about $600 per pole [71]. Pole are typically spaced 125 feet apart from one another, requiring about 10 poles for the system. The total cost of the materials for the poles is $6,000. Insulator strings are estimated to $100 a piece, and spacers are estimated at $10 a piece [70]. The total final cost of materials is estimated to

$13,947. Utilizing the parts of total cost chart, the final cost of installing the transmission is estimated to $26,000.

The expensive component that has to be considered is the charge controller. The charge controller is estimated to cost $165 per kilowatts, and has life expectancy of 10 years and maintenance cost of $0.5 per kilowatt per year [72]. The last component to consider is the capacitor corrector for the busses, estimating at about $4.00 per kvar.

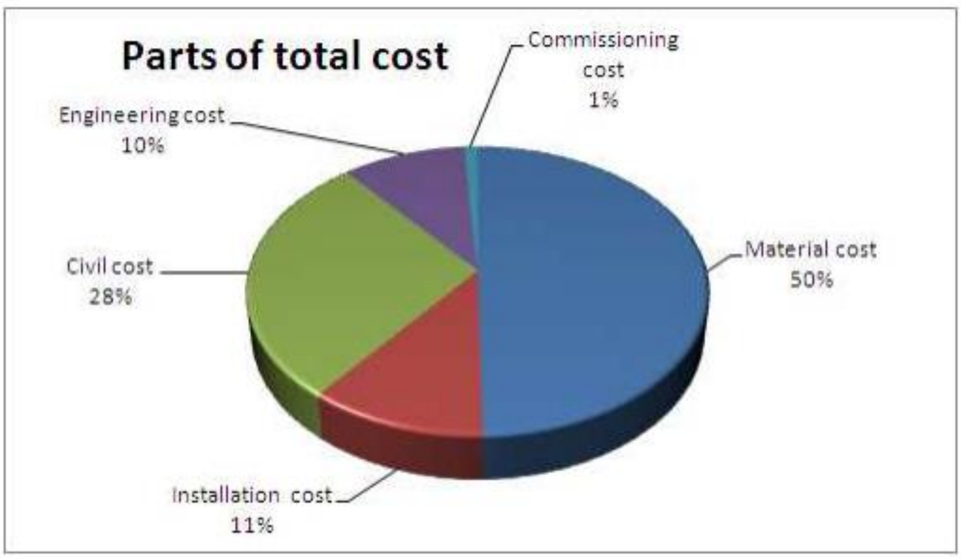

Figure 5-62: Parts of Total Cost by Juho Yli-Hannuksela [70]

Table 5-13 summarizes and breaks down the cost by components. The component quantity and sizes for each system design is listed in Table 5-14. Combining the information from both tables yields the cost breakdown of each system design shown in

Table 5-15. The full AC design has the lowest upfront cost while the full DC design has the highest upfront cost as predicted. The main source of costs incurred comes from the batteries. The full AC design assumes a battery system for backup power operating about 200 kW – equal to the AC bus power flow. The battery bank in the full DC design accounts for 74.34 percent of the total costs. From a cost standpoint, the full DC system is impractical. The full AC design has the lowest upfront cost, but will cost more over time when buying power from the utility.

Table 5-13: Cost Breakdown by Components

Parameter	**PV panels**	**Inverter**	**Battery**	**Transformer**	**Transmission Line**	**Charge Controller**
Life Span	20 years	10 years	10 years	20 years	80 years	10 years
Capital Cost	$135 per panel	$6750 per unit	$230 per kWh	$9,000	$26,000	$165 per kW
Operation & Maintenance Cost	$47 per kW per Year	$0.77 per kW per year	$15 per kWh per year	$0.77 per kva per year	-	$0.5 per kW per year

Table 5-14: Component Quantity and Size per System Design

System Design	# of Panels	Battery Size (kWh)	# of Inverters	# of Transformer	# of Transmission Line	Controller Size (kW)	Capacitor Size (kvar)
100 AC	0	525	0	1	1	240	200
90 DC	2300	525	8	1	1	552	150
80 DC	2050	525	7	1	1	492	150
70 DC	1800	525	6	1	1	432	150
60 DC	1550	525	6	1	1	372	200
50 DC	1275	525	5	1	1	306	200
40 DC	1025	525	4	1	1	246	200
30 DC	775	525	3	1	1	186	200
20 Dc	525	525	2	1	1	126	200
10 DC	275	525	1	1	1	66	200
100 DC	2800	7019	10	0	0	671	200

Table 5-15: Cost of Each System in 1000s of dollars (Unit * $1000)

System Design	Panels	Battery Bank	Inverter	Transformer	T_Line	Controller	Capacitor Size	Total
100 AC	0.0	120.8	0.0	9.0	26.0	33.0	0.8	189.6
90 DC	310.5	120.8	54.0	9.0	26.0	91.1	0.6	611.9
80 DC	276.8	120.8	47.3	9.0	26.0	81.2	0.6	561.5
70 DC	243.0	120.8	40.5	9.0	26.0	71.3	0.6	511.1
60 DC	209.3	120.8	40.5	9.0	26.0	61.4	0.8	467.7
50 DC	172.1	120.8	33.8	9.0	26.0	50.5	0.8	412.9
40 DC	138.4	120.8	27.0	9.0	26.0	40.6	0.8	362.5
30 DC	104.6	120.8	20.3	9.0	26.0	30.7	0.8	312.1
20 Dc	70.9	120.8	13.5	9.0	26.0	20.8	0.8	261.7
10 DC	37.1	120.8	6.8	9.0	26.0	10.9	0.8	211.3
100 DC	378.0	1614.4	67.5	0.0	0.0	110.7	0.8	2171.4

Although the cost of the full AC design is the lowest, the cost to buy energy from the utility company adds up. According to an article posted on Reuters, "the average tariff will be increased from 242.34 Tanzania shillings ($0.1114) per kilo-watt-hour to 263.02 shillings ($0.1209) per kWh [73]." The college is predicted to consume 845,000 kWh annually, equivalent to 102.16 thousand of dollars per year. The upside of integrating a PV system is the payback it can save owners. In Table 5-13, the lifetime of the DC components vary between 10 and 20 years. In order to analyze a full cost analysis, the cost of operation, maintenance, and payback must be considered. The following cost analysis assumes a 20 year period, in which the inverter, battery, and charge controller has to be replaced once. The analysis includes the operation and maintenance costs. The transmission line maintenance cost of capacitor cost is ignored. Table 5-16 shows the new cost of each system for a 20 year span and Table 5-17 breaks down the maintenance cost and totals the cost for a 20 year span.

Table 5-16: Component Cost in 1000s of dollars (Unit * $1000) for a 20 Year Span

System Design	Panels	Battery Bank	Inverter	Transformer	T_Line	Controller	Capacitor Size	Total
100 AC	0.0	241.5	0.0	9.0	26.0	66.0	1.6	344.1
90 DC	310.5	241.5	108.0	9.0	26.0	182.2	1.2	878.4
80 DC	276.8	241.5	94.5	9.0	26.0	162.4	1.2	811.3
70 DC	243.0	241.5	81.0	9.0	26.0	142.6	1.2	744.3
60 DC	209.3	241.5	81.0	9.0	26.0	122.8	1.6	691.1
50 DC	172.1	241.5	67.5	9.0	26.0	101.0	1.6	618.7
40 DC	138.4	241.5	54.0	9.0	26.0	81.2	1.6	551.7
30 DC	104.6	241.5	40.5	9.0	26.0	61.4	1.6	484.6
20 Dc	70.9	241.5	27.0	9.0	26.0	41.6	1.6	417.6
10 DC	37.1	241.5	13.5	9.0	26.0	21.8	1.6	350.5
100 DC	378.0	3228.7	135.0	0.0	0.0	221.4	1.6	3964.8

Table 5-17: Maintenance and Total Cost in 1000s of dollars (Unit * 1000) for a 20 year span

System Design	Panels	Battery Bank	Inverter	Transformer	T Line	Controller	Maintenance Cost	Total Cost in 20 years
100 AC	188	157.5	3.1	7.7	-	2	358.3	702.4
90 DC	518.88	157.5	8.5	7.7	-	5.52	698.1	1576.5
80 DC	462.48	157.5	7.6	7.7	-	4.92	640.2	1451.5
70 DC	406.08	157.5	6.7	7.7	-	4.32	582.3	1326.5
60 DC	349.68	157.5	5.7	7.7	-	3.72	524.3	1215.4
50 DC	287.64	157.5	4.7	7.7	-	3.06	460.6	1079.3
40 DC	231.24	157.5	3.8	7.7	-	2.46	402.7	954.3
30 DC	174.84	157.5	2.9	7.7	-	1.86	344.8	829.4
20 Dc	118.44	157.5	1.9	7.7	-	1.26	286.8	704.4
10 DC	62.04	157.5	1.0	7.7	-	0.66	228.9	579.4
100 DC	630.74	2105.7	10.3	7.7	-	6.71	2761.2	6726.0

The cost to purchase and maintain the batteries is once again the main contributor to the total cost of the systems, prevalent in the full DC system. The best option is to avoid using a large battery storage. Avoiding a large battery means limiting the amount of power the PV system can effectively generate. As mentioned before, The DC designs above 70 percent should not be considered as the power system of choice because of the limit of the battery. The extra PV generation during the sun hours combined with the charging and discharging duty cycle of the battery goes to waste. Table 5-18 shows the effective cost over a 20 year span; including the total cost of generated power minus the total cost of the entire system for a year. The maximum effective daily usage is calculated from the amount of energy consumed during the sun hours plus the amount of energy needed to charge the batteries over its duty cycle of three days. The maximum load usage during the sun hours is equal to 1,275 kWh and the charge load of the battery is 525 kWh divided by 3 days, equaling to 175 kWh. The same assumption and calculation are used for the full DC design. The cost of electricity is assumed to remain constant at $0.1209 over the 20 years.

Table 5-18: Effective Cost Analysis in 1000s of dollars (Unit * 1000) for a 20 year span

System Size	Generated Daily (kWh)	Effective Energy Daily Usage (kWh)	Cost Savings in 20 years	System Cost in 20 Years	Effective Cost Savings
100 AC	0.0	0.0	0.0	702.4	-702.4
90 DC	2284.0	1450.0	1279.7	1576.5	-296.7
80 DC	2035.7	1450.0	1279.7	1451.5	-171.8
70 DC	1787.4	1450.0	1279.7	1326.5	-46.8
60 DC	1541.3	1450.0	1279.7	1215.4	64.3
50 DC	1266.1	1266.1	1117.4	1079.3	38.1
40 DC	1017.8	1017.8	898.3	954.3	-56.0
30 DC	769.6	769.6	679.2	829.4	-150.1
20 Dc	521.3	521.3	460.1	704.4	-244.3
10 DC	273.2	273.2	241.1	579.4	-338.3
100 DC	2781.4	2750.0	2427.1	6726.0	-4298.9

The effective cost analysis table shows that after 20 years, both the 50 and 60 percent DC design have a payback on the entire system – including the AC portion. At 70 percent and above, the payback is negative because energy is wasted once the battery is fully charged and the PV generates more power than the load. The full DC design generates 2.42 million dollars in revenue over the 20 years, but has the largest negative effective cost because of the battery system that has to be integrated with an isolated system. The cost of the full AC design eventually costs more than the 10 percent DC design because of the cost to maintain the controller. The controller is connected to the DC bus, operating at the specific DC power in all of the mixed DC designs. The controller is connected to the AC bus, operating at the AC power of 200 kW. Overtime, the full AC design overlaps the cost of the mixed designs. After the 20 year span, the DC system and most of the AC system will have to be replaced. The infrastructure and build of the systems can remain, reducing the overall cost of the next life cycle.

5.15 Design Choice

Cost is the primary factor in choosing the design. Based on the cost analysis, the 60 percent DC mixed design is the obvious choice for the system. The problem with the 60 percent DC mixed design is that it takes two days to charge the battery system. The battery is assumed to have a three day duty cycle, assuming a blackout occurs about twice a week during peak hours. In time, the blackouts will occur less often with improvements and advances made on the power system design. A lot of the power system in Tanzania relies on hydro-power generation. These hydro-generated power is unsustainable due to the unpredictable weather – mainly droughts. The inconsistent production of natural energy on the utility side will increase the cost of energy, but is currently being dealt with. The ramification of relying on hydro production has already affected the national utility company and measures are being made to make up for the lack of production. The 60 percent DC mixed design will eventually exceed the energy storage and load, wasting the energy through a dump load.

The 50 percent DC mixed design generates up to 127.3 kilowatts DC, while the maximum load during the sun hours is 128.3 kilowatts AC. The problem with choosing the 50 percent mixed design is that the battery will have to rely on the grid to charge. To avoid this problem, another mixed design is proposed - a mixed within the 50 and 60 percent rage. The proposed mixed design utilizes five PV arrays, set with 12 strings of 25 panels – totaling to a 359.4 kilowatts DC design. This design adds up to a 58.9 percent design. All of the MPPTs are utilized in this design, reducing the amount of wasted MPPTs and increasing the amount of power output per inverter. The assumptions regarding the output of the inverter, the DC load flow, and the degradation factor remain.

The AC load flow in Figure 5-63 shows that the voltages and power flow meet the requirements to support the load. With the capacitor set to 150 kvar, the bus voltage of Bus 3 operates at 100.5 percent, remaining within the acceptable 5 percent range. The PV array is able to reduce the amount of power drawn from the utility by a total of 150 kilowatts. Figure 5-64 shows the normal operating current at a high of 209.8 amperes at the capacitor. Table 5-19 lists the short circuit current at varying faults – highest fault current of 3.29 kilo-amperes at Bus 2. Figure 5-65 overlays the energy generated by the 50, 60, and propose 58.9 PV system with the energy used by the college. In this mixed design, the PV generation is able to supply enough energy to the load during the sun hours. The PV system is estimated to generate an extra 210 kWh of energy per day. The extra energy is used to charge up the battery. As mentioned in Section 5.4, the battery is sized to store up to 525.6 kWh of energy. The PV system can charge the battery within two and a half days according to these estimations.

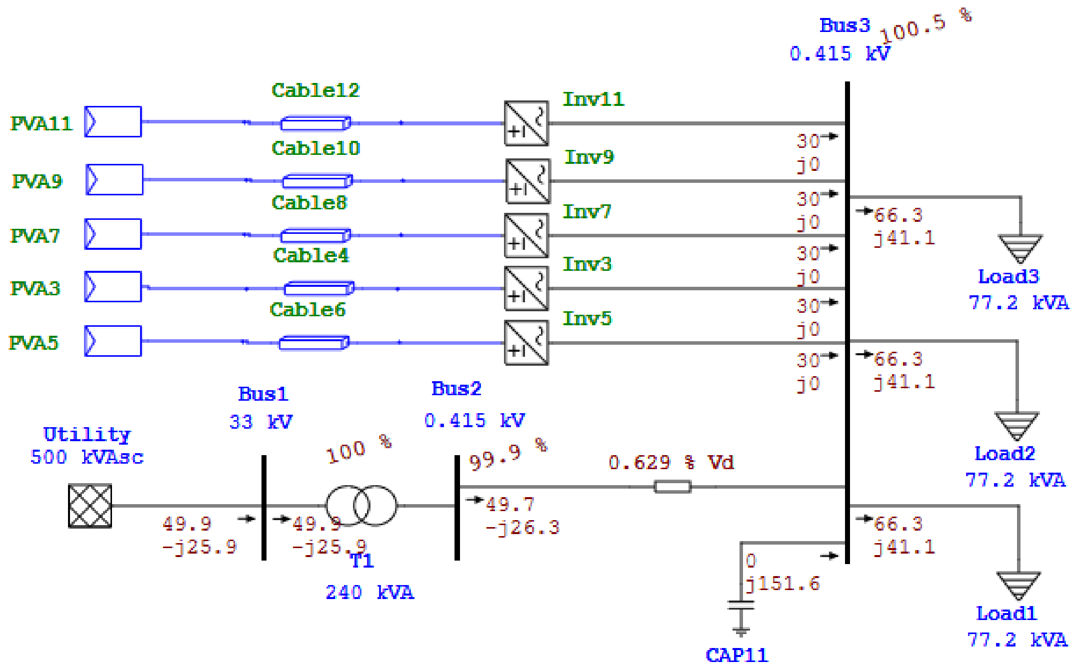

Figure 5-63: Load Flow Analysis of Mixed Design – 58.9% DC

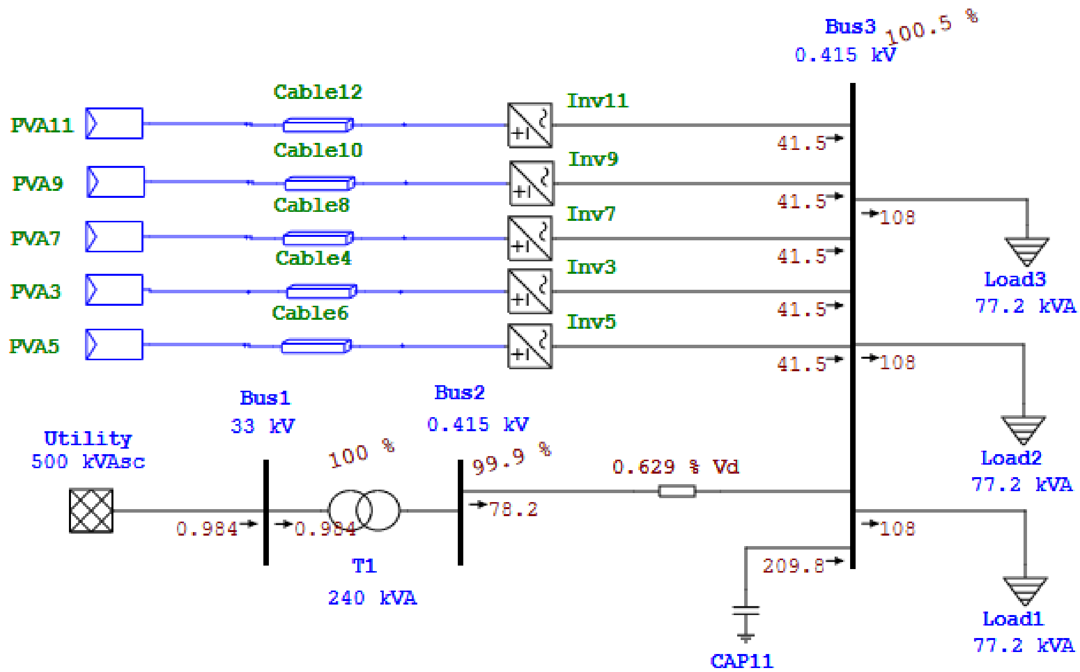

Figure 5-64: Current Flow Analysis of Mixed Design – 58.9% DC

Table 5-19: Short Circuit Analysis of Mixed Design – 58.9% DC

Bus Fault	Results		3-Phase	L-G	L-L	L-L-G
Bus 1	Initial Symmetrical Current (kA, rms)	:	0.015	0.020	0.013	0.021
	Peak Current (kA), Method C	:	0.030	0.041	0.026	0.044
	Breaking Current (kA, rms, symm)	:		0.020	0.013	0.021
	Steady State Current (kA, rms)	:	0.015	0.020	0.013	0.021
Bus 2	Initial Symmetrical Current (kA, rms)	:	1.103	1.560	0.955	1.660
	Peak Current (kA), Method C	:	2.188	3.094	1.895	3.292
	Breaking Current (kA, rms, symm)	:		1.560	0.955	1.660
	Steady State Current (kA, rms)	:	1.103	1.560	0.955	1.660
Bus 3	Initial Symmetrical Current (kA, rms)	:	1.012	0.779	0.877	1.091
	Peak Current (kA), Method C	:	2.258	1.737	1.955	2.433
	Breaking Current (kA, rms, symm)	:		0.779	0.877	1.091
	Steady State Current (kA, rms)	:	1.012	0.779	0.877	1.091

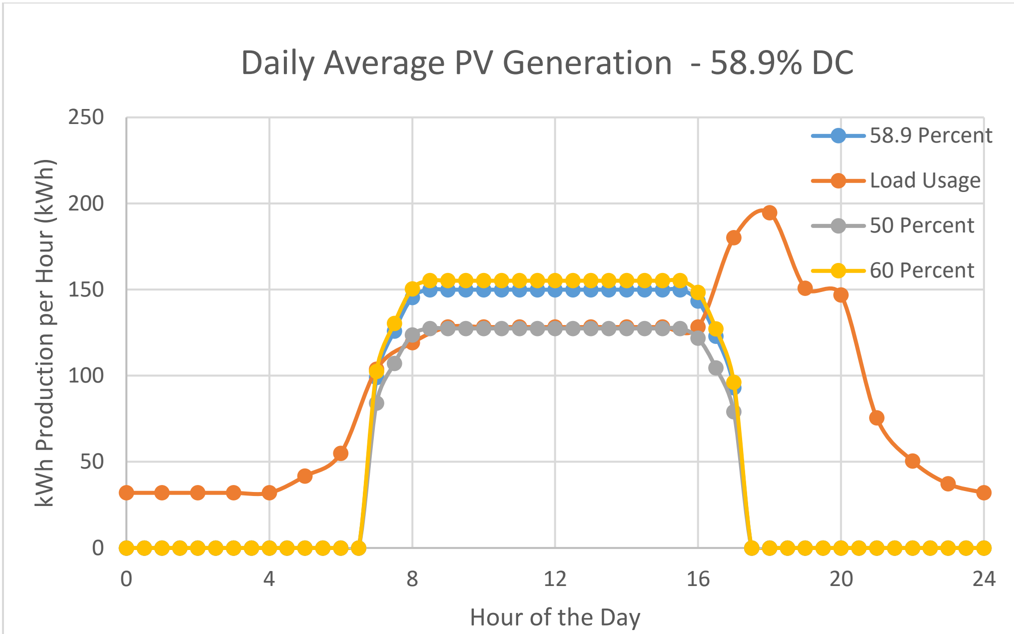

Figure 5-65: Daily Average PV Generation and Load Usage – 58.9% DC Mixed Design

Table 5-20: Full Cost Analysis of Proposed Design

Table 5-20 runs through the full cost analysis of the proposed DC mixed system design. This system design generates a net positive of 101.3 thousand dollars, higher than any of the other designs. The cost savings comes from the full utilization of each inverter. The additional PV panels increase the input power of the inverter, increasing the effective output power of the inverter. All of the MPPT available from the inverter is fully utilized, allowing the inverter to operate closer to its DC ratings. This design wastes less energy than the 60 percent mixed design, while providing enough energy to charge the battery in two and a half days. Each panel is 65.04 inches by 39.37 inches, totaling to an area of 2560.6 square inches or 1.652 square inches. The solar panels take an area of about 2,478 square meters. The area is doubled to account for the worst case spacing requirements that includes the inverters, battery bank, and transformer – leaving room for error.

Table 5-20: Full Cost Analysis of Proposed Design

System Design	# of Panels	Battery Size (kWh)	# of Inverter	Transformer	T Line	Controller Size (kW)	Capacitor Size (kvar)	
59.8 DC	1500	525	5	1	1	360	150	
Cost Per Component →	Panels	Battery Bank	Inverter	Transformer	T Line	Controller	Capacitor	Total
(1k-$)	202.5	241.5	67.5	9.0	26.0	118.6	1.2	666.3
Cost to Maintain Over 20 Years →	Panels	Battery Bank	Inverter	Transformer	T Line	Controller	Maintenance Cost	Total Cost
(1k-$)	349.68	157.5	5.7	7.7	-	3.72	524.3	1215.4
Effective Cost Analysis In 20 Years →	Daily Energy Gen (kWh)	Effect Energy Daily Usage (kWh)	Cost Savings in 20 years	System Cost in 20 Years	Effect Cost Savings			
(1k-$)	1489.5	1450.0	1279.7	1178.5	101.3			

The proposed 58.9 percent DC mixed design offers the largest payback when compared to the other designs as seen in Figure 5-66. The figure does not account for the 100 percent DC design because of its significance cost difference as shown in Figure 5-67. The full DC design has the largest upfront cost and effectively costing the most in 20 years. The space to integrate both the AC and DC portion of the system can fit within 5,000 square meters – 27.78 percent of the anticipated full DC design outlined in the original master plan. The original master plan predicted an area of 18,000 meters squared of land to support an isolated DC design. An isolated DC design is impractical because of the battery size needed to support the system during days of autonomy. The proposed design offers a better solution to charge and discharge the battery regularly while keeping the energy wasted through the dump load at a minimal. The proposed system is the optimal power system choice that incorporates high reliability, smaller system size, and higher return costs.

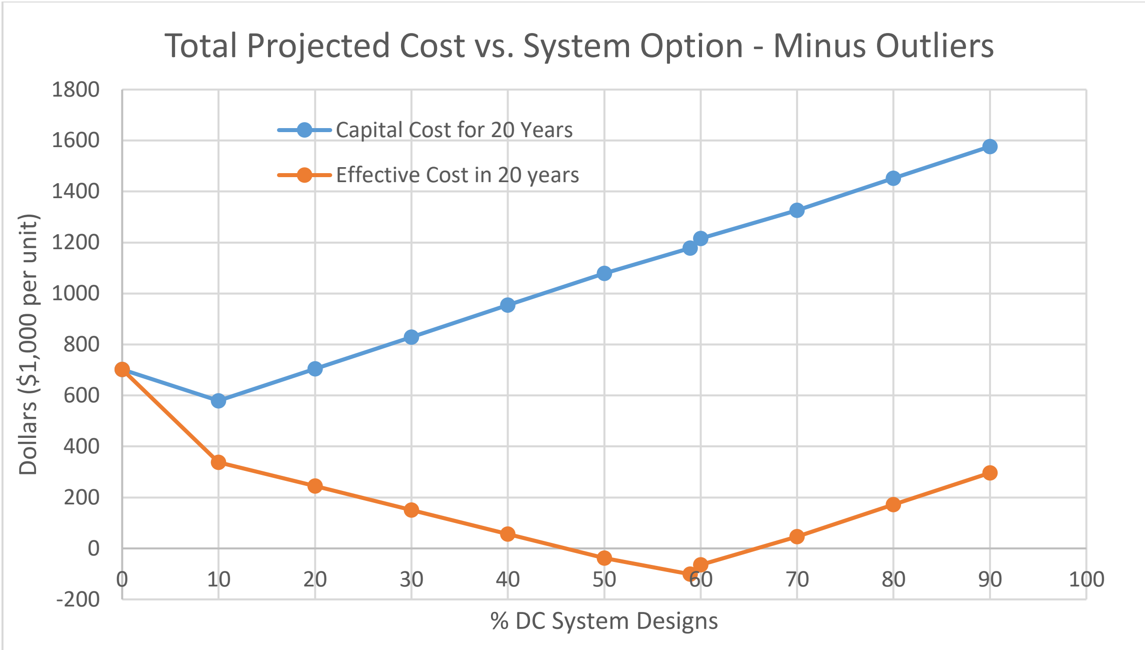

Figure 5-66: Total Projected Cost and System Options Minus 100% DC Outlier

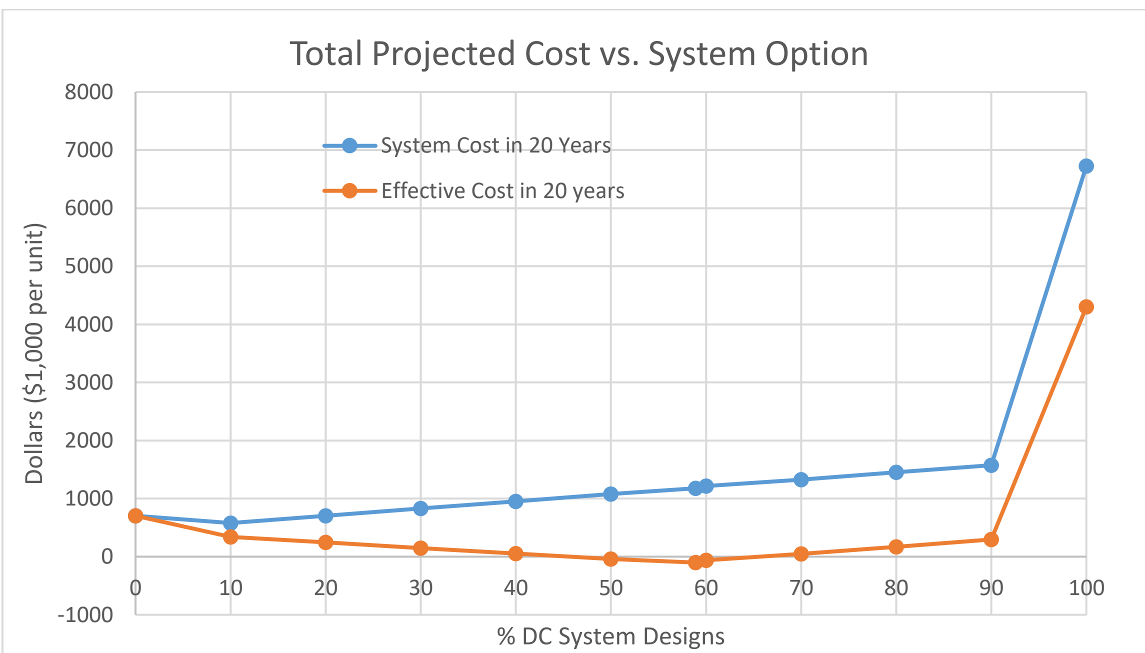

Figure 5-67: Total Projected Cost and System Options

Chapter 6 : Conclusion

The main purpose of this thesis is to ultimately choose an optimal power system design for a college that will be built in Same, Tanzania. The optimization factors include the development of a load profile, the study of varying power system designs, and the cost for each design – including the usage of land. Load Profile Two, developed using the Same Polytechnic Master Plan's strategies, predicts an annual energy consumption of 854 mega-watt-hours. This load profile makes up 45 percent of the original load profile developed in the original master plan, published in 2012. The load profile has been greatly reduced to accommodate for the advance in technology. The load flow for varying mixes of AC and DC systems shows how each design operates during peak load hours - using Load Profile Two as its model for the load. The integrated power systems heavily rely on the utility grid for the system designs that have 40 percent or less DC. The 50 percent DC design operates right under the load profile, relying slightly on grid power generation during the sun hours. All designs with 60 or more percent DC generate more power than necessary. Designs above 70 percent DC have a lot of wasted energy burned through the dump load. To optimize the utilization of each components, the 58.9 percent DC mixed design proposes the best solution for power flow and energy conservation. It minimizes the waste of energy and utilizes the inverters more effectively. From a cost stand point, only the 50 percent and 60 percent DC mixed designs have a positive net return over the span of 20 years – 38.1 thousand and 61.3 thousand dollars in return. The proposed 58.9 percent DC mixed design provides the largest net return of 101.3 thousand dollars in 20 years. The proposed design is the optimal power system choice that incorporates high reliability and high return costs while utilizing 27.8 percent of the predicted 18,000 square meters of land.

This thesis incorporates three heavy sections: the load profile, the system design analysis, and the cost analysis. The system design relies on the load profile and the cost analysis relies on the system design. The load profile is theoretical and future work on the load profile section will allow the system design and cost analysis to be more accurate. For the future work on the load profiling, weather data at the actual site will allow for more realistic energy averages. Currently, students are planning to install a weather station and pyranometer to measure the local wind speeds and solar irradiance at the site location. Other future work for the load profile is to build the full AC system design first and measure the actual load seen on the site. A more effective DC integrated power system can be designed using the real loads instead of the theoretical load. This may clear up any considerations that may not have been addressed. It will also allow the designers to understand how the differently the system may operate throughout the year with different seasons.

There are much future work to be done for the system design. Establishing a contact with the local utility company, Tanesco, will help future system designers to understand the capabilities of the voltage line the college plans to tap into. It also helps them confirm any assumption made regarding the line voltage, transmission line ampacity, and the power available on the utility side. Future electrical engineering students that plan to work on this project should also look into obtaining the proper licensing for ETAP's battery integration and simulation. The students can also integrate the protection scheme for the system design and perform a stability and N-1 contingency analysis on each design.

From the cost perspective, the future work may include the cost of the protection components – circuit breakers, fuses, relays, and more. Establishing a contact with the utility company can also help understand how much the company itself charges for the extra load. The cost analysis can also include the amount of dollars each system buys from the utility company to further prove which system saves the most amount money. The load profile, system design, and cost analysis can be more accurate and detailed with these future works.

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