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Design and Analysis of a Solar Panel Mount for Existing Utility Scale Wind Turbines

Senior Design Report

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ENGR 491 – Senior Design

Fall 2021

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ACKNOWLEDGEMENTS

We would like to acknowledge the University of Southern Indiana engineering staff for their continued support and dedication to this senior design team and their fellow students. Special acknowledgements are to be made to a select few for their dedication of time and mind to the senior design team, those people are as follows: Dr. Glen Kissel for advising us through our semester in Engineering 491, and Dr. Paul Kuban for facilitating the Engineering Department along with the Engineering 491 Senior Design class, which provided the us to be engaged with situations that would be considered “Real World Applicable”. The final acknowledgement to be made is to our friends and family for their continued support and encouragement in our continued education.

CONTRIBUTIONS

Contributions made to the senior design team were not in the way of material goods or grants for money but access to knowledge, knowledge about codes and standards for different types of towers. The codes and standards given to the senior design team was TIA-222-H, this is thanks to James Ruedlinger at ERI (Electronics Research Incorporated) who offered the use of the publication to the team when first hearing about the project from one of the senior design team members.

ABSTRACT

This project consists of a design and analysis of a solar panel mount for existing utility scale wind turbines. This project aims at a design that will attach to an existing wind turbine tower and hold an array of ten solar panels without causing serious deflection or stress onto the wind turbine tower. First, small scale examples were researched and discussed by the senior design team. The advantages and disadvantages of each example were analyzed to aide in creating a final design for this project. Then, four critical design iterations were considered before coming to the final design. Design Iteration 1 has solar tracking capabilities and therefor required too much maintenance. Design Iteration 2 was bulky and above the allowable weight. Design Iteration 3 was reduced in weight by almost 75% and unnecessary stress points were removed. This design had too much deflection on the solar panel frame when applicable loads were applied according to load analysis and FEA. The final chosen design, Design Iteration 4, had a reduced solar panel frame deflection, as the upper and lower arms were spread apart to evenly distribute the loaded weight. A finite element model of the final mount was made to ensure the mount's structural integrity under normal loading and 90 mph wind loads. The project resulted in a designed solar panel mount for existing utility scale wind turbine towers that: weighs less than 15,000 pounds, fits a specific wind turbine (GE 1.5 MW), holds 10 individual solar panels, angles the solar panels 50 degrees form horizontal, has a factor of safety greater than 6, and does not cause damage to the wind turbine tower.

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List of Acronyms and Abbreviations

FEA	Finite Element Analysis
HRES	Hybrid Renewable Energy System
RWF	Roscoe Wind Farm
GE	General Electric
MW	Megawatt
NIMBY	Not in My Backyard
BOM	Bill of Materials
FBD	Free Body Diagram
ERI	Electronic Research Incorporated

1 INTRODUCTION

Solar panel mounts are devices used to support solar panels in a wide variety of configurations and locations. This project focuses on designing a solar panel mount that attaches the solar panels to the 15.25-foot diameter tower of a GE 1.5 MW wind turbine located at Roscoe Wind Farm in Roscoe, TX. The mount will hold 10 SunPower Maxeon solar panels. In the ever-changing energy sector, it is important to be innovative and creative when developing new methods for collecting energy. The team has taken an innovative approach by integrating solar power with utility scale wind power in a way that has never been done before. This mount allows for the integration of standard solar panels with utility scale wind power while not covering any ground area and that is what makes this design truly unique. The scope of this project covers a wide variety of aspects regarding the design and testing of the solar panel mount and its effects on the wind turbine tower. It is important to note that it does not capture the design of the solar panels, wind turbine, or connecting the solar panels to the electrical grid. The final design has been put through a rigorous Finite Element Analysis and has been modeled through various hand calculations. The results of these simulations have concluded that the mount has a safety factor of 53 and will safely accomplish the necessary goals of the project. A scaled image of the final design for the solar panel mount for utility scale wind turbines as well as a close comparison of the mount with and without solar panels can be seen below in Figures 1 and 2.

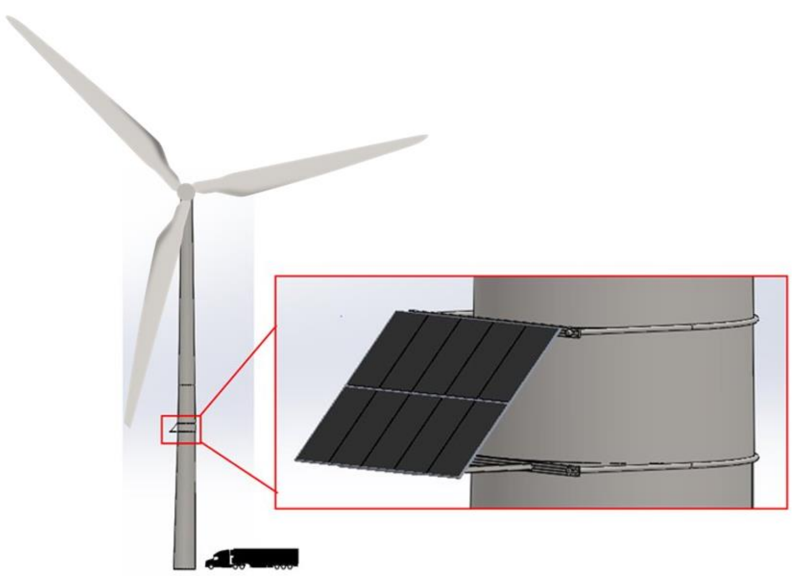

Figure 1: Scale Image of Completed Mount Design on Wind Turbine Tower

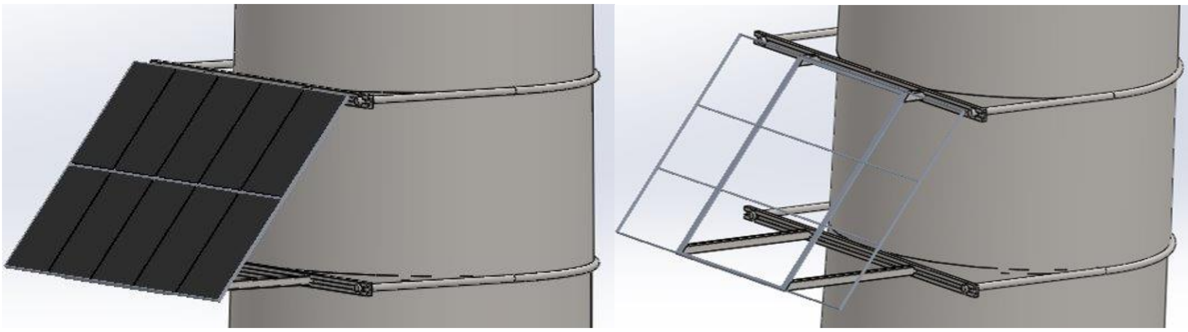

Figure 2: Side by Side View of Solar Panel Mount with and Without Solar Panels on the Wind Turbine Tower

1.1 OBJECTIVE AND DELIVERABLES

1.1.1 Objective

The objective of this senior design project was to:

"Design an effective mount to attach solar panels to utility scale wind turbines."

This project is simply combining pre-existing solar panels and wind turbines with a designed solar panel mount. This mount is what is discussed and analyzed in this report and will only include information relevant to the mount's design process and final design specification. A quick overview of the senior design team's project can be seen in Figure 3.

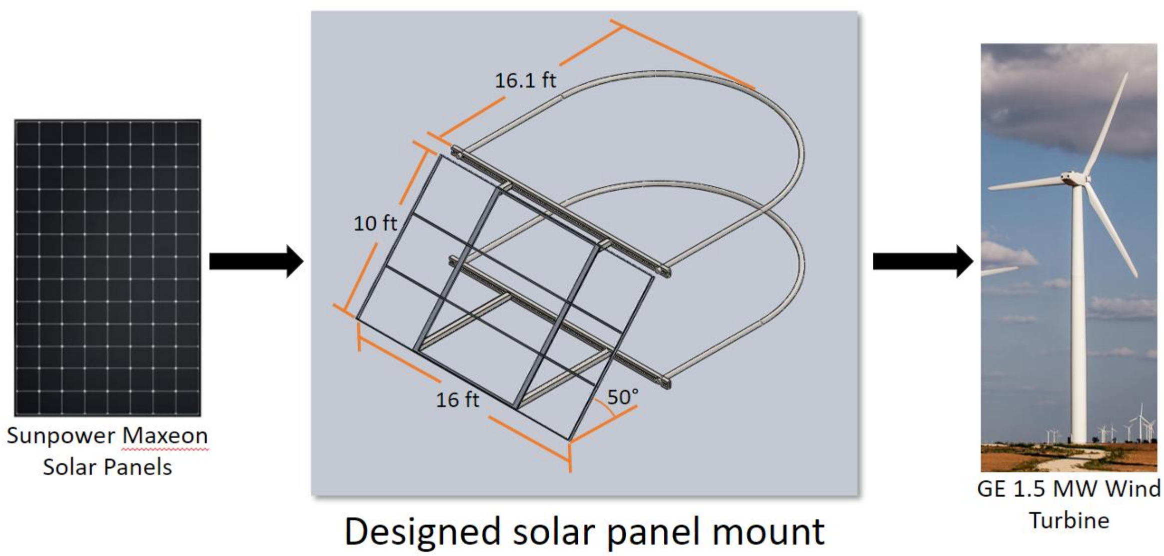

Figure 3: Brief Overview of Designed Mount and Wind and Solar Aspects [20] [21]

As seen above in Figure 3 the SunPower Maxeon solar panels are attached to the designed solar panel mount and the solar panel mount is then attached to the GE 1.5 MW wind turbine tower. To reiterate, the solar panels will not be designed and the SunPower Maxeon solar panels are pre-existing solar panels and are used for a base point of solar power generated and dimensions for the mounts design. Also, the GE 1.5 MW wind turbine is already installed at the Roscoe, TX wind farm. The only thing the senior project team is designing is the solar panel mount.

1.1.2 Motivation

The first driving motivation behind this senior project is the growing and ever-expanding abilities of renewable energy resources. With the growing need for more eco-friendly and eco-cautious energy solutions, there is a need for the increase in renewable energy resources and their abilities. Thus, the movement of creating hybrid renewable energy sources. An example of the traditional hybrid wind and solar power farm can be seen in Figure 4.

Figure 4: Solar and wind farm in Woodstock, Minnesota [4]

As seen above this hybrid farm combines the use of solar panels and wind turbines to combine energy resources. If applicable, this hybrid power farm could be using the solar panel field to fulfill government regulations of having a small percentage of power come from solar [4]. This hybrid farm can be found in Woodstock, Minnesota and can be seen to take up copious amounts of land.

The second motivation for the senior design team is diversification of utility energy portfolios. Energy diversification is utilizing different energy resources, suppliers, and transportation routes to reduce dependence on a single source or provider [11]. This is important to utilities as well as to a nation, and it might seem trivial to the lay person, but it is highly sought after. This is because the benefits of portfolio diversification provide energy as well as political security through the form of political independence, economic growth, environmental protection, and fallback energy sources. This project allows for the addition of solar to a utility that might not have been able to implement it previously thus diversifying their portfolio. Particularly in our case developing renewable resources such as solar and wind power diminishes the threat of energy scarcity. Renewable resources emit little or no pollutants and have minimal impact on the environment. Investments in renewable energy also spur innovation and job growth [11]. Additionally, many states have implemented Renewable Portfolio Standards (RPS) that require a specific percentage of electric utility sales come from renewable resources. States have created these standards to diversify their energy resources, promote domestic energy production and encourage economic development.

A third major motivation for the senior design team is the fact that renewable energy resources take up a considerable amount of land to be implemented on. When researching solar and wind farms it was immediately noticed just how much space was needed for these farms and how many of the combined farms did not use or have room on the ground for other purposes like farming or livestock. An example of a wind farm that utilizes its ground space for livestock can be seen below in Figure 5.

Figure 5: Wind Farm with Alternative Ground Use [22]

The design team began immediately researching ways people were combining wind and solar energy to preserve the use of the ground like in Figure 5 and began noticing very limited results and ideas for combining the two resources [22]. The idea of combining industrial sized wind and solar farms together was too fresh of an idea besides the farm in Figure 5 where the solar panels covered the ground [4]. The design team wanted to make a leap forward in the investigation and implementation of ideas for combining wind and solar in ways that preserved the ground for other uses and decided to design a mount for attaching solar panels to utility scale wind turbine towers.

The fourth motivation for the senior design team is the various issues of acquiring and developing land. The senior design team wanted to avoid the issues of Not in My Backyard or NIMBY by placing the designed mount on pre-existing wind turbines. Towns can be for or against renewable energy resource farms and an example of the latter can be seen in Figure 6.

Figure 6: Anti Solar Power Plant Sign Found in Poseyville [19]

As seen in Figure 6 above, communities will protest and veto renewable energy farms and the process to get the farms approved is very difficult. Therefore, the senior design project team is going to avoid the NIMBY issues/complications by implementing their designed solar panel mount on pre-existing wind turbine towers.

The fifth and final motivation for the senior design team's project was the idea of designing a non-intrusive mount to attach to the outside of a pre-existing wind turbine. The wind turbines were not designed with the intention of having anything affixed to the outside of the tower. Through thorough research, the design team was unable to find a mounting mechanism that was to that size scale. Research was done into smokestacks, wind turbine towers, silos, and many more cylindrical hollow items that paired to the turbine towers scale, but nothing was found that matched that size scale. This is where the interest and desire for the project started. The idea of being at the beginning of something new that could potentially lead to a collaboration of wind and solar was exciting. Knowing that this project would help future endeavors, the senior design team became most interested in this project.

1.1.3 Deliverables

The deliverables of this senior design project will be as follows:

- SolidWorks renderings for the final design of the mount
- Load analysis ensuring that the industries factor of safety of 6 is met
- Hand calculations to show that the mount does not fail from bending stress, hand finite element analysis (FEA) showing that the tower does not fail in torsion with the added stress the mount causes
- SolidWorks FEA showing that the mount can support the weight of the solar panel array
- Load analysis using SolidWorks FEA showing wind loading from various directions and the designed mount withstanding the changing loads,
- Economic analysis determining roughly how much an individual mount would cost to manufacture and install
- Bill of materials showing how much the individual materials would cost at the current market cost
- Payback period showing how long one mount would take to pay its self-off
- Maintenance plan for making sure the mount operates at max capabilities
- Disposal plan for the mount after its life span is over
- Lessons learned
- Future recommendations.

Due to the sheer size and mass of the designed solar panel mount, risk of COVID-19 complications, and number of hours dedicated to research the team will not be building a prototype of their project. A scaled down prototype was discussed as a possible option for the team to undergo and was considered heavily for its use in portraying exactly what the team was trying to do but the senior design team decided against the prototype at the beginning of the Fall 2021 semester. It was determined that the project would be better and full of more details if the team focused all its energy on the research and development of the mount rather than spending their time on constructing a scaled prototype.

1.1.4 *Requirements*

The List of Requirements for the designed solar panel mount are as follows:

The Solar Panel Mount:

1. Shall weigh less than 15,00 pounds
2. Shall fit the GE 1.5 MW wind turbine at Roscoe Wind Farm
3. Shall be equipped to safely withstand the standard 100-year wind speed of 90-mph
4. Shall hold a solar array that will consist of 10 individual solar panels
5. Shall be fixed at 50 degrees from the horizontal
6. Shall follow the government and industry standard of a factor of safety greater than 6
7. Shall not cause damage to the turbine tower

For the first requirement the solar panel mount shall weigh less than 15,000 pounds came from the fact that the senior design team wanted the mount to weigh less than the section of tower they were mounting to which happened to weigh roughly 15,000 lbs.

For the second requirement, the solar panel mount shall be able to fit the GE 1.5 MW Wind Turbine at the Roscoe Wind Farm came from the senior design team deciding that a good location to implement their mount at would be in a rather sunny location that already had a pre-existing wind farm located there. After research the team stumbled upon Roscoe Wind Farm which had the specification they were looking for, sunny, wind farm already located there, and the fact that the land was being used to grow cotton. A specific turbine design was chosen at Roscoe Wind Farm and the design was modeled to fit accordingly.

The third requirement, the solar panel mount shall be equipped to safely withstand the standard 100-year wind speed average of 90-mph was determined through knowing that the mount was going to be subject to high wind locations and be affected by the turbulent wind forces created by the wind turbine blades spinning. The 90-mph speed was found as an average max wind speed in and near Roscoe, Tx and from that wind speed a constant wind load would be loaded onto the designed mount from different directions to determine if the mount would be able to withstand the turbulent wind forces [25].

The fourth requirement, the solar panel mount shall hold a solar array that consists of 10 individual solar panels came from the senior design teams design of keeping the mount small to create the least amount of stress applied to the wind turbine tower. Ten solar panels were chosen to make the solar array slightly wider than the wind turbine tower at the mounting location and two rows high to keep the section of tower introduced to new stresses at a minimum. With the design team’s success of their project in successfully designing their mount for a wind turbine tower it will leave open the chance for future designers to design the mount to attach more solar panels to make the array bigger and more complex in size.

The fifth requirement, the solar panel mount shall be fixed at 50 degrees from the horizontal came from trying to capture the most solar radiation as possible in each day without solar tracking. For the location of the wind farm in Roscoe, Tx the optimal angle based off their lateral position from the equator happened to be 50 degrees from the horizontal 0 degrees according to Vivantsolar [16].

The sixth requirement, the solar panel mount shall follow the government and industry standard of a factor of safety greater than 6 was determined through the industry’s standard factor of at least 6. This factor of safety must be followed if the senior design team ever wanted their design to come to fruition, so shall follow the government and industry standard of a factor of safety greater than six was created.

The seventh requirement, the solar panel mount shall not cause damage to the turbine tower. This is because if the mount causes damage to the wind turbine tower that means the design failed. The senior design team used this requirement to push themselves to design a solar panel mount that distributed the stresses applied to the mount evenly across the wind turbine tower to cause displacement and stresses only within an allowable range.

1.1.5 Standards

From literature review the following standards were considered in the design of the solar panel mount for existing utility scale wind turbines. The standard, ANSI/TIA-222-H/2.3, was specifically used to determine the combined loading scenarios the mount would be subjected to and gave the senior design team the loads that needed to be applied to the mount to withstand it would be considered structurally safe for implementation [37].

ANSI/TIA-222-H/2.0-2.8: This standard section is over the different possible loads similar structures are subjected to. This standard section goes into depth about 2.3 combination loads, 2.4

temperature effects, 2.5 Dead Loads, 2.6 Wind and Ice Load, 2.7 Seismic Loads, and 2.8 Serviceability Requirements.

ANSI/TIA-222-H/4.0-4.9: This standard section goes over the design strength of structural steel and is used in this project since the majority of the of the designed solar panel mount is made from structural steel as well as the tower. Some of the subsections of the standards section are 4.5 Compression Members, 4.6 Tension Members, 4.7 Flexural Members, 4.8 Combined Bending and Axial Forces, and 4.9 Connections.

ANSI/TIA-222-H/15.0-15.8: This standard section goes over existing structures and is important due to the wind turbines the solar panel mounts would be installed on are already preexisting structures. Some of the subsections for the standards section are 15.3 Changed Conditions Requiring an Evaluation, 15.4 Risk Category, 15.5 Evaluation of Changed Condition, 15.6 Structural Analysis, and 15.8 Modifications of Existing Structures.

ANSI/TIA-222-H/17.0-17.18: This standard section goes over wind turbine support structures and is important because again the design mount is being attached to a wind turbine tower. Some of the subsections for the standards section are 17.4 Turbine Manufacturing Data, 17.5 Effective Projected Area, 17.6 Extreme Wind Condition, 17.7 Extreme Ice Condition, 17.11 Dynamic Requirement, and 17.12 Design for Fatigue.

The standard stated above are not directly related to the solar panel designed mount for utility scale wind turbines, however they were used as a guideline for the team to abide by. Per example ANSI/TIA-222-H/2.0-2.8 led the team to test multiple wind loading directions and the added weight due to ice loads and how to treat the mount as a hanging dead load, using the remaining standards similar test and design decisions were done.

2 BACKGROUND

2.1 STATEMENT OF THE PROBLEM

Renewable energy resources as they stand today are not as reliable as the standard fossil fuel resources the world has become accustomed to. As a result, there has been an increase in hybrid renewable energy systems (HRES) research, development, and design. The most prevalent form of HRES is a combination of wind and solar. Wind and solar complement each other well because they tend to peak at opposite times. There has been a large amount of research into creating new combined wind and solar energy production systems. Some examples of new combined wind and solar devices can be seen below in Figures 7 and 8 [1], [2].

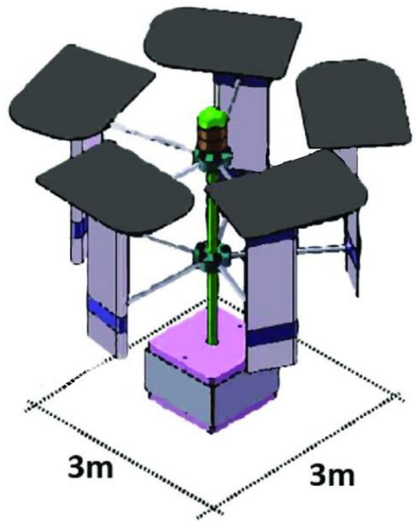

Figure 7: Design of true hybrid solar wind turbine [1]

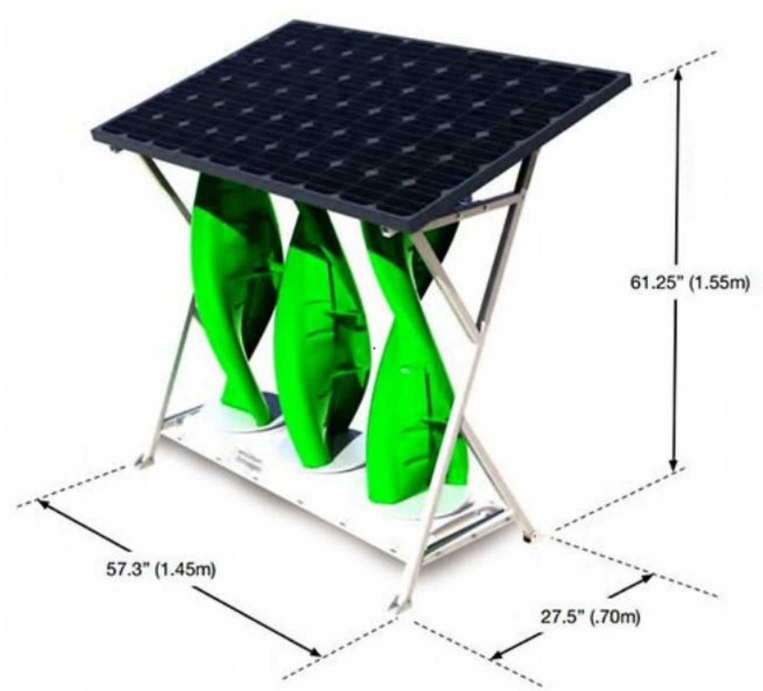

Figure 8: WindStream Technologies - Solarmill [2]

The HRES seen in Figures 7 and 8 are innovatively combining wind and solar, however, they would require brand new investments of land to place them on. They do not address the current problem that there have already been vast investments in large windfarms across the country. Implementation of HRES such as the ones seen in Figures 7 and 8 would require new investments of time, money, and land. Finding a location for such devices as well as getting government approval to build these sites is a long and difficult process. The problem intended to be solved by this senior design project is integrating solar with windfarms that already exist. Limiting the focus to locations where wind farms already exist allows the team to forgo common "not in my back yard" (NIMBY) issues because these problems would have already been addressed when the original wind farm was implemented. Issues that will have already been accounted for include, noise, aesthetics, visual impairment, bird kills, and interference with television reception [7]. It also allows the project to require less investment from future businesses that would want to implement the design. Additionally, it would not require any new land which is becoming increasingly scarce.

2.2 Solar Tracking

While the team has chosen not to implement solar tracking in our system it was considered, thus an explanation has been provided. Solar trackers are automated modules fitted to a solar panel array system that read the angle of the sun and adjusts the panels to compensate to capture more sunlight. There are two different types of trackers: single-axis and dual-axis. Single-axis trackers rotate panels on only one axis. Dual-axis trackers rotate panels back and forth, but they also rotate to the left and right. In this case a dual axis tracker would not be an option for a mount affixed to wind turbine towers.

The advantage of a solar tracking array is that it would improve energy output by increasing the efficiency in the range of 10 – 20 % depending on where the solar array is located. Fixed angle panels are tilted at the degree that gets the most sun all year, but because the earth is constantly moving around the sun the exact optimal angle at any moment depends both on the time of day and the time of year.

The team has opted not to include solar tracking in our final design because the addition of solar trackers greatly increases the cost and complexity of the mount. Adding a solar tracker also adds mechanical and electrical components to the device and thus increases the amount of maintenance our mount would require. The mount will be attached to the wind turbine 120 ft off the ground and will not be easily accessible for maintenance, so the team wants to limit maintenance as much as possible.

2.3 SunPower Maxeon Solar Panels

SunPower Maxeon solar panels were chosen to model the design after because they lead the solar industry in panel efficiency. The economic, generation, and weight analysis for the mount is done assuming the use of SunPower Maxeon solar panels. The frame attached to the mount is designed specifically to hold ten "SunPower Maxeon 3" solar panels. These panels come in a range of sizes and configurations. Some specifications for this panel can be seen below in Table 1 as well as an image of the panels in Figure 9 [8].

Table 1: SPR-MAX3-400 Specifications [8]

SunPower Maxeon 3	
Nominal Power	400 W
Panel Efficiency	22.6%
Weight	42 lbs.
Width	38.4 in.
Height	60 in.
Thickness	1.5 in.

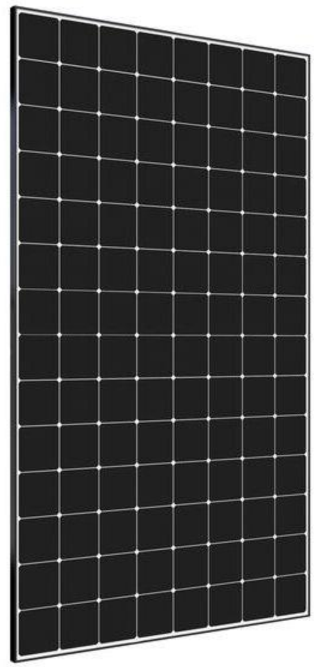

Figure 9: SunPower Maxeon Solar Panel [8]

While the design was built with the solar panels in mind it is outside of the scope of this project to incorporate the panels into the design. It is assumed that the utility choosing to implement the design would attach the solar panels themselves both physically and electronically. It is also outside of the scope of this project to connect the energy produced from the solar panels to batteries or the electric grid in the area. Specific details for the SunPower Maxeon Panels can be found in Appendix A.

2.4 GE 1.5 MW Wind Turbine

The General Electric 1.5 MW series wind turbine model is one of the wind turbines located on Roscoe Wind Farm and has been chosen as the model for the solar panel mount design. The team chose this turbine over the others found at Roscoe Wind Farm because it is the second most popular utility scale wind turbine as of 2020 [35]. This would mean that the designed solar panel mount could easily fit many other GE 1.5 MW wind turbines across the globe. This turbine is represented by three-blade, upwind, horizontal axis wind turbine with a rated capacity of 1.5 megawatts [14]. This wind turbine's tower is a tapered tubular steel. Some more specifications for this wind turbine can be seen below in Table 2.

Table 2: GE 1.5 MW Specifications [15]

GE 1.5 MW Wind Turbine	
Nominal Power	1.5 MW
Weight	593,000 lbs.
Tower Height	328 ft.
Diameter at Mount Location	15 ft
Thickness	1 in.
Material	ASTM A572 Grade 50 Steel

Below in Figure 10 are more of the turbine specifications. As mentioned, it is one of our requirements that the mount fits this turbine, so these specific dimensions were used to develop the size of the mount.

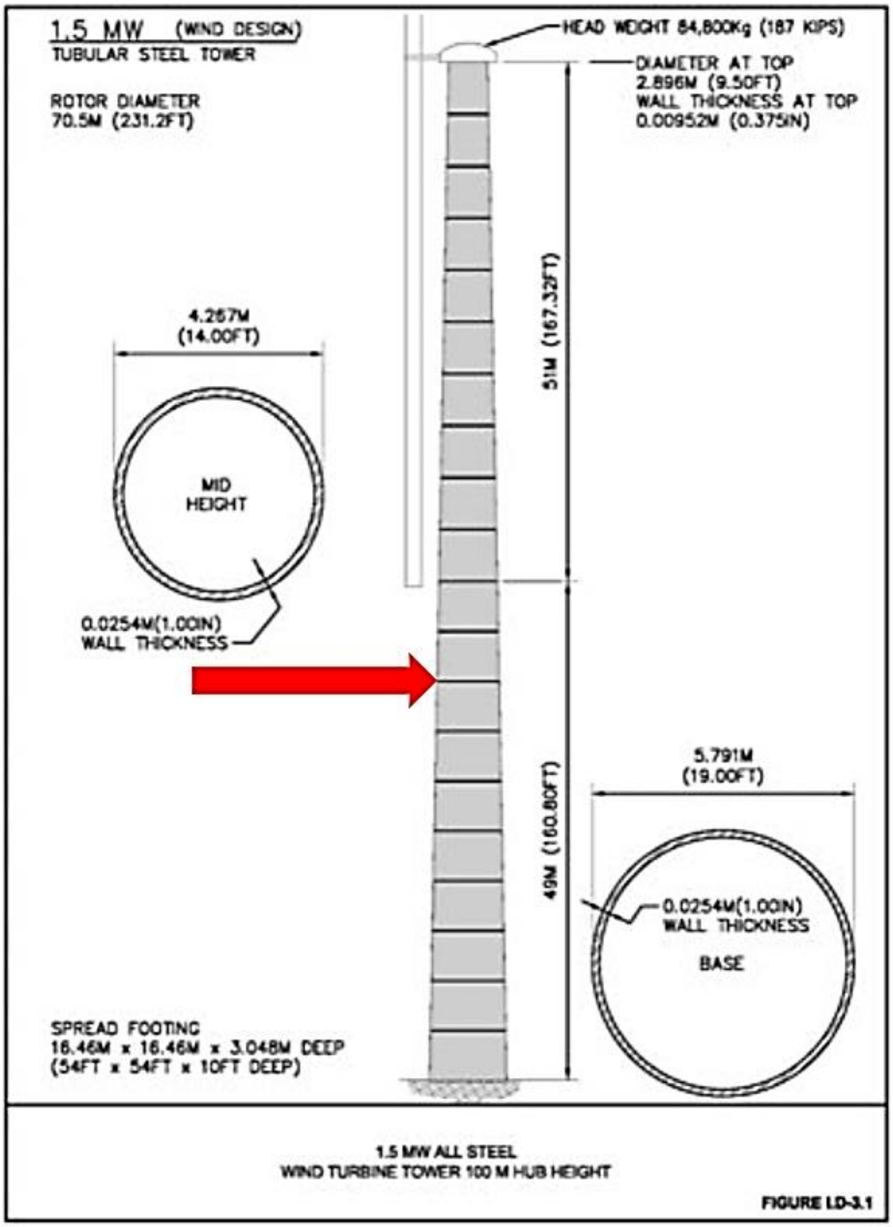

Figure 10: GE 1.5 MW Wind Turbine Specs

The mount will specifically be located 120 feet from the ground of this wind turbine. This location is indicated by the red arrow in Figure 10. The location of the mount on the wind turbine was chosen with two factors in mind: interference with the wind turbine blades and addition of other mounts to the wind turbine tower. With those two factors in mind the team chose to place the mount at the highest location possible on the tower without interfering with the wind turbine blades with the idea that any mounts added below this location would be safe.

2.5 ROSCOE WIND FARM

Roscoe Wind Farm (RWF) opened in 2008 and is located primarily in Roscoe, Texas but stretches into the counties of Mitchell, Nolan, and Scurry. It is owned by RWE Renewables Americas LLC which is a German multinational energy company that generates and trades electricity in Asia-Pacific, Europe, and the United States. RWF is the largest onshore wind farm in the world with an installed capacity of 781.5 MW, 627 wind turbines, and covering 100,000 acres of land. This large swath of land is leased from dryland cotton farmers. The power generated by the wind farm is supplied to Texas Utility (TXU) Energy Corporation's subsidiary TXU Wholesale, under a five-year sales contract. The location of the windfarm in reference to the state of Texas can be seen below in Figure 11.

Figure 11: Location of Roscoe Wind Farm

The Roscoe Wind Farm project was built in four phases and contains four different types of wind turbines. Wind turbines found on the farm are as follows: Siemens 2.3 MW, two different Mitsubishi 1 MW models, and GE 1.5 MW [10]. These turbines range in size, material, and power output. The GE 1.5 MW turbine was chosen to model the mount design because it is a very common turbine design throughout the industry and is a model that is still manufactured today. Roscoe Wind Farm and the GE 1.5 MW turbine can be seen below in Figures 12 and 13.

Figure 12: GE 1.5 MW Wind Turbine [21]

Figure 13: Roscoe Wind Farm – Cotton Growth around the Turbines

RWF was chosen by the team to model our mount for various reasons. The primary reason is that there is cotton grown on the ground area surrounding the wind turbines as seen in Figure 13. This circumstance was important to the team because it meant that Roscoe Wind Farm would not be a viable location for the standard implementation of combining wind and solar where solar arrays are placed on the ground area in between turbines. This leaves a need for innovative ways to incorporate solar at the site, thus the perfect location to implement our mount.

Another critical component of the location was that it is in a high sun area suitable for solar power generation. While the sun does shine almost everywhere there are areas of high generation capabilities and Roscoe, TX is one of them. Located in west central Texas, this area experiences on average 5.8 to 6.2 sunny hours per day. Comparing that to our location of Evansville which experiences 4.7 hours a day and the notoriously cloudy city of Seattle which is 3.7 hours a day you can see that there is great potential for solar in the Roscoe, TX area [9]. While the team has designed this in theory with Roscoe Wind Farm, there was no partnership or assistance from the farm itself in creating the solar panel mount.

2.6 PAST COMBINED WIND AND SOLAR SOLUTIONS

2.6.1 Solar Arrays on the Ground

The most common method for integrating utility scale wind power with solar is placing standard solar panel arrays on the ground area surrounding the wind turbines. Examples of this can be found all over the world illustrating a desire to integrate wind and solar. One example can be seen below in Figure 14.

Figure 14: JA Solar Wind / Solar Farm, South Korea [12]

Figure 14 depicts a 133 MW hybrid solar/wind power plant in a mountainous area of South Korea. There are many energy farms that follow this model as it is the easiest way to combine wind and solar. There are 226 solar/wind hybrid farms in the United States alone ranging in size from less than 1 MW to greater than 500 MW [13]. This method allows for an abundance of solar panel arrays to be installed and put into service. It is important to the owners of these utility scale wind farms to be able to generate enough power to make it economically worth the investment. The problem presented with this method is that placing the solar panel arrays intermittently in between the wind turbines requires large amounts of land to be covered by solar arrays. An aerial view of the farm seen in Figure 14 can be seen below in Figure 15 which illustrates how much area is covered by the solar panels.

Figure 15: Aerial View of JA Solar Wind / Solar Farm, South Korea [12]

Once the solar panels are placed on the ground that area is no longer able to be used for farming or livestock. For a wind farm such as Roscoe Wind Farm this would not be an option for them as they currently use the ground area for cotton farming. One of the main complaints about solar farms is that they have a very large footprint. Placing these arrays on the towers of the wind turbines allows the land around wind turbines to still be utilized. The problem comes with placing them on the towers while still generating enough power to be feasible.

2.6.2 Solar Panels on Wind Turbine Blades

This example of solar combined with utility scale wind turbines comes from the University of Liverpool where a team of researchers, led by Dr. Joe King, upgraded an everyday wind turbine with an innovative set of spinning solar blades. A simulation of this innovation can be seen below in Figure 16.

Figure 16: University of Liverpool Solar Panel Blade Simulation [11]

During the simulation phase of this project, it was revealed that it was not a viable option because the blades could blind aircraft pilots and anyone living in the vicinity. Additionally, on hot days the turbines would create lethal solar rays which could set buildings on fire if concentrated. This can be counteracted by implementing tinted solar panels which do not mirror sunbeams, but as it stands today this iteration will not be moving forward. While we were initially inspired to investigate adding photovoltaic cells to the blades as a way of combining wind and solar, we quickly gravitated away from this idea once the outcome of this simulation was revealed. What the team took from this simulation was that a negative result is still a viable result and shows future researchers what needs more investigation and further improvements.

2.6.3 Flexible Solar Panels on Wind Turbine Towers

After learning from the first two examples the team quickly decided that if solar panels were going to be added to the wind turbine itself, they would need to be added to the wind turbine tower. One method for adding solar panels directly to wind turbine tower can be seen in Figure 17 below.

Figure 17: Acconia Wind Turbine with Flexible Solar Panels [3]

Figure 17 depicts wind turbine towers owned by the energy division of Acconia Infrastructure in Breña Wind Farm in Albacete, Spain. This company has installed flexible organic photovoltaic modules on a wind turbine tower to cover the consumption of the turbine's auxiliary systems. This project will allow for the testing of organic PV panels and their application to optimize the efficiency of wind power generation.

This arrangement allows for ground area beneath the wind turbines to be utilized while still implementing solar effectively which aligns with the goals of the senior project. To accomplish this method flexible solar panels are used and placed directly on the shaft of the wind turbine tower. Flexible panels like the ones depicted in Figure 17 are light weight and durable causing less strain on the wind turbine. They are also very easily configurable leading to lower installation costs. The downside of this iteration is that flexible solar panels are made of very thin material that has a lower efficiency rate than your classic solar panel. The efficiency rating of your average solar panel is somewhere between 18% and 24% whereas flexible solar panels are 7% and 15% [5]. Because of this the team would like to accomplish a way to utilize standard solar panels on wind turbine towers.

2.7 Non-Intrusive Pole Mounts

The goal of this project revolves around working with existing wind turbine towers. Considering this the team determined early on that as little interference as possible needed to be made to the wind turbine tower. This meant welding, cutting, and drilling into the turbine tower needed to be avoided. To accomplish this the team conducted research into non-invasive mounting methods. One thing to take note of when looking through these examples is that they are all on a much smaller scale than a utility scale wind turbine tower. The examples are fitted for structures such as streetlights and telephone poles.

The example seen below in Figure 18 was one of the first non-invasive mounting methods for cylindrical structures found by the team [28]. While it was intriguing at first because of its relative simplicity the team quickly decided that this mount would be more suitable for a circumstance where a device needed to be mounted on multiple sides of a circular structure.

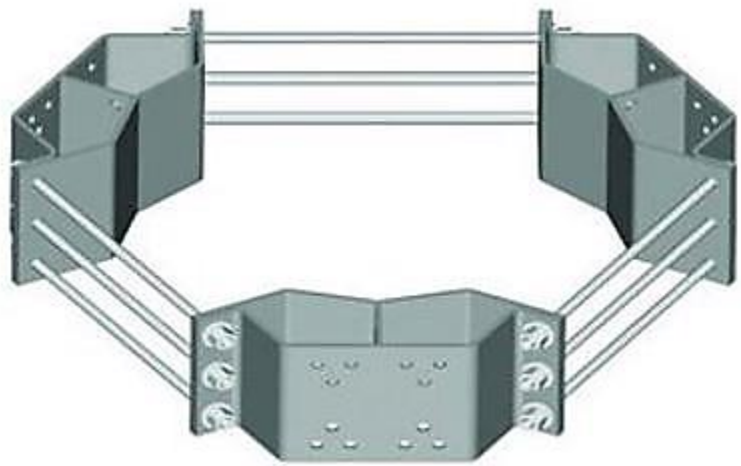

Figure 18: Monopole 3-Sector Ring Mount [28]

If the team had elected to pursue a mount with this design, it would have created unnecessary material costs and complications.

Shown in Figure 19 is another example of a non-intrusive mount for cylindrical structures. This was closer to the goals of the team but scaling this design up to the size of a wind turbine would have required a large amount of material and been very heavy and the team has set weight limitations for the final mount design [29].

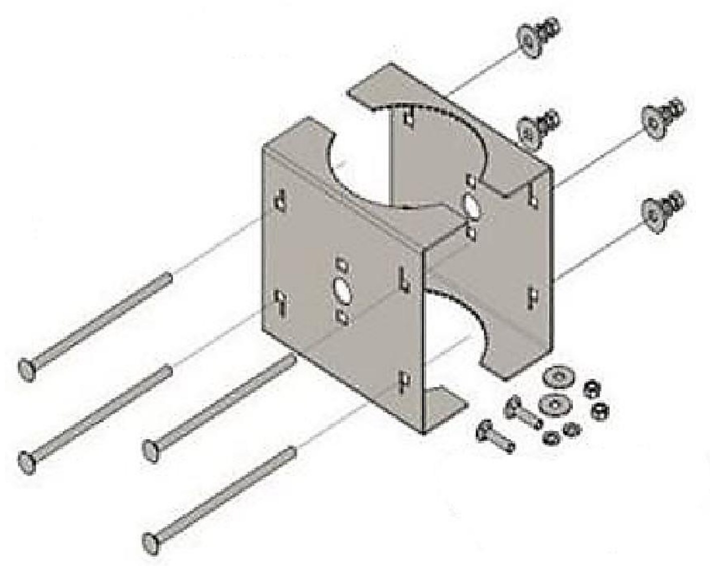

Figure 19: Round Pole Mounting Kit [29]

It was also a concern that the open sides of this design would be at high risk for collecting water and other debris. The collection of this material could increase the rate at which our material aged, so the team continued to investigate other designs.

The method seen below in Figure 20 grabbed the team's attention because it seemed simple yet effective. The groove and channel approach seen in this design would allow for easy install and since the mount will be 120 ft. off the ground this is an important aspect for the project [30].

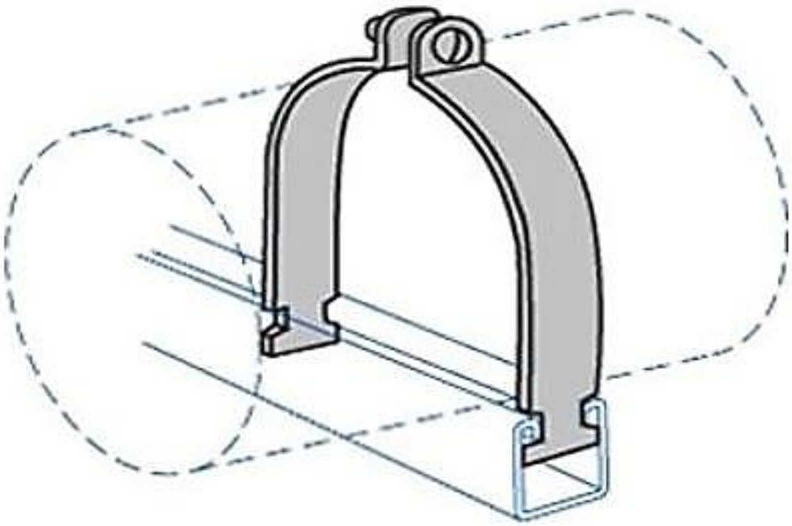

Figure 20: Cushion Pipe Clamps for Uniform Struts [30]

While the team was very attracted to the groove and channel approach seen in this mount the bolted attachment on the back was not as appealing. With the weights this mount will be experiencing this part of the design was not considered.

2.8 SMALL SCALE NON-INTRUSIVE SOLAR PANEL MOUNTS

While this project is truly unique in terms of its incredibly large scale what the team aims to accomplish has been achieved on a much smaller scale. Since there are no examples of a hanging solar panel mount for large cylindrical structures, the team relied heavily on the research done to execute the same goal on a much smaller scale. Some examples of these configurations can be seen below in Figures 21 and 22 [31], [32].

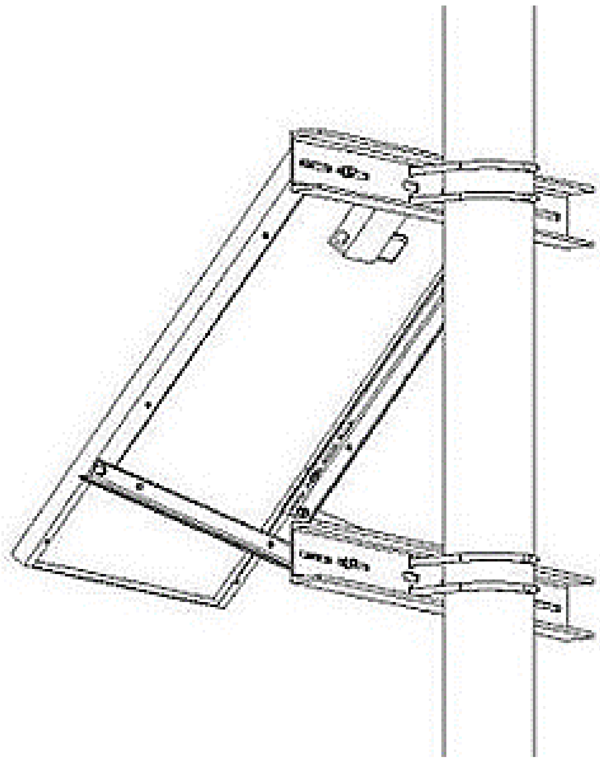

Figure 21: Sunwize PVK 65 W Solar Kit [31]

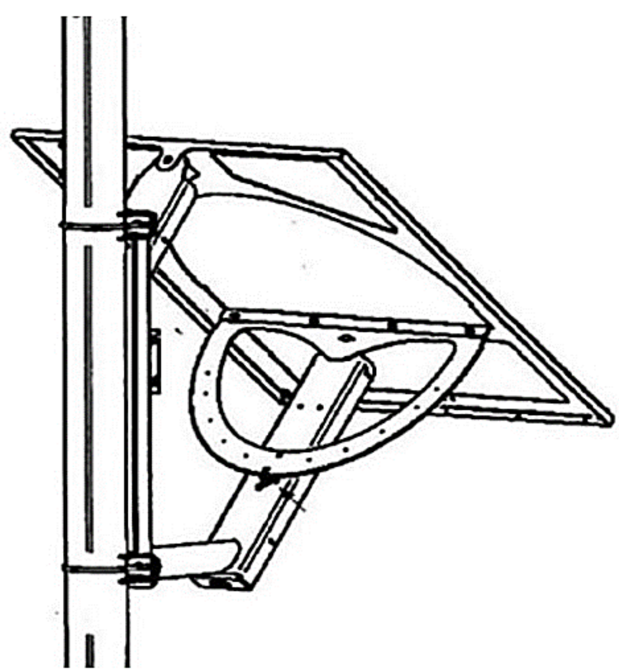

Figure 22: Sun tracking Pole Mount for Solar Panels [32]

Both examples are suited for cylindrical structures such as telephone poles and streetlights. However, there was still knowledge to be learned from them regarding mounting to much larger poles. For instance, both mounts are non-intrusive, which as previously mentioned is an important aspect of our project. The most important component taken from both mounts is that they wrap around their poles using a U-Bolt. This was a common method seen across many of the solar panel mounts we encountered, and this is where the team got the idea to use a much larger U-Bolt in our final design.

3 INITIAL CONCEPTUAL DESIGNS

Using the information collected during the background investigation the team developed three initial conceptual designs for brainstorming purposes. The pros and cons of each of these designs were analyzed and used to determine which direction the team would pursue.

3.1 DESIGN 1

Design 1 is pictured in Figure 23. This design is a fixed mount placed between 45° and 60° relative to the horizontal ground. The design features a U-bolt mounting method that includes a support plate and a main channel for added support.

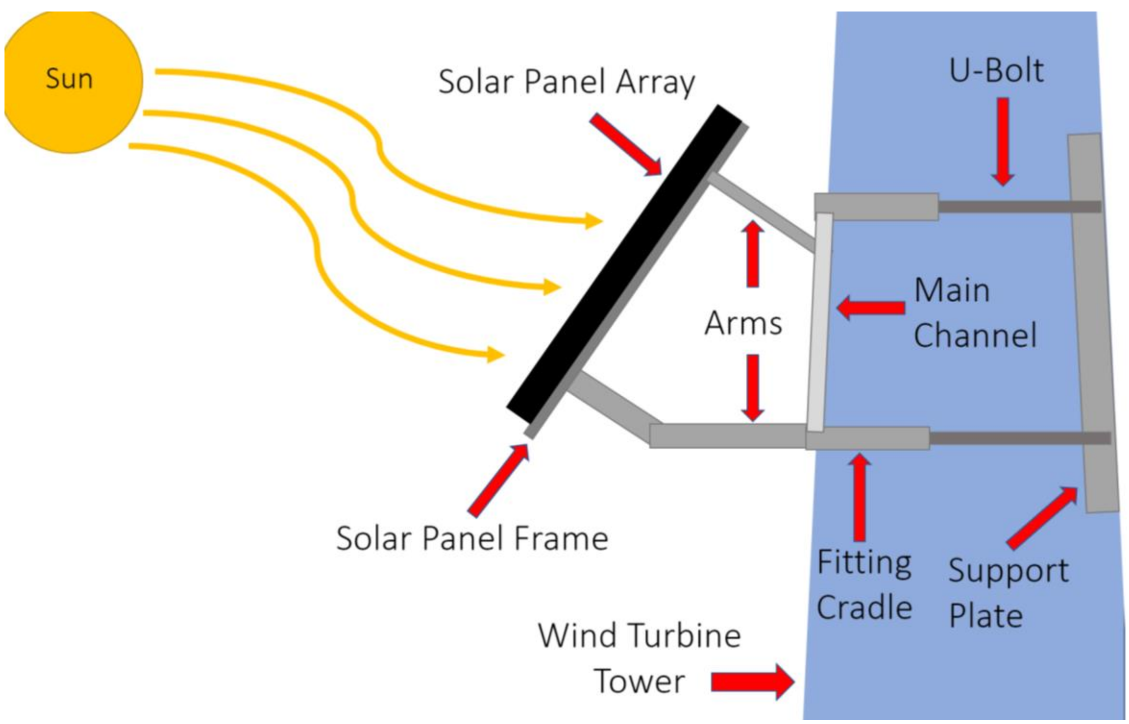

Figure 23: Conceptual Design 1: Fixed Mount

3.1.1 Pros of Design 1

This design is lower in cost because it is a simple, fixed design with no moving parts. This design would require less design time and would be easier to manufacture than a solar tracking/actuating mount. Considering its stationary state, the design allows the application of more solar panels to be placed on the mount. Design 1 is a good baseline for the final design.

3.1.2 Cons of Design 1

The team initially thought this design lacked engineering problems that may be seen in a design that included solar tracking. Since the solar panels on the designed mount will be stationary, less solar power is collected throughout the day when compared to a design with solar tracking.

3.2 DESIGN 2

Design 2 is pictured in Figure 24. This design features a dual axis solar tracking method with a circular mount that wraps around the turbine tower. One actuator controls the north and south solar tracking yearly. The other actuator controls east and west solar tracking daily.

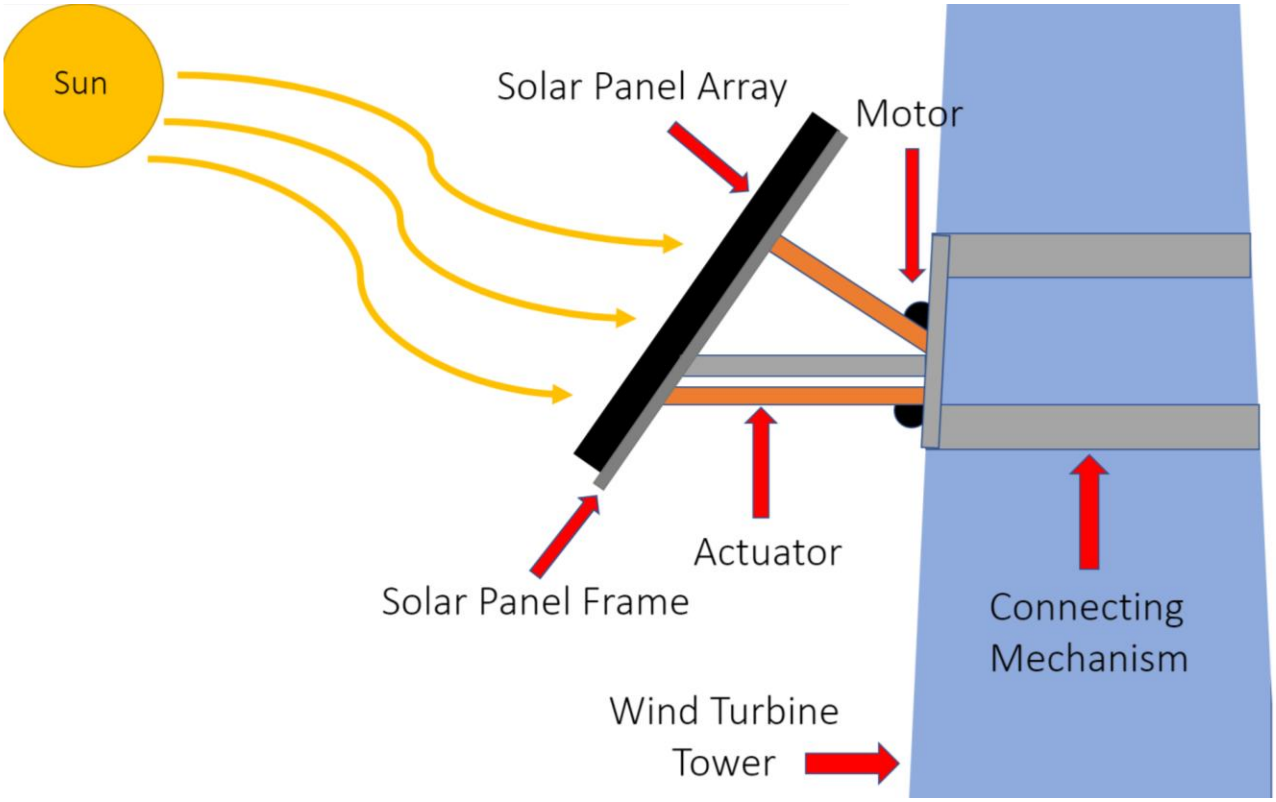

Figure 24: Conceptual Design 2: Dual Axis Solar Tracking Mount

3.2.1 Pros of Design 2

The dual axis design provides higher efficiency than Design 1 because more sun is collected throughout the day. The design has moving parts providing the team with a more challenging engineering problem and more design opportunities.

3.2.2 Cons of Design 2

Though more efficient, Design 2 is a more costly design, given the added actuators. More material is required for this design as the connecting mechanism wraps around the entire turbine t0wer and is rather bulky. The weight of Design 2 is more significant than that of Design 1 that may cause damage to the turbine tower. The moving parts require more electrical work that adds to cost and design time.

3.3 DESIGN 3

Design 3 is pictured in Figure 25. This design features a truss connection with a safety cable and single axis solar tracking. Design 3 has multiple connecting points and is drilled directly into the turbine tower.

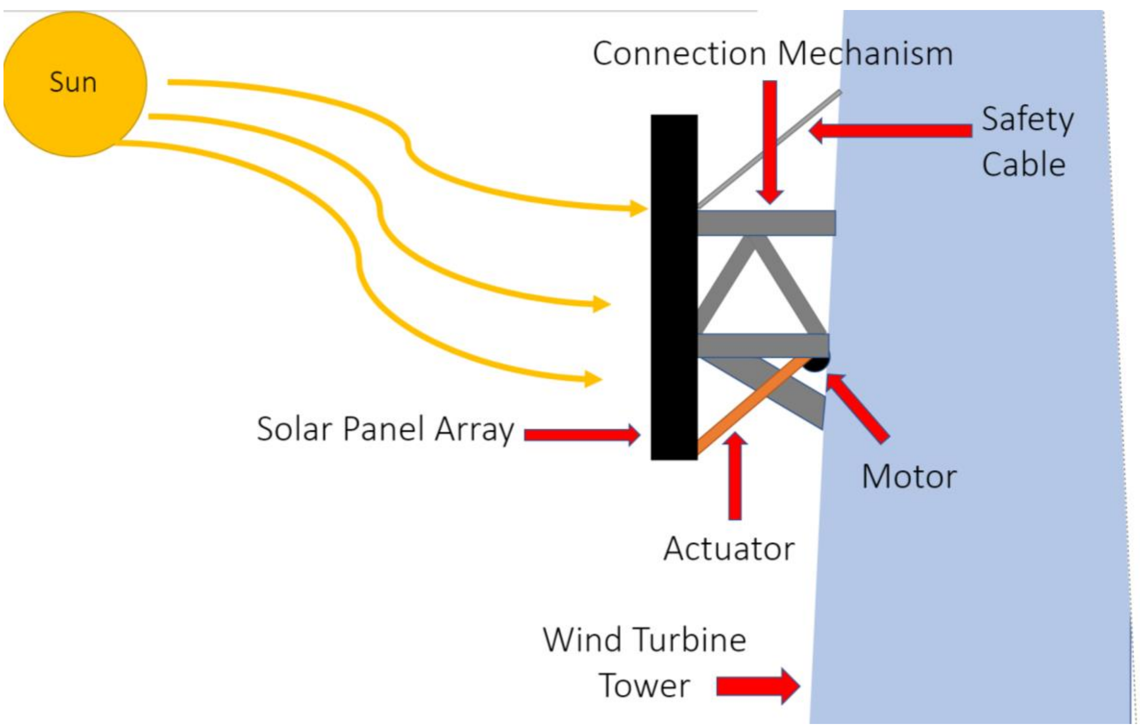

Figure 25: Conceptual Design 3: Truss Connection Method Featuring a Safety Cable and Single Axis Solar Tracking.

3.3.1 Pros of Design 3

The design provides the team with design opportunities that feature aspects from Design 1 and Design 2. The multiple connecting points provide added safety. The single axis solar tracking provides more efficiency than that of the fixed mount.

3.3.2 Cons of Design 3

The biggest downfall to Design 3 is the design time required to perfect the iteration. This design features more complexity as it is a combination of fixed and actuating mounts.

3.4 CONCEPT ANALYSIS

The team analyzed the pros and cons of each conceptual design to create an optimal final design. Through that analysis the following conclusion was made: the final design should have straight connecting arms, a standard U-bolt, an easy installation method, and an adequate distribution of the weight of the solar panels in addition to meeting the standard requirements for the design.

3.5 DESIGN ITERATION PROCESS

Figure 26 shows the major design changes made throughout the project. Each of these changes were made to meet the requirements of the project through the evaluation of hand calculations, FEA analysis, and load analysis processes.

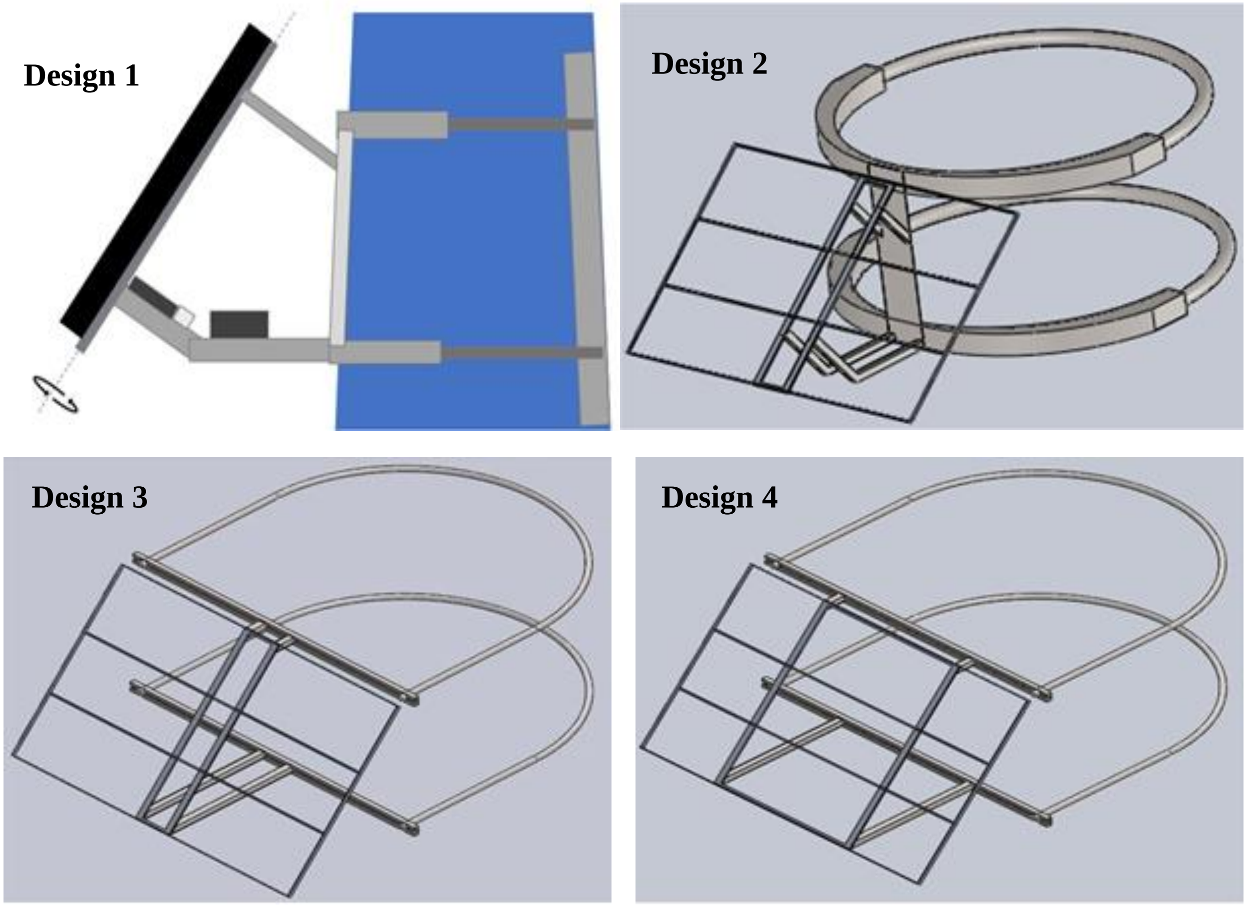

Figure 26: Design Iterations 1 – 4

3.6 DESIGN ITERATION 1

The team initially planned to design a mount that allowed for solar tracking in a single axis. Solar tracking was initially considered by the team because it can increase the efficiency by up to 17%. However, the team has noted that solar tracking is not often implemented commercially as they have not been proven to be cost effective given the added cost and design complexity [26]. Considering this observation design iteration 1 was retired and the next iteration would not contain solar tracking capabilities. The team also had to consider design time constraints and cost of the final mount; solar tracking solar panel mount was out of the picture. The team designed three new fixed mount iterations in SolidWorks, decreasing the complexity, stress, strains, and bending deflections each time while maintaining the efficiency of the solar panel array. The initial design 1 can be seen below in Figure 27 for reference.

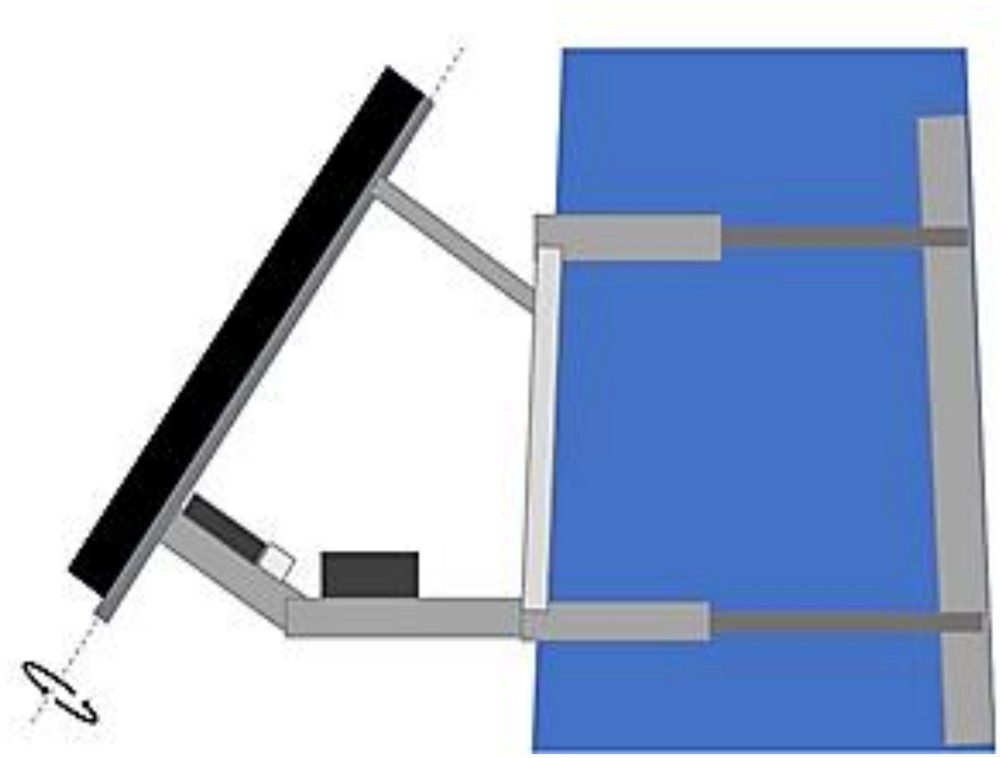

Figure 27: Design Iteration 1

3.7 DESIGN ITERATION 2

After establishing that solar tracking would not be a feature in the final design the team began designing a fixed mount. This fixed mount will be referred to as design iteration 2. This can be seen below in Figure 28 and important terminology is noted in Figure 29.

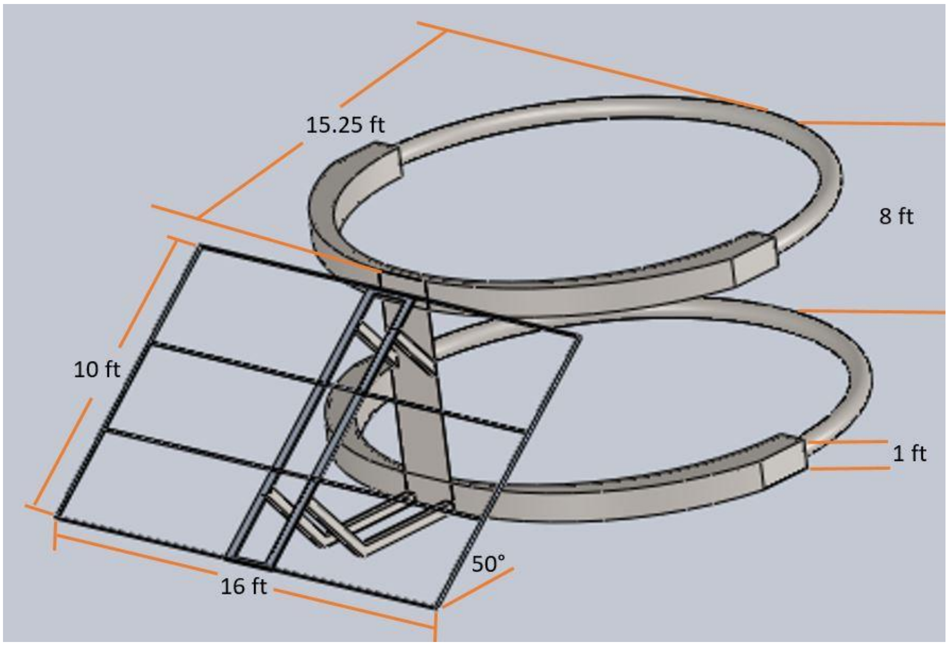

Figure 28: Design Iteration 2

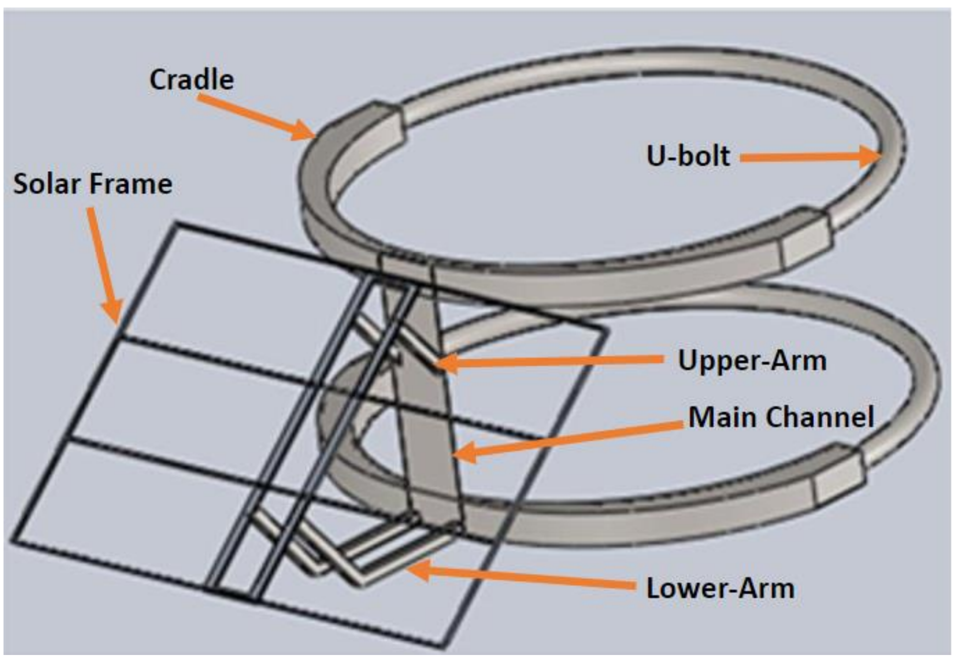

Figure 29: Design Iteration 2 - Terminology

Depicted in Figure 29 (along with some key dimensions) is the initial SolidWorks design of a fixed solar panel mount for the GE 1.5 MW wind turbine. While the first iteration did accomplish some of our requirements such as holding the panels and affixing to the correct tower it did not accomplish these requirements in the optimal way. Some of the downfalls of design iteration 2 is it being unnecessarily bulky and weighing over 20,000 pounds as evaluated in SolidWorks. The installation of this mount is also unnecessarily difficult as the U-bolts must be tightened by coming in from underneath the cradles. In this iteration the diameter of the U-bolts was 8 inches leading to difficulty in manufacturing and installation as well as substantial weight increases. The upper and lower U-bolts are also 8 feet apart in this iteration which was unnecessary and meant that a main channel had to be added to have something to affix our upper and lower arms to adding unnecessary weight. The upper and lower arms are attached to the solar frame at an angle. This angle in the beams creates stress concentrations that can be eliminated by making the upper and lower arms straight. The team concluded that while this design was a good place to start it needed a major overhaul.

3.8 DESIGN ITERATION 3

Design iterations 3 addressed all the major concerns that the team had with design iteration 2 and can be seen below in Figure 30 and important terminology can be seen in Figure 31.

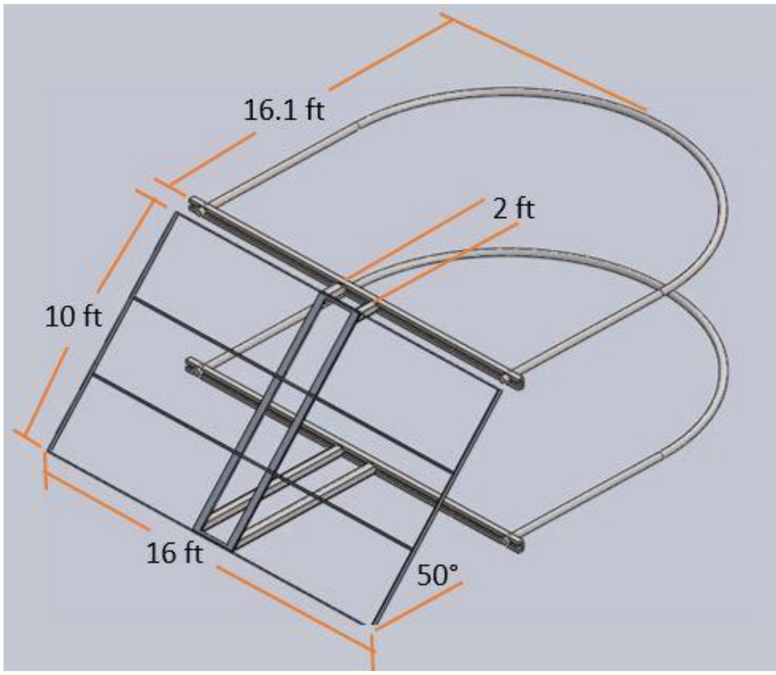

Figure 30: Design Iteration 3

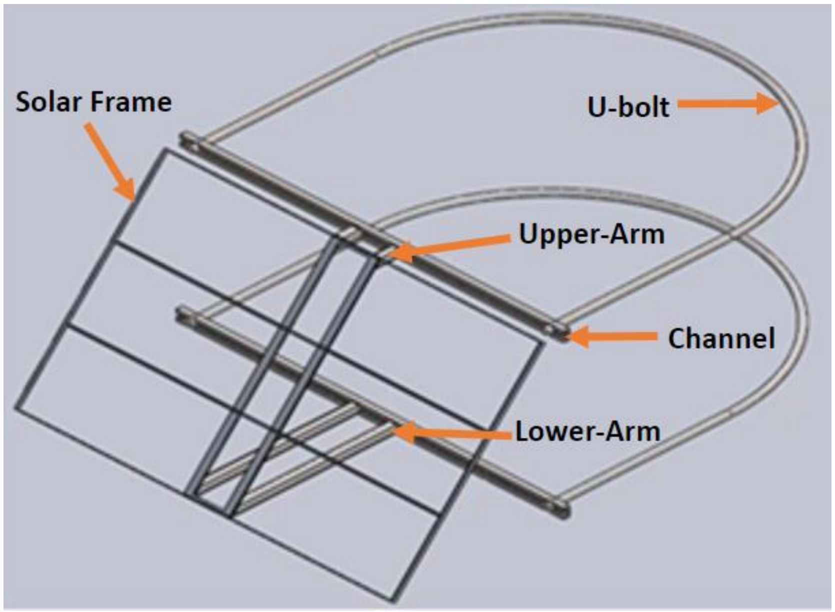

Figure 31: Design Iteration 3 - Terminology

In design iteration 3 the weight was reduced by nearly 75%. This was accomplished by reducing the diameter of the U-bolts to 3.5 inches and adopting a more standard U-bolt approach with channels instead of cradles. The U-bolts are easier to install as they are lighter, and the nuts can be accessed through the channel straight on without coming in from underneath. The U-bolts are 6.41 feet apart vertically as opposed to 8 feet, taking up less room on the turbine tower. The upper and lower channels took place of the giant cradles in design 2 for support as well as easier installation of the upper and lower arms. The upper and lower arms can now be slid into the channels. The upper and lower arms are now straight which eliminates the stress concentrations that were a concern with design 2. According to SolidWorks, the weight of the new design is 4,932 pounds. The remaining issue with this design 3 was high deflection on the edge of the solar frame once the weight from the solar panels was applied. This remaining issue is addressed in design iteration 4.

3.9 DESIGN ITERATION 4

This is the final iteration of the mount. The difference between design iteration 3 and design iteration 4 is the placement of the upper and lower arms on the upper and lower channels. There was a significant drop in deflection on the edges of the solar panel frame when the distance between the arms went from 2 feet to 8 feet. This change caused the load of the solar panel array to be distributed more evenly across the solar frame. All stress points in this iteration meet the requirements and guidelines of the projects. Details of the simulation of this design as well as proof of meeting the requirements are detailed in the remainder of the report. Design iteration 4 is the final chosen design and can be seen below in Figure 32 and the same terminology is used as in design iteration 3 (see Figure 31).

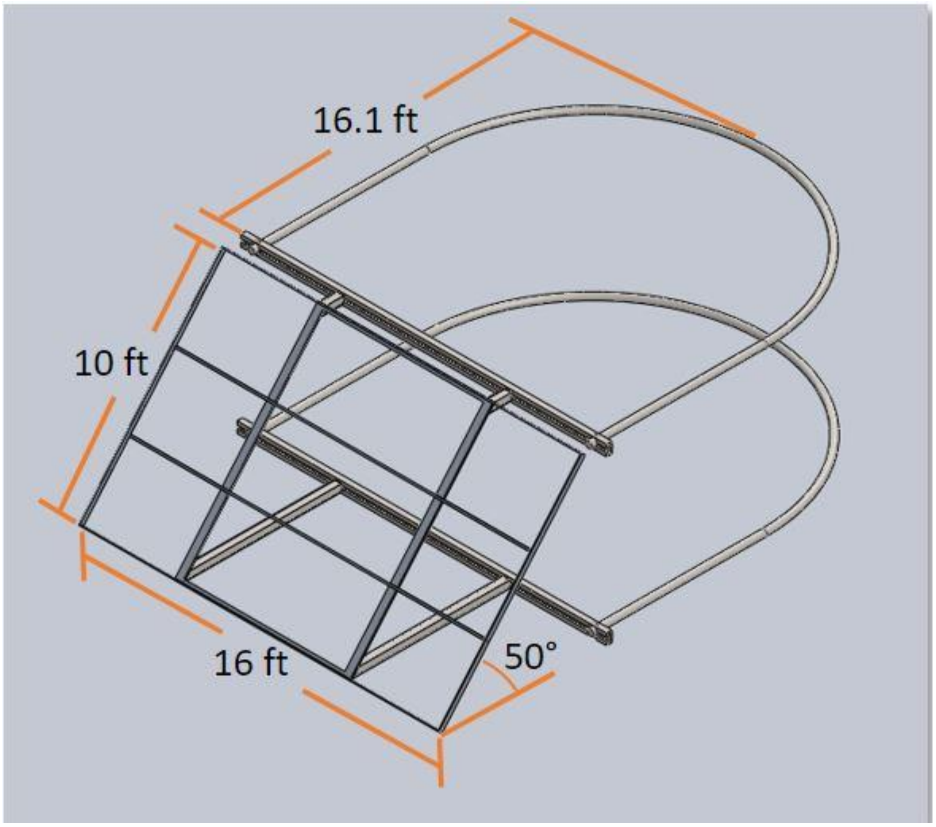

Figure 32: Design Iteration 4: Final Design

4 FINAL DESIGN

4.1 CHOSEN DESIGN JUSTIFICATION

The team chose this design because the final weight dropped 78% from the first SolidWorks Iteration, ending at 4,932 pounds. It is easier to install and manufacture. Given the added changes and improvements, Design 4 is the cheapest option of the three.

4.2 COMPONENTS

The components for this design can be seen detailed in Figure 33 which is a mechanical block diagram containing the terminology used to refer to each of the components. The weight of each component can be found in Appendix C and more detailed dimensions can be found in Appendix E.

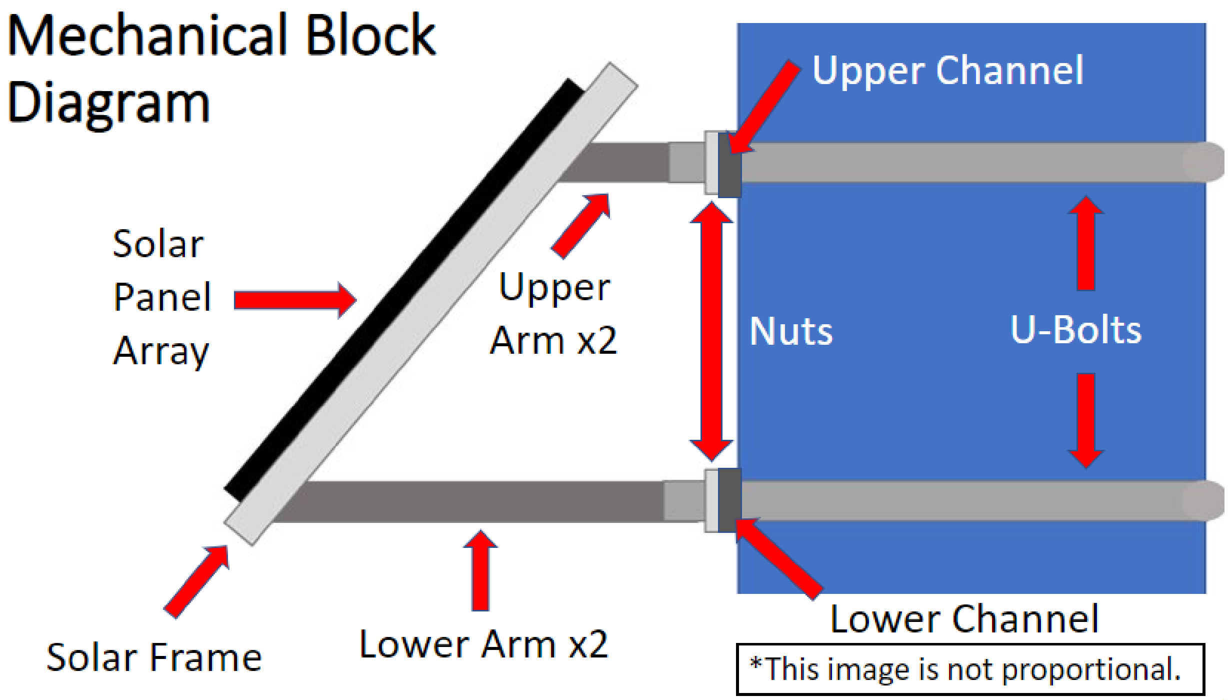

Figure 33: Mechanical Block Diagram

4.2.1 U-bolts and Nuts

Below are SolidWorks renderings of the U-bolts and nuts that will be used to wrap around the wind turbine tower and secure the solar frame. They can be seen in Figure 34 and Figure 35.

Figure 34: SolidWorks Rendering of U-bolts

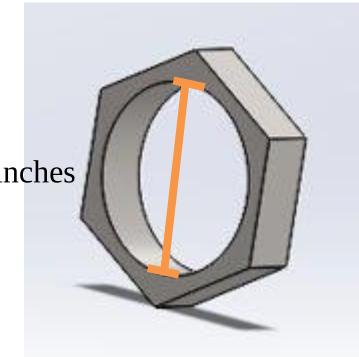

Figure 35: SolidWorks Rendering of Nuts

The U-bolts and nuts are both made of ASTM A572 Grade 50 Steel. This is the same material as the wind turbine tower. Because the U-bolts come into direct contact with the tower, the same material was chosen to prevent the dielectric effect. The dielectric effect causes corrosion between two materials. The best way to prevent this is by using similar materials. The weight of both U-bolts is 2,618 pounds. The total weight of the four nuts is 8 pounds. The SolidWorks renderings of the U-bolts and nuts can be seen in Figure 34 and Figure 35.

The U-bolts need to be pretensioned to assure the mount will not spin around the tower when it is exposed to vibrations from the wind turbine tower and a wind load greater than 90 mph.

4.2.2 Arms

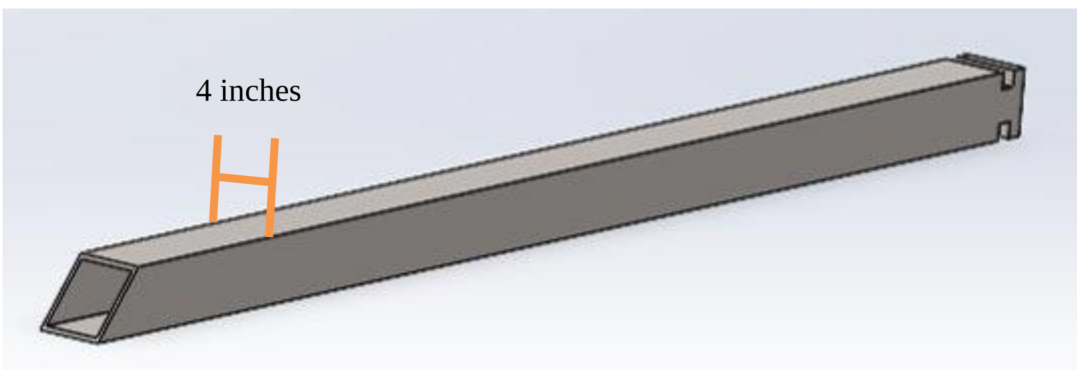

Figure 36: SolidWorks Renderings of Arms

The final design has four arms, two upper arms and two lower arms. A rendering of one lower arm can be seen in Figure 36. All four arms are made from ASTM A513 Grade B Tubular Steel with a four-inch cross-section. The lower arms are significantly longer than the upper arms to create the 50° angle. The arms will be hot dip aluminized to prevent any dielectric effect between the steel arms and aluminum frame. This will also help the process of welding the two components together [27]. The upper arms weigh 64 pounds combined and the lower arms weigh 376 pounds combined.

4.2.3 Channels

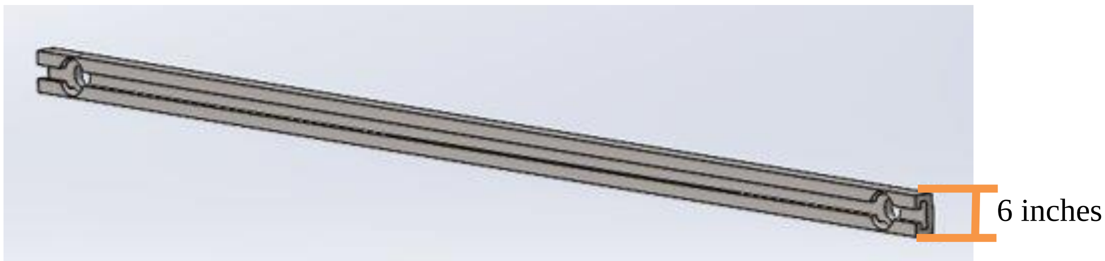

Figure 37: SolidWorks Renderings of Channels

There are two channels, an upper and a lower channel, that connect the U-bolts to the arms, as shown in Figure 37. These channels are slotted so the arms can slide into place. The upper channel is slightly shorter than the lower channel, because of the tapering of the wind turbine tower. The channels are made from the same ASTM A572 Grade 50 Steel of the U-bolts, nuts, and wind turbine tower. The channels weigh 1,476 pounds combined.

4.2.4 Solar Frame

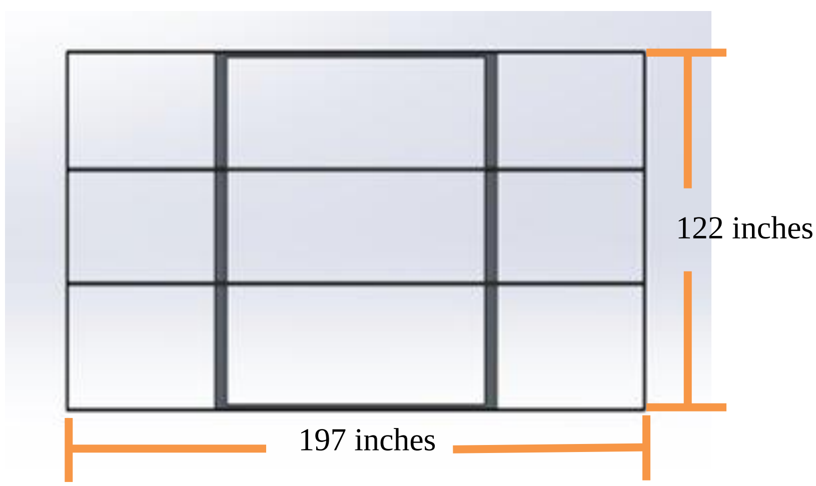

Figure 38: SolidWorks Renderings of Solar Frame

Pictured in Figure 38 is the solar frame. It is designed to hold 10 solar panels that are individually 10 feet by 16 feet and is made from 6063 T6 Aluminum. The size of the frame was determined by the average size of solar panels. The team's research [24] showed that most solar frames are made of an aluminum alloy. Using an aluminum alloy also decreased the weight of the frame. The final weight of the frame was 183 pounds.

4.2.5 Solar Array

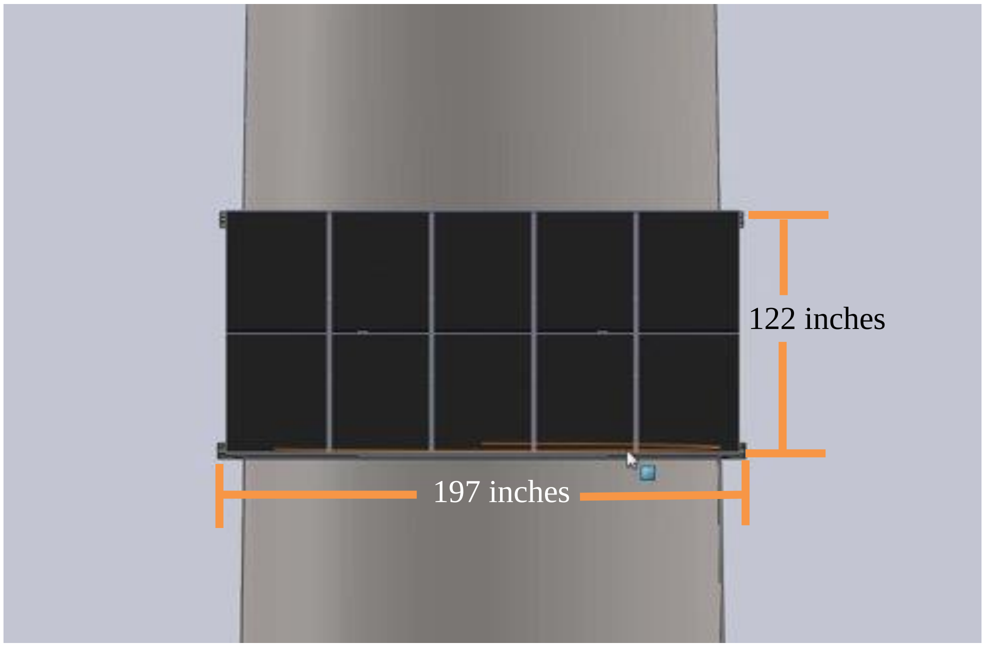

Figure 39: SolidWorks Rendering of Solar Panel Array on Wind Turbine Tower

Figure 39 above shows a front view of the solar panel mount on the turbine tower with the solar panels placed in the solar panel frame. The solar array was not designed by the team. The "SunPower Maxeon 3" solar panels were used as a model for the mount design and the economic analysis. The total solar array weighs 420 pounds.

4.3 CONSTRUCTION

This mount comes in 4 different parts: the U-bolts, nuts, arms and frame, and channels. The hot dip aluminized arms and frame will be welded together and will slide into the channels. The U-bolts will wrap around the tower and go through the channel. The nuts will attach to the U-bolts on the other side of the channel.

4.4 WRITTEN CALCULATIONS

Written calculations were completed using various equations based on assumptions found through the process of researching example problems that are similar to the circumstances of the project. These calculations aided in showing the mount will not fail and will not cause damage to the wind turbine tower. The written calculations were performed on engineering paper and can be viewed in Appendix H.

The written calculations for the solar panel frame are explained using Equations 1-4. Some factors that play into the failure of the solar panel frame are bending stress and deflection. Both factors are caused from the weight of the solar panel array acting on the solar panel frame. The team needed to prove that the bending stress on the mount caused by the weight of the solar panel array would not cause the solar panel frame to fail or yield. Bending stress is defined as compressive stress that occurs on top of a beam and tensile stress that occurs on bottom of a beam due to a load placed on the beam [41]. The deflection of the frame also had to be accounted for to ensure the weight of the solar panel array did not cause failure [39]. The remaining concerns were the recommended pretension torque of the nuts on the U-bolts, the buckling of the tower, and the bending stress of the arms. The pretension torque of the nuts had to be solved to ensure the mount does not spin around the tower as high-speed winds encountered the mount. The buckling of the tower was solved to ensure the weight of the mount does not cause failure to the existing turbine tower. The bending stress of the arms were solved for to ensure the weight of the solar panel array and frame did not cause failure to the arms.

Some calculations required an area moment of inertia to be calculated. The values used for each area moment of inertia can be seen in Table 3.

Table 3: Area Moment of Inertia Values

Area Moment of Inertia							
Component	**b(outer) (in.)**	**b(inner) (in.)**	**h(outer) (in.)**	**h(inner) (in.)**	**d(outer) (in.)**	**d(inner) (in.)**	**I-value (in^4)**
Solar Frame Outer Beam	0.5	-	2.5	-	-	-	0.651
Upper & Lower Arms	4	3.75	4	3.75	-	-	4.85
Tower for Bending Stress	-	-	-	-	228	226	4,593,522.89

4.4.1 Hanging Portion

There are two main components in the hanging portion: the frame, and the arms. The important calculations for the frame included bending stress and deflection.

Different sizes of beams were put together to create the solar panel frame. All the outer beams of the frame have the same area moment of inertia since they all have the same cross-section. Figure 40 shows the solar panel frame that is composed of different sized beams.

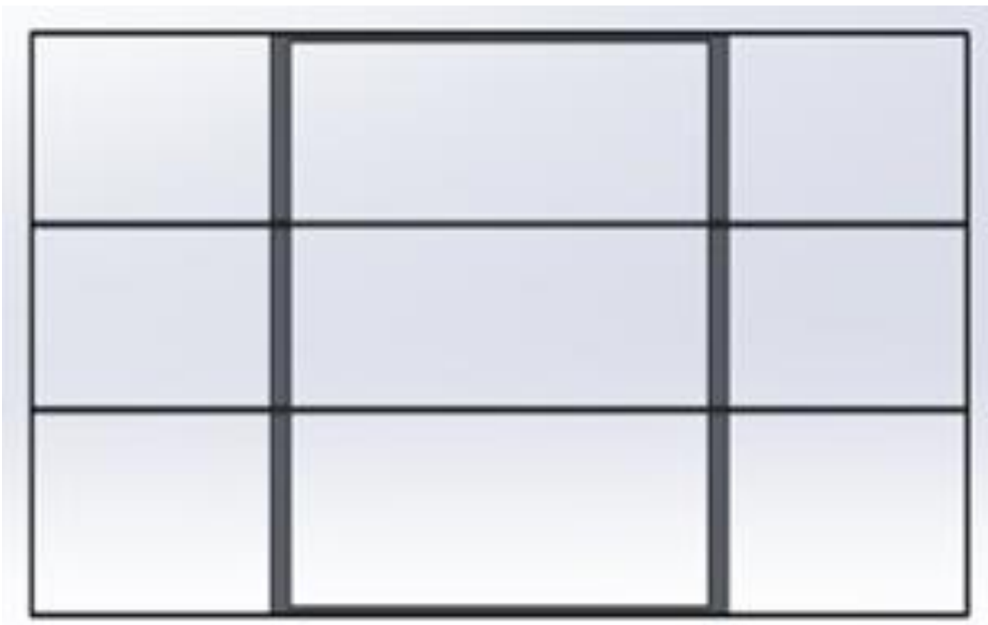

Figure 40: Solar Panel Frame Composed of Different Sized Beams

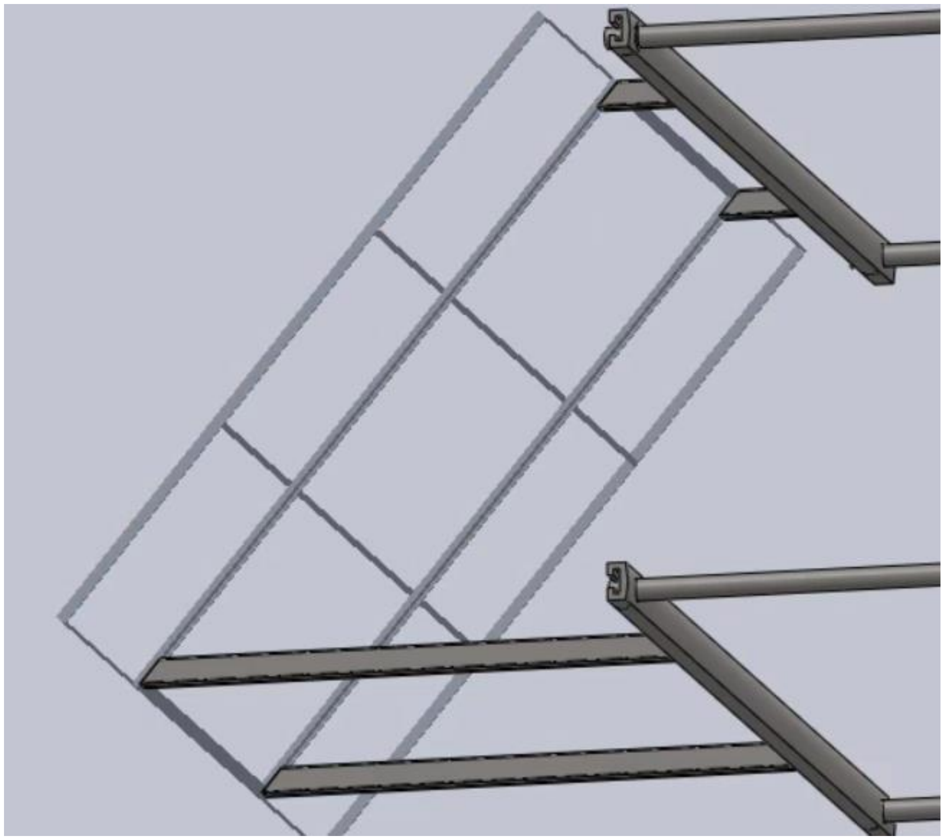

Figure 41: Frame Attached to Upper and Lower Arms Showing Fixed Points

As shown in Figure 41, the outer beams of the solar panel frame attach to the arms of the mount, so the fixed points on the frame are located on the outer beams.

Figure 42 shows the free body diagram of the moments solved for on the solar panel frame. The free body diagram is drawn as the solar panel array is acting straight down on the outer beam of the solar panel frame.

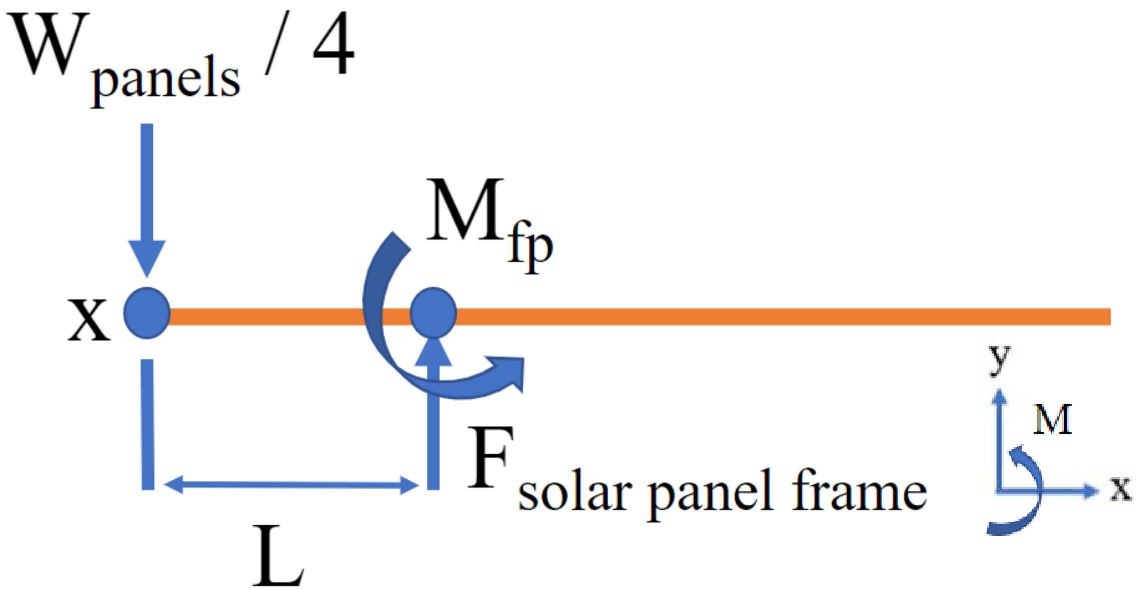

Figure 42: Free Body Diagram of Solar Panel Array Acting on Solar Panel Frame.

To solve for the moments at the fixed points on the frame, the outer beams were treated as a cantilever beam and were solved for using Equation 1 which can be seen in Appendix I (Figure 90) [39]. In this equation, *F* is equal to the weight of the solar panel array divided by four. The weight of the solar panel array was divided by four to provide the team with an estimated force acting at the moment location. Dividing the weight of the solar panel array by four shows the weight of the solar panel array acts as a distributed load. In Equation 1, *L* is equal to the distance from the fixed point to the outer edge of the solar panel frame as shown in Figure 42 and *x* is equal to zero. For this equation, $(L - x)$ is the moment arm.

$$\Sigma M = -F(L - x) = 0 \quad \textbf{(1)}$$

After finding the moments acting on the frame, the area moment of inertia of the outer beams were determined using Equation 2 which can be seen in Appendix I (Figure 91) [38]. The area moment of inertia for the outer beams were calculated since they are attached to the arms. This relates to the fixed-point moments solved for in Equation 1. In the following equation, *b* is the base of the cross-section and *h* is the height for the outer beams as shown in Figure 43.

$$I = \frac{1}{12} bh^3 \quad \textbf{(2)}$$

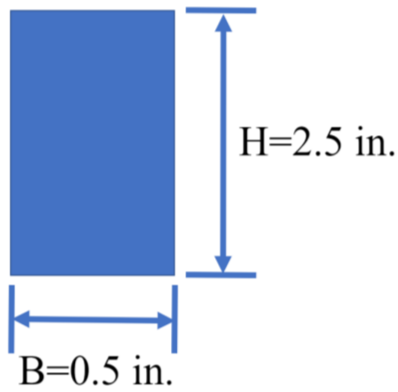

Figure 43: Cross section of outer beams on solar panel frame.

The bending stress of the solar panel frame due to the weight of the solar panel array is calculated using Equation 3 which can be seen in Appendix I (Figure 92) [40]. The *y* value in this equation is the distance from the neutral axis of the outer beam which is found using the cross-sectional area of the frame. *M* is equal to the moment at the fixed point solved for using Equation 1 and *I* is the value for the outer beams of the solar panel frame found in Equation 2. The final value of the bending stress due to the weight of the solar panel array can be found in Table 4.

$$\sigma_{bending} = \frac{My}{I} \quad \textbf{(3)}$$

Equation 4 is used to calculate the safety factor of the solar panel frame where S_y is the yield strength of the aluminum alloy used for the frame and σ_{total} is the bending stress of the frame found in Equation 3.

$$\eta_{stress} = \frac{S_y}{\sigma_{total}} \quad \textbf{(4)}$$

The deflection of the solar panel frame due to the weight of the solar panel array was calculated using Equation 5. This ensured the solar panel array was not too heavy and can be seen in Appendix I (Figure 90) [39]. In this equation, *E* is the modulus of elasticity of the material. *L* is equal to *x*, which is the length from the fixed point at the arm to the end of the frame. Because this is the maximum deflection, the entire section from the fixed point to the end of the frame needs to be accounted for.

$$\delta_D = \frac{-Fx^2}{6EI}(3L - x) \quad \textbf{(5)}$$

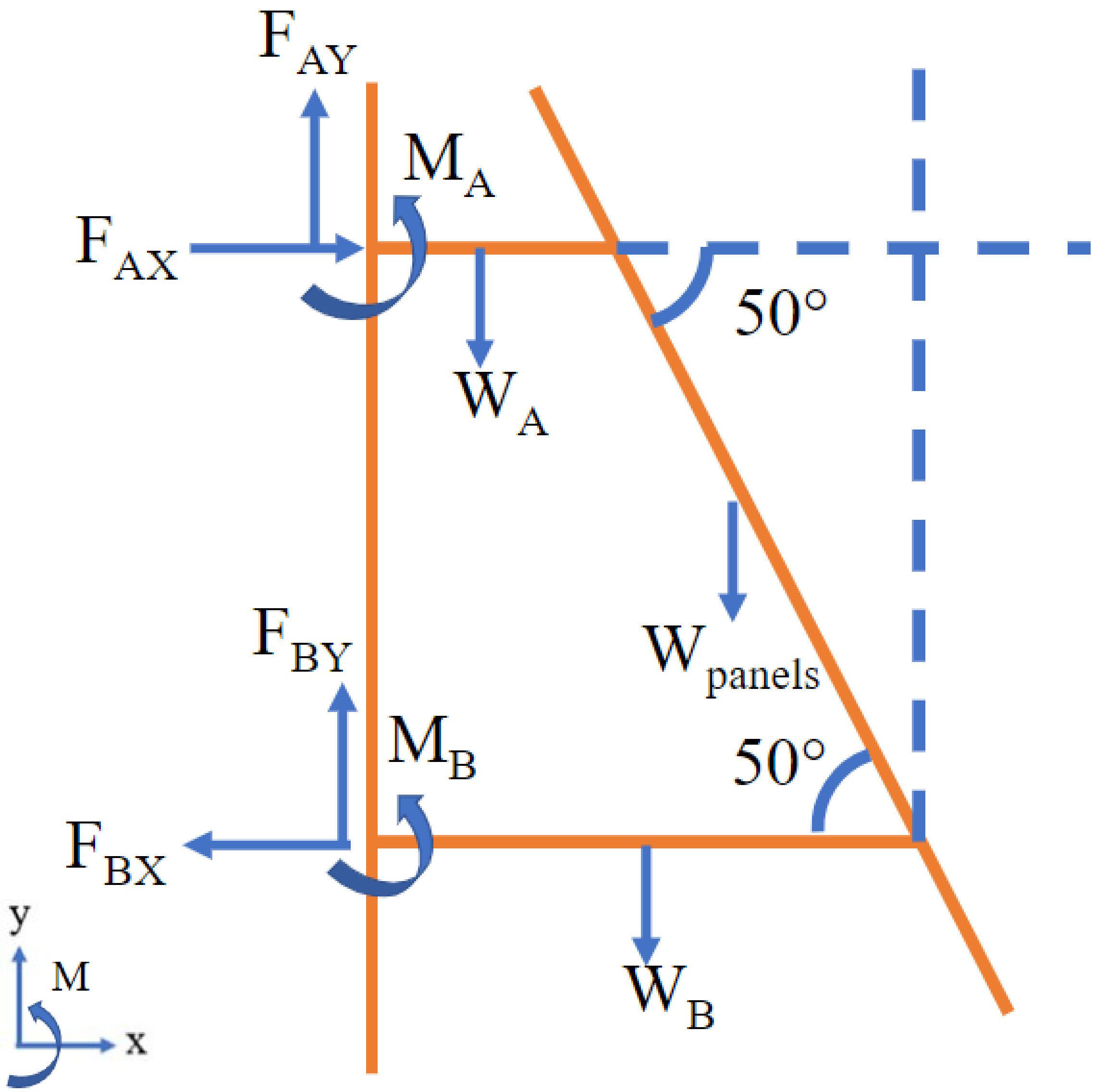

Figure 44: Free Body Diagram of Upper and Lower Arms

The other important component of the hanging portion is the arms. The focus of the arms was the bending stress. Before any calculations were done on the arms, the team needed to determine what the maximum bending stress could be. This was done in Equation 6 which can be seen in Appendix I Figure 90 [40]. In this equation η represents the safety factor, which has an industry standard of 6 [42]. S_y is the yield strength of the material of the arms, which is equal to 46,000 psi. The maximum bending stress can be found in Table 4.

$$\sigma_{max} = \frac{S_y}{\eta} \quad \textbf{(6)}$$

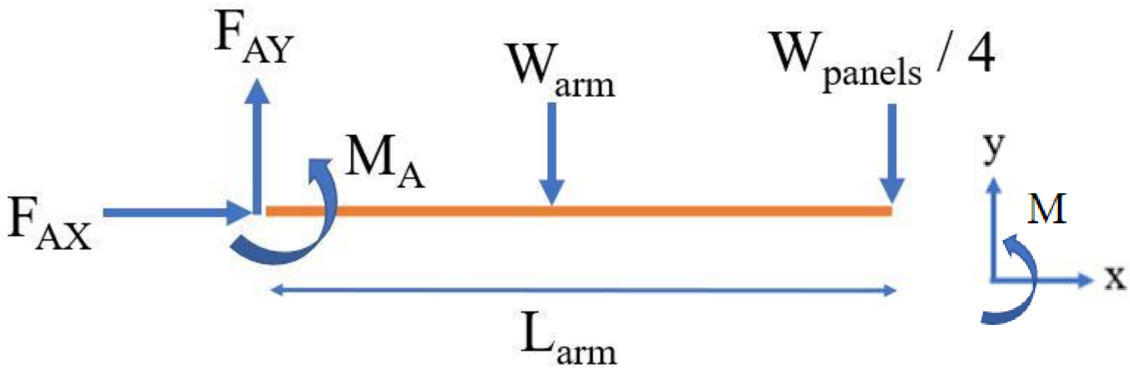

Figure 45: Free Body Diagram of Single Upper Arm

The reaction forces and moments, shown in Figure 44, needed to be found before the bending stress could be found. In Equation 7, the reaction force, F_{Ax}, acting on a single upper arm in the x-direction is calculated which can be seen in Appendix I (Figure 89) [38]. Since the reaction force is the only force in the x-direction for. Since the reaction force is the only force in the x-direction, it is equal to zero.

$$\Sigma F_x = 0 = F_{Ax} \quad \textbf{(7)}$$

Figure 45 shows the force of the solar panel array and frame acting on a single upper arm as a direct load. The upper arms need to hold the solar panel array and the frame in place, while the lower arms will be acting as the main supports. Equation 8 shows the calculation of the reaction force, F_{Ay}, acting on the arm in the y-direction which can be seen in Appendix I (Figure 89) [38]. The forces acting on the arm in the y-direction can be seen in Figure 45. The w_{panels} term is divided by four as an assumption that the weight of the panels is evenly distributed across the beam.

$$\Sigma F_y = 0 = F_{Ay} - w_{arm} - \frac{w_{panels}}{4} \quad \textbf{(8)}$$

The reaction moment, M_A, was calculated in Equation 9 which can be seen in Appendix I (Figure 89) [38]. The two forces that create a moment on the arm are the weight of the arm, w_{arm}, and the weight of the solar panel array and the frame, w_{panels}. Because the weight of the arm is acting in the middle, the moment arm is half the total length. The moment arm for the w_{panels} term is the total length of the arm, which can be seen in Figure 45.

$$\Sigma M_A = 0 = M_A - \left(w_{arm} \times \frac{L_{arm}}{2}\right) - \left(\frac{w_{panels}}{4} \times L_{arm}\right) \quad \textbf{(9)}$$

Since the area moment of inertia for the arms is different than the frame, it was calculated again in Equation 10 which can be seen in Appendix I (Figure 89) [38]. Because the arms are made of hollow tubular steel, the area moment of inertia of the inside needed to be subtracted from the outside. The values of *b* and *h* can be seen in Appendix H.

$$I = \frac{b_{outer}h_{outer}^3 - b_{inner}h_{inner}^3}{12} \tag{10}$$

Using the area moment of inertia, calculated in Equation 10, and M_A, calculated in Equation 9, the bending stress was calculated in Equation 11 which can be seen in Appendix I (Figure 90) [40]. The *y* value is based on the cross section of the arms.

$$\sigma_{bending} = \frac{M_A \times y}{I} \tag{11}$$

To ensure the factor safety is above the industry standard of six, Equation 12 was performed. In this equation S_y is equal to the yield strength of the material, 46,000 psi, and $\sigma_{bending}$ is the result from Equation 11. The result of Equation 12 can be found in Table 4.

$$\eta_{stress} = \frac{S_y}{\sigma_{bending}} \tag{12}$$

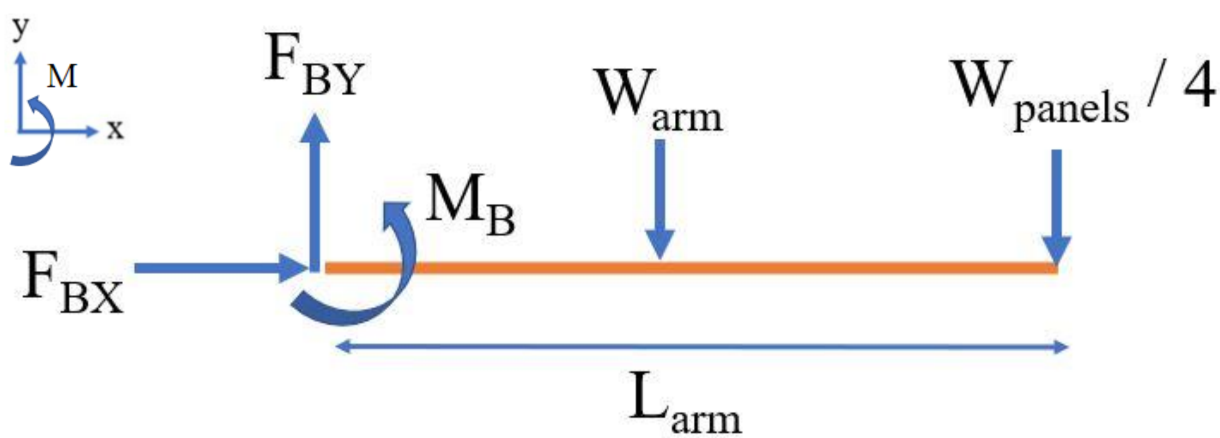

Figure 46: Free Body Diagram of Single Lower Arm

For the single lower arm, the area moment of inertia and the *y* value stayed the same as the upper arm. The calculation for the reaction force in x-direction, F_{Bx}, is shown in Equation 13 and can be seen in Appendix I (Figure 89) [38]. As seen in Figure 46, the reaction force is the on acting force in the x-direction, which means it is equal to zero.

$$\Sigma F_x = 0 = -F_{Bx} \tag{13}$$

Equation 14 shows the calculation for the reaction force, F_{By}, acting on the arm in the y-direction, as seen in Figure 46. Equation 14 can be seen solved in Appendix I (Figure 87) [38]. Just like in the calculations for the upper arm, the w_{panels} term is divided by four as an assumption that the weight is equally distributed across the four arms.

$$\Sigma F_y = 0 = F_{By} - w_{arm} - \frac{w_{panels}}{4} \quad \textbf{(14)}$$

The reaction moment acting on the arm, M_B, was calculated using Equation 15 which can be seen in Appendix I (Figure 87) [38]. The two forces creating a moment on the arm are the weight of the arm and the weight of the solar panel array and the frame. The weight of the arm acts in the middle, so the moment arm is the half the total length. The moment arm for the weight of the solar panel array and the frame is the entire length of the arm.

$$\Sigma M_B = M_B - \left(w_{arm} \times \frac{L_{arm}}{2}\right) - \left(\frac{w_{panels}}{4} \times L_{arm}\right) = 0 \quad \textbf{(15)}$$

Equation 16 calculates the bending stress for the lower arms. This calculation is the same as the upper arms except for the M_B value which is found in Equation 15. The total bending stress of the lower arms can be found in Table 4. The team made sure that this value was significantly below the value found in Equation 6 before continuing with the calculations.

$$\sigma_{bending} = \frac{M_B \times y}{I} \quad \textbf{(16)}$$

After the bending stress for the lower arms was calculated, the factor of safety needed to be calculated. Equation 17 calculates the factor of safety for the lower arms, which is the same as the equation for the upper arm factor of safety, except the value from Equation 16 is used.

$$\eta_{stress} = \frac{S_y}{\sigma_{total}} \quad \textbf{(17)}$$

The total moment acting on the mount was calculated in Equation 18 which can be seen in Appendix I (Figure 89) [38]. This equation uses the values of M_A, found in Equation 8, and M_B, found in Equation 13. Both components are multiplied by two to account for all four arms. This calculation was not used to determine any of the critical values.

$$M_{mount} = 2M_A + 2M_B \quad \textbf{(18)}$$

4.4.2 U-Bolts

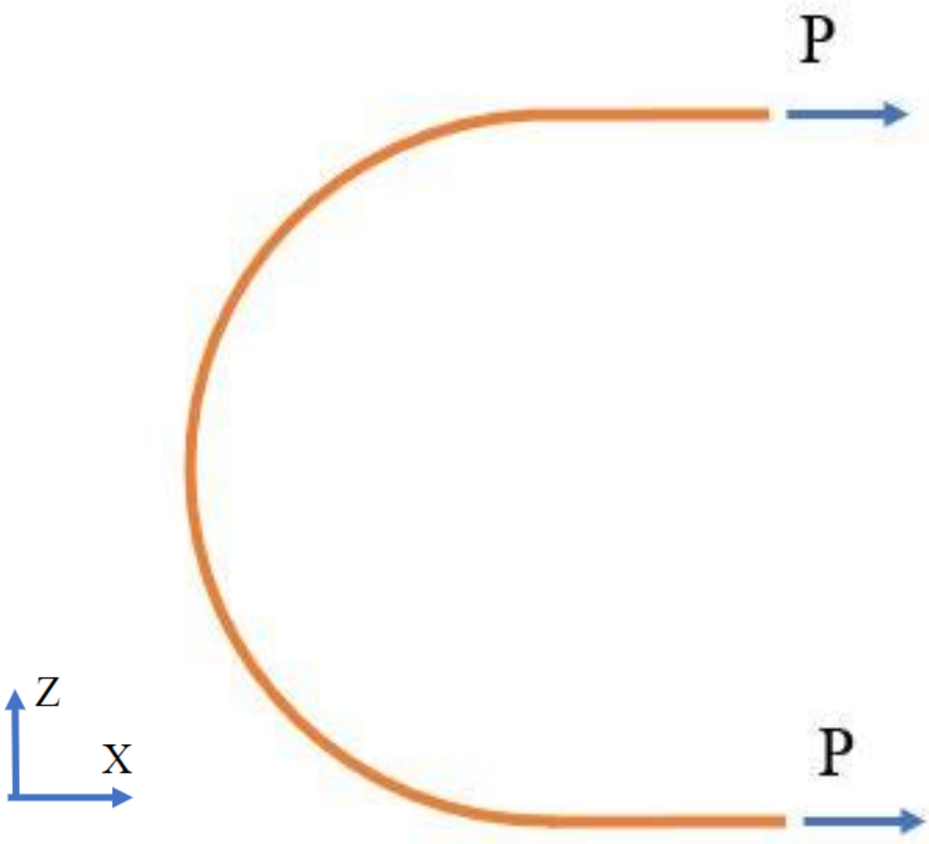

Figure 47: U-Bolt Free Body Diagram

The main focuses for the U-bolts were making sure one bolt was in compression, while the other was in tension and finding the recommended torque to pretension the bolts. Equation 19 is the equation for static friction and shows the calculation used to determine which U-bolt was in compression. $F_{friction}$ is equal to the total weight of the mount and solar panels plus an extra 25% to account for ice and dynamic loading and can be seen in Appendix I (Figure 94) [38]. The equation was solved for P, shown in Figure 47, which is the force acting on the U-bolts. If P was negative, that U-bolt was in compression.

$$F = \mu 2P \tag{19}$$

Equation 20 shows the calculation for the recommended torque, F_i, needed to pretension the U-bolts and can be seen in Appendix I (Figure 95) [40]. The pretension was important to ensure the mount would not move around the tower when it was subjected to the high wind speeds created from the wind turbines. A_t is the tensile stress area that is found in a table provided by Shigley's Mechanical Engineering Design [36] and S_p is the proof strength which is 85% of the yield strength.

$$F_i = 0.9 \times \left(A_t S_p\right) \quad \textbf{(20)}$$

4.4.3 Tower

Because this is a pre-existing wind turbine, these calculations were done to assure the mount would not cause any damage to the wind turbine tower. Buckling was a main concern, so Equation 21 was performed to ensure the added weight of the mount would not cause the wind turbine tower to buckle, this equation can be seen in Appendix I (Figure 91) [40]. In this equation, I_{avg} is the average area moment of inertia and C is the end condition constant. The blades and nacelle were heavy enough to consider the tower fixed on both ends, because of this C is equal to 1.2. E is the modulus of elasticity of the tower.

$$P_{critical} = \frac{C\pi^2 E I_{avg}}{l^2} \quad \textbf{(21)}$$

The buckling safety factor, in Equation 22, was calculated to assure the tower would not fail due to buckling, this equation can be seen in Appendix I (Figure 92) [40]. The $P_{critical}$ value was found in Equation 21, while the weights of the tower components were given by General Electric [21].

$$\eta_{buckling} = \frac{P_{critical}}{w_{head} + w_{blades} + w_{tower} + w_{mount}} \quad \textbf{(22)}$$

Another concern was the bending and axial stresses in the tower. The bending stress calculation is shown in Equation 23, this equation can be seen in Appendix I (Figure 90) [40]. The moment acting on the tower, M, is the weight of the hanging portion of the mount. The M term breaks into the force, $w_{hanging}$, and the moment arm, d. The y value is the distance from the neutral axis, and I is the area moment of inertia of the tower.

$$\sigma_{bending} = \frac{My}{I} = \frac{(w_{hanging} \times d)y}{I} \quad \textbf{(23)}$$

The axial stress calculation is shown in Equation 24 where A is cross-sectional area of the tower and w_{total} is the total weight of the tower, blades, head, and mount. Equation 24was performed to ensure the tower would not fail due to any additional axial stress caused by the mount's weight; this equation can be seen in Appendix I (Figure 93) [39].

$$\sigma_{axial} = \frac{w_{total}}{A} \quad \textbf{(24)}$$

Using the bending and axial stresses, the total stress acting on the tower was calculated using Equation 25, this equation can be seen in Appendix I (Figure 93) [39]. This was done to find the stress safety factor.

$$\sigma_{total} = \sigma_{bending} + \sigma_{axial} \quad \textbf{(25)}$$

Equation 25 calculates the safety factor for the total stress on the tower, this equation can be seen in Appendix I (Figure 92) [40]. According to an industry standard [18], the factor of safety needed to be above six. This calculation was done to ensure the mount would not cause the factor of safety to go below six. In this equation, S_y is the yield stress of the tower, and the total stress was solved for in Equation 25. The safety factor was high enough, that there was no concern of the tower failing. As seen in Table 4, the safety factor could have been lowered, to get closer to the industry standard. The team discussed ways to lower the factor of safety. These recommendations can be found in Section 12. The shear and moment diagrams for the tower can be found in Appendix D.

$$\eta_{stress} = \frac{S_y}{\sigma_{total}} \quad \textbf{(26)}$$

Table 4 shows the results of the critical calculations from above. The yield strength for the frame is 31,000 psi. This means that the bending stress from Equation 3 needed to be below 31,000 psi. For the arms, the yield strength is 46,000 psi. This means all the stresses for the arms needed to be below 46,000 psi.

Table 4: Critical Values

Equation	Value
Equation 3 – Frame Bending Stress	2,036 lbf/in^2
Equation 4 – Frame Safety Factor	15
Equation 5 – Frame Deflection	0.69 inches
Equation 6 – Maximum Bending Stress	7667 psi
Equation 11 – Upper Arm Bending Stress	234 psi
Equation 12 – Upper Arm Safety Factor	196
Equation 16 – Lower Arm Bending Stress	1954 psi
Equation 17 – Lower Arm Safety Factor	24
Equation 20 – Pretension Torque	33,250 ft-lb
Equation 22 – Buckling Safety Factor	794,08
Equation 25 – Total Stress on Tower	1,122 lbf/in^2

4.5 SOLIDWORKS RENDERINGS

In Figures 48 – 50 you can find the completed SolidWorks renderings of the mount both on and off the wind turbine tower. The mount is also depicted with and without the solar panels.

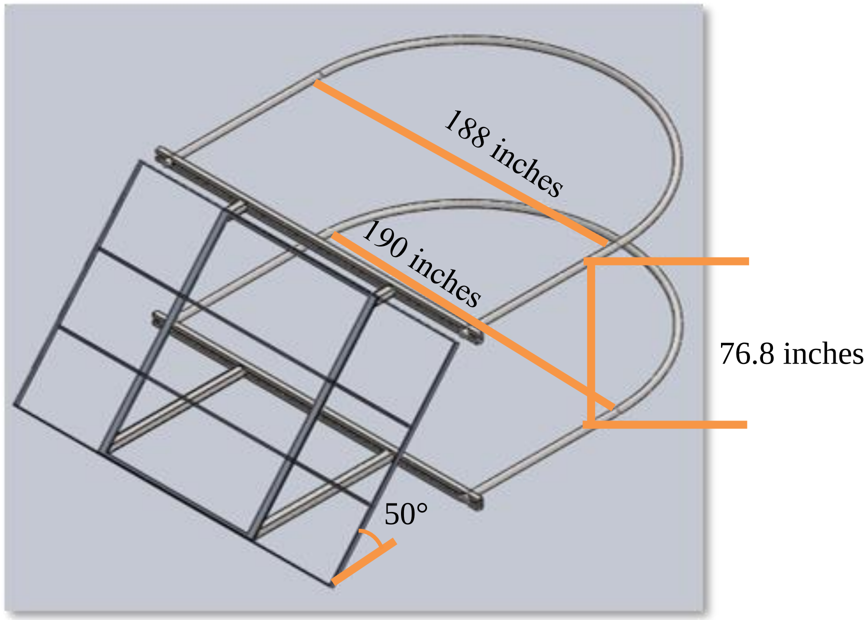

Figure 48: Completed Solar Panel Mount with Dimensions

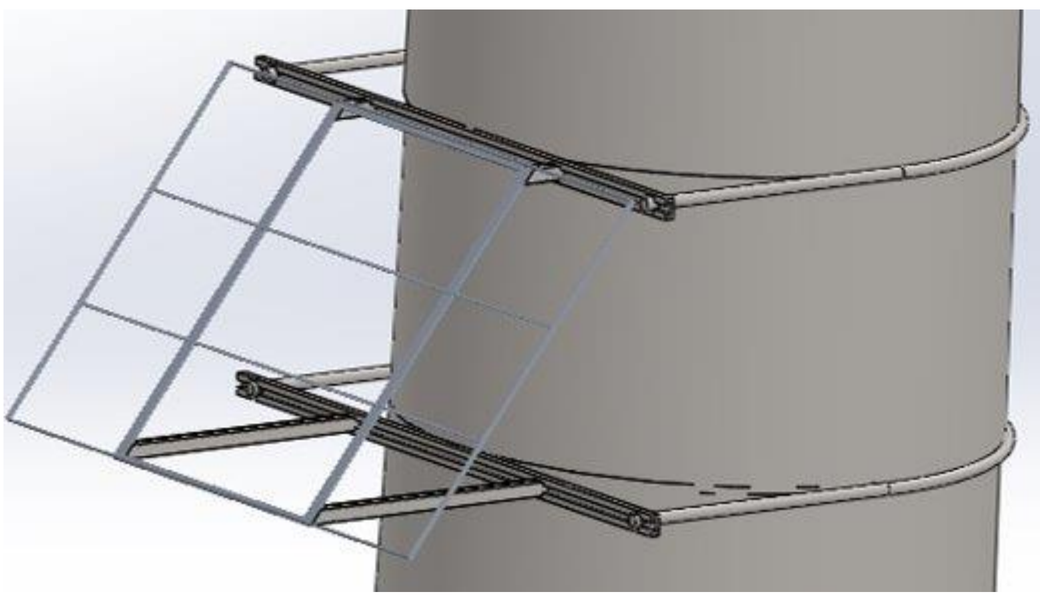

Figure 49: Solar Panel Mount on Wind Turbine Tower Without Solar Panels

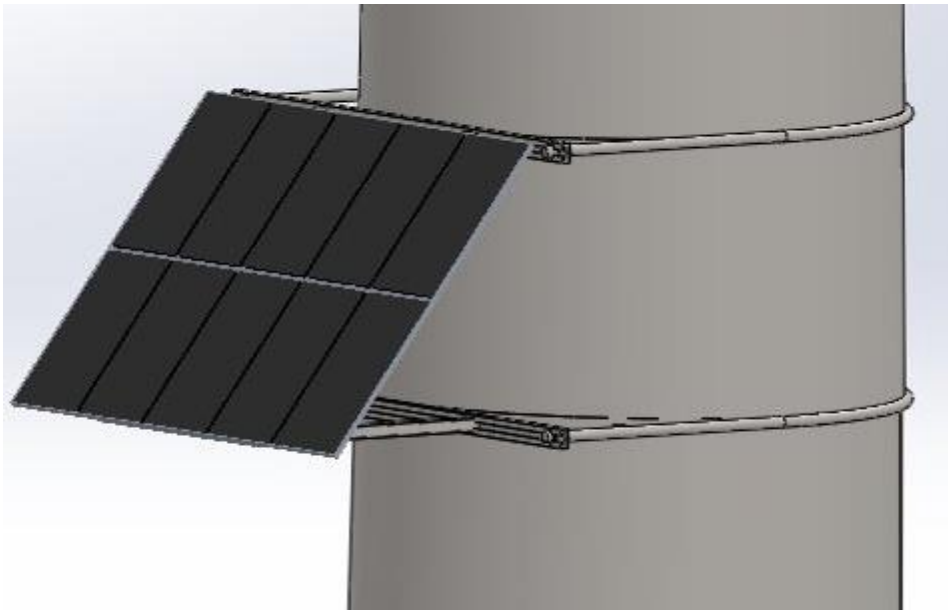

Figure 50: Solar Panel Mount on Wind Turbine Tower Without Solar Panels.

4.6 FEA ANALYSIS

4.6.1 Simulation Steps and Parameters

For recreating the following FEA findings the senior design team created a list of steps to follow on how they performed their analysis with their designed mount assembly which can be found online in the University shared drive (Note: steps given are assuming the reader has basic knowledge of SolidWorks Simulation software):

1. Open the SolidWorks file named “Tower_With_Mount”
2. Create a new static study
3. Create a fixed fixture located at the bottom of the tower on the underside where they are fixed to ground
4. Three external loads will need to be created as follows:
   1) 420 pound load located on the solar panel mount where the solar panels would lay going directly down like in Figure 51 below
   2) 90-mph load in the form of pressure going in the normal direction like in Figure 54
   3) 90-mph load in the form of pressure going in the transverse direction like in Figure 57 (Note: these are the loads the will be turned on and off depending on

what is being tested for and the loads that will change depending on the solar panel loading and wind pressure).

5. Create a mesh by adjusting the Mesh Density to Fine and using the Mesh Parameter- Blended curvature-based mesh and click run. (The mesh found can be seen in Appendix G.)
6. Run the study and set up how the results are displayed depending on the individual's preference

4.6.2 Finite Element Analysis Results

Three different Finite Element Analyses were performed to assure the mount would not fail. Each analysis provided two results, displacement, and stress. Before any extra load from the wind could be added, the team needed to be sure the solar frame would not fail under the weight of the solar panel array. This was a distributed load of 420 pounds, as seen in Figure 51.

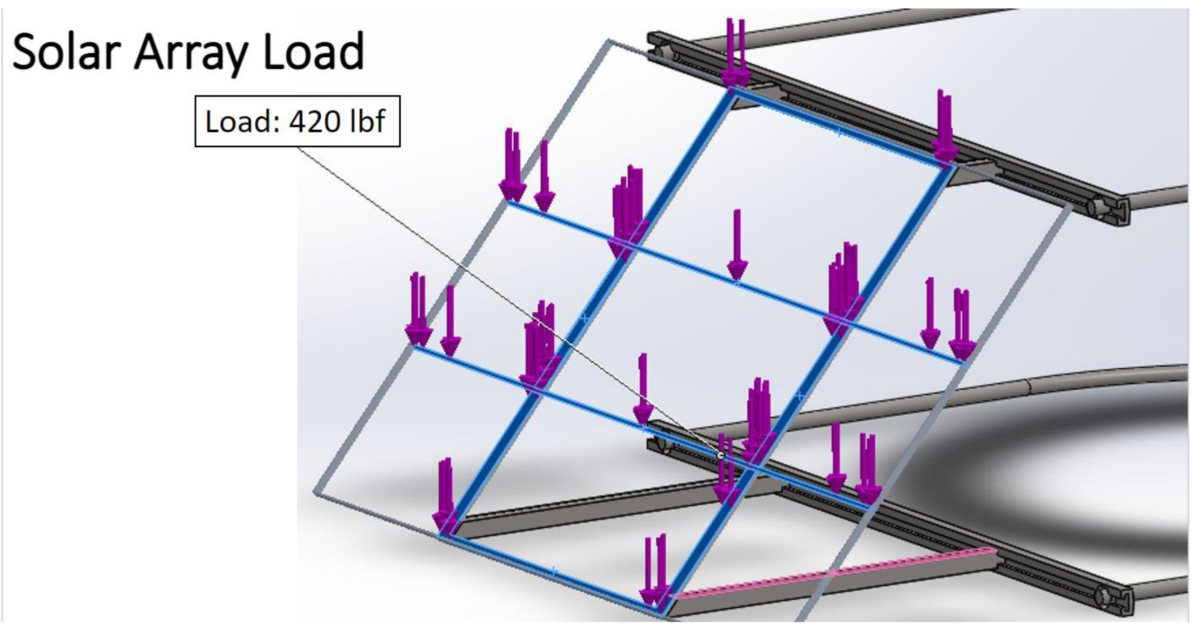

Figure 51: FEA of Solar Array Load

For this first test, the displacement was very low at 0.046 inches. This is shown by the arrow in Figure 52. This proved that the weight of the solar panels would not cause the frame to displace enough to cause any issues.

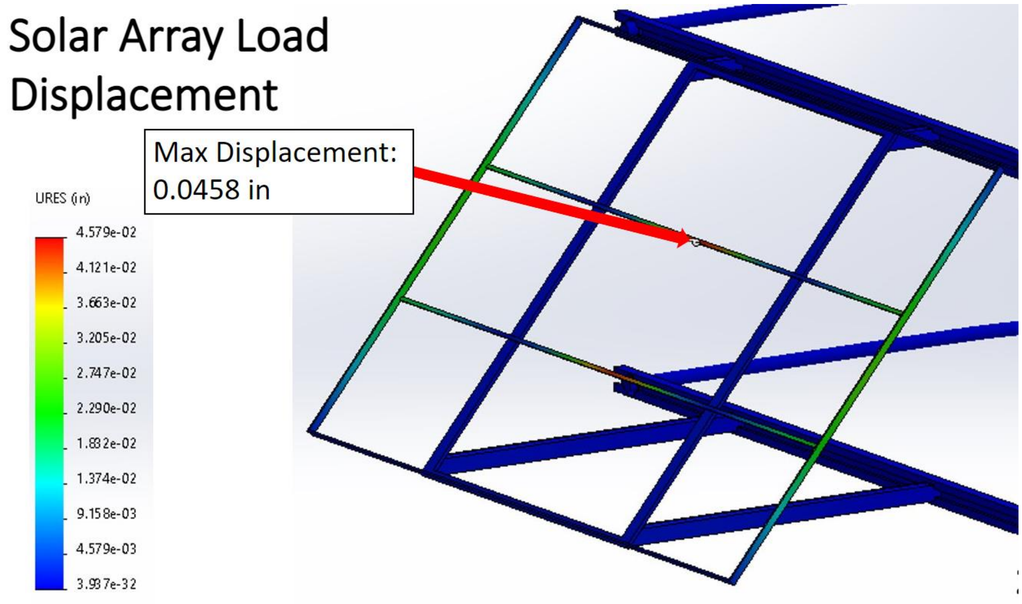

Figure 52: Displacement of Solar Array Load

The maximum stress of the first test was 578.4 psi, as shown in Figure 53 by the arrow. This value needed to be under the yield strength of the frame, which is 31,000 psi. This proved that the frame would not fail under the weight of the solar array.

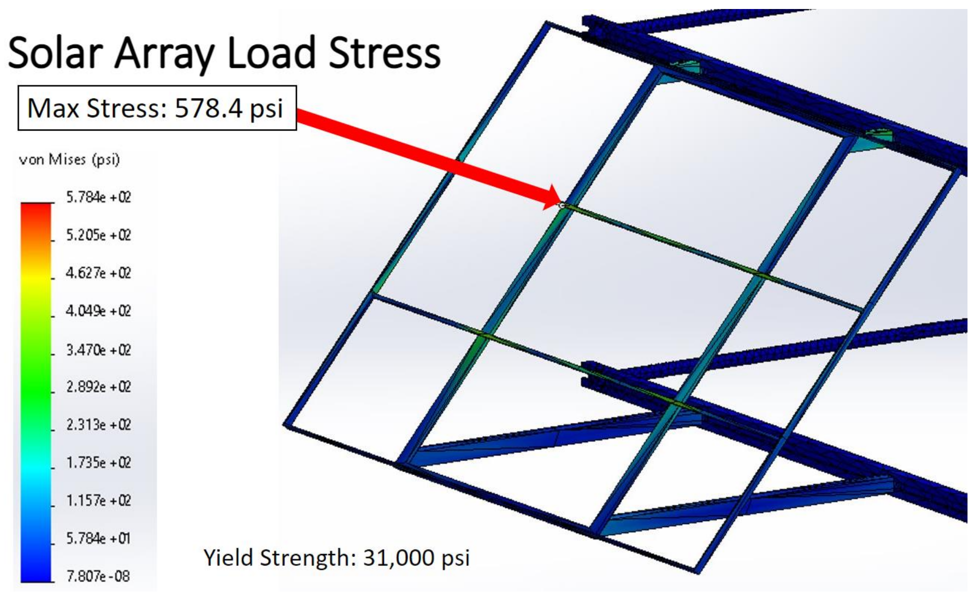

Figure 53: Stress of Solar Array Load

The second FEA analysis ran was the combined loading of the solar array and normal wind loading. Figure 54 shows the normal wind loading that was applied to the frame. The team used a wind load of 90 mph, which is the 100-year return wind speed for the area of the RWF [7].

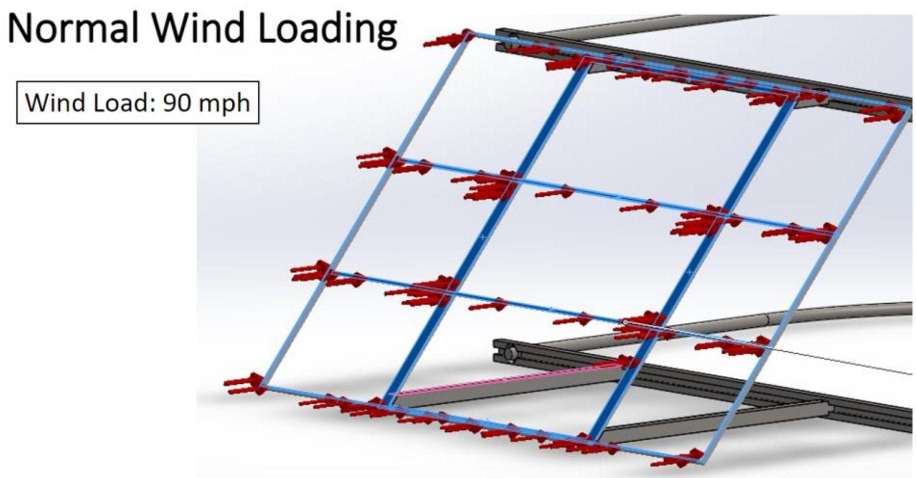

Figure 54: FEA of Normal Wind and Solar Array Loading

As shown by the arrow in Figure 55 below, the displacement of this combined loading was 0.0904 inches. This showed that the combination of the solar panel weight and a 90-mph force would not cause the frame to deflect enough to cause any issue.

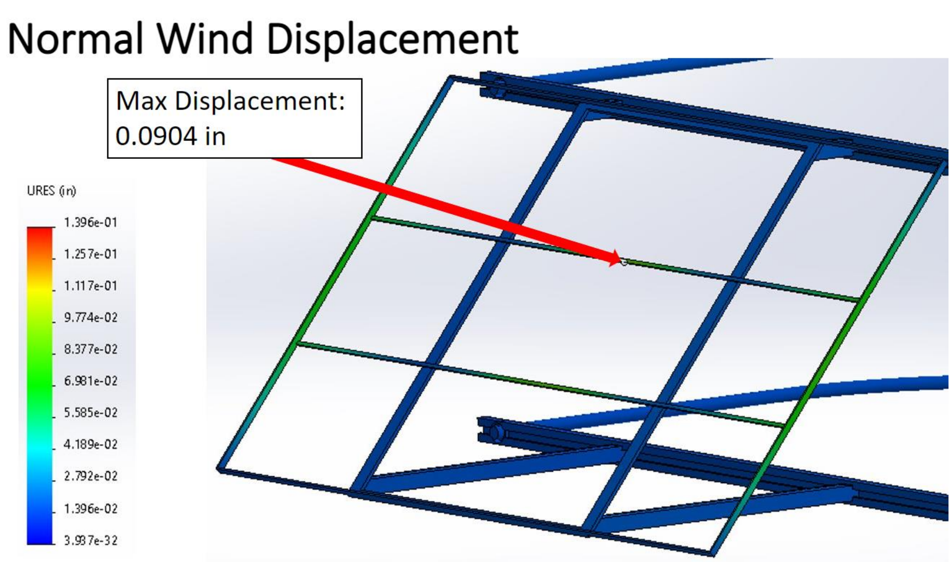

Figure 55: Displacement of Normal Wind and Solar Array Loading

Figure 56 shows the stress of the combined loading. The maximum stress was 827.8 psi, which needed to be under the yield strength of 31,000 psi. The maximum stress is shown by the arrow below.

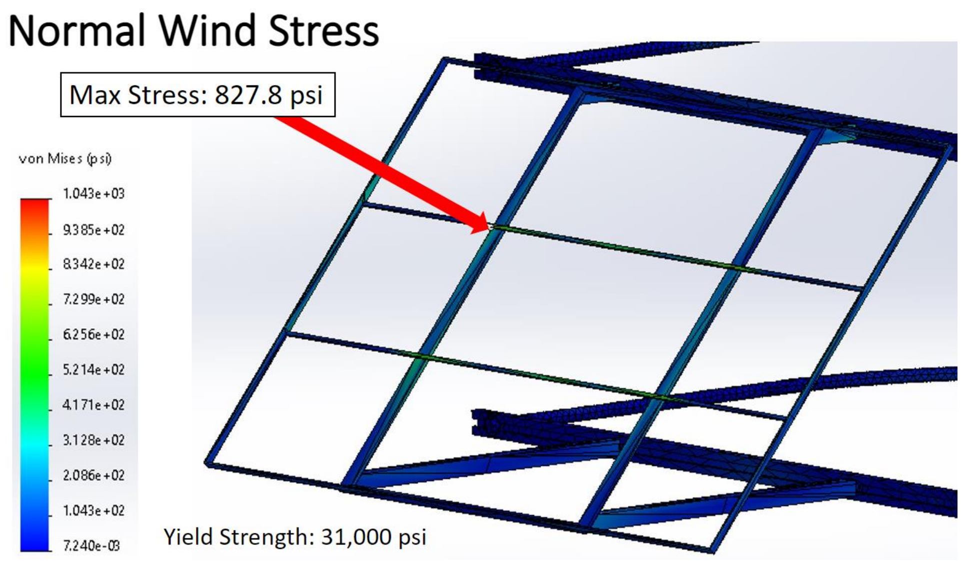

Figure 56: Stress of Normal Wind and Solar Array Loading

The final analysis was a combined loading of the solar array load and a transverse wind load. The transverse wind load was the same magnitude as the normal wind load done previously. This loading can be seen in Figure 57.

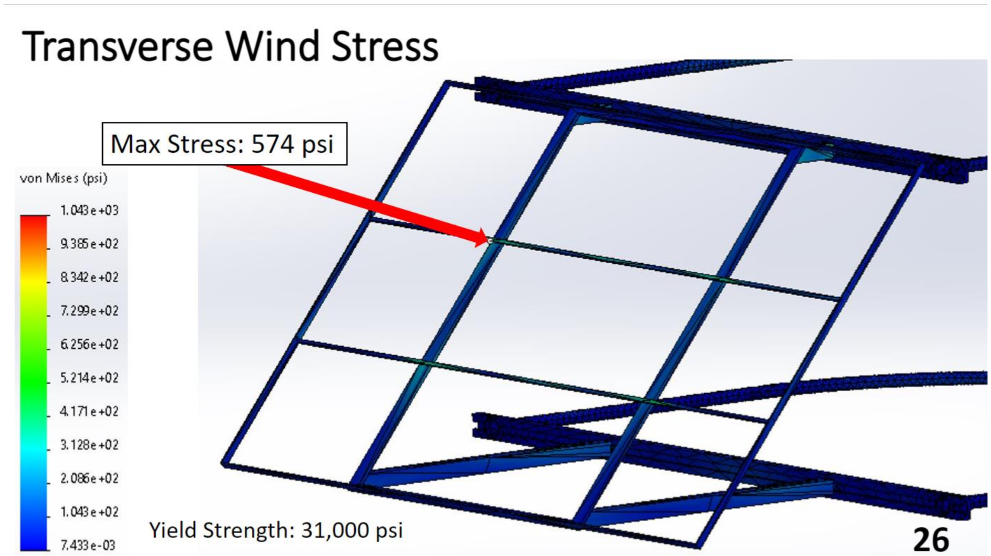

Figure 57: FEA of Transverse Wind and Solar Array Loading

The displacement of this combined loading was 0.0603 inches and is indicated by the red arrow. This proved that the combination of a transverse wind load and the solar array weight would not affect the frame enough to cause any concern and these results can be seen in Figure 58.

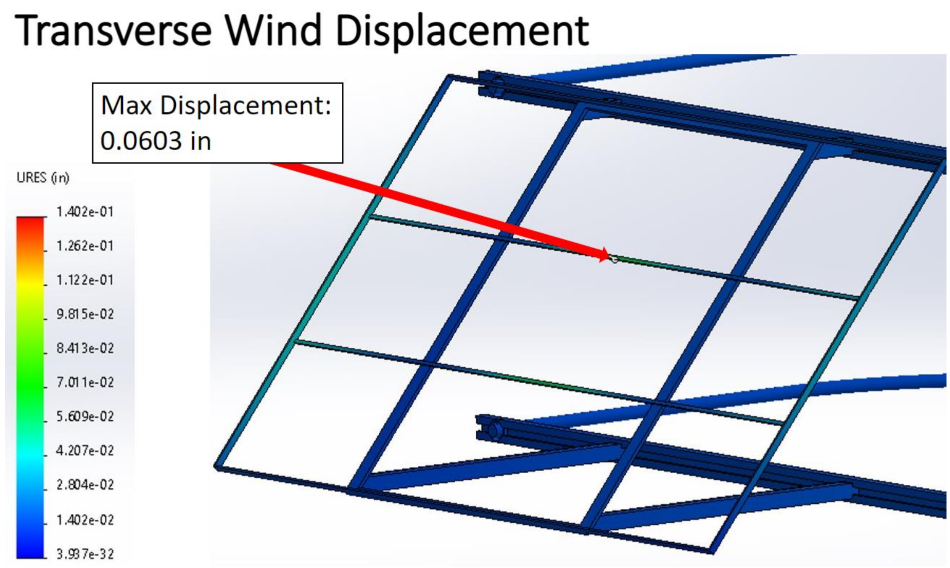

Figure 58: Displacement of Transverse Wind and Solar Array Loading

The maximum stress of this combined loading is 574 psi. Because the maximum stress, marked by the red arrow, was located on the frame, it needed to be less than 31,000 psi. This shows that the mount would not fail under a transverse wind load and this result can be seen in Figure 59.

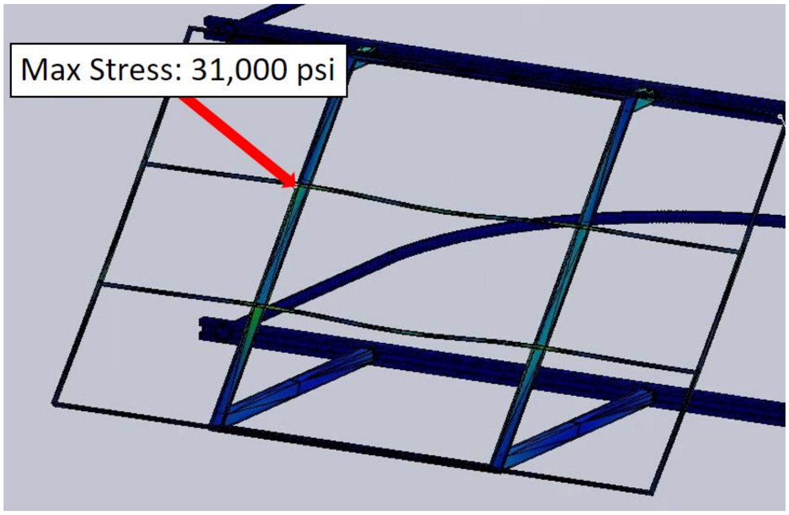

Figure 59: Stress of Transverse Wind and Solar Array Loading

4.6.3 Simulations to Failure

When testing the senior design team wanted to setup a known max loading for their design at yield failure in the aluminum material that the solar frame is comprised of. Knowing the max load can help future improvements and determine the factor of safety through FEA. Below is Figure 60 showing the how the load is being loaded and the roughly the max load the designed mount can withstand without wind pressure.

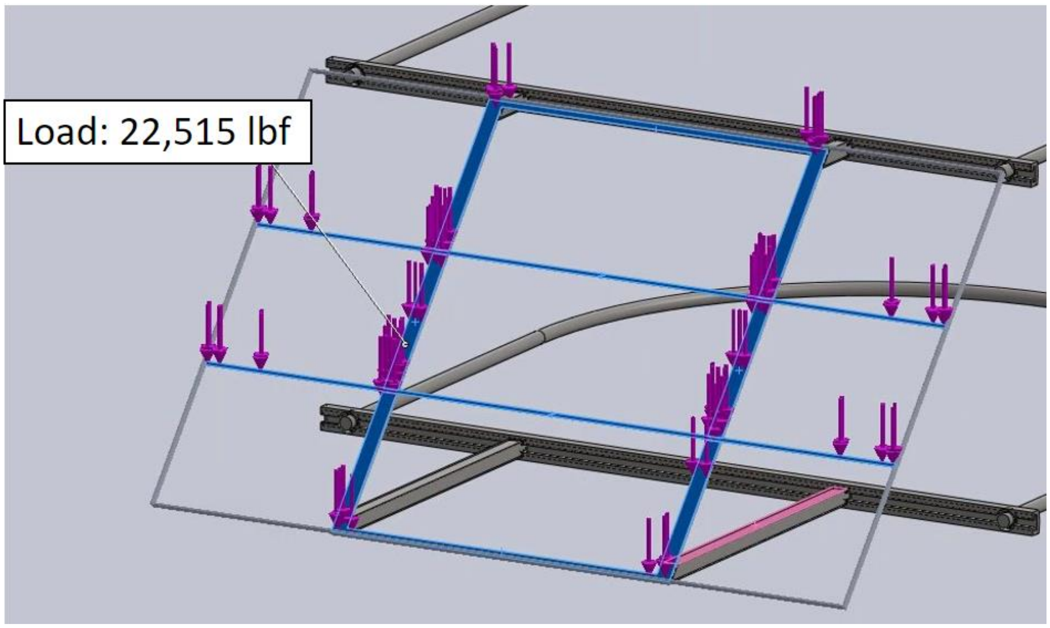

Figure 60: Solar Array Load at Max Loading

The resulting stress from the load in Figure 60 was found through trial and error by looking for the point where the max stress at the critical point which is indicated by a red arrow in any of the stress figures. For this specific load the max stress was 31,000 psi and can be seen below in Figure 61.

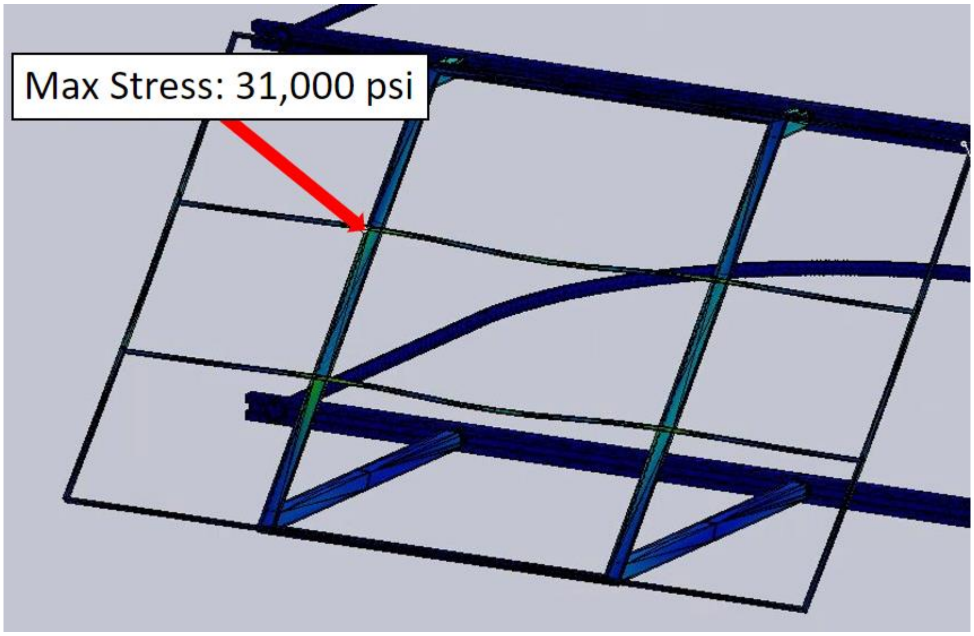

Figure 61: Stress of Solar Array Load at Max Loading

The resulting displacement for the 22,515 lbf load can be seen below in Figure 62 and shows how much the designed mount deflects at the yield point for the aluminum material the solar array is comprised of.

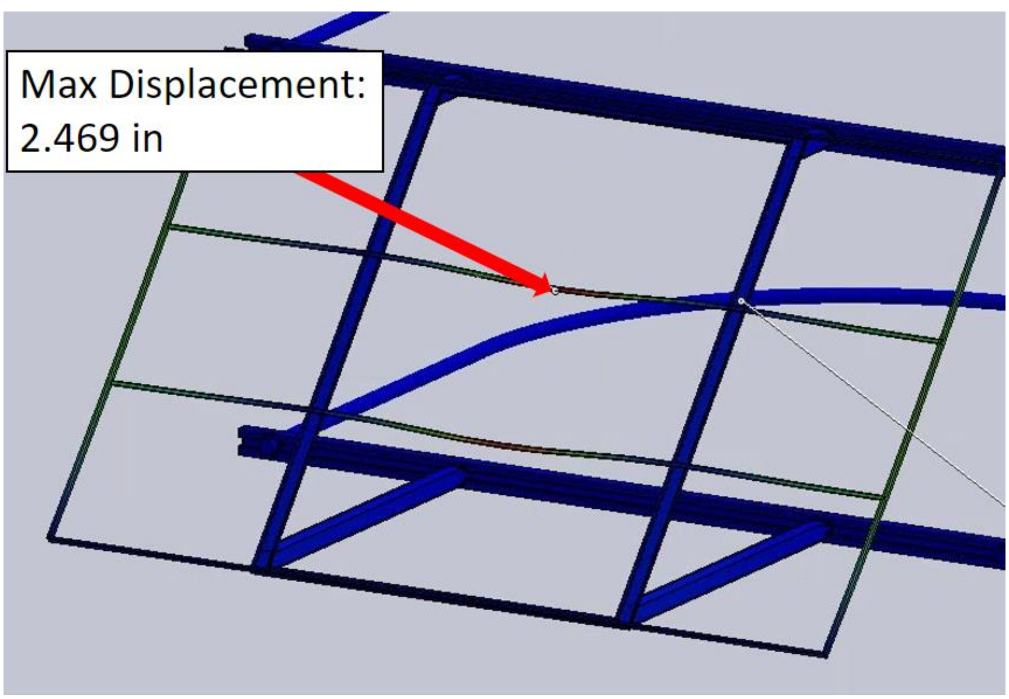

Figure 62: Displacement of Solar Array at Max Loading

From the above loading scenario with only the solar array load the factor of safety determined through FEA was 53. This lets the senior design team know that the mount is over engineered and could either be reduced in weight or the number of solar panels on the mount could be significantly increased.

The following Figures 63 – 71 are the max loading and the resulting stress and displacements from the various loading that include wind loading which are the solar array loading with normal wind loading, solar array loading with transverse wind loading and solar array loading with normal and transverse wind loading respectively. These were run for the finding the factor of safety and having a basis for how much this designed mount can handle while including wind pressures.

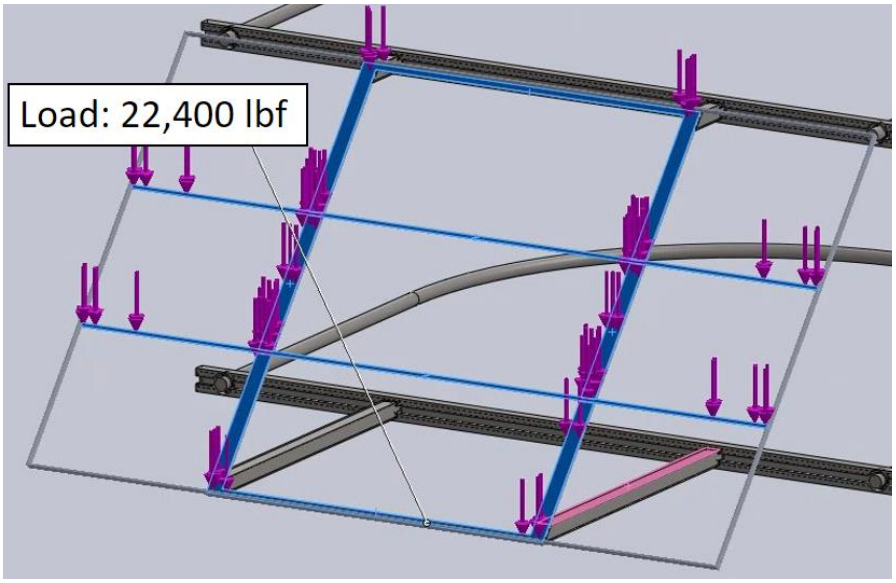

Figure 63: Normal Wind Loading with Max Solar Array Load

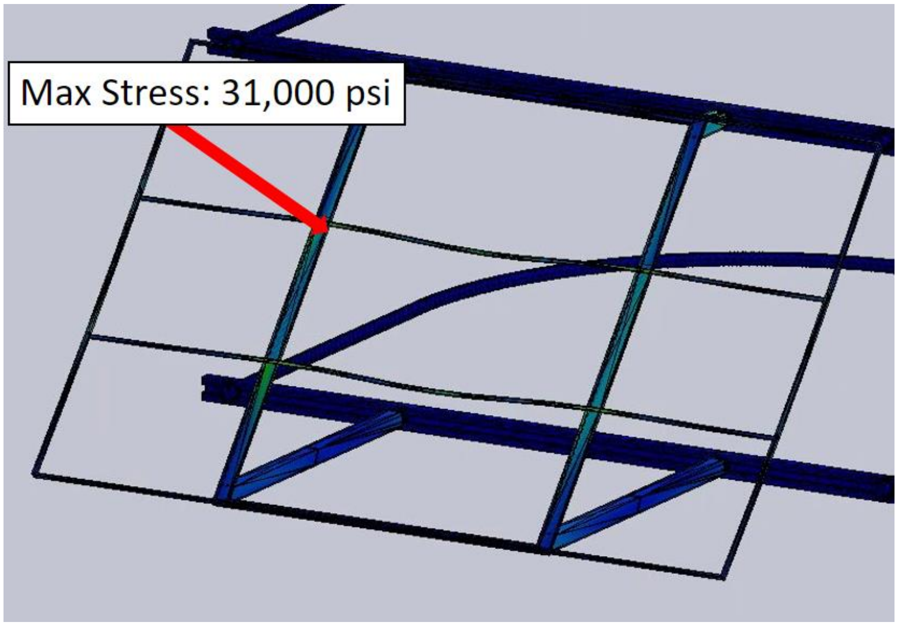

Figure 64: Stress from Normal Wind Loading with Max Solar Array Load

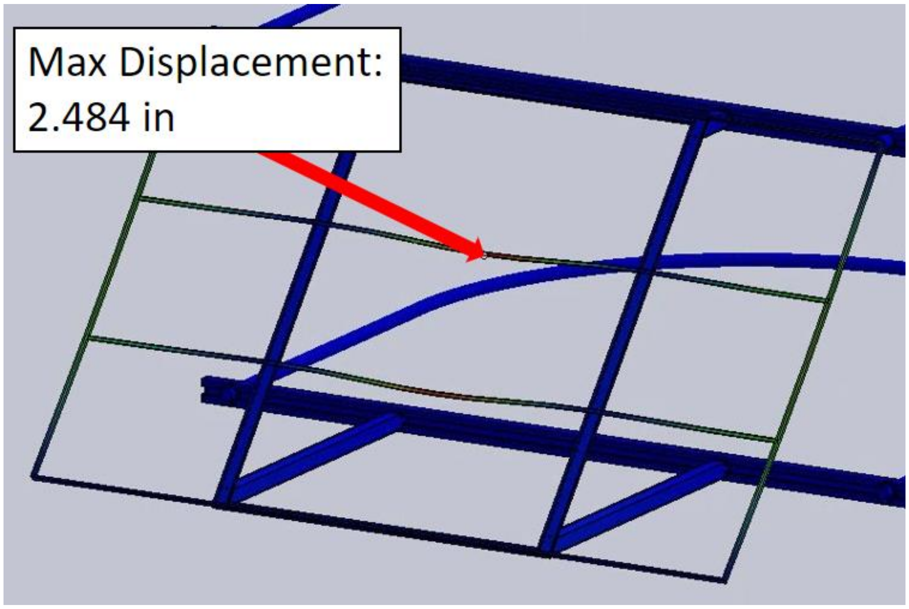

Figure 65: Displacement from Normal Wind Loading with Max Solar Array Load

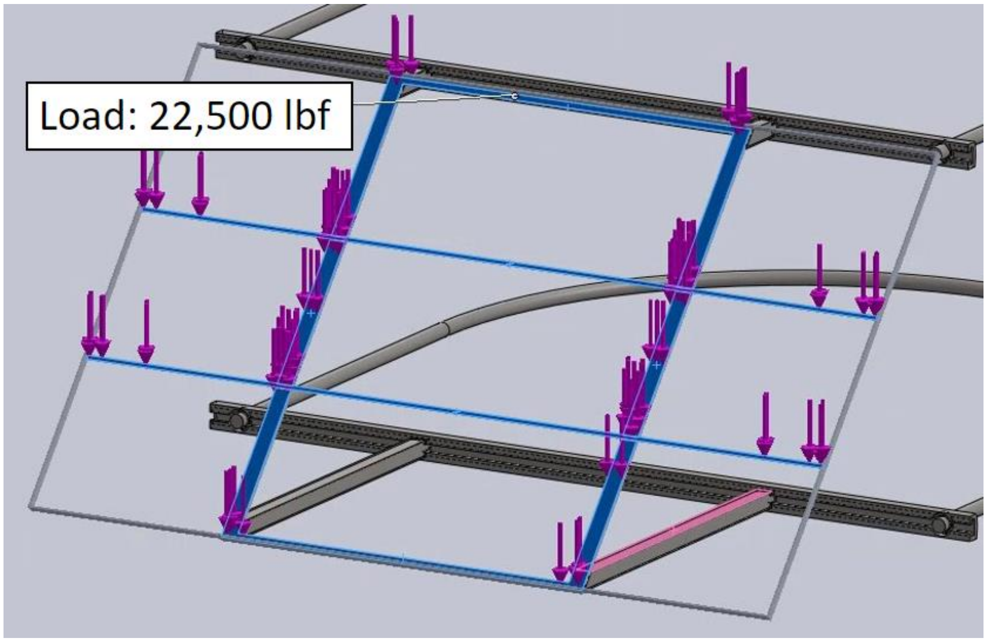

Figure 66: Transverse Wind Loading with Max Solar Array Load

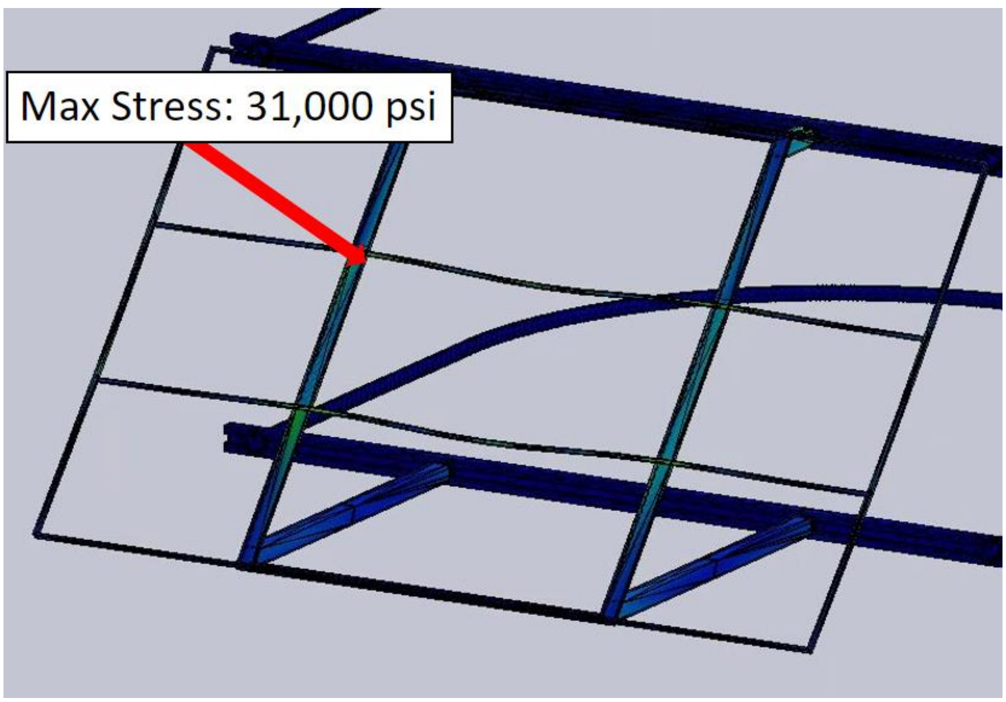

Figure 67: Stress from Transverse Wind Loading with Max Solar Array Load

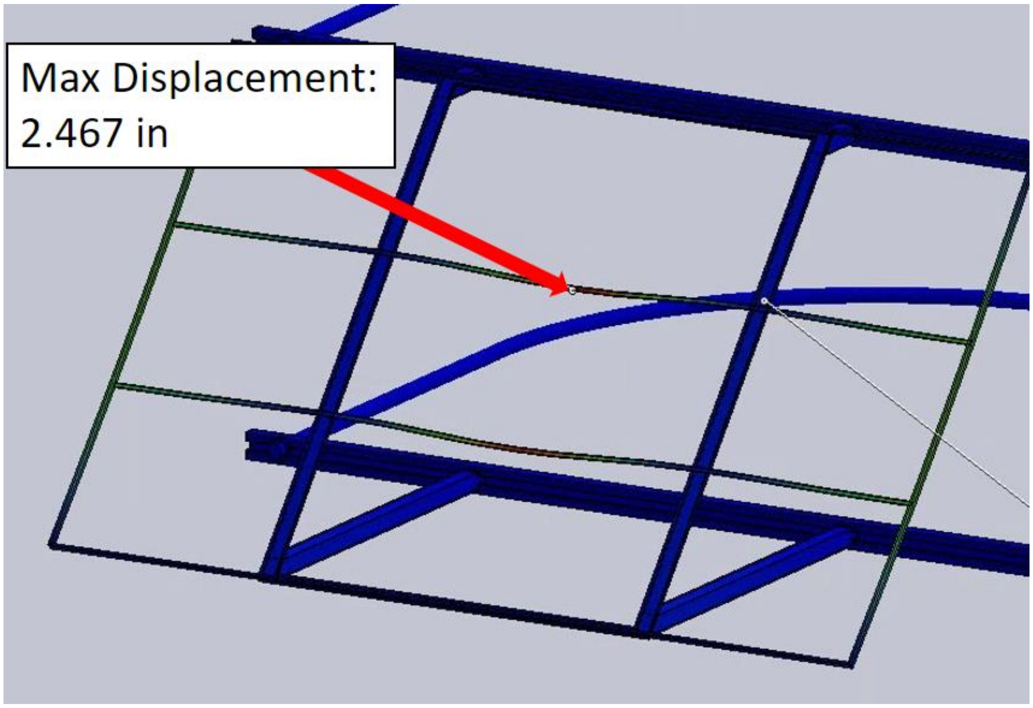

Figure 68: Displacement from Transverse Wind Loading with Max Solar Array Load

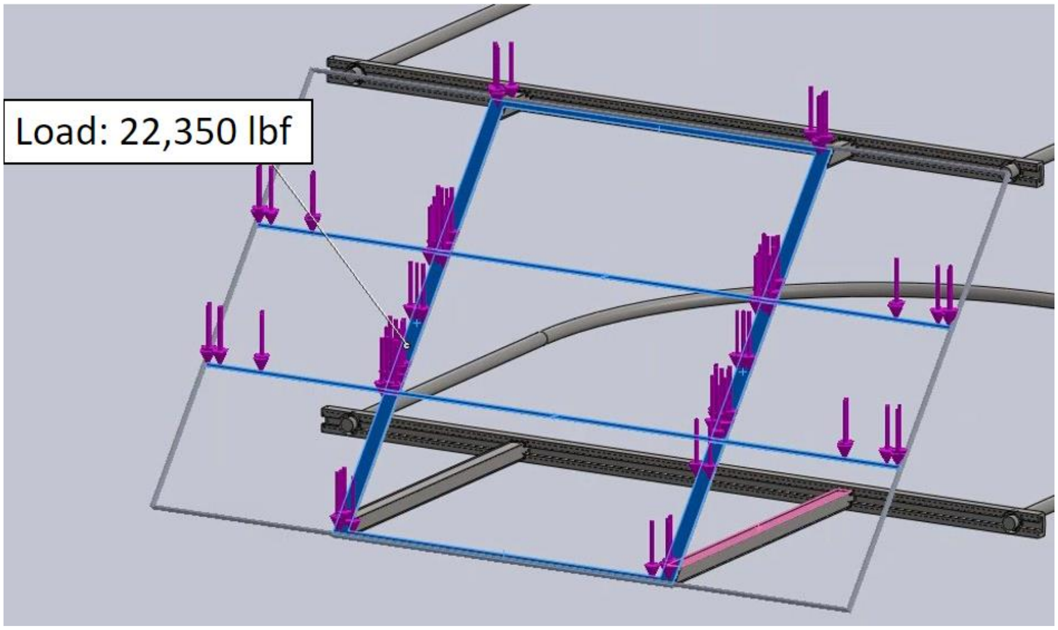

Figure 69: Normal and Transverse Wind Loading with Max Solar Array Load

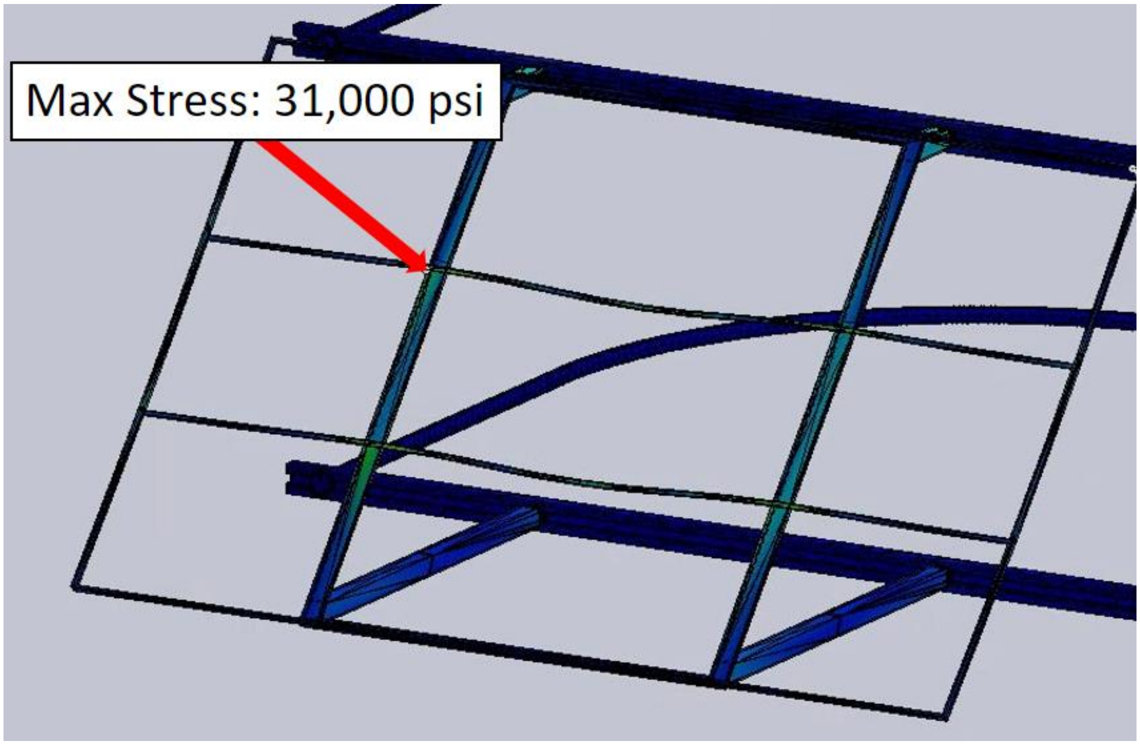

Figure 70: Stress from Normal and Transverse Wind Loading with Max Solar Array Load

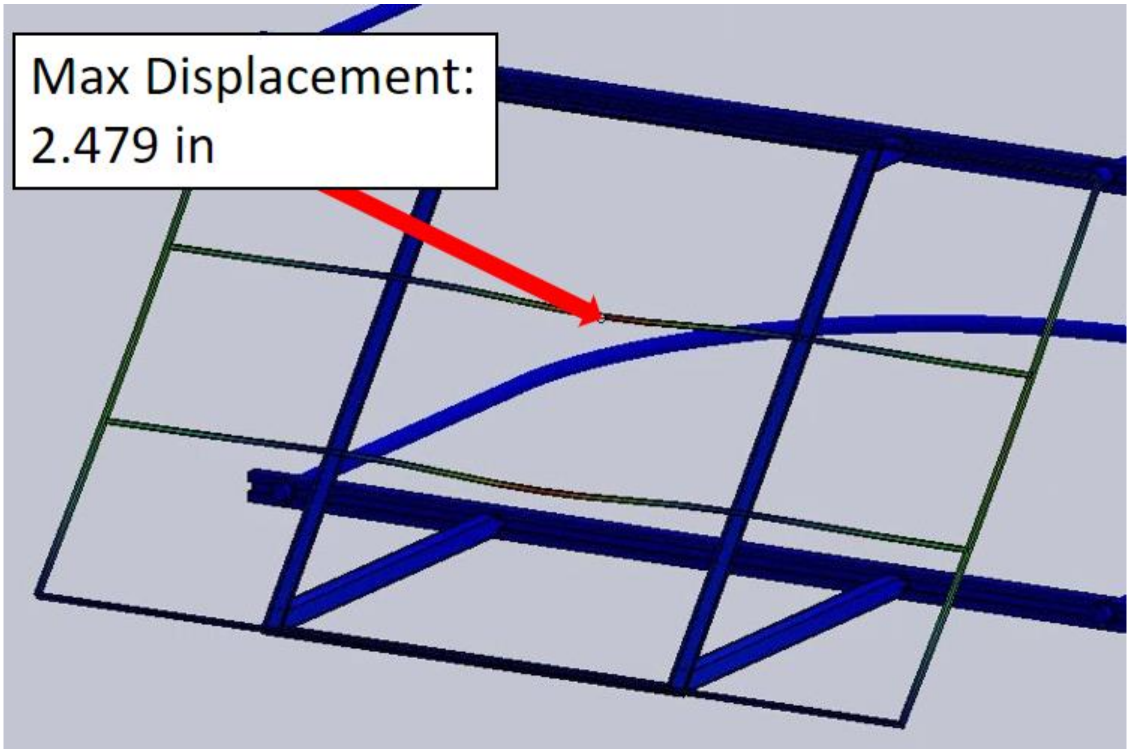

Figure 71: Displacement of Normal & Transverse Wind Load with Max Solar Array Load

From the above Figures 63 - 71 it is clear that the effects of the wind at 90-mph is not very evident even when loading both the normal and transverse wind direction. The biggest factor in the loading was still the amount of weight being applied by the solar array, this leads to the conclusion that if you leave room for wind variability and keep load and the wind load above the factor of safety of six the designed solar panel mount will not fail. From the worst-case scenario above loading the solar panel mount with transverse wind direction and normal wind direction the max load of the solar array is 22,350 lbf which gave the senior design team a factor of safety of 53

5 ECONOMIC ANALYSIS

This project is aimed towards power generation companies and thus the profit margin is very important for them. Solar panels do not have the same generating capacity as wind turbines and thus cannot be compared on a one-to-one basis in terms of their power output. It would also be important to note that the average cost of a solar panel is between $200 - $250 and the average cost of a 1.5 MW wind turbine is $2,000,000 - $3,000,000, so this initial cost is reflected in their vastly different power generation abilities. However, the team has calculated the predicted income and cost of the solar panel mount.

5.1 *BILL OF MATERIALS*

First, all the materials necessary are laid out below in the Bill of Materials seen in Table 5. By opting to keep this mount as simple as possible while remaining effective the team can offer a very brief BOM.

Table 5: Bill of Materials

Solar Panel Mount for GE 1.5 MW Wind Turbine	
Component	**Quantity**
U-Bolt	2
Channel	2
Upper Arm	2
Lower Arm	2
Frame	1

5.2 *BUDGET*

The budget for this project is outlined below in Table 6 followed by an explanation of how the team arrived at this value.

Table 6: Budget

Budget	
Item	***Price***
ASTM A572 Grade 50 Steel	**$ 790**
ASTM A513 Grade B Steel	**$ 70**
6063-T6 Aluminum	**$ 210**
Fabrication	**$ 1,100**
Welding	**$ 350**
Machining	**$ 2,000**
Installation	**$ 8,000**
TOTAL:	**$ 12,520**

This budget does not include the price of the solar panels as the mount would not come equipped with them. This budget is formulated using the current cost of material for the various components but is subject to fluctuation as material prices change. Looking at the budget gives key insight as to why the team wanted to try to keep the weight of the mount down as more weight meant more material and more material would have a large impact on the final cost of the mount. It is important to note that estimates given for fabrication, welding, machining, and installation are estimated based off average cost per hour for each of the services combined with the team's assumptions of how much time each service would take.

5.3 *ECONOMIC ANALYSIS*

There are many key parts in calculating the economic analysis of this mount that the team is unable to collect exact values for and in these instances, averages will be used. This economic analysis is also done assuming that there is one mount affixed to one wind turbine, however, it would be possible to affix multiple mounts to one wind turbine.

It is important to know that the U.S. government provides subsidies or renewable energy projects. In addition to subsidies there are also certain governmental requirements pertaining to renewable energies that utilities need to abide by. In the state of Texas Commercial and Utility investors in solar can claim a 30% tax credit for the installation, development, or financing of solar projects through the Federal Investment Tax Credit (ITC). There is also the Modified Accelerated Cost Recovery System (MACRS) which reduces the income subject to federal taxes for solar projects. The Public Utilities Regulatory Act (PURA) which requires utilities to purchase from energy producers known as qualifying facilities (QF's). For a location to fall under a QF it needs to produce 80 MW or less in capacity and generate renewable energy (such as solar, wind, and geothermal). If the solar component can be treated as a separate entity from the wind farm in this scenario, then the solar portion would qualify as a QF. Thus, making it a source for meeting PURPA requirements [23].

Other economic factor to consider are the cost of production and installation. As previously mentioned, the cost to weld, machine, fabricate, and install the mount are best estimates made by the team, thus they have a substantial amount of margin to their accuracy. By taking this project a step further and gathering quotes for installation and production a much more accurate economic analysis could be generated. The labor rates used to estimate the cost of fabrication, machining, welding, and installation can be seen below in Table 7 [33] [34].

Table 7: Labor Cost Prediction Sheet [33] [34]

Labor Cost	
Labor	***Rate/Hour***
Machining	**$ 120**
Fabrication	**$ 90**
Welding	**$ 75**
Installation	**$ 2000**

Determining these rates assisted the team in developing our cost, but the amount of time required to complete the work was estimated. All of these would be economic factors to consider in addition to the overall cost of the product. Considering these subsidies would also greatly decrease the payback period determine in section 5.4 below.

5.4 PAYBACK PERIOD

The payback period has been determined using the generation capacity of the solar panels (which varies depending on the model), the number of panels on the mount, the average number of sunny hours, and the average cost of electricity in Texas. The generation capacity of the solar panels is 400 W, there are 10 panels per mount, there is a yearly average of 8.02 sunny hours a day in Roscoe, TX, and the average cost of electricity in Texas is $0.1206 per kW. From these values we can determine that designed mount would generate $3.86 worth of electricity a day. Considering this and the cost of the mount the payback period would be 8 years and 10 months. As mentioned, this payback period could be greatly decreased by adding multiple mounts to a turbine, adding mounts to multiple turbines, and by considering the government subsidies.

6 INSTALLATION PLAN

All manufactured parts will be installed with the use of heavy machinery: cranes and bucket trucks. The upper U-bolt must be held in place on the tower with a crane while another crane slides the upper channel on the U-bolt and the nuts are tightened with an impact drill. Technicians in bucket trucks may be necessary to guide the upper channel in place. Levels may be used to ensure the U-bolt is level on the tower. The lower U-bolt should be installed the same as the upper U-bolt. The U-bolts should be 6.41 ft apart vertically. The upper arms are slid into the grooves of the upper channel in Figure 72 and placed 8 ft apart from each other due center. The arms may be held in place with a crane, one at a time. The lower arms should be installed the same as the upper arms and placed 8 ft apart due center. The solar panel frame may be held in placed with two cranes and placed 50° from the horizontal ground. The orientation of the frame is also shown in Figure 72. The arms should be welded to the frame by proper welding procedure. The upper arms are welded with the top of the arm flush to the top of the frame. The lower arms are welded with the bottom of the arm flush to the bottom of the frame. Finally, the solar panels may be placed in the frame via crane or bucket truck. All electrical components must be installed by a certified technician.

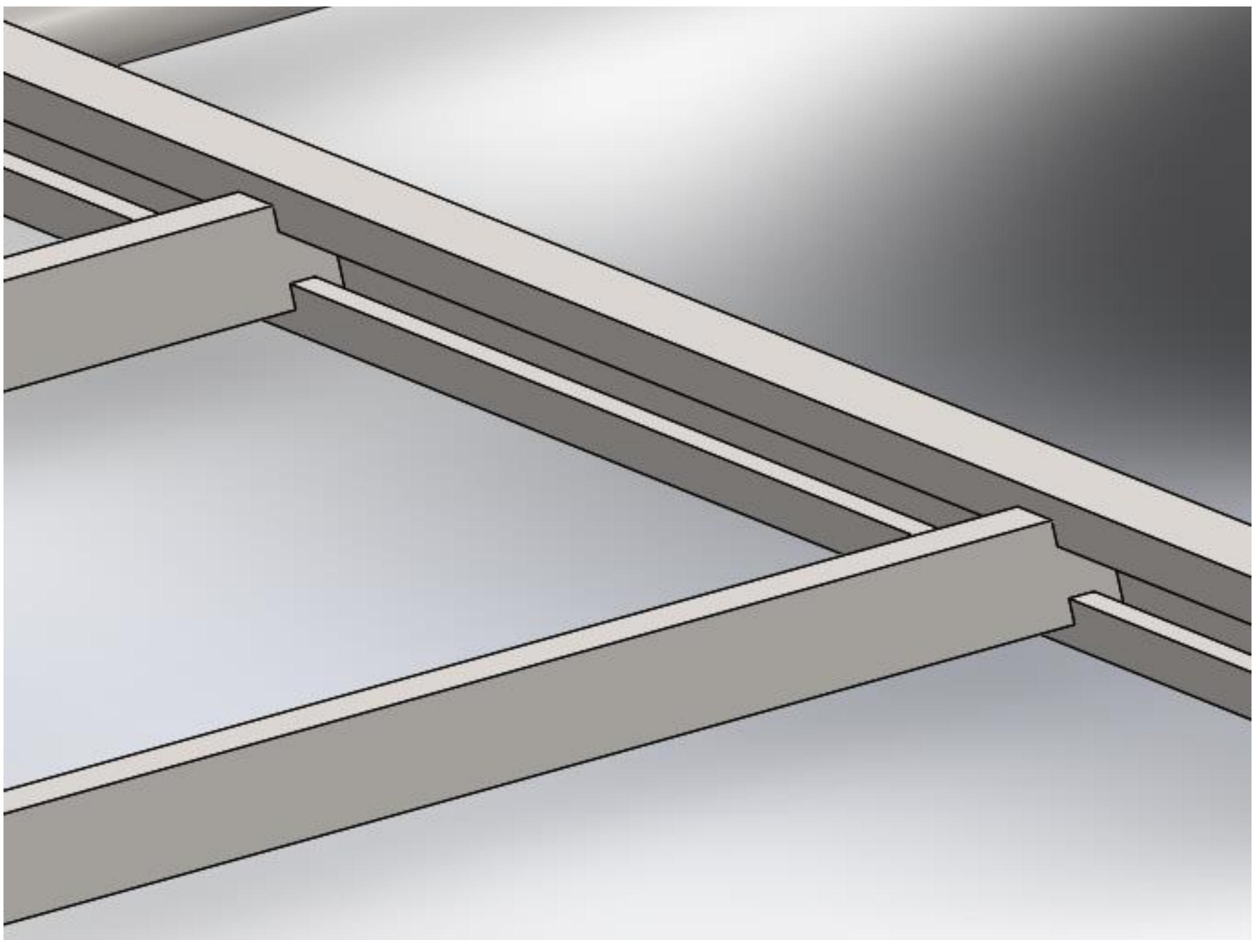

Figure 72: Upper and lower arms placed in grooves of upper and lower channels.

7 MAINTENANCE PLAN

The GE 1.5 MW wind turbine is maintained twice a year, so it is pertinent that the designed solar panel mount be maintained twice a year. Since there are no moving parts, the maintenance plan of this design is relatively short. It is necessary to check for rust or fatigue on all sections of the mount, including stress on the tower from the U-bolts. The tension in the nuts should be checked to be sure they are still tight. The solar panels must be cleaned off and treated as a window. The welds around the arms must be checked every two months. The solar panels must be replaced every 40 years [25].

8 DISPOSAL PLAN

All components of the mount should be recycled. The solar panels may be sent to a recycling facility to be reproduced into new solar panels. The metal components of the mount should be sent to a recycling facility to be melted down and refurbished.

9 SENIOR PROJECT TEAM EVALUATION

The team worked together to complete the project in a timely manner. The team researched for many months to provide background information and the motivation of the project. After the team concluded that a fixed solar panel mount was the best choice for design, each teammates' strong suit was utilized as the design portion of the project was in full swing. Eric and Katie focused on SolidWorks components and modeling, while McKenzie and Kaitlyn focused on hand calculations. As hand calculations and SolidWorks drawings were completed, the team compared and evaluated notes to finalize a fixed solar panel mount for existing utility scale wind turbines. Eric provided wind and ice loading and topographical calculations from ERI. Katie maintained the schedule of the project and ensured each team member met necessary due dates. The team met with numerous professors for guidance in hand calculations and FEA analysis. The team designed and completed the presentation together.

10 ABET REQUIREMENTS

10.1 PUBLIC HEALTH, SAFETY AND WELFARE

A big designing factor for the senior design team when designing the solar panel mount to attach to a wind turbine tower was keeping the public's health, safety, and welfare in mind. The biggest concern was keeping the lowest calculated factor of safety above 6 for this design, this is because there is no room for failure. This is because one of the motivations for the project was trying to keep the ground clear so it could be used for farming or agriculture, this would be the reason for not wanting any room for failure so that the user of the land would not be in fear of their life or their property.

10.2 GLOBAL

The global impact this project has is making sure to diversify our energy portfolio and ensure that no one is reliant on just one source of energy. With the diversification of the energy portfolio countries that can afford renewable resources could then sell their nonrenewable energy resources to the poorer countries. This gives the poorer countries access to energy sources that often are cleaner and more proficient than what they were using or had access to beforehand.

10.3 ENVIRONMENTAL

The environmental impact that this project has is helping to make the switch over to renewable energy resources. Helping to switch over to renewable energy resources means that since they are producing higher energy rates using green energy there will be less need and use for fossil fuels.

10.4 ECONOMIC

This project can scale in size depending on how many wind farms would take on adding these solar panel mounts. If this project were to become large scale, it would create many new job opportunities in the welding, manufacturing, fabrication, and engineering positions along with the need for crews to install these mounts on the tower. More jobs in the country means more money being spent, the increase in money spent greatly increase the economy and lets everyone prosper together.

11 LESSONS LEARNED

Throughout the process of developing this solar panel mount for utility scale wind turbines the team has grown and developed their engineering, time management, teamwork, professional, public speaking, and technical writing skills. The team has also had to adapt from using their engineering skills to solve textbook like engineering problems to solving design problems which is a very different process. The design process is an iterative one and oftentimes the right answer to a problem is not known until an intense amount of research and calculations have been conducted. At the beginning the team was hesitant to make decisions in fear of them being incorrect, but once the mind set of learning from incorrect decisions was adopted the team was able to work through problems much more quickly.

Throughout this project you will also see that the team boasts about developing a simple design. This is largely because throughout this process it was proven time and time again that often the best answer was the simplest one. While it is not easy to develop a simple design because that means fewer components must be able to work together to accomplish your goal, the result is a much more marketable product with a lower overall cost, simpler maintenance plan, and simpler installation plan. It also makes it easier for your consumer to understand your product.

As mentioned, the team developed various non-engineering skills throughout this process as well. Throughout our professional careers it will be vital that these skills continue to grow and improve as more experience is gained. One of the most important skills learned is keeping excellent documentation. Various times throughout this project critical items were forgotten or lost, and this was a result of our documentation techniques. Throughout the year we continued to revise and improve this through the implementation of a folder system for hand calculations, and shared drives for any digital information with throughout revision history. Once the team adopted these practices the amount of information or forgotten was greatly decreased.

12 FUTURE RECOMMENDATIONS AND IMPROVEMENTS

The completed iteration of the project's final design is simple and robust, but it could be improved upon. The completed design has a factor of safety of 53 which far exceeds the industry standard of 6. Components such as the U-bolts could be decreased in diameter or perhaps a cable could be used instead of a rigid U-Bolt which would in turn lower the weight and bring the factor of safety down, but while remaining in a safe range. This could also be affected by changing the materials of the mount to aluminum for all components and adding a sacrificial metal to the aluminum in order ensure there is no dielectric effect. Components could also be made thinner or shelled to further lower the weight.

The design is currently built for 10 solar panels and the power generation abilities are also based on this limitation. The power generation abilities of the mount could be increased by designing the frame to hold more than 10 solar panels. This would require a new analysis of the frame but considering the high safety factor and stability of the mount it should only require dimensional changes to the frame to accommodate more panels. Another aspect of the mount that would only require dimensional changes would be determining the necessary configurations to place the mount in various heights on the turbine shaft. This could be done by determining the diameter at said locations and adjusting the U-Bolts and Channels accordingly. Geometric considerations would also need to be taken to ensure that the shadow from the mount above will not cover the panels below it. The team has investigated this possibility and determined that 5 additional mounts (six total) could fit on the wind turbine tower. For this configuration the top mount would be at 120 ft from the ground with each remaining mount 13.59 ft below the previous mount. This configuration would mean that the lower mounts would miss approximately 30 minutes of sunlight from the shadows of the mounts above them. Proper addition of more mounts to the turbine would greatly decrease the payback period.

The team has deemed it out of scope to configure the electrical requirements necessary to attach the solar panels and tie them into the grid. This was largely because of our lack of background in electrical engineering and our focus on the mechanical aspects of the project, however, it would be crucial to determine these elements before the mount could be used by a utility. A future recommendation would be for a senior design team consisting of electrical engineering to determine the various electrical requirements that would be necessary to allow the solar panels to be connected to the wind turbine system.

13 CONCLUSION

The final solar panel mount for utility scale wind turbines detailed in this report will serve to meet the needs and motivations for the senior design project. This design will allow for the conservation of land, diversification of a utility's energy portfolio, compliance with the Public Utilities Regulatory Act, and increase efficiency of power generation. The team is aware that the payback period for the project is longer than typically desired by investors, however, as solar panels become more affordable and efficient, traditional energy production methods become more expensive, government subsidies are applied, multiple mounts are placed on each turbine, and the mount is installed on multiple turbines throughout the farm the feasibility of our project will continue to increase. Nonetheless the goals of the team are still accomplished, and a safe effect mount design has been created.

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APPENDICIES

APPENDIX A: SOLAR PANEL DETAILS

MAXEON 3 **POWER: 390-400 W | EFFICIENCY: Up to 22.6%**

Electrical Data	SPR-MAX3-400	SPR-MAX3-395	SPR-MAX3-390
Nominal Power (Pnom) [9]	400 W	395 W	390 W
Power Tolerance	+5/0%	+5/0%	+5/0%
Panel Efficiency	22.6%	22.3%	22.1%
Rated Voltage (Vmpp)	65.8 V	65.1 V	64.5 V
Rated Current (Impp)	6.08 A	6.07 A	6.05 A
Open-Circuit Voltage (Voc) (+/-3%)	75.6 V	75.4 V	75.3 V
Short-Circuit Current (Isc) (+/-3%)	6.58 A	6.56 A	6.55 A
Max. System Voltage		1000 V IEC	
Maximum Series Fuse		20 A	
Power Temp Coef.		−0.27% / °C	
Voltage Temp Coef.		−0.236% mV / °C	
Current Temp Coef.		0.060% mA / °C	

Operating Condition And Mechanical Data	
Temperature	−40°C to +85°C
Impact Resistance	25 mm diameter hail at 23 m/s
Solar Cells	104 Monocrystalline Maxeon Gen III
Tempered Glass	High-transmission tempered anti-reflective
Junction Box	IP-68, Stäubli (MC4), 3 bypass diodes
Weight	19 kg
Max. Load [11]	Wind: 2400 Pa, 244 kg/m² front & back Snow: 5400 Pa, 550 kg/m² front
Frame	Class 1 black anodized (highest AAMA rating)

Tests And Certifications	
Standard Tests [10]	IEC 61215, IEC 61730
Quality Management Certs	ISO 9001:2015, ISO 14001:2015
Ammonia Test	IEC 62716
Desert Test	IEC 60068-2-68, MIL-STD-810G
Salt Spray Test	IEC 61701 (maximum severity)
PID Test	1000 V: IEC 62804, PVEL 600 hr duration
Available Listings	TUV

Sustainability Tests and Certifications	
IFLI Declare Label	First solar panel labeled for ingredient transparency and LBC-compliance.[12]
Cradle to Cradle Certified™ Bronze	First solar panel line certified for material health, water stewardship, material reutilization, renewable energy & carbon management, and social fairness.[13]
Green Building Certification Contribution	Panels can contribute additional points toward LEED and BREEAM certifications.[14]
EHS Compliance	RoHS, OHSAS 18001:2007, lead free, REACH SVHC-163

Figure 73: SunPower Maxeon Solar Panel Specs [8]

APPENDIX B: TOWER DETAILS

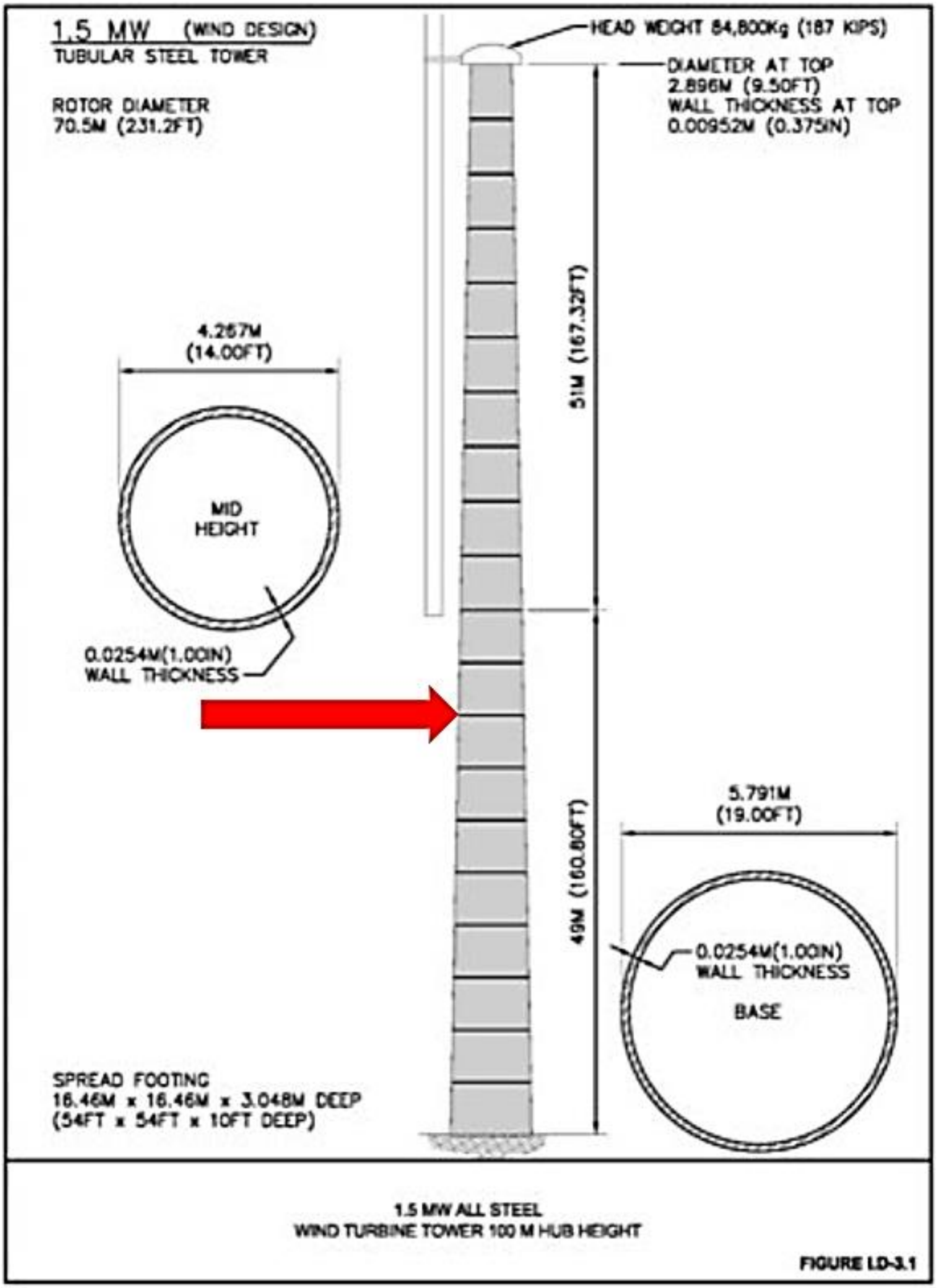


Figure 74: Wind Turbine Details [15]

APPENDIX C: WEIGHT TABLE

Table 8: Weight Table

Component	Weight (lbs)
Solar Panel Array (SunPower Maxeon)	420
Aluminum Frame	183
Upper Arms	32
Lower Arms	188
Electrical Components	10
Upper Channel	734
Lower Channel	742
Nuts (quantity of 4)	8
Upper U-Bolt	1,308
Lower U-Bolt	1,310
TOTAL:	**4,932**

APPENDIX D: SHEAR AND MOMENT DIAGRAM

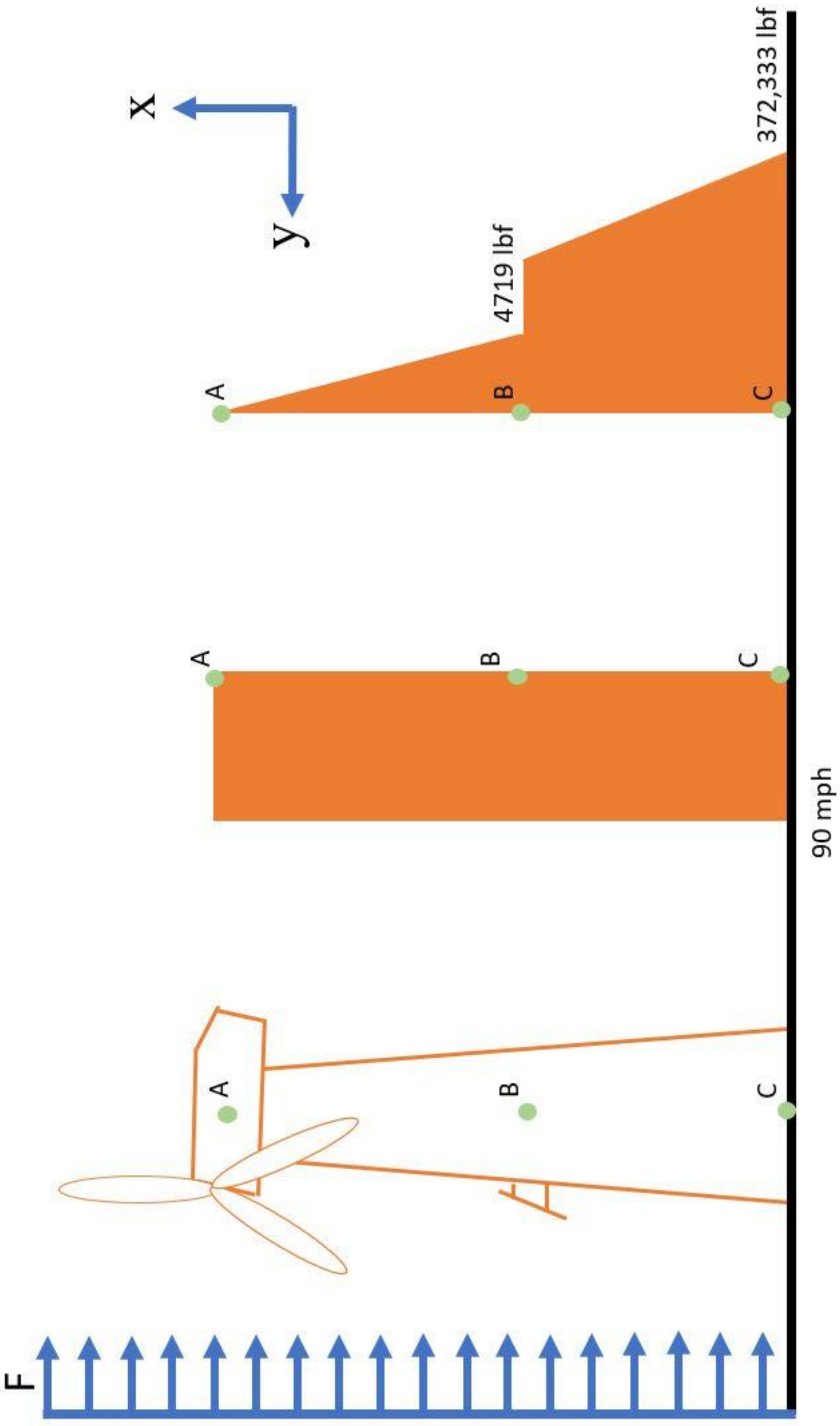


Figure 75: Shear and Moment Diagram

APPENDIX E: SOLIDWORKS DRAWINGS

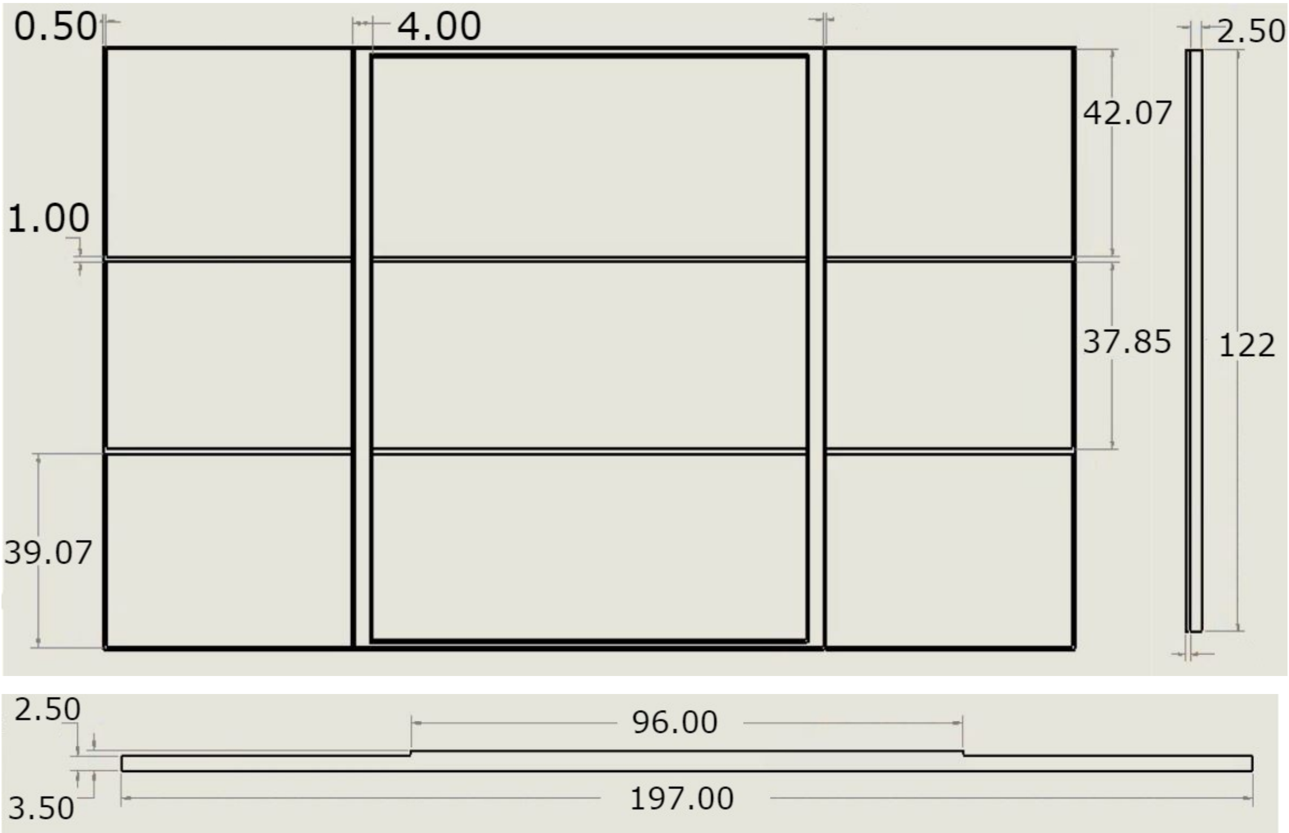


Figure 76: Solar Frame Dimensions (in)

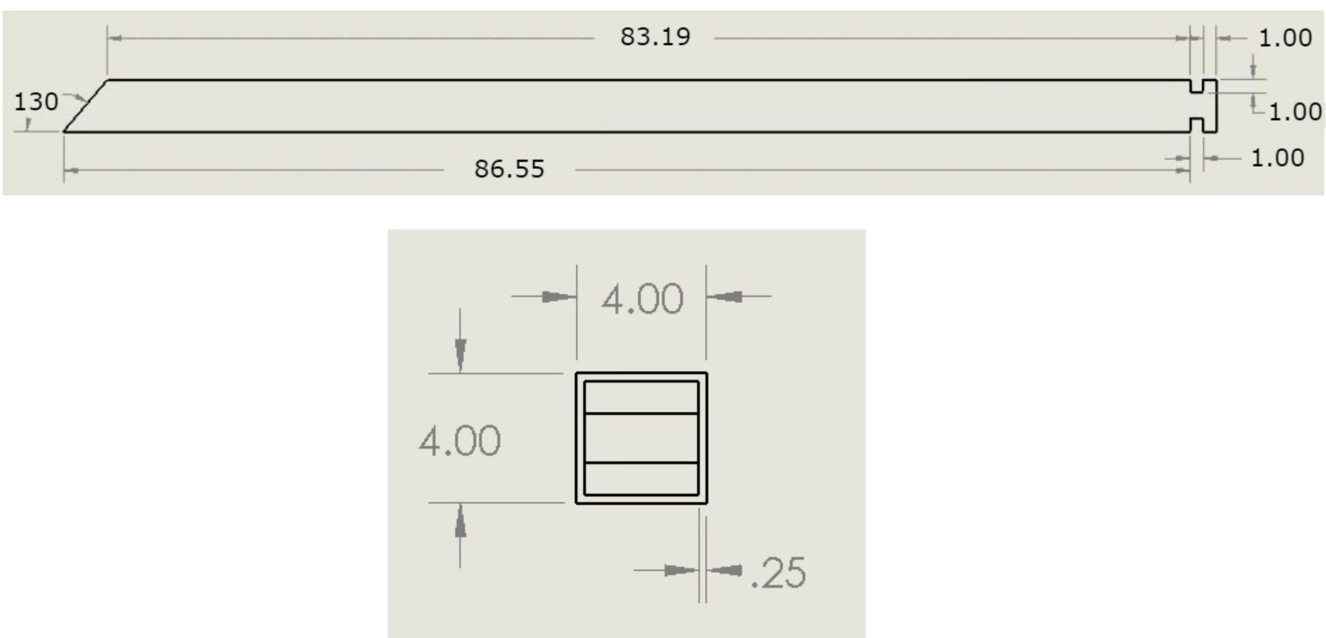


Figure 77: Lower Arm Dimensions (in)

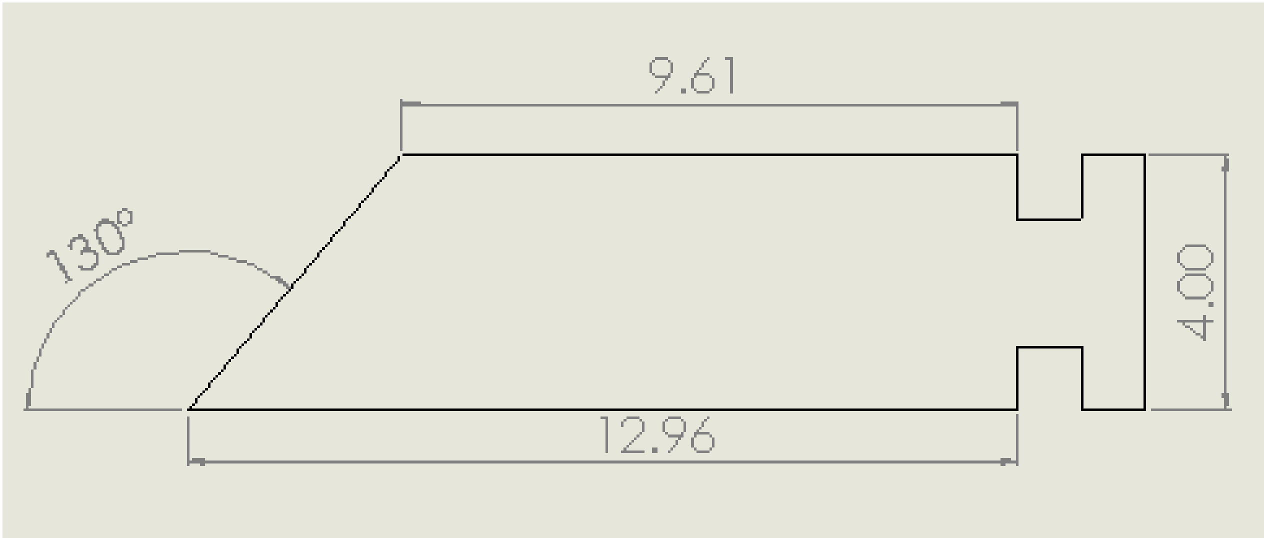


Figure 78: Upper Arm Dimensions (in)

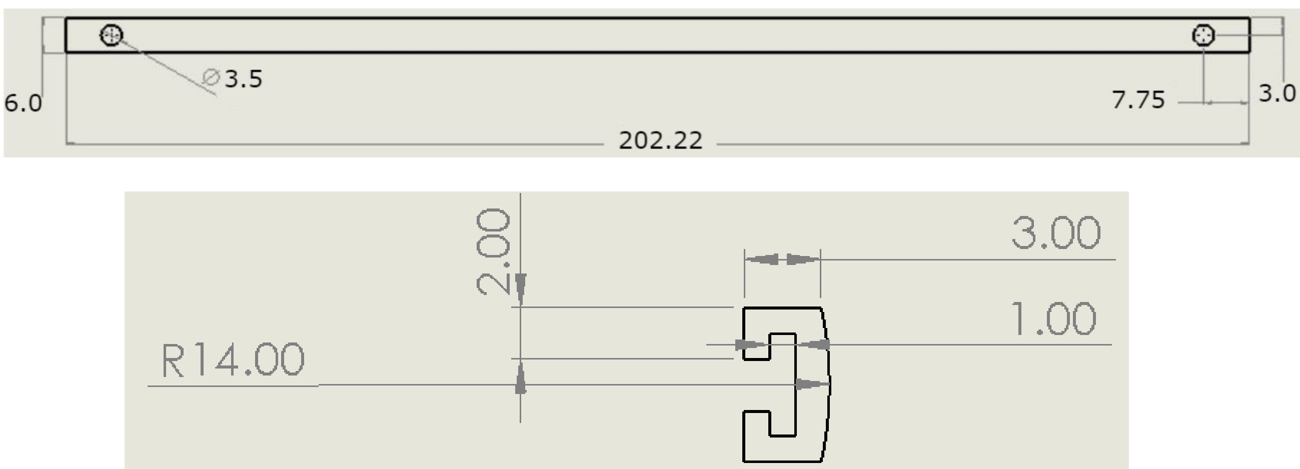
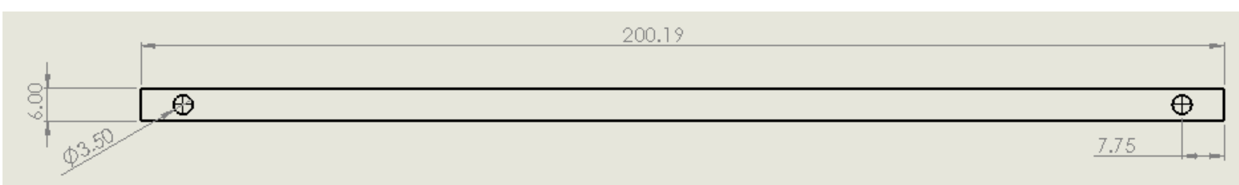


Figure 79: Lower Channel Dimensions (in)



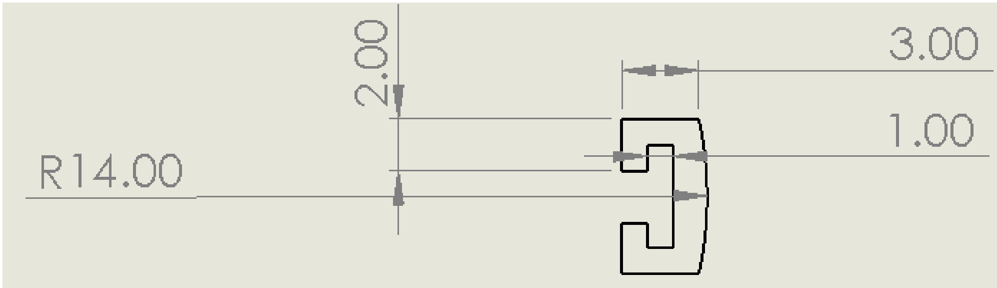


Figure 80: Upper Channel Dimensions (in)

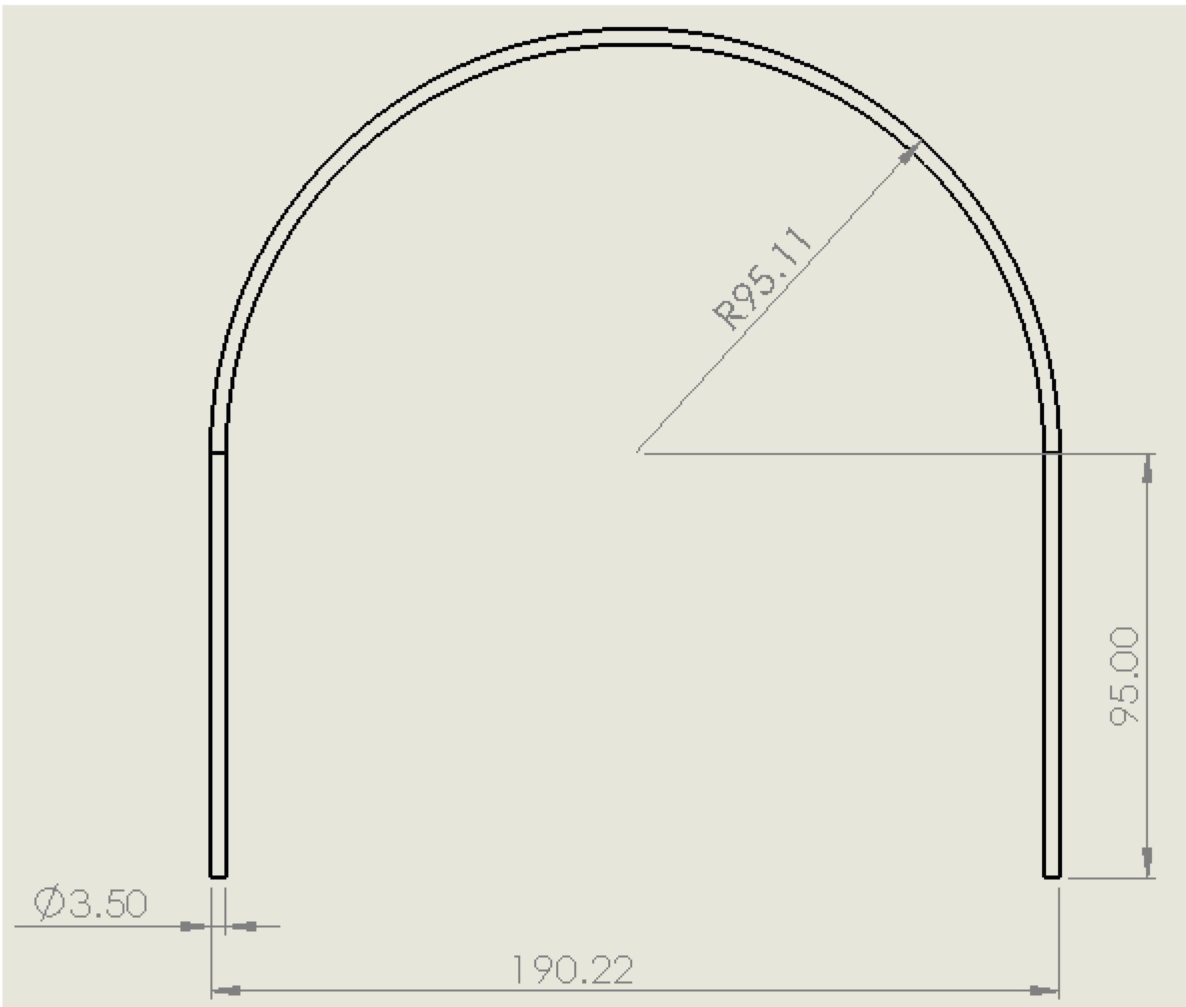


Figure 81: Lower U-Bolt Dimensions (in)

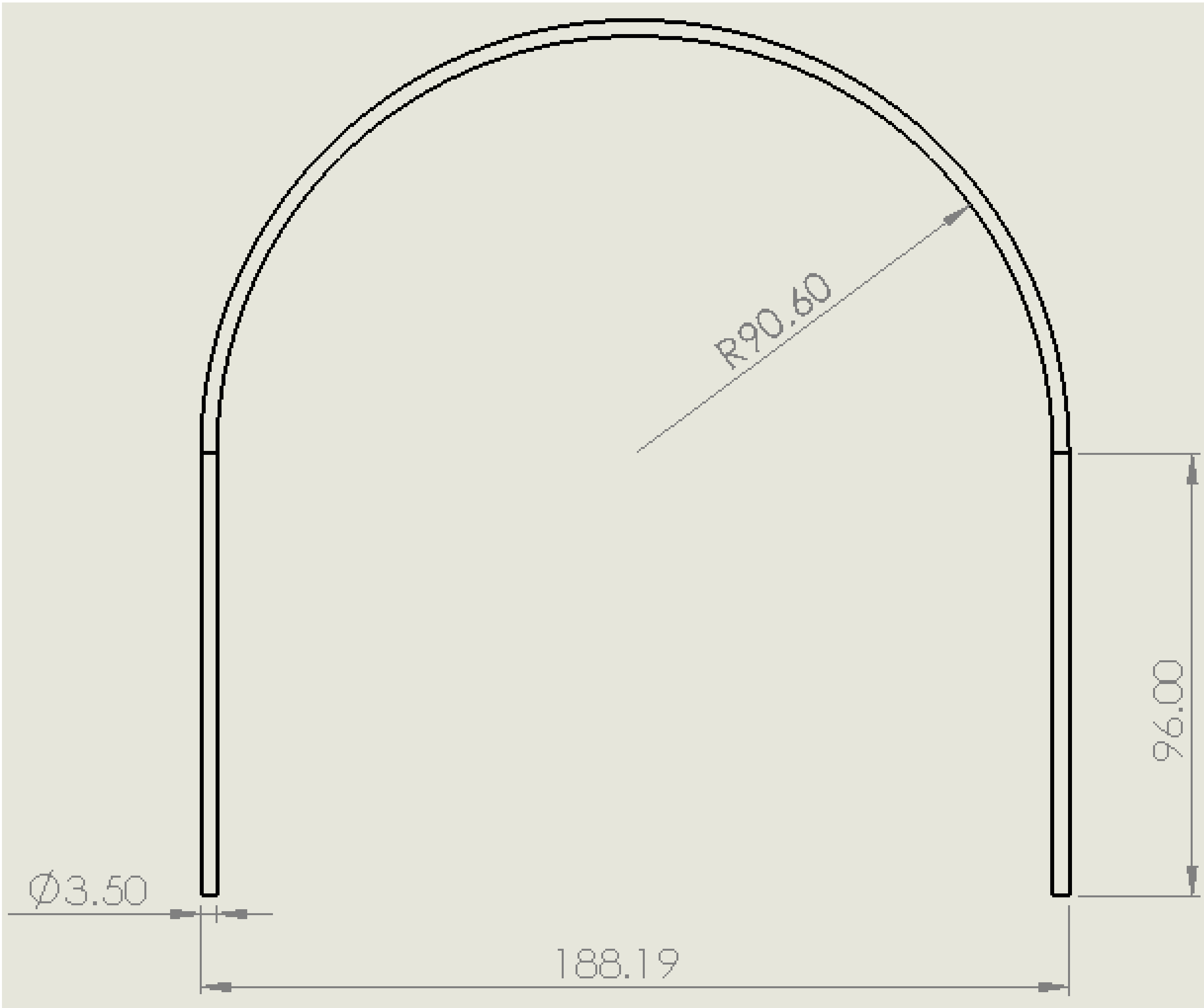


Figure 82: Upper U-Bolt Dimensions (in)

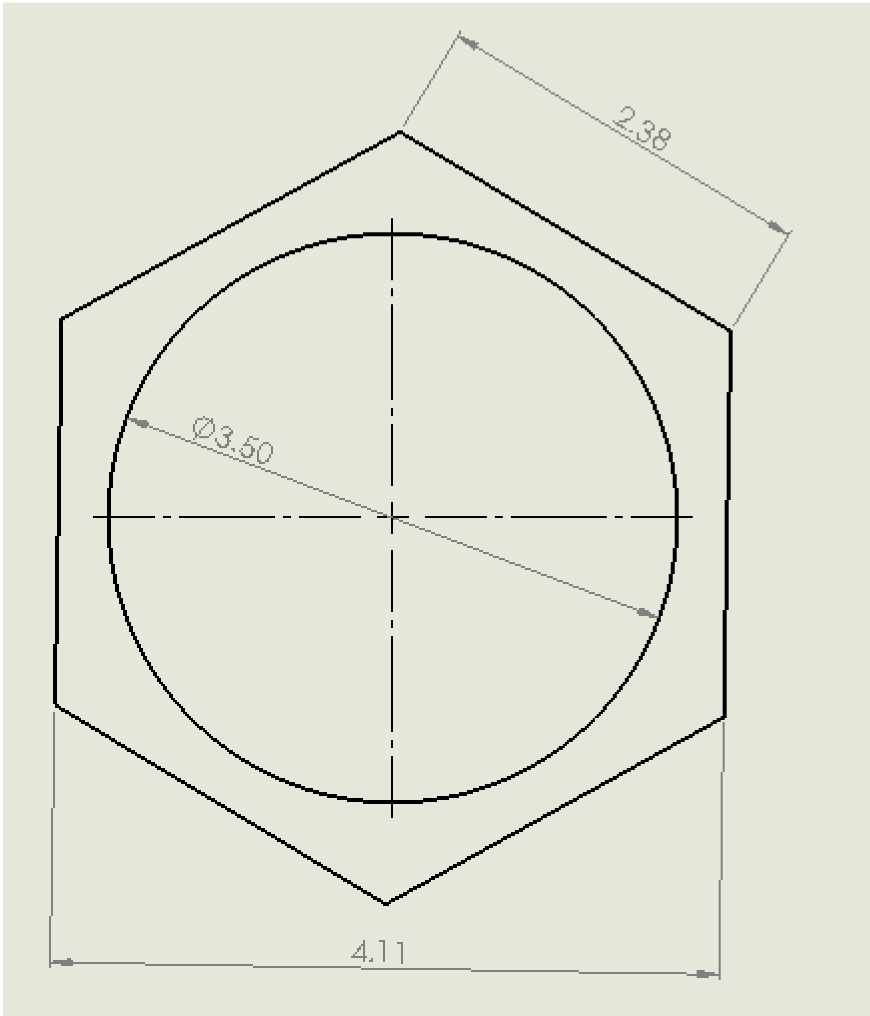


Figure 83: Nut Dimensions (in)

APPENDIX F: FAILURE MODES AND EFFECTS ANALYSIS

Table 9: Failure Mode and Effects Analysis

Item	Failure modes	Cause of Failure	Possible Effects	Prob.	Level	Possible Action to Reduce Failure Rate or Effects
Mount Design	Weight Overloading	Not enough factor of safety for ice loading	Collapse of mount	Low	Critical	Design mount to withstand high loads and pressures with a high factor of safety.
Tower	Collapse	Mount causing too high of stresses on turbine tower	Collapse of tower	Low	Not Critical	When running simulations, test tower failure and assure the mount will not get close to failure stresses.
Mount Design	Corrosion	Corrosion of materials till failure point	Failure of Mount/ Failure of tower	Medium	Not Critical	When designing the mount choose materials that will not cause a dielectric effect with the turbine tower material.
Solar Panels	Ripped off mount	Not calculating the stress of weather and wind correctly	Losing solar panels	High	Critical	In calculations and design make sure panels can withstand forces and are securely mounted.
U-Bolts	Shear	The weight, wind and ice loading	Failure of mount	Medium	Critical	Design the U-bolts with a higher factor of safety to anticipate wind and ice loading.

APPENDIX G: MOUNT AND TOWER MESH CONVERGENCE

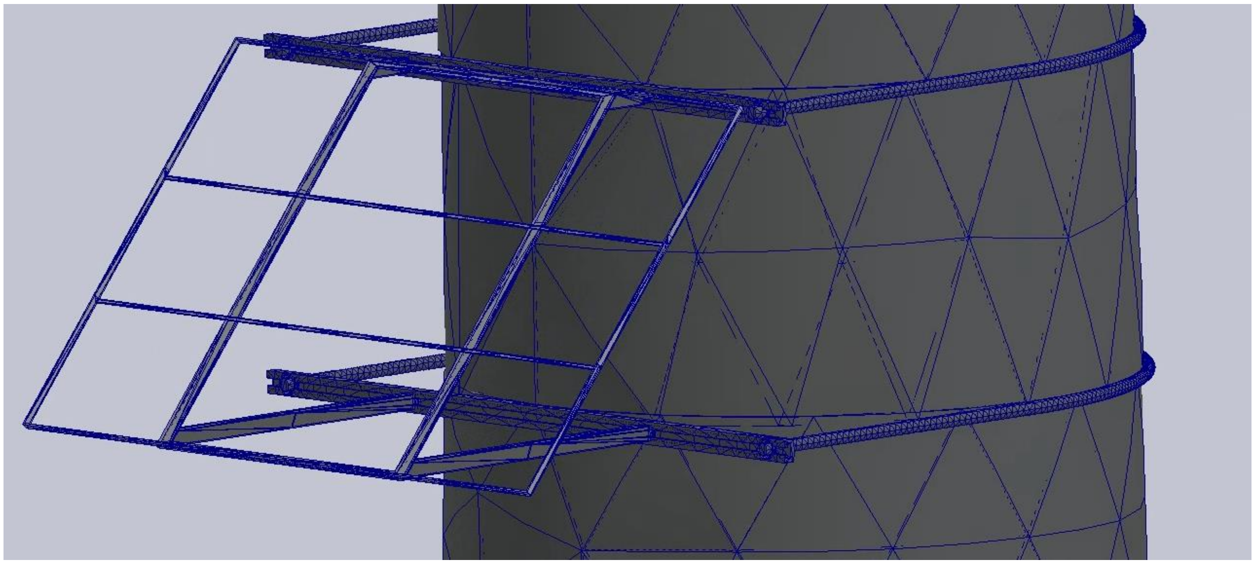


Figure 84: Mesh of Mount and Tower

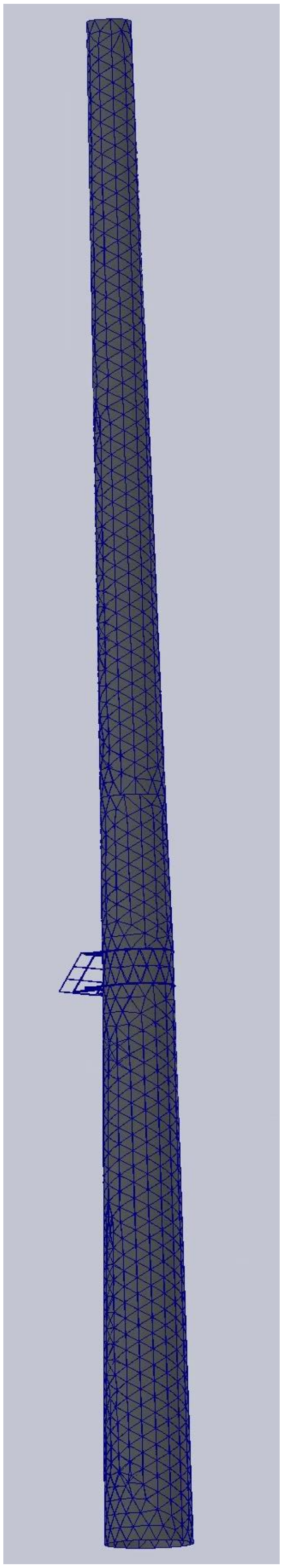
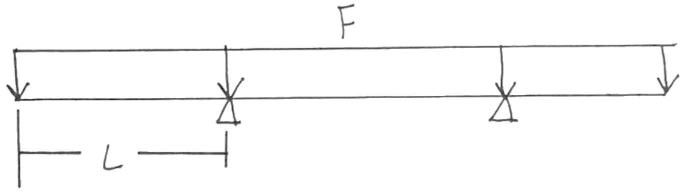


Figure 85: Mesh of Mount and Tower in Full View

APPENDIX H: HAND CALCULATIONS

Deflection of Frame



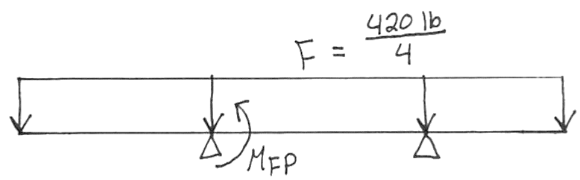
$$\delta_{\text{outer beam wrt F}} = \frac{-Fx^2}{6EI}(3L-x)$$

$E = 10\times10^6\,\text{psi}$, $I = 0.651\,\text{in}^4$, $L = x = 50.5\,\text{in}$

$$\delta = \frac{-\frac{420}{4}(50.5\,\text{in})^2}{6(10\times10^6\,\text{psi})(0.651\,\text{in}^4)}\left(3(50.5)-50.5\right)$$

$$\boxed{\delta = 0.692\,\text{in}}$$

Moment at Fixed Points of Frame



$$\Sigma M = -F(L-x) = 0$$

$x = 0$, $L = 50.5\,\text{in}$, $F = \frac{420\,\text{lb}}{4}$

$$\Sigma M = -\left(\frac{420\,\text{lb}}{4}\right)(50.5\,\text{in} - 0) = -5{,}302.5\ \text{lb}\cdot\text{in}$$

$$\boxed{\Sigma M = -5302.5\ \text{lb}\cdot\text{in}}$$

Bending of Frame at Fixed Points

$$\sigma = \frac{My}{I}$$

I = moment of inertia for outer beam

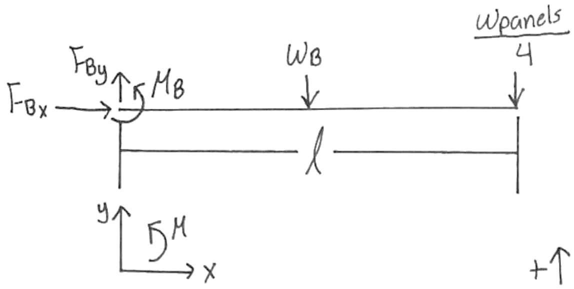
$$I = \frac{bh^3}{12} = \frac{(0.5in)(2.5in)^3}{12} = 0.651\,in^4$$

$$y = \frac{0.5in}{2} = 0.25in$$

$$\sigma = \frac{-5302.5\ lb\cdot in\,(0.25\,in)}{0.651\,in^4}$$

$$\boxed{\sigma = 2{,}036.3\ lb/in^2}$$

Lower Arms:



$W_B = 47$ lbs

$W_{panels} = 120$ lbs

$\ell = 7.379$ ft

$\overset{+}{\rightarrow}\sum F_{Bx}: \boxed{F_{Bx} = 0}$

$+\uparrow \sum F_{By}: F_{By} - W_B - \frac{W_{panels}}{4} = 0$

$F_{By} - 47 - \frac{120}{4} = 0$

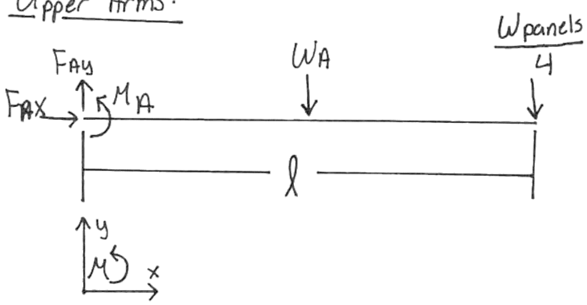
$\boxed{F_{By} = 77 \text{ lbf}}$

$\circlearrowleft + \sum M_B: M_B - W_B\left(\frac{\ell}{2}\right) - \frac{W_{panels}}{4}(\ell) = 0$

$M_B - (47)\left(\frac{7.379}{2}\right) - \frac{120}{4}(7.379) = 0$

$\boxed{M_B = 394.78 \text{ lb}\cdot\text{ft}}$

Upper Arms:



$W_{panels} = 420$ lbs

$W_A = 16$ lbs

$\ell = 1.247$ ft

$\overset{+}{\rightarrow}\sum F_x: F_{Ax} = 0$

$\uparrow + \sum F_y: F_{Ay}: F_{Ay} - W_A - \frac{W_{panels}}{4} = 0$

$F_{Ay} - 16 - \frac{120}{4} = 0$

$\boxed{F_{Ay} = 46 \text{ lbf}}$

$\circlearrowleft + \sum M_A: M_A - W_A\left(\frac{\ell}{2}\right) - \frac{W_{panels}}{4}(\ell) = 0$

$M_A - 16\left(\frac{1.247}{2}\right) - \frac{120}{4}(1.247) = 0$

$\boxed{M_A = 47.37 \text{ lbf}\cdot\text{ft}}$

Bending Stress: Upper and Lower Arms

$$I = \frac{b_o h_o^3 - b_i h_i^3}{12} = \frac{4^4 - 3.75^4}{12} = \boxed{4.85 in^4 = I}$$

$$\sigma_{upper} = \frac{M_A y}{I} = \frac{(568.44)(2)}{4.85} = \boxed{234.41 psi = \sigma_{upper}}$$

$$\sigma_{lower} = \frac{M_B y}{I} = \frac{(4737.36)(2)}{4.85} = \boxed{1953.55 psi = \sigma_{lower}}$$

Safety Factor: Upper and Lower Arms and Frame

upper:

$$\eta_{stress} = \frac{S_y}{\sigma} = \frac{46000}{234.41} = \boxed{196.24 = \eta}$$

lower:

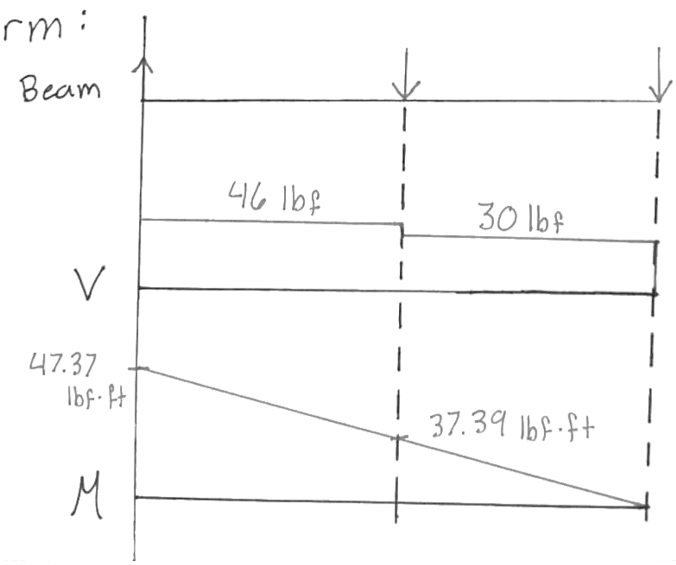
$$\eta_{stress} = \frac{S_y}{\sigma} = \frac{46000}{1953.55} = \boxed{23.55 = \eta}$$

frame:

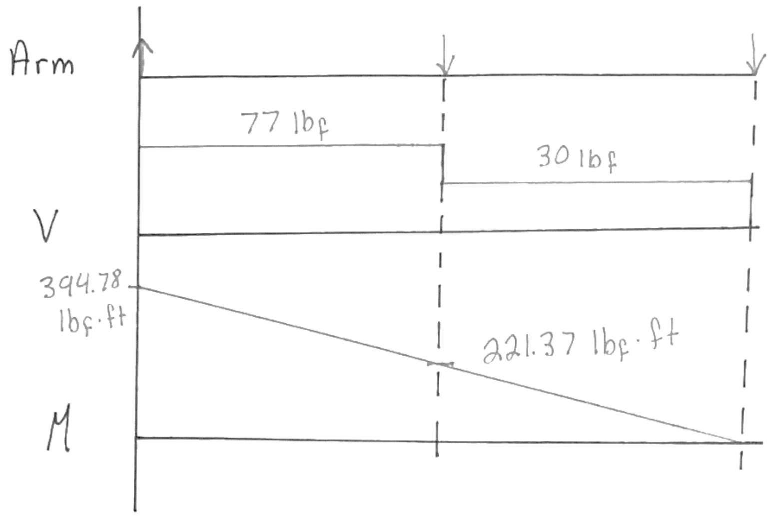
$$\eta_{stress} = \frac{S_y}{\sigma} = \frac{31000}{2036.3} = \boxed{15.22 = \eta}$$

Shear and Moment Diagrams

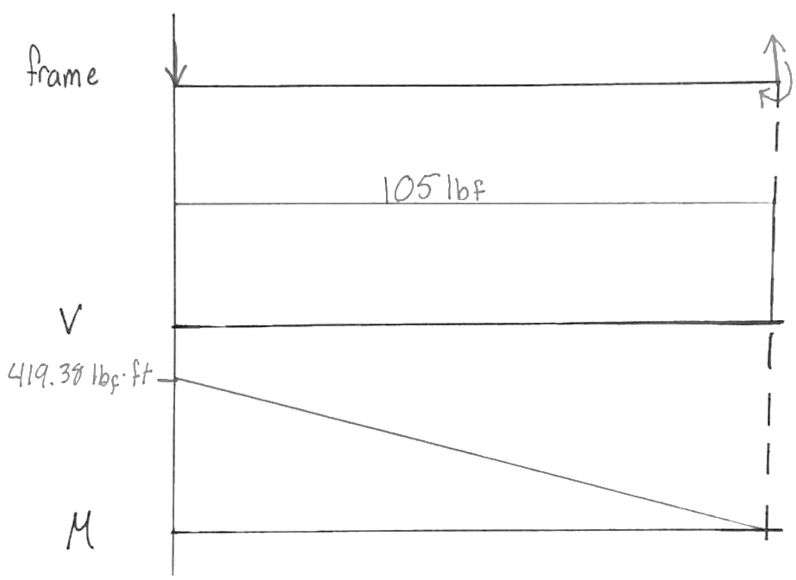
upper arm:



Lower arms:



Frame:



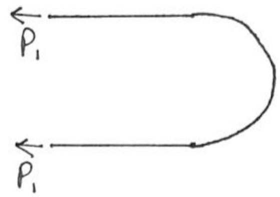
Max Stress in Arms:

$$\sigma = \frac{S_y}{\eta} = \frac{46000\,psi}{6}$$

$$\boxed{\sigma = 7667\,psi}$$

U-Bolt Calculations

Upper U-Bolt:



$F = \mu 2P$

$P_1 = \frac{F}{\mu 2}$

$P_1 = \frac{6165}{2(0.74)} = 4165.5 \text{ lbf}$

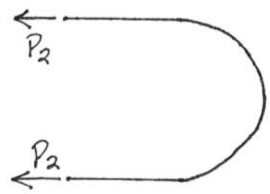
$F = W_{tot} + 25\%$

$= 4932 + 1233$

$= 6165 \text{ lbf}$

$\boxed{P_1 = 4165.5 \text{ lbf}}$ (in tension)

Lower U-Bolt:



$P_2 = \frac{F}{2\mu} = -4165.5 \text{ lbf}$

$\boxed{P_2 = -4165.5 \text{ lbf}}$ (in compression)

Bolt Pre Tension

Our method of loading has a 35% accuracy

Thread: 3-4 UNC 3 2.8

$S_p = S_y = 50{,}000 \text{ psi}$

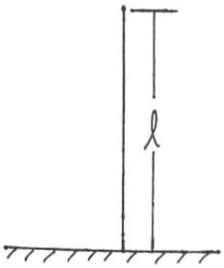
$A_t = 5.97 \text{ in}^2$

$C = 0.9$

$F = C A_t S_p = 0.9(5.97 \text{ in}^2)(50{,}000 \text{ psi})$

$\boxed{F = 268{,}650 \text{ lbf}}$

Buckling (Euler) for Tower



$$P_{critical} = \frac{C\pi^2 E I_{avg}}{\ell^2}$$

$C_{fixed\text{-}fixed} = 1.2$, $E = 29{,}000{,}000$ psi

$I_{avg} = 2.4265 \times 10^6$ psi , $\ell = 120$ ft $= 1440$ in

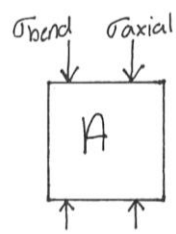
$$P_{critical} = \frac{(1.2)\pi^2(29{,}000{,}000\text{ psi})(2.4265\times10^6\text{ in}^4)}{1440\text{ in}} = \boxed{5.7876\times10^{11}\text{ lbs} = P_{critical}}$$

Buckling Safety Factor

$$\eta = \frac{P_{critical}}{W_{head} + W_{blades} + W_{tower} + W_{mount}} = \frac{5.7876\times10^{11}\text{ lbs}}{186{,}952\text{ lbs} + 90000\text{ lbs} + 512924\text{ lbs} + 4932\text{ lbs}}$$

$$\boxed{\eta = 794.808}$$

Tower Axial Stress



$$A = \pi\left(\frac{d_{base}}{2}\right)^2 - \pi\left(\frac{d_{base} - 2\text{in}}{2}\right)^2$$

$$= \pi\left(\frac{228\text{in}}{2}\right)^2 - \pi\left(\frac{228\text{ in} - 2\text{in}}{2}\right)^2$$

$$A = 713.142\text{in}^2$$

$$\sigma_{axial} = \frac{F}{A} = \frac{W_{tower+blades+head} + W_{mount}}{A} = \frac{4932\text{ lbs} + 794880\text{ lbs}}{713.142\text{in}^2}$$

$$\boxed{\sigma_{axial} = 1121.53\text{ psi}}$$

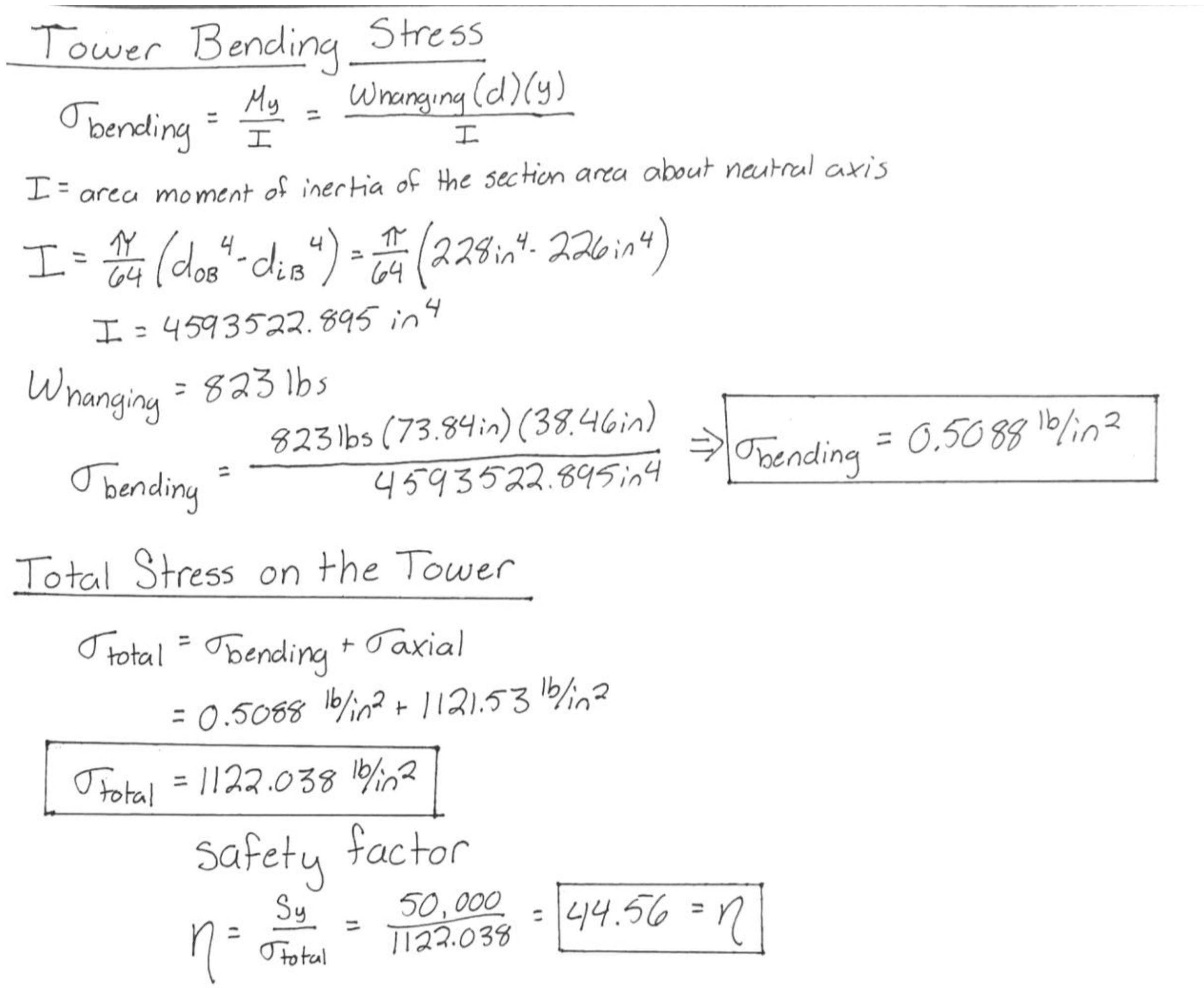


Figure 86: Various Hand Calculations Used to Analyze Solar Panel Mount

APPENDIX I: TEXTBOOK EQUATIONS REFERENCED

5.3 Equations of Equilibrium

In Sec. 5.1 we developed the two equations which are both necessary and sufficient for the equilibrium of a rigid body, namely, $\Sigma \mathbf{F} = \mathbf{0}$ and $\Sigma \mathbf{M}_O = \mathbf{0}$. When the body is subjected to a system of forces, which all lie in the x–y plane, then the forces can be resolved into their x and y components. Consequently, the conditions for equilibrium in two dimensions are

$$\begin{aligned} \Sigma F_x &= 0 \\ \Sigma F_y &= 0 \\ \Sigma M_O &= 0 \end{aligned} \qquad (5\text{–}2)$$

Here ΣF_x and ΣF_y represent, respectively, the algebraic sums of the x and y components of all the forces acting on the body, and ΣM_O represents the algebraic sum of the couple moments and the moments of all the force components about the z axis, which is perpendicular to the x–y plane and passes through the arbitrary point O.

Figure 87: Equations of Equilibrium [38]

Beam Deflection Tables

The tables below give equations for the deflection, slope, shear, and moment along straight beams for different end conditions and loadings. You can find comprehensive tables in references such as Gere, Lindeburg, and Shigley. However, the tables below cover most of the common cases.

Deflection:

$$\delta = -\frac{Fx^2}{6EI}(3L - x)$$

$$\delta_{max} = \frac{FL^3}{3EI} \qquad @\, x = L$$

Moment:

$$M = -F\,(L - x)$$

$$M_{max} = -FL \qquad @\, x = 0$$

Figure 88: Deflection and Moment Equations [39]

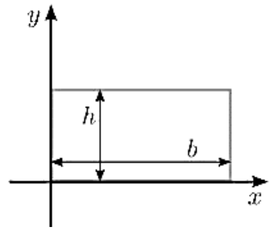
A filled rectangular area as above but with respect to an axis collinear with the base		$I_x = \frac{bh^3}{3}$ $I_y = \frac{b^3h}{3}$ [4]	This is a result from the parallel axis theorem

Figure 89: Area Moment of Inertia for a Rectangle [38]

The stress distribution given by Equation (3–24) is shown in Figure 3–14. The maximum magnitude of the bending stress will occur where y has the greatest magnitude. Designating σ_{max} as the maximum *magnitude* of the bending stress, and c as the maximum *magnitude* of y

$$\sigma_{max} = \frac{Mc}{I} \quad (3\text{–}26a)$$

Figure 90: Bending Stress Equation [40]

$$P_{cr} = \frac{C\pi^2 EI}{l^2}$$

$$\frac{P_{cr}}{A} = \frac{C\pi^2 E}{(l/k)^2}$$

I is the smallest I for a cross section

C depends on the end conditions
See Table 4-2 in Shigleys

$I = Ak^2$ where k is the radius of gyration

Table 4-2	End Condition Constant (C)		
Column End Conditions	**Theoretical Value**	**Conservative Value**	**Recommended Value**
Fixed-free	¼	¼	¼
Rounded-Rounded	1	1	1
Fixed-Rounded	2	1	1.2
Fixed-Fixed	4	1	1.2

Figure 91: Bucking Equations [40]

1–11 Design Factor and Factor of Safety

A general approach to the allowable load versus loss-of-function load problem is the deterministic design factor method, and sometimes called the classical method of design. The fundamental equation is Equation (1–1) where n_d is called the *design factor.* All loss-of-function modes must be analyzed, and the mode leading to the smallest design factor governs. After the design is completed, the *actual* design factor may change as a result of changes such as rounding up to a standard size for a cross section or using off-the-shelf components with higher ratings instead of employing what is calculated by using the design factor. The factor is then referred to as the *factor of safety, n.* The factor of safety has the same definition as the design factor, but it generally differs numerically.

Because stress may not vary linearly with load (see Section 3–19), using load as the loss-of-function parameter may not be acceptable. It is more common then to express the design factor in terms of a stress and a relevant strength. Thus Equation (1–1) can be rewritten as

$$n_d = \frac{\text{loss-of-function strength}}{\text{allowable stress}} = \frac{S}{\sigma(\text{or } \tau)} \qquad (1\text{–}3)$$

The stress and strength terms in Equation (1–3) must be of the same type and units. Also, the stress and strength must apply to the same critical location in the part.

Figure 92: Factor of Safety Equation [40]

Eccentric Loading

Consider an axial member loaded in tension or compression. If the load path is not along the neutral axis, then a bending moment develops in addition to the axial load.

The weight of a traffic light hanging from a cantilever arm creates an axial stress $\sigma_{axial} = -P/A$ in the vertical support pole (negative because the load is compressive), while the weight times the moment arm creates a bending moment in the support pole, causing a bending stress.

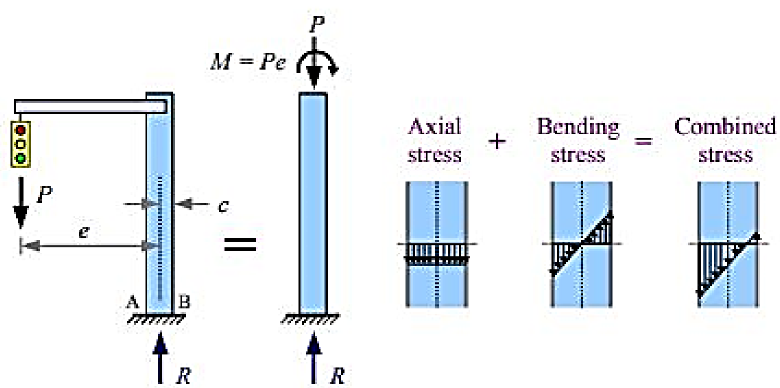


Figure 93: Axial Stress and Combined Stress Equation [39]

Characteristics of Dry Friction. As a result of *experiments* that pertain to the foregoing discussion, we can state the following rules which apply to bodies subjected to dry friction.

- The frictional force acts *tangent* to the contacting surfaces in a direction *opposed* to the *motion* or tendency for motion of one surface relative to another.

- The maximum static frictional force F_s that can be developed is independent of the area of contact, provided the normal pressure is not very low nor great enough to severely deform or crush the contacting surfaces of the bodies.

- The maximum static frictional force is generally greater than the kinetic frictional force for any two surfaces of contact. However, if one of the bodies is moving with a *very low velocity* over the surface of another, F_k becomes approximately equal to F_s, i.e., $\mu_s \approx \mu_k$.

- When *slipping* at the surface of contact is *about to occur*, the maximum static frictional force is proportional to the normal force, such that $F_s = \mu_s N$.

- When *slipping* at the surface of contact is *occurring*, the kinetic frictional force is proportional to the normal force, such that $F_k = \mu_k N$.

Figure 94: U-Bolt Force Equation [38]

8–7 Tension Joints—The External Load

Let us now consider what happens when an external tensile load P is applied to a bolted connection, as shown in Figure 8–18. The nomenclature used is:

F_i = preload

P_{total} = Total external tensile load applied to the joint

P = external tensile load per bolt

P_b = portion of P taken by bolt

P_m = portion of P taken by members

$F_b = P_b + F_i$ = resultant bolt load

$F_m = P_m - F_i$ = resultant load on members

C = fraction of external load P carried by bolt

$1 - C$ = fraction of external load P carried by members

N = Number of bolts in the joint

If N bolts equally share the total external load, then

$$P = P_{total}/N \qquad (a)$$

In Figure 8–18*a*, a bolted joint is shown where the nut is in contact with the members, but not yet tightened to introduce a preload. The members and the bolt can be modeled as springs in parallel. The figure schematically represents the members with a large stiff spring and the bolt with a low-stiffness spring, each starting in an undeformed equilibrium condition. In Figure 8–18*b*, the nut is tightened to introduce a preload F_i to the joint. In doing so, the stiff spring of the members is compressed by an amount $\delta_m = F_i/k_m$, while the soft spring of the bolt is stretched by an amount $\delta_b = F_i/k_b$. Figure 8–19 shows a plot of these force-deflection characteristics, where the linear spring stiffness relationships are evident. Note that the ordinate $|F|$ represents the absolute value of the force in each member, where the force in the bolt is positive, and the force in the members is negative. As both the bolt and the members experience the preload F_i, the member loading moves up its stiffness line to point a, while the bolt loading moves to point b. Since the member stiffness is usually much greater than the bolt stiffness, this results in δ_m being significantly smaller than δ_b.

When an external tensile load P is applied to the members (not directly to the bolt), the bolt elongates further by $\Delta\delta_b$, whereas the members' deflection *decreases* by $\Delta\delta_m$, as shown in Figure 8–18*c*. By inspection of the figure, it can be realized that these deflections must be equal. From Figure 8–19, observe that the external load P is split into two portions, P_b applied to the bolt and P_m applied to the members, apportioned as necessary to ensure that $\Delta\delta_b = \Delta\delta_m$. Thus,

$$\Delta\delta_b = \frac{P_b}{k_b} = \Delta\delta_m = \frac{P_m}{k_m} \qquad (b)$$

or,

$$P_m = \frac{k_m}{k_b} P_b \qquad (c)$$

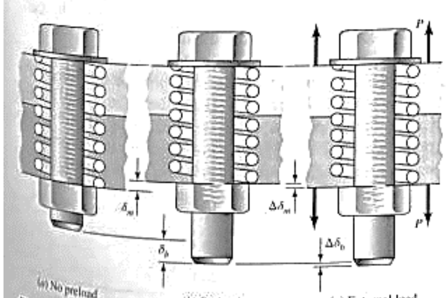


Figure 8–18
Spring model of the effect of preload and external tensile load to a bolted joint.

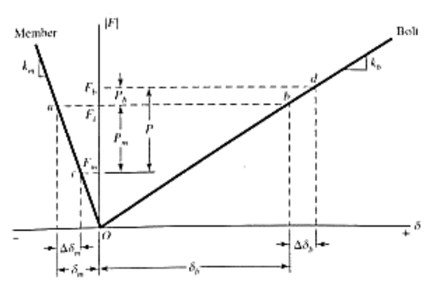


Figure 8–19
Force-deflection characteristics of an externally loaded bolted member with an initial bolt preload force, F_i. The external load is P.

Figure 95: Pre-Tension Torque Equation [40]