Solar District Cup
Final Proposal

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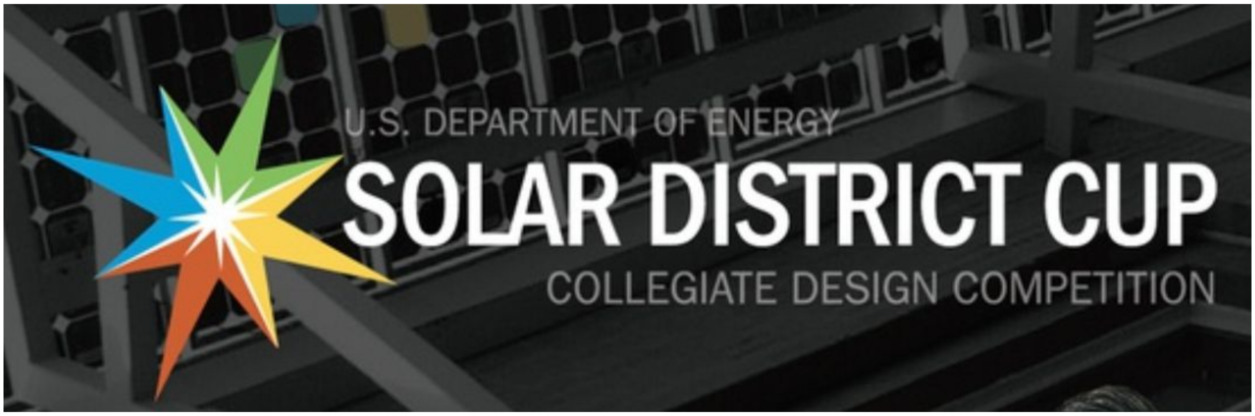

Figure 1: Solar District Cup Collegiate Design Competition [1]

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DISCLAIMER

EXECUTIVE SUMMARY

The Solar District Cup is a competition created by the Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL). This competition encourages multidisciplinary teams that will be designing and evaluating a solar energy network for a specified district. Each team is given one of three districts and competes against the other teams assigned the same district. This team was assigned to the New Mexico State University district. The first step to design this system was defining the customer needs and then translating those into engineering requirements. It was found that the most important customer need is to maximize the financial savings over a 20 year period. The team then created a black box model and functional decomposition to better understand the inputs and outputs of the system and what functions the system needs to complete. The main function of the system found is to generate and deliver power. With the functions defined the team got a better understanding of the customer needs and engineering requirements and were able to create a house of quality. The house of quality relates the customer needs to the engineering requirements and then shows the most important engineering requirements. The house of quality showed the most important engineering requirement was minimizing energy loss. The last factor needed to create a valid design is to identify any and all standards and regulations that the design must conform to. To test the different aspects of the design, the team has and will use the online tools System Advisor Model (SAM), Aurora Solar, and OpenDSS. These tools help the team to create and run simulations of the hypothetical system. A failure modes and effects analysis (FMEA) was then created to identify the most common and problematic modes of failure in the design. Next a risk trade off analysis was done on the different failure modes. With all of these aspects taken into account, the team was able to select a final design for this semester. For this project the team will be continually altering their design in order to optimize the system. With this said, three designs were chosen as finalists to be used in the final system: a ground mount system in the Dirt Lot, a rooftop design on the American Center, and solar awnings in the Horseshoe Quad. The ground mount design was chosen because it performed very well in the energy production and financial analyses. The American Center did not perform as well in the analyses but would come with minimal losses and provide about 8% of the power desired because it is the largest building in the district. The solar awning would not provide much power and would cost the campus a significant amount of money, but it was chosen because it would be a way for the campus to show a move towards renewable energies. With these designs chosen the team plans to continue optimizing the system and to do this the team plans to continue to iterate on the current designs selected after checking their compatibility with the grid and implementing battery storage. The team plans to have a completed design that meets all the requirements and expectations of the project by April 1st to give time to write up the final deliverables for the project.

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1 BACKGROUND

1.1 Introduction

The Solar District Cup is a new competition proposed, conducted, and evaluated by the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL). The basic premise of this project is to design and model a solar powered network for an assigned area and evaluate this design for both financial viability and financial savings for the district over a twenty year timespan.

This project is of interest to the sponsors because with the increasing advancements in solar energy and battery storage technology, employers have found an increasing lack of experience and technical capabilities of new graduates entering the renewable energy sector. Additionally, solar energy is a more sustainable long term source of energy than natural gas and coal, and has the capability to provide more benefits to utility companies and homeowners than they might currently have. By forming teams of individuals doing research in solar radiation and learning how the solar industry works, the sponsors are bringing more minds into the field that could help progress the technology involved in the energy process.

This project is of high importance because growing research in global warming and the ozone layer has shown that the world’s current sources of energy are damaging the planet and the ozone layer. These damages are considered irreversible and unless a change to the energy sources used is made, the problems associated with global warming and the ozone layer will increase in magnitude. Knowing this, the United States is making a push to move more towards renewable energy sources as opposed to the current sources being used. With the need for more renewable sources of energy, however, more research needs to be done in these fields and these fields have not had as large of employment numbers compared to other, more established fields of non-renewable energy in the past. By encouraging people to work on this project, the DOE and NREL are increasing the preparedness and skills of potential graduates entering the field, as well as potentially introducing students to a field they had not considered pursuing previously.

1.2 Project Description

Following is the original project description provided by the sponsor [1].

> “The Solar District Cup challenges multidisciplinary student teams to design and model optimized distributed energy systems for a campus or urban district. These systems integrate solar, storage, and other distributed energy capabilities across mixed-use districts, or groups of buildings served by a common electrical distribution feeder. The competition engages students across the engineering,

urban planning, and finance disciplines to reimagine how energy is generated, managed, and used in a district.

Teams compete in one of multiple divisions, each structured around a distinct district use case. A winner is selected for each division, based on the quality of their solar energy system design. The strongest designs provide the highest offset of annual energy and greatest financial savings. This will be determined by a techno-economic analysis conducted by students and evaluated by judges. The goal is to design, model, and present the most reliable, resilient, and cost-effective system possible.

Students will present their solutions to judges at the 2020 Solar Power Southeast conference in Atlanta, where the winners will be selected and announced.”

2 REQUIREMENTS

The team's goal is to design a photovoltaic solar energy and storage system for New Mexico State University that maximizes energy offset and financial savings over a 20 year time period. With this goal in mind the team determined specific requirements from the customer, the competition guidelines, and Dr. Oman. The given Customer Requirements (CRs) need to be fulfilled in order to ensure the project is completed successfully. The CRs were then used to create Engineering Requirements (ERs). Turning the CRs into ERs gives the team a quantifiable measurement that helps the team meet and optimize the client's CRs. The ERs and CRs were then put into a House of Quality (HoQ). The HoQ relates the CRs to ERs giving the team the relative importance of each requirement compared to the others. The initial goal for gathering these requirements is interpreting the competition guidelines to gather the Customer Requirements.

2.1 Customer Requirements (CRs)

After reviewing the competition guidelines listed in Table 1A in Appendix A the team created a goal statement that summarizes the purpose of this competition. The overall goal is to design a photovoltaic solar energy and storage system for New Mexico State University that maximizes energy offset and financial savings over a 20 year time period. Using this statement along with the other given requirements in Appendix A, the Customer Requirements were generated. CRs are a particular characteristic and/or specification of a product determined by the customer or client. Table 1 below provides the CRs gathered from the Solar District Cup Rules 2020. In addition to the individual requirements, the relative weights of these requirements against each other are listed as well.

Table 1: Generated Customer Requirements

Customer Requirement	Weight	Customer Requirement	Weight
Offset annual energy and power consumption	5	**Maximizes financial savings over 20 years**	2
Aesthetically pleasing	3	Energy output based on a reasonable yield factor	4
Optimized distributed energy system	2	Voltage within expected bandwidth	3
Includes solar photovoltaic generation	4	All network elements satisfy loading and voltage constraints	4
Has battery electric storage	5	Active elements have realistic settings, responses, and dead times	4
Power purchase agreement	3	Optimal battery use	4
Financial viability	5	Cost within budget	1
Reasonable PV location	4	Durable and robust design	3
Reliable design	4		

The first row in Table 1 provides the most important CRs according to the guidelines set by the DOE and NREL. To distinguish the relative importance of the customer requirements, each CR was given a weight between 1 and 5, with 5 carrying the most weight. A summary of the weighted customer requirements are shown in the House of Quality in Table 2A.

Four customer requirements were determined to be the most important: the system offsetting the annual energy and power consumption, the system containing battery electric storage, financial viability of the system, and total cost with respect to the budget. In the proposal given to the team by NMSU, the university established and explained in their proposal for solar panels that they wish to become a completely sustainable campus by the year 2050. The four customer requirements mentioned have been weighted the highest because of their impact and potential solution for the university's goal.

Another goal of the system is to maximize financial savings over a 20 year time period. If the system is not optimized it may not provide enough energy which would in turn increase the University's expenditures. The counterpart to this being that the system generates too much energy and currency is lost through unused energy. Neither of these situations will maximize the financial savings. The financial savings over a 20 year time period is weighted at a 2 because it depends greatly on offsetting the energy and power consumption, which has been determined to be a 5.

As with any design being interacted with by the general public, the design needs to be aesthetically pleasing. The way the system looks will be very dependent on its location, so being aesthetically pleasing will only really apply to the sections of the system that the students and faculty will interact with in their day to day activities on the campus. Any solar placement on/or around the Horseshoe Quad cannot take away from the aesthetics of the area because it has high visibility to the university leadership and campus visitors. Since this is only a small portion of the campus, its given weight is a 3.

To offset the annual energy and power consumption, the team wants to maximize energy output based on a reasonable yield factor. This means eliminating as much energy loss as possible. Optimizing the amount of energy the system can yield as well as minimizing energy losses was given a weight of 4 due to its direct relationship with offsetting annual energy and power consumption.

Another CR is optimizing the distributed energy system. This CR is weighted at a 2 because the system will connect directly to the campus energy grid resulting in optimized energy distribution. The next CR is that the voltage must be within the expected bandwidth. This is weighted as a 3 because if the voltage is not sufficient enough for the bandwidth, unnecessary energy losses are created that will have to be compensated for in another area of the system.

Photovoltaic generation is the most efficient type of solar panel to date which is why including this type of system is weighted at a 4, although it is not necessary it is highly encouraged. It is extremely important that all network elements satisfy loading and voltage constraints. If the grid is overloaded it may fail and if it is underloaded the system will not have its optimum energy output so its weight is a 4.

The systems can only generate energy when the sun is present, however, energy is consumed continuously. This brings us to the importance of electric battery storage. Without battery storage the system would not be able to supply energy when the sun is not present (e.g. at night and on cloudy days) which in turn would make it impossible to offset the annual energy and power consumption. With battery storage the system can harvest the excess energy generated during the day and supply the campus with energy/power when the sun is absent. This gives electrical battery storage a weight of 5.

A power purchase agreement is a legal contract between an electricity generator, the proposed solar energy system, and a power purchaser. The power purchase agreement is weighted as a 3. It is an important aspect of the financial savings but since New Mexico has a specific range of agreements there will not be much flexibility within the contract. Optimal battery use is weighted heavily. Without this, the university would lose money and waste energy, giving it a weight of 4.

The next CR is financial viability with a weight of 5. If the system is overloaded or underloaded the project will not offset the energy and power consumption and will cost money instead of saving it. Reasonable photovoltaic location is weighted a 4 because the solar panels' placement directly affects the efficiency of the system.

Durable and robust design was given a weight of 3. Although, this is an important aspect of many design solutions, the team was given a 20 year time period and solar energy systems have a lifespan much greater than that. The final CR states the system must have a reliable design with a weight of 4. If the system is not reliable, none of the CRs will be met and the system will fail.

Safety was a customer requirement given by Dr. Oman but does not apply to this design project. The competition guidelines tells us to assume structural integrity for all buildings, mitigating the safety concern. Additionally, solar panels do not pose a risk to safety as there is no human interaction and the team was instructed to ignore manufacturing and maintenance interaction.

The determined customer requirements listed were analyzed and turned into quantifiable measurements called engineering requirements (ERs) the team could use as targets toward creating a successful final design. These quantifiable measurements are the engineering requirements, also displayed in the House of Quality in Table 2A.

2.2 Engineering Requirements (ERs)

After determining the CRs and their appropriate weights, the team then converted them into engineering requirements. As stated previously, engineering requirements give the team a quantifiable measurement that helps the team meet and optimize the customer requirements for the client. The ERs were determined by researching each subfunction that affects the CRs in order to find the measurement that has the greatest impact on the CR and determining a goal/requirement for each measurement.

The first ER is power generated and will be measured in kilowatts hours. The target value for power generated is 50% of the total power used during peak energy usage hours. The reasoning behind this is because low energy usage hours and peak energy production hours are at the same time, collecting 166% more energy than what is being used and offsetting the total energy and power consumption. The tolerance is set at anything greater than 50% because any excess energy can and will be sold through the power purchase agreement.

Placement is another ER being measured, and is measured in hours of sun per day. The target value for this is 11 hours of sun per day with a tolerance of plus one hour. In order to optimize the system the solar panels need to be receiving sunlight at least 11 hours of the day. This tolerance was given because there is only a total of 12 hours of sunlight in a day.

Energy loss will be measured in kilowatt hours. The target value for this is 20% which may seem high but with a large scale system is minimal. With a 20% energy loss the team will still have enough energy stored in the batteries to offset power consumption. The tolerance will be plus or minus 5%. If the percentage decreases it allows the team to increase the amount of energy available to sell through the PPA. If it increases, the batteries with still have excess energy to offset power consumption.

Cost will be measured in dollars. Since this system has no budget there is no specific target value or tolerance for this ER. The goal is to minimize the overall cost of the project in order to optimize financial savings. Additionally, the competition asked that the team hold off on financial aspects until the next deliverable in March.

Battery storage capacity is the next ER and will be measured in kilowatt hours. This portion of the project, just like cost, will not be considered until next semester, which is why there is not a target value or tolerance.

Reliability and durability are encompassed by the life cycle of the system and will be measured in years. In order for the system to maximize financial savings it must last 20 years giving the target value. The tolerance for this 0% because solar energy systems have a lifespan 30 years and greater, which extends past the requirement given.

Replacement parts will be measured in dollars. To minimize financial expenditures it is desired that the system lasts its entire lifespan without needing any replacement parts. The target value for this is $0 because of this and the tolerance is 0%.

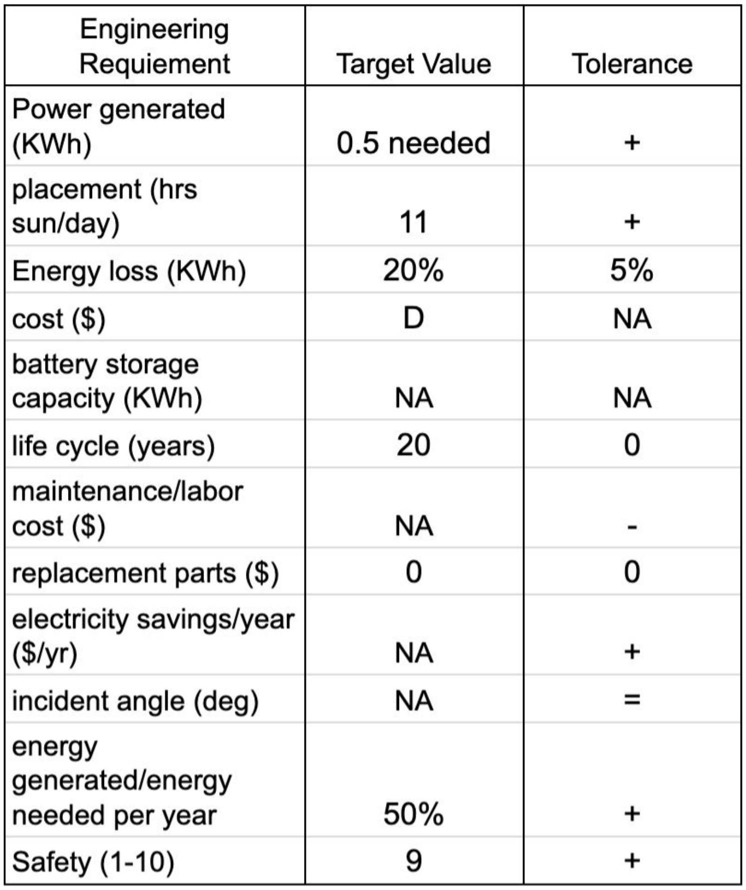
Energy savings per year will be the next ER and is measured in dollars per year. At this point the team is unsure of the amount of energy the campus consumes so it is difficult to predict the energy that needs to be created. In order to come up with a target value and tolerance, the team will have to wait two more weeks when the energy data is scheduled to be given.

The incident angle will be measured in degrees. Since the roofs vary from being completely flat to 45 degrees and solar tracking is being considered, there is not a set target value or tolerance for the incident angle considering the different roof types and rotating solar panels. The main goal with each incident angle is to optimize the amount of solar energy the panels receive.

Safety is another important ER that is measured on a 1-10 scale. The target value is a 9 to ensure that the system does not pose a threat to human/wildlife safety. The tolerance is plus one because of engineering ethics. The team does not want to implement a system that could potentially threaten any type of species. Fortunately, the team can assume structural integrity for all systems implemented on the university's buildings.

This information is summarized below in Table 2.

Table 2: Engineering requirements, target values, and tolerances



Engineering Requiement	Target Value	Tolerance
Power generated (KWh)	0.5 needed	+
placement (hrs sun/day)	11	+
Energy loss (KWh)	20%	5%
cost ($)	D	NA
battery storage capacity (KWh)	NA	NA
life cycle (years)	20	0
maintenance/labor cost ($)	NA	-
replacement parts ($)	0	0
electricity savings/year ($/yr)	NA	+
incident angle (deg)	NA	=
energy generated/energy needed per year	50%	+
Safety (1-10)	9	+

2.3 Functional Decomposition

To develop a plan for solar panel layout, the team constructed a black box model and functional model of the system. The system being analyzed in both of these diagrams is the entire campus of New Mexico State University that has been approved for solar panel placement.

2.3.1 Black Box Model

The inputs and outputs of the system have been characterized into three separate groups: materials, types of energy, and signals. The primary material components that will be interacting with the system are people, animals, and dust. These three materials can impact the system by shading the panels or potentially adjusting the incident angles of the panels. The most active types of energy flowing through the system are heat energy and solar radiation energy. The primary signal flows are shaded and dirty panels. These are the most important signals because the amount of shade or dust on the panel will directly affect the efficiency of the individual panels. The entire Black Box Model is shown in Figure 2.

Figure 2: Black Box Model of NMSU solar panel system

The Black Box Model was used by the team to create a functional model, as well as to analyze the system for potential barriers to efficiency and sources of unsafe environments.

2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

To fully understand the connections between the solar panels, transformers, and the grid, the team created a Functional Model. This allowed the team to better analyze the parts that comprised the whole system. The final Functional Model is shown below in Figure 3.

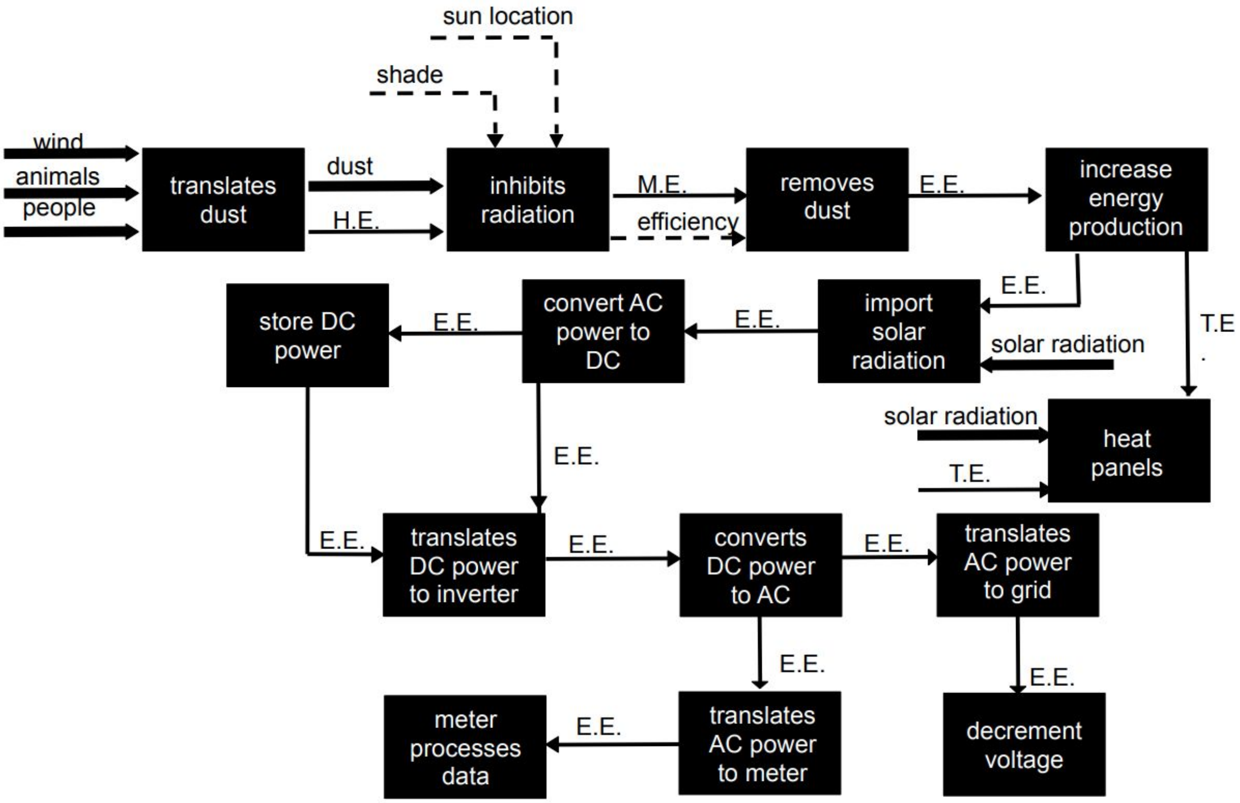


Figure 3: Functional Model of New Mexico State University solar panel system

Although this model shows how the entire system interacts, the mechanical team will only be focused on a portion of the system. This includes accounting for dust, people, and animals, increasing energy production, and determining optimum incident angles for each panel. Although these will be the mechanical team's primary focus in the functional model, the team will still need to be cognizant of the other working parts such as the distance each panel is from the center of the grid--the Tortugas building--and the battery storage connected to specific panels.

2.4 House of Quality (HoQ)

A house of quality is a diagram used for defining the relationship between customer requirements and engineering requirements. This helps the team interpret the top engineering requirements in relation with each other, designating specific ERs to focus on. Using the house of quality template provided by Dr. Oman, the team came up with the most important engineering requirements. As seen in Table 2A in Appendix A, the primary ERs are placement, energy loss, life cycle, and energy generated in comparison to the energy needed per year. The house of quality also shows the testing procedures that will be used to ensure the requirements are met.

The most important engineering requirements provided by the HoQ is minimizing energy loss, which is measured in kilowatt hours. As stated in the previous section, the target value for the amount of energy loss is 20% energy loss with a tolerance of plus or minus 5%. This is why the team decided to incorporate a solar tracking system that follows the sun throughout the day in order to optimize the amount of sun each panel receives. Energy can also be lost when translating over some distance so keeping the system as close to the grid as possible is crucial.

Placement is the second most important engineering requirement according to the HoQ. It is measured in hours of sun per day. The target value for this requirement is 11 hours and it has a tolerance of plus one hour. With this in mind, the team made sure to only incorporate buildings and parking structures that do not have any solar obstructions into the potential final design.

2.5 Standards, Codes, and Regulations

This section discusses the standards, codes, and regulations that apply to the proposed photovoltaic solar energy system. Standards, codes, and regulations are developed and maintained by regulatory agencies, engineering societies, trade organizations, and private companies to provide guidelines based on ethics that promote the betterment of the society. The standards provide the “how to” of executing the codes while the regulations incorporate the codes and standards mandated by the government and required by law.

Standards and codes come from many organizations and societies. The organizations and societies that affect this project are listed below [2].

- American National Standards Institute (ANSI)
- Institute of Electrical and Electronics Engineers (IEEE)
- North America Semiconductor Equipment Industry (SEMI)
- National Fire Protection Association (NFPA)
- International Electrotechnical Commision (IEC)
- National Institute for Standards and Technology (NIST)
- Underwriters Laboratories (UL)

Table 1B in Appendix B provides a summary of the standard number/code, title of the standard, and how it applies to the photovoltaic solar energy system. Following these standards and codes is critical to ensure the legality and viability of this project. Following are the specifics of the codes and standards the team will be adhering to.

ATSM

ATSM E1830-09 - The Standard Test Methods for Determining Mechanical Integrity of Photovoltaic Modules discusses the proper testing methods to determine the mechanical integrity of PV systems. If this standard is not met, the system will fail due to a lack of mechanical integrity. Because the team is purchasing the PV system from an accredited company, this standard is already being met [2].

IEC

IEC 60891 - This code discusses the proper procedures for temperature and irradiance corrections. The photovoltaic systems must be able to correct its temperature to prevent the cells from overheating and igniting. Additionally, the system must correct the solar irradiance to preserve the cell life cycle. The team has taken this standard into consideration by placing the PV system in optimal positions to prevent overheating and to ensure even solar irradiance [2].

IEC 62548 - This code discusses the installation and safety requirements for photovoltaic systems. Installing the solar energy system is crucial to a successful project. Without proper installation the system could potentially fail in several ways. Since this project is only a proposal this requirement can be mitigated because it is the installation companies duty to abide by this requirement [2].

IEEE

IEEE 937 - This code provides proper installation and maintenance guidelines for batteries connecting to photovoltaic systems. Batteries are a key subcomponent of the system. Proper battery installation and maintenance will optimize the energy storage during downtimes which in turn offsets energy consumption and creates financial savings. This standard will be taken into consideration when implementing maintenance costs over the given 20 year time period [2].

IEEE 1013 - Explains solutions to selecting the proper battery size for PV systems using requirements focusing on the size of the system. Optimizing the battery size for the system will provide the necessary storage needed to supply New Mexico State University with the needed energy which minimizes the amount of photovoltaic panels needed. This allows for substantial financial savings [2].

IEEE 1547 - This code provides standards for interconnecting distributed resources with electric power systems. It also provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the innerconnection. Many of the requirements can be mitigated since the team is implementing a pre-existing system but the team must consider the interconnections maintenance throughout the project’s life-cycle [2].

IEEE 1562 - This code provides guided standards for array and battery sizing in stand-alone photovoltaic systems. These standards outline the necessary requirements for the dirt lot and parking shade system since it is not connected to the university's infrastructure, but does not apply to the rest of the team’s designs [2].

IEEE 2030 - This standard provides guidelines in understanding and establishing smart grid for electric power systems for end use applications and loads. This standard will affect how the system distributes energy through the grid for its end use applications throughout the campus [2].

NFPA

NFPA 690 - The National Fire Protection Association Article 690 provides fire safety codes for solar electric systems. All of these codes must be met in order for the system to meet the federal regulations. If the system does not pass this project cannot be implemented [2].

SEMI

SEMI PV2-0709E - This code provides a guide for photovoltaic equipment communications through the grid, meters, and control panel interfaces. The system must communicate accurate information regarding its performance in order to ensure optimized energy usage and storage. If the system does not communicate properly it will create a financial loss [2].

3 Testing Procedures (TPs)

To ensure the engineering requirements are properly met, various testing procedures need to be implemented. The majority of these tests will be performed by the System Advisory Model, but several other tests will be performed using irradiance profiles, grid compatibility, and financial off-set analysis.

3.1 Testing Procedure 1: System Advisory Model (SAM)

SAM is a virtual modeling instrument used for renewable resources and financial analysis [3]. SAM was used to analyze the energy production, electrical losses, and system cost for the Dirt Lot's solar generation field. This software was extremely helpful for calculating the amount of solar energy that could be generated as well as monthly and yearly rates of generation.

3.1.1 Testing Procedure 1: Objective

The objective of this testing procedure is to have an estimate for how much power can be generated using a solar field in the Dirt Lot. This will be done by testing a 30,000 m^2 area which is only a 7th of the full Dirt Lot given. The team will calculate the cost and generation of this entire area using fixed and solar tracking panels.

3.1.2 Testing Procedure 1: Resources Required

This test runs by inputting the longitude and latitude of the testing area (New Mexico State University). This data is provided via NREL (National Renewable Energy Laboratory) who are the creators of SAM and also provide the weather data for the competition. After having the weather data, solar panels, inverters, and the size of the array were chosen. The array was optimized based on the amount of solar generation the team wanted. Tests were run for both half and all of the yearly energy needed. These values were were 17,000 MWh for half and 34,000 MWh for a full year.

3.1.3 Testing Procedure 1: Schedule

The test itself is almost instant. The software calculated the number of solar panels and inverters needed, and the only input was the $/Wdc. The team found $/Wdc using an NREL presentation where they stated the average utility cost to be $1.11/Wdc. The team will continue to run this test for the Dirt Lot depending on how much the team wants to spend and how much more energy is needed. The team will also be testing and calculating the cost if solar tracking is implemented.

3.2 Testing Procedure 2: Aurora Solar

The second testing procedure is a test to find the required deliverables of an irradiance profile and the total energy off-set.

3.2.1 Testing Procedure 2: Objective

The irradiance profile and and the energy off-set will be tested using Aurora Solar [4]. Aurora Solar is able to calculate the irradiance profile of the final design using 3D models of the buildings and trees to simulate the shading on the solar panels. With the irradiance profile, Aurora Solar will be able to simulate the energy production of the system and compare that to the energy consumption. This will be tested to see the validity of the final design chosen and provide the requested deliverables for the competition preliminary proposal.

3.2.2 Testing Procedure 2: Resources Required

The only resource required for this test is Aurora Solar which has been generously provided through the competition.

3.2.3 Testing Procedure 2: Schedule

This testing simulation will not take a long time, but the test will need to be run many times on each iteration of each potential design. The creation of the model for each potential design takes an average of 30 minutes and then the simulation takes about 5 minutes. Each iteration on the design takes about 5 minutes as well. This short testing time will give the team plenty of opportunities to run lots of iterations on each design in order to find the most optimal design.

3.3 Testing Procedure 3: OpenDSS

The third testing procedure is the compatibility of the design with the grid.

3.3.1 Testing Procedure 3: Objective

To test the compatibility of the design with the grid the team will use openDSS to analyze how the proposed design will interact with the grid. OpenDSS simulates how the energy output of the design will be taken in by the grid, determining if a different output voltage is required to connect the system to the grid and how the battery storage will affect how much energy is needed from the grid. This is a required deliverable for the competition, but more importantly will help the team determine the validity of the proposed design and show how the design needs to be modified to become valid.

3.3.2 Testing Procedure 3: Resources Required

The required resource for this testing procedure is the openDSS software. This is a free software.

3.3.3 Testing Procedure 3: Schedule

The openDSS simulation only takes about 10 minutes to run. This means the team will be able to iterate on the potential designs quickly, keeping the team on track to find the optimal design by the deadline.

4 Risk Analysis and Mitigation

40 potential critical failures have been determined and analyzed by the team to ensure the success of the final design. All 40 failures can be seen in Tables 1C-3C in Appendix C.

4.1 Critical Failures

4.1.1 Potential Critical Failure 1: Panel cells covered in debris

Panel cells being covered in dirt or debris has the highest risk of failure and has an RPN value of 48. This has the highest risk because it is a very common form of failure in the solar industry. The causes of thermal energy loss failure could come from a variety of sources: wind, dust storm, rain, human traffic, or wildlife. All sources have the capability to transmit dust, dirt, and debris to the solar panels. The primary effect of the debris and thermal energy loss failure is that the cells that compose the panels will no longer be able to take in the solar radiation from the sun and cannot convert the solar radiation into power. To mitigate this potential critical failure, routine maintenance checks should be performed to keep the panels clean, and some sort of system should be employed to ensure the panels stay clean. One such system could be equipping each panel with a duster that swipes across the surface when lower levels of radiation are detected in the panel.

4.1.2 Potential Critical Failure 2: Panels under cloudy weather

Cloudy weather is another high ranked potential critical failure with an RPN of 12. This ranked lower than debris because it is likely that this will occur less frequently than the panels getting dirty. This failure would also be classified as a thermal energy loss failure and will inhibit the panels energy output. The cause of this failure is clouds blocking the sun from transmitting the entirety of its solar radiation to the panels. The effect of this, similar to dirty panels, will be a significant loss in energy output from the panels. To mitigate this failure, weather can be closely monitored and panels can be turned off when in the path of clouds to minimize the losses associated with the underloading of the system.

4.1.3 Potential Critical Failure 3: Batteries overheating

Batteries overheating also has an RPN value of 12. The critical failure associated with the batteries overheating is semiconductor failure. The causes of the overheating could be overuse or overvoltage supplied to the battery, or the battery attempting to match an output that is to great for its output capacity. The effects of this failure could be loss of battery potential lifespan, loss of energy, and battery failure altogether. To mitigate this failure, scheduled downtimes will be implemented to ensure the battery is not working for too continuously of a time. Additionally, maintenance checks will be performed on the entirety of the system to ensure each component is functioning properly.

4.1.4 Potential Critical Failure 4: Vegetation growth around ground-mounts

Vegetation growth around ground-mounts has an RPN of 9. The failure associated with this is fretting wear on the ground-mount system. The causes of the fretting wear is the vegetation growing around and under the system, and pushing up against the components. After time, this could cause damage to the system and weaken the support of the panels. To mitigate this failure, maintenance will be routinely performed on all ground-mount systems to ensure there is not anything growing under or around the system that could interfere with the stability and integrity of the support.

4.1.5 Potential Critical Failure 5: Connection wire damage on panels

Connection wire damage on panels has an RPN value of 9 and the potential critical failure associated with it is fretting damage on the wires. The potential causes of this failure could be vibrations in the earth or buildings that carry up the mounting systems to the connection wires, inclement weather, or animal damage to wires. The effects of the failure would be loss of energy output from the panel, and if severe enough, loss of panel functionality. To mitigate this failure, routine maintenance checks will be performed with special care to check all connection wires and ensure solid connections between all components.

4.1.6 Potential Critical Failure 6: Thermal insulator damage in panels

Thermal insulator damage has a RPN of 8. The causes of the insulator damage could be vibrations from the support systems, inclement weather, or animal interaction with the panels. The critical failure that could happen as a result would also be fretting wear because of the consistent rubbing of materials with the vibrations. The effects of the failure could be loss of energy and loss of efficiency because of the lower levels of insulation inside of the panels. To mitigate this failure, routine maintenance checks will be performed and components will be replaced if damage to the thermal insulation shows signs of causing losses in the system.

4.1.7 Potential Critical Failure 7: Under-voltage in inverters

Undervoltage in inverters has an RPN of 8. The failure that corresponds to this damage is semiconductor failure inside the inverter. The main cause of this failure would be under-voltage to the battery and the effects of this failure would be loss of storage capabilities and large amounts of energy losses during peak hours of the day. This will be mitigated by ensuring the system is not active during off-peak hours of energy production.

4.1.8 Potential Critical Failure 8: Battery storage damage in inverters

Battery storage damage in inverters also has an RPN of 8. The potential critical failure of this damage is fretting wear on the battery and the wires connecting the battery to the inverter. The causes of the damage could be from vibrations, inclement weather, or animal interaction with the inverters. The effects of the failure would be loss of storage capabilities and a large amount of energy loss during peak hours because of the lack of storage available to the system. Instead of using the energy at a different time, the energy would be lost. This will be mitigated by routinely checking for battery damage and replacing the batteries if apparent damage is seen.

4.1.9 Potential Critical Failure 9: Connection wire damage on inverters

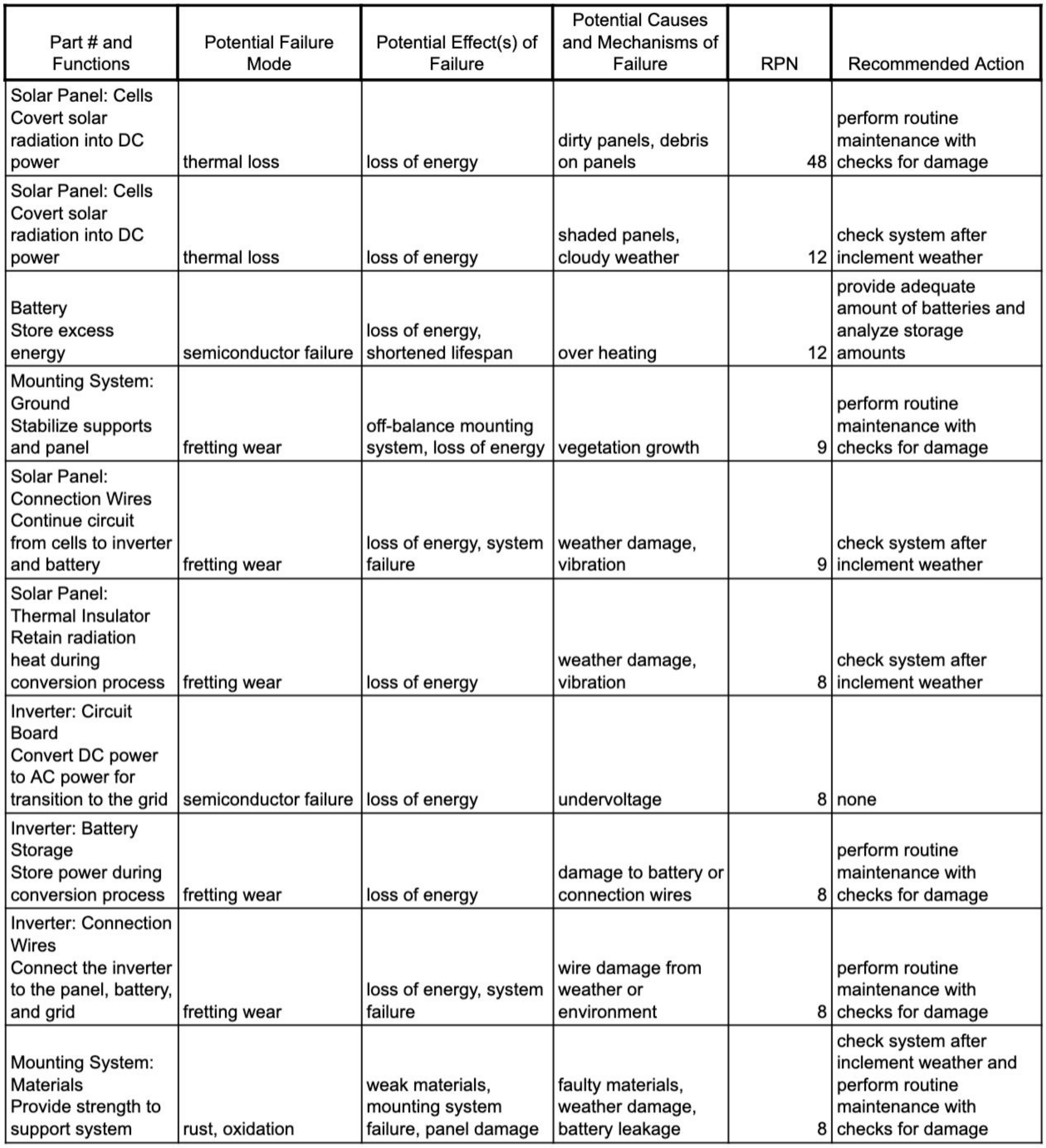
Connection wire damage on the inverters has an RPN of 8. The potential failure of the wire damage is fretting wear that could cause a loss of energy or overall system failure. Causes of the damage could be interaction with people or animals, or weather that causes vibrations that make the wires rub up against another component of the system. This will be mitigated by performing routine checks on the system.

4.1.10 Potential Critical Failure 10: Corrosion on mounting system

Corrosion on the mounting system has an RPN value of 8. The failure associated with the corrosion is rust and oxidation on the mounting system. This could be caused by faulty materials, weather damage, or a leaking battery. The effects of corrosion would be weakened materials, mounting system damage, and potentially panel damage if the mounting system failed. This will be mitigated by checking the system after rainy weather and performing routine checks to ensure the system does not have any damage.

This information is summarized in Table 3.

Table 3: Top 10 Most Critical Failures



Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended Action
Solar Panel: Cells Covert solar radiation into DC power	thermal loss	loss of energy	dirty panels, debris on panels	48	perform routine maintenance with checks for damage
Solar Panel: Cells Covert solar radiation into DC power	thermal loss	loss of energy	shaded panels, cloudy weather	12	check system after inclement weather
Battery Store excess energy	semiconductor failure	loss of energy, shortened lifespan	over heating	12	provide adequate amount of batteries and analyze storage amounts
Mounting System: Ground Stabilize supports and panel	fretting wear	off-balance mounting system, loss of energy	vegetation growth	9	perform routine maintenance with checks for damage
Solar Panel: Connection Wires Continue circuit from cells to inverter and battery	fretting wear	loss of energy, system failure	weather damage, vibration	9	check system after inclement weather
Solar Panel: Thermal Insulator Retain radiation heat during conversion process	fretting wear	loss of energy	weather damage, vibration	8	check system after inclement weather
Inverter: Circuit Board Convert DC power to AC power for transition to the grid	semiconductor failure	loss of energy	undervoltage	8	none
Inverter: Battery Storage Store power during conversion process	fretting wear	loss of energy	damage to battery or connection wires	8	perform routine maintenance with checks for damage
Inverter: Connection Wires Connect the inverter to the panel, battery, and grid	fretting wear	loss of energy, system failure	wire damage from weather or environment	8	perform routine maintenance with checks for damage
Mounting System: Materials Provide strength to support system	rust, oxidation	weak materials, mounting system failure, panel damage	faulty materials, weather damage, battery leakage	8	check system after inclement weather and perform routine maintenance with checks for damage

4.2 Risks and Trade-offs Analysis

The main safety concern for solar generation and storage falls on the inverters or the batteries. Both of these components have the largest chance for failure which is still close to impossible under correct conditions. Inverters can get overloaded and potentially explode but many inverters have programs built in to stop this from happening. The inverters also only operate during the solar generation period which is approximately 10am to 6pm. Inverters can also be shut down to let cool and then be turned back on to continue converting energy, it will just make the others less efficient. Batteries can overheat, especially Lithium Ion batteries, which will most likely be used due to their long lifespan and high efficiency. These batteries can overheat and catch fire but only if they're mismanaged, Programs will be in place to tell the batteries charge and # of cycles left. Having a monitoring software for the batteries is essential for maximizing their life span as well as safety. Because all of these parts are bought from distributors and the team is not allowed to manufacture anything or design anything from scratch, a proper trade-off analysis cannot be conducted.

5 DESIGN SELECTED – First Semester

The designs selected were determined using a decision matrix, pugh chart and financial viability. The three designs that were selected are what the team believes to be the most financially beneficial over 20 years. These designs were tested using the SAM and Aurora Solar software.

5.1 Design Description

The technical criteria used to evaluate the designs were the customer needs and engineering requirements previously defined in the house of quality (Table 2A). The customer needs were used in a pugh chart shown in appendix D (Table 1D) to evaluate the use of different buildings for the system. The team learned from the pugh chart that the buildings with slanted roofs would not perform as well as those with flat roofs. The team then used a decision matrix to further reduce the ideas that will be used in the system by comparing them to the engineering requirements. The decision matrix created is shown in appendix D (Table 2D) and revealed that the designs that will be used in the system will be the American Center, solar tracking in the Dirt Lot and a solar awning in the Horseshoe Quad.

The American center and Dirt Lot are the two largest areas given and will generate the most energy from two areas instead of a couple small PV arrays. The Dirt Lot will produce a large percent of the energy production due to it having the largest area for a solar field. The disadvantages of the Dirt Lot is the lack of infrastructure already there. The solar awning will provide the desired creative solar energy array given for the project even though it will not provide much power.

To initially design and evaluate the final final concepts the team used Aurora Solar. Aurora Solar is an online tool provided by NREL the competition holders and is used to make 3D models of the proposed designs and then evaluate them based on panel performance. The models of the three final designs are shown in figures 3, 4 and 5 below.

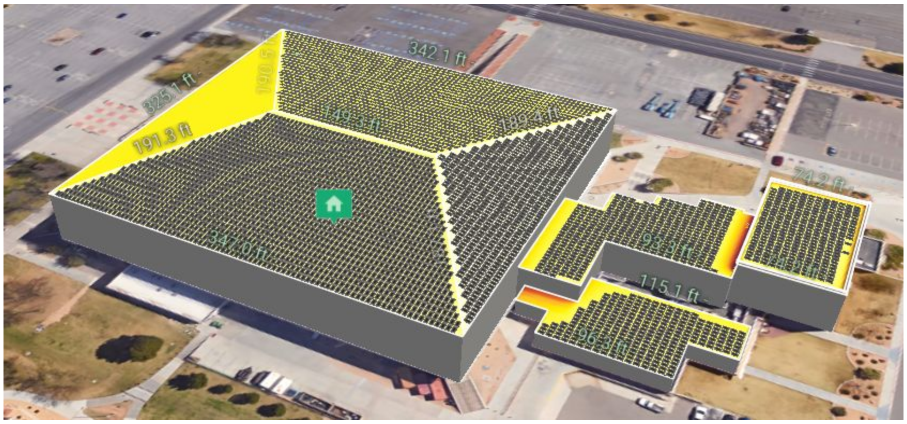
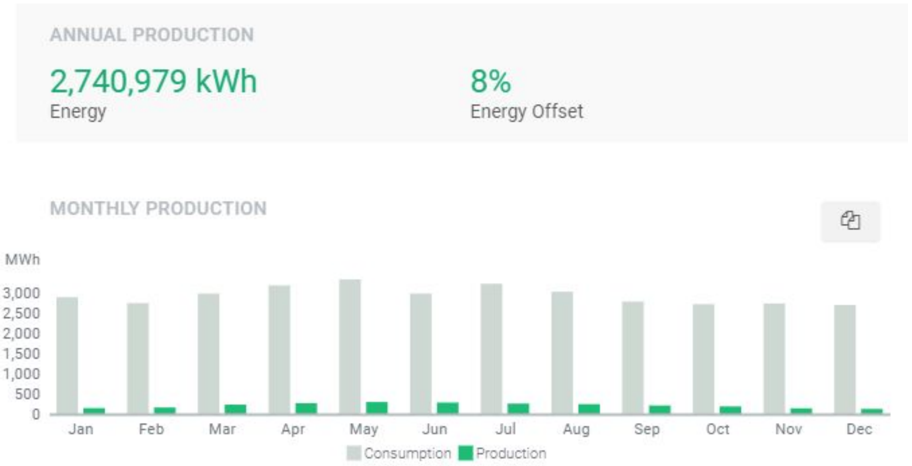


Figure 3: American Center design [4]

Figure 4: Dirt Lot Design [4]

Figure 5: Solar Awning Design [4]

Once the 3D models were created in Aurora Solar the team input the costs of the solar panel installation, the different known incentives, and made a custom utility provider in order to run a performance and financial simulation on the design. This simulation provides the monthly energy production and the energy offset it provides to the campus, the monthly energy bill savings, the payback period, and how much money that will be saved over a 25 year period. Figures 6-14 below show the energy production and financial simulations of each design.

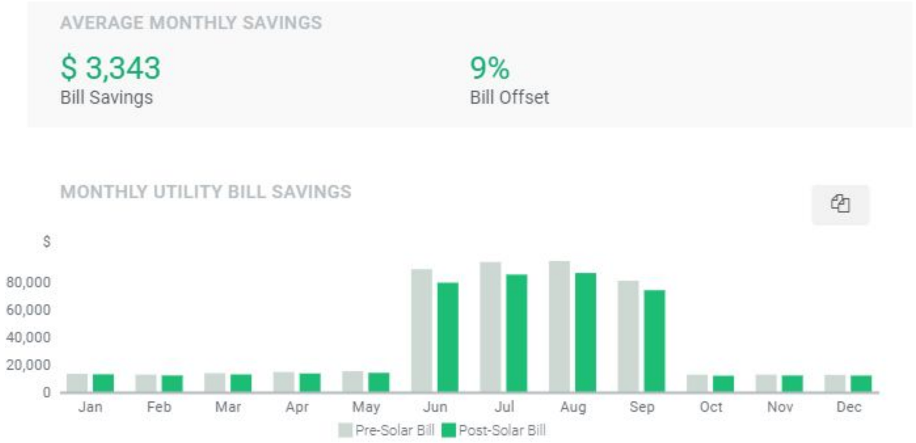


ANNUAL PRODUCTION

2,740,979 kWh
Energy

8%
Energy Offset

Figure 6: Energy Production of American Center [4]



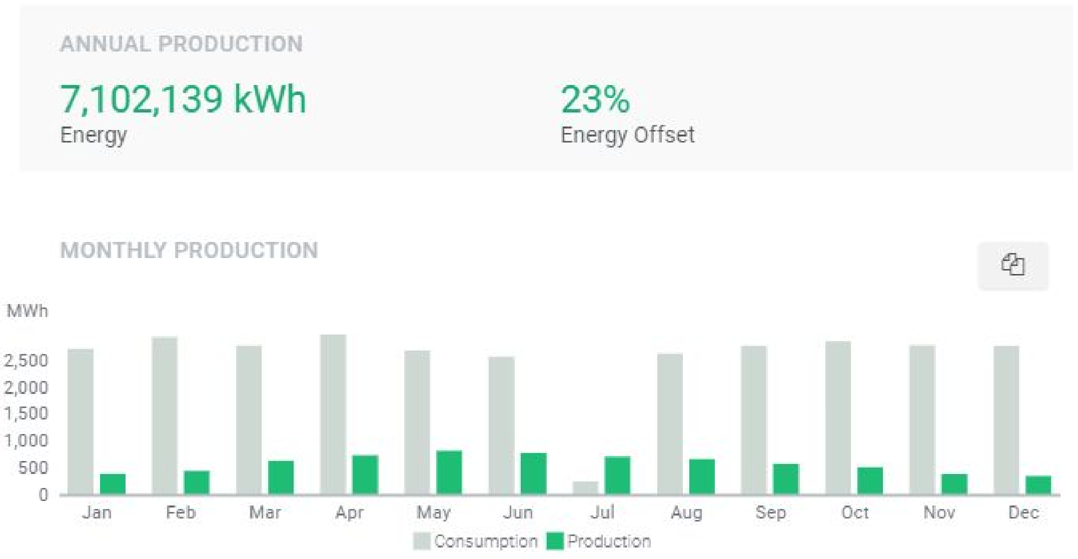
AVERAGE MONTHLY SAVINGS

$ 3,343
Bill Savings

9%
Bill Offset

Figure 7: Energy Bill Savings of American Center [4]

As shown in Figures 6 and 7 the American Center will provide 8% of the energy used by the buildings provided through the competition and offset the bill by 9%. Next, the energy and bill offsets for the dirt lot are shown in figures 8 and 9 below.



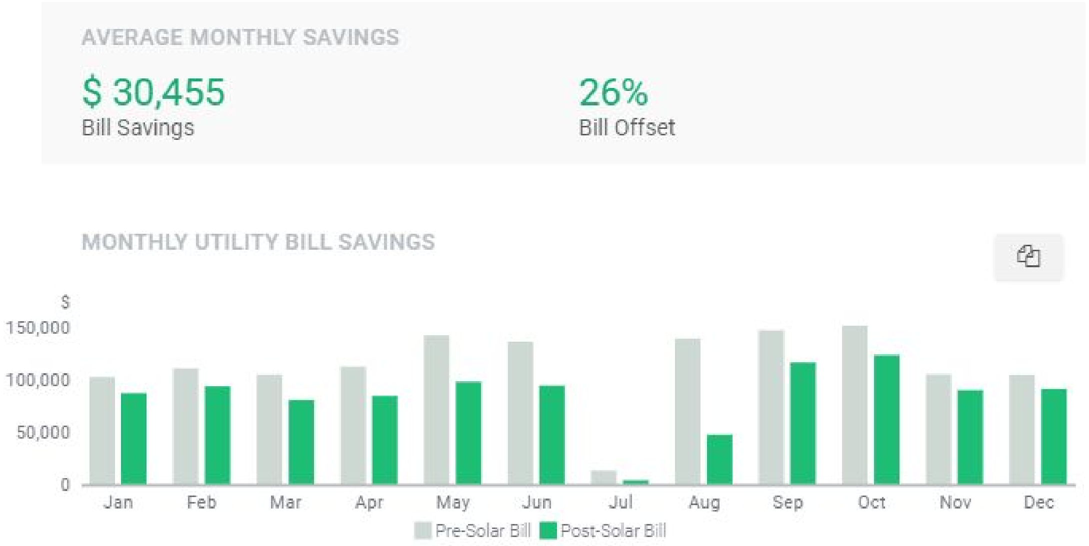
ANNUAL PRODUCTION

7,102,139 kWh
Energy

23%
Energy Offset

MONTHLY PRODUCTION

Figure 8: Energy Production of Dirt Lot [4]



AVERAGE MONTHLY SAVINGS

$ 30,455
Bill Savings

26%
Bill Offset

MONTHLY UTILITY BILL SAVINGS

Figure 9: Energy Bill Savings of Dirt Lot [4]

Figures 8 and 9 show that the dirt lot will provide 23% of the energy for the campus and offset the energy bill by 26%. This shows that using only a portion of the dirt lot will provide a quarter of the energy needs of the buildings provided. Lastly, the solar awning in the Horseshoe quad energy and bill offsets are shown in figures 10 and 11 below.

ANNUAL PRODUCTION

345,460 kWh
Energy

1%
Energy Offset

MONTHLY PRODUCTION

Figure 10: Energy Production of Solar Awning [4]

AVERAGE MONTHLY SAVINGS

$ 456
Bill Savings

1%
Bill Offset

MONTHLY UTILITY BILL SAVINGS

Figure 11: Energy Bill Savings of Solar Awning [4]

Figures 10 and 11 show that the solar awning will not provide much power to the campus nor will it save NMSU much money, but that is not the point of the solar awning, the point is to show the campus's efforts towards renewable energy. With this said the team still needed to look at the costs of the designs. Aurora Solar provides this data that is shown in figures 12, 13, and 14 below.

CASH
Default Financing

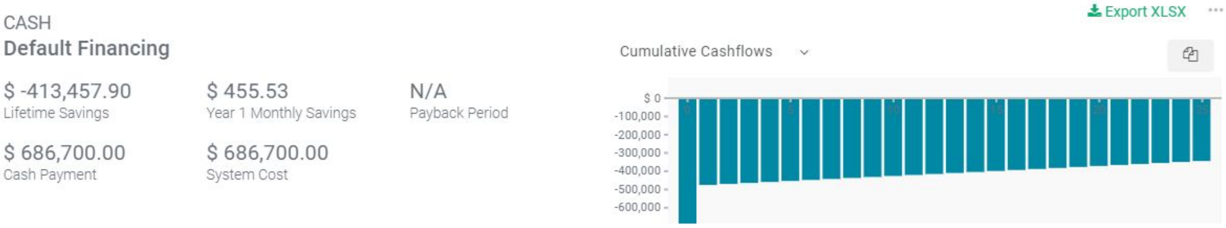
$ -1,709,538.23 Lifetime Savings
$ 3,686.44 Year 1 Monthly Savings
N/A Payback Period
$ 3,266,222.00 Cash Payment
$ 3,266,222.00 System Cost

Figure 12. American Center Financing [4]

CASH
Default Financing

$ 1,792,433.05 Lifetime Savings
$ 30,455.45 Year 1 Monthly Savings
9.01 Years Payback Period
$ 4,701,782.40 Cash Payment
$ 4,701,782.40 System Cost

Figure 13. Dirt Lot Financing [4]



CASH
Default Financing

$ -413,457.90 Lifetime Savings
$ 455.53 Year 1 Monthly Savings
N/A Payback Period
$ 686,700.00 Cash Payment
$ 686,700.00 System Cost

Figure 14. Solar Awning Financing [4]

The financing simulation performed by Aurora Solar show that the dirt lot will eventually save NMSU about 1.79 million dollars while the American Center will cost NMSU a total of 1.71 million dollars and the solar awning will cost about $400,000. This means that NMSU will lose close to $310,000 from these three designs but this does not reflect the end of this project, iterations will be done on both of these designs to optimize the energy and financial offsets. The reason the team is still considering the rooftop solar is that putting panels on the roofs of buildings is a very efficient use of space which NMSU finds appealing. The Solar Awning is being used in the quad because the university wants there to be a place on campus where people can see that solar is being used as the campus moves towards being completely powered by renewable energy by the year 2050. Even if this project costs NMSU money, their goal of becoming completely powered by renewable energy should be enough to justify a costly project, so long as it provides a decent energy offset.

5.2 Implementation Plan

The objectives to complete the project are; create a complete conceptual system design, analyze the financial viability of the design, implement battery storage into the design, and verify the compatibility of the design with the grid. This process will be repeated as many times as needed to create the optimal solar energy system.

To create the conceptual system design, the team will be using SAM and Aurora Solar. SAM has some customization tools that Aurora Solar does not have, but Aurora Solar has great visuals and the ability to factor in obstructions when designing a rooftop solar design. Corey and Daniel will be leading system design.

To test the financial viability of the design, the team will use a custom made excel sheet. This excel sheet is a requirement for the competition and will provide the team with useful insight into where the system is losing money, where it can be improved or if it is a good design. Grant will be leading the testing of financial viability.

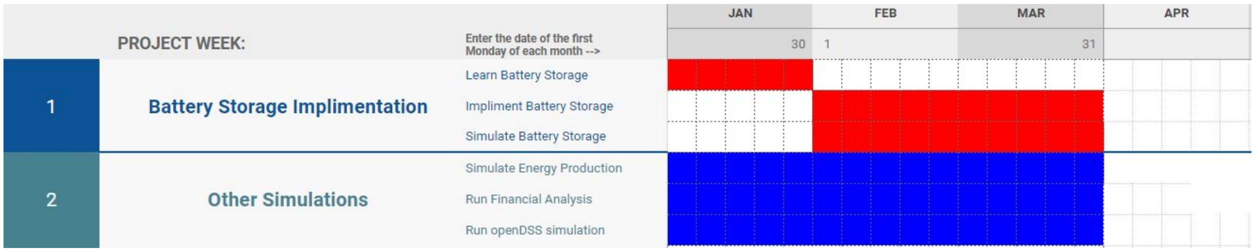
Battery storage will be added using REOpt Lite. This tool takes in energy production and usage data and then optimizes the amount and size of batteries that should be implemented into the design. Elizabeth will be leading the implementation of battery storage, but the whole team will be helping as it will be a large task.

Testing the design compatibility with the grid will be done using the open-source software openDSS. OpenDSS is a tool that will factor in the design created and the battery storage added in order to see how it will interact with the grid, showing any areas of the design that are incompatible or could be redesigned to maximize efficiency. The electrical engineering team will be heading grid compatibility.

Once a final optimized design is chosen, both the mechanical and electrical engineering teams will work together to create the PPA and complete all of the final deliverables that are due in April.

All of these simulations will be done throughout the entirety of the next semester except the battery storage. No one simulation will take enough time for the team to need to plan out a specific schedule however the team plans to complete all simulations by April 1st to give time for the team to write up the final deliverables. The schedule the team has created is shown in table 4 below.

Table 4. Schedule for Spring Semester



	PROJECT WEEK:	Enter the date of the first Monday of each month -->	JAN 30	FEB 1	MAR 31	APR
1	Battery Storage Implimentation	Learn Battery Storage	🟥			
		Impliment Battery Storage		🟥	🟥	
		Simulate Battery Storage		🟥	🟥	
2	Other Simulations	Simulate Energy Production	🟦	🟦	🟦	
		Run Financial Analysis	🟦	🟦	🟦	
		Run openDSS simulation	🟦	🟦	🟦	

6 CONCLUSIONS

The Solar District Cup is a collegiate competition where teams design the most financially viable solar generation and storage system for a district use case. This is done by proposing a PPA for the district (NMSU). This is done through calculating the energy consumption of the district and comparing it to the net energy production. These requirements will be met by creating a solar generation system for the Dirt Lot and the Amercan Center building. The bulk of the energy generation will come from the dirt lot as it is an extremely large open area roughly 3 miles from campus. This lot is flat and has no obstructions that could shade the panels making it the most efficient area for solar generation. The American Center is a large building that is close to the center of campus which will decrease energy lost due to transportation. The Solar Awnings will generate a small amount of power due to their size but will also double as a shaded area for people to relax in the quad. The Horseshoe Quad is also a great destination for campus tours and will help showcase the campus's priorities on a renewable future. These different solar generation systems were tested using Aurora Solar and SAM, two renewable modeling software programs with built-in financial analysis. The rules of the competition clearly state the team will not have to worry about roof structural integrity which would be the main safety concern for a large rooftop solar array. Other safety concerns include overheating batteries or inverters which can be easily managed with monitoring software. Based on the results from SAM and Aurora the team believes the proposed design is the most financially viable and safe option to move New Mexico State University to a renewable future.

7 REFERENCES

[1] HeroX, “Solar District Cup,” HeroX, 2019. [Online]. Available: https://www.herox.com/SolarDistrictCup.

[2] Solar America Board for Codes and Standards, "Codes and Standards," Solar America Board for Codes and Standards, [Online]. Available: http://www.solarabcs.org/codes-standards/index.html. [Accessed 15 November 2019].

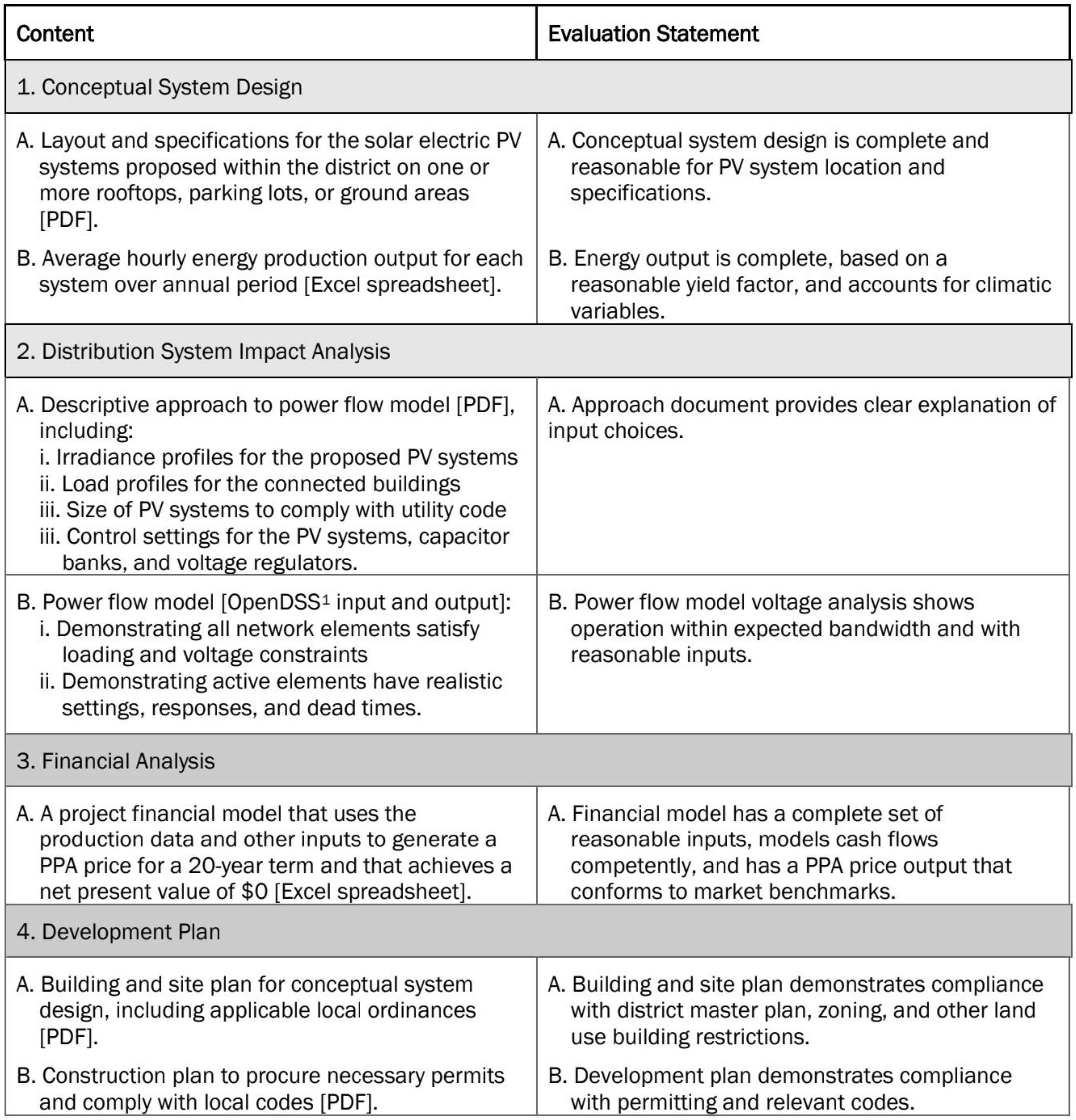
[3] National Renewable Energy Laboratory, “System Advisor Model,” National Renewable Energy Laboratory, 2019. [Online]. Available: https://sam.nrel.gov/.

[4] Aurora Solar, “Powerful Software for Solar Sales and Design,” Aurora Solar. [Online]. Available https://www.aurorasolar.com/.

8 APPENDICES

8.1 Appendix A: Competition Requirements and House of Quality

Table 1A: Competition requirements established by HeroX



Content	**Evaluation Statement**
1. Conceptual System Design	
A. Layout and specifications for the solar electric PV systems proposed within the district on one or more rooftops, parking lots, or ground areas [PDF].	A. Conceptual system design is complete and reasonable for PV system location and specifications.
B. Average hourly energy production output for each system over annual period [Excel spreadsheet].	B. Energy output is complete, based on a reasonable yield factor, and accounts for climatic variables.
2. Distribution System Impact Analysis	
A. Descriptive approach to power flow model [PDF], including: i. Irradiance profiles for the proposed PV systems ii. Load profiles for the connected buildings iii. Size of PV systems to comply with utility code iii. Control settings for the PV systems, capacitor banks, and voltage regulators.	A. Approach document provides clear explanation of input choices.
B. Power flow model [OpenDSS[1] input and output]: i. Demonstrating all network elements satisfy loading and voltage constraints ii. Demonstrating active elements have realistic settings, responses, and dead times.	B. Power flow model voltage analysis shows operation within expected bandwidth and with reasonable inputs.
3. Financial Analysis	
A. A project financial model that uses the production data and other inputs to generate a PPA price for a 20-year term and that achieves a net present value of $0 [Excel spreadsheet].	A. Financial model has a complete set of reasonable inputs, models cash flows competently, and has a PPA price output that conforms to market benchmarks.
4. Development Plan	
A. Building and site plan for conceptual system design, including applicable local ordinances [PDF].	A. Building and site plan demonstrates compliance with district master plan, zoning, and other land use building restrictions.
B. Construction plan to procure necessary permits and comply with local codes [PDF].	B. Development plan demonstrates compliance with permitting and relevant codes.

Table 2A: House of Quality

Customer Requirement	Weight/Engineering Requirement	Power generated (KWh)	placement (hrs sun/day)	Energy loss (KWh)	cost ($)	battery storage capacity (KWh)	life cycle (years)	maintenance/labor cost ($)	replacement parts ($)	electricity savings/year ($/yr)	incident angle (deg)	energy generated/energy needed per year	Safety (1-10)
offset annual energy and power consumption	5	9	9	9	9	9	9	3	3	9	9	9	3
aesthetically pleasing	3		9		3		9	9	9		1		9
optimized distributed energy system	2	3	9	9		9	9	3	3	1	9	9	9
includes solar photovoltaic generation	4	9	9	3	9	1	9	3	3	9	9	9	3
has battery electric storage	5	3	9	9	9	9	9	3	3	9		9	9
maximizes financial savings over 20 years	2	9	9	9	9	9	9	9	9	9	9	9	9
power purchase agreement	3	9	9	9	9	9	9	3	3	9	3	9	9
financial viability	5	9		9	9	3	9	3	3	9	3	9	3
reasonable PV location	4	9	9	9	3	3	9	9	3	9	9	3	9
energy output based on a reasonable yield factor	4	9	9	9	3	9	3	3	3	3	9	9	
voltage within expected bandwidth	3	9	9	9	3	9	3			3	9	9	3
all network elements satisfy loading and voltage constraints	4	9	9	9	3	9	3	3	3	9	9	9	9
active elements have realistic settings, responses, and dead times	3	9	9	9	3	3	3	3	3	9	9	9	3
optimal battery use	4	3	3	9		9	9	9	9	9	3	9	1
cost within budget	5	3	3	3	9	3	3	9	9	3	3	3	3
durable & robust design	3	3	3	3	3	3	3	9	3	3	3	3	9
Reliable design	4	3	9	9	3	3	9	9	3	3	9	3	3
Absolute Technical Importance (ATI)		402	450	468	345	364	435	330	264	410	378	444	325
Relative Technical Importance (RTI)		6	2	1	9	8	4	10	12	5	7	3	11
Target ER values		0.5 needed	11	20%	D		20		0			50%	9
Tolerances of Ers		+	+	5%			0	-	0	+	=	+	+
Testing Procedure		SAM	Irradiance/Grid Compat.	SAM	SAM	SAM	SAM	SAM	SAM	Energy Off-Set	Irradiance profile	Energy Off-Set	SAM

8.2 Appendix B: Relevant Standards and Codes

Table 1B: Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ATSM E1830-09	Standard Test Methods for Determining Mechanical Integrity of Photovoltaic Modules	Provides technical guidelines for testing methods to determine the mechanical integrity of the system
IEC 60891	Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics	Provides a procedure for temperature and irradiance corrections in order to optimize the system
IEC 62548	Installation and Safety Requirements for Photovoltaic (PV) Systems	Provides installation and safety requirements for PV systems

IEEE 937	Practice for Installation and Maintenance of Batteries for Photovoltaic Systems	Provides proper installation and maintenance guidelines for batteries connecting with PV systems
IEEE 1013	Practice for Sizing Batteries for Stand Alone Photovoltaic Systems	Helps optimize the proper battery size for PV systems
IEEE 1547	Standard for Interconnecting Distributed Resources with Electric Power Systems	Helps with interconnecting distributed resources connecting to the electric power system
IEEE 1562	Guide for Array and Battery Sizing in Stand-Alone Photovoltaic Systems	Provides a guide for the proper array and battery sizing in PV systems
IEEE 2030	Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and End-Use Applications and Loads	Helps create a smart grid that operates the electric power system for end use applications and energy loads
NFPA 690	Solar Electric Systems	Provides fire safety codes for solar electric systems
SEMI PV2-0709E	Guide for PV Equipment Communication Interfaces (PVECI)	Provides a guide for photovoltaic equipment communication interfaces
UL 2703	Rack Mounting Systems and Clamping Devices for Flat-Plate Photovoltaic Modules and Panels	Helps determine the appropriate mounting system and clamping devices for photovoltaic modules and panels

8.3 Appendix C: Potential Critical Failures

Table 1C: FMEA page 1

Product Name: Solar District Cup	Development Team: 19F09 Solar District Cup	FMEA Number: 1/3
System Name: NMSU Solar Campus		Date: 11/10/19

Part and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Solar Panel: Cells Covert solar radiation into DC power	high-cycle fatigue	burnt out cells	2	over-use, temperatures above 80 celsius	1	monitoring temperature	3	6	none
Solar Panel: Cells Covert solar radiation into DC power	thermal loss	loss of energy	2	dirty panels, debris on panels	6	routine maintenance	4	48	perform routine maintenance with checks for damage
Solar Panel: Cells Covert solar radiation into DC power	thermal loss	loss of energy	3	shaded panels, cloudy weather	4	weather monitoring	1	12	check system after inclement weather
Solar Panel: Thermal Insulator Retain radiation heat during conversion process	fretting wear	loss of energy	2	weather damage, vibration	2	weather monitoring	2	8	check system after inclement weather
Solar Panel: Frame Hold cells and glass in place	fretting wear	bent frame, fractured frame, broken glass, damaged cells	2	weather damage, vibration	1	weather monitoring	3	6	check system after inclement weather
Solar Panel: Glass Protect solar cells from debris	fretting wear	broken glass, damaged cells	2	weather damage, vibration	1	weather monitoring	3	6	check system after inclement weather
Solar Panel: Connection Wires Continue circuit from cells to inverter and battery	fretting wear	loss of energy, system failure	3	weather damage, vibration	1	weather monitoring	3	9	check system after inclement weather
Solar Panel: Incident angle Direct cells towards the sun at their latitudonal location	fretting wear	loss of energy	2	weather damage, vibration	1	weather monitoring	1	2	check system after inclement weather
Solar Panel: Rotation Arm Balance the panel at the correct incident angle	fretting wear	loss of energy	2	weather damage, vibration	3	weather monitoring	1	6	check system after inclement weather
Solar Panel: Mounting Arm Attach the panel to the support fixture	fretting wear	loss of energy, mounting system failure, panel damage	2	weather damage, vibration	1	weather monitoring	2	4	check system after inclement weather
Solar Panel: Expected Lifespan Provide information on maintenance and replacement	brittle fracture	system failure	4	faulty materials	1	routine maintenance	1	4	perform routine maintenance with checks for damage
Inverter: Circuit Board Convert DC power to AC power for transition to the grid	semiconductor failure	loss of energy	2	overheating	2	scheduled downtimes	1	4	none
Inverter: Circuit Board Convert DC power to AC power for transition to the grid	semiconductor failure	loss of energy	2	overloading	2	scheduled downtimes	1	4	none
Inverter: Circuit Board Convert DC power to AC power for transition to the grid	semiconductor failure	loss of energy	2	underloading	1	scheduled downtimes	1	2	none

Table 2C: FMEA page 2

Product Name: Solar District Cup	Development Team: 19F09 Solar District Cup	FMEA Number: 2/3
System Name: NMSU Solar Campus		Date: 11/10/19

Part and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Inverter: Circuit Board Convert DC power to AC power for transition to the grid	fretting wear	loss of energy, system failure	2	weather damage	1	weather monitoring	2	4	check system after inclement weather
Inverter: Circuit Board Convert DC power to AC power for transition to the grid	semiconductor failure	loss of energy	2	arching	1	scheduled downtimes	1	2	none
Inverter: Circuit Board Convert DC power to AC power for transition to the grid	semiconductor failure	loss of energy	4	undervoltage	1	scheduled downtimes	2	8	none
Inverter: Battery Storage Store power during conversion process	fretting wear	loss of energy	4	damage to battery or connection wires	1	routine maintenance	2	8	perform routine maintenance with checks for damage
Inverter: Connection Wires Connect the inverter to the panel, battery, and grid	fretting wear	loss of energy, system failure	4	wire damage from weather or environment	1	routine maintenance	2	8	perform routine maintenance with checks for damage
Inverter: Connection Wires Connect the inverter to the panel, battery, and grid	fretting wear	loss of energy, system failure	3	loss of wire connections from weather or environment	1	routine maintenance	2	6	perform routine maintenance with checks for damage
Inverter: Capacitor Stores energy inside the inverter	semiconductor failure	loss of energy, system failure	5	overheating capacitor	1	scheduled downtimes	1	5	none
Inverter: Expected Lifespan Provide information on maintenance and replacement	brittle fracture	system failure	2	faulty materials	3	routine maintenance	1	6	perform routine maintenance with checks for damage
Mounting System: Ground Stabilize supports and panel	fretting wear	off-balance mounting system, loss of energy	3	shifting ground, flooding	1	routine maintenance	1	3	perform routine maintenance with checks for damage
Mounting System: Ground Stabilize supports and panel	fretting wear	off-balance mounting system, loss of energy	3	vegetation growth	1	routine maintenance	3	9	perform routine maintenance with checks for damage
Mounting System: Support Arm Balance panel at an angle	impact fracture	off-balance mounting system, loss of energy, panel damage	2	weather damage, vibration	1	weather monitoring	3	6	check system after inclement weather
Mounting System: Materials Provide strength to support system	rust, oxidation	weak materials, mounting system failure, panel damage	2	faulty materials, weather damage, battery leakage	2	weather monitoring and routine maintenance	2	8	check system after inclement weather and perform routine maintenance with checks for damage
Mounting System: Materials Provide strength to support system	brittle fracture	mounting system failure, panel damage, loss of energy	2	weak materials	1	routine maintenance	1	2	perform routine maintenance with checks for damage

Table 3C: FMEA page 3

Product Name: Solar District Cup
Development Team: 19F09 Solar District Cup
FMEA Number: 3/3
System Name: NMSU Solar Campus
Date: 11/10/19

Part and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Mounting System: Fasteners Connect support, panel, battery, and inverter components	buckling, fastener failure	loss of energy, mounting system failure, panel damage	3	faulty materials, weather damage, vibration	1	weather monitoring and routine maintenance	1	3	check system after inclement weather and perform routine maintenance with checks for damage
Mounting System Hold panel at desired location	yielding	building structural integrity	2	heavy panels, focused forces on structure	1	avoiding old buildings, analyzing structural integrity with imposed weight forces	1	2	none
Mounting System Hold panel at desired location	system deformation	loss of energy	2	off-balance mounting system	1	routine maintenance	2	4	perform routine maintenance with checks for damage
Mounting System Hold panel at desired location	surface fatigue wear	off-balance mounting system, loss of energy	3	un-sturdy supports	1	routine maintenance	2	6	perform routine maintenance with checks for damage
Mounting System Hold panel at desired location	fretting wear	loss of energy, system failure	2	weather damage	1	weather monitoring	3	6	check system after inclement weather
Battery: Connection Wires Continue circuit from inverter and panel	fretting wear	loss of energy, system failure	2	weather damage, vibration	1	weather monitoring	3	6	check system after inclement weather
Battery Store excess energy	semiconductor failure	loss of energy, shortened lifespan	2	over heating	3	scheduled downtimes	2	12	none
Battery Store excess energy	semiconductor failure	loss of energy, shortened lifespan	3	overcharging	1	scheduled downtimes	2	6	none
Battery Store excess energy	galvanic corrosion	system failure, loss of energy	4	corrosion	1	routine maintenance	1	4	perform routine maintenance with checks for damage
Battery Store excess energy	semiconductor failure	loss of energy, shortened lifespan	3	repeated cycling	1	scheduled downtimes, lifecycle analysis	1	3	none
Battery Store excess energy	semiconductor failure	loss of energy	2	undercharging	1	scheduled downtimes	1	2	none
Battery Store excess energy	semiconductor failure	loss of energy, shortened lifespan, system overload	3	over discharge	1	scheduled downtimes	2	6	none
Battery Store excess energy	fretting wear	system damage	2	vibration	1	routine maintenance	3	6	perform routine maintenance with checks for damage
Battery Store excess energy	thermal wear	loss of efficiency, loss of energy	2	low temperature	1	weather monitoring	1	2	check system after inclement weather
Battery Store excess energy	fretting wear	loss of energy, system failure	1	weather damage	1	weather monitoring	1	1	check system after inclement weather

8.4 Appendix D: Pugh Chart and Decision Matrix

Table 1D: Pugh Chart

PUGH CHART

Customer Requirement	Jett Hall	American Center	Dominici Hall	Zuhl Library	Branson Hall Library	Regents Residence Center	Hadley Hall	Science Hall
offset annual energy and power consumption	-	+	DATUM	+	+	-	-	+
aesthetically pleasing	S	+		+	+	-	+	+
optimized distributed energy system	-	-		+	+	S	+	+
includes solar photovoltaic generation	S	S		S	S	S	S	S
has battery electric storage	S	S		S	S	S	S	S
maximizes financial savings over 20 years	+	+		+	+	-	+	+
power purchase agreement	S	S		S	S	S	S	S
financial viability	+	-		-	S	S	S	-
reasonable PV location	+	+		+	+	-	S	+
energy output based on a reasonable yield factor	S	S		S	S	S	S	S
voltage within expected bandwidth	S	S		S	S	S	S	S
all network elements satisfy loading and voltage constraints	S	S		S	S	S	S	S
active elements have realistic settings, responses, and dead times	S	S		S	S	S	S	S
optimal battery use	S	S		S	S	S	S	S
cost within budget	+	-		-	S	-	S	-
durable & robust design	S	S		S	S	S	S	S
Reliable design	S	S		S	S	S	S	S
TOTAL SUM	2	1	0	3	5	-5	2	3

Table 2D: Decision Matrix

	Weight	Jett Hall	American Center	Science Hall	Zuhl Library	Parking Shade	Streetlight	Trash Can	Bench Awning	Dirt Lot - Fixed	Dirt Lot - Solar Tracking	Dirt Lot - Concentrated	Branson Hall Library
Intallation Price	4	3	1	3	4	1	4	1	3	2	2	1	3
Net Energy Produced (kWh)	5	4	5	2	1	3	1	1	1	4	5	5	2
Aesthetics	2	5	5	5	5	5	4	5	5	2	2	2	5
Safety	4	3	3	3	3	4	5	5	4	4	4	1	3
Maintenance	3	2	1	3	4	2	3	5	4	2	2	1	3
Accessibility	3	4	4	3	4	3	1	5	4	5	5	5	5
Ethics	3	5	5	5	5	5	5	5	5	3	3	3	5
Lifespan	3	5	5	5	5	5	4	4	5	5	5	5	5
Distance from Distribution	2	3	3	5	5	3	3	3	3	2	2	2	4
Dust Accumulation	2	4	5	4	4	3	5	3	3	1	1	1	4
Weighted Sum > 100		116	112	110	115	102	104	108	109	99	104	85	114