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# Solar Panel Sun-Tracking System for Home Use
# Final Project Report

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Friday, May 6, 2022

# Executive Summary

Team 2 of the Sun-Tracking Solar Panels for Home Use seeks to design a residential solar panel system that has the ability to track the sun. The main objectives of this project are to design and construct a sun-tracking solar panel system that is able to maximize the amount of sunlight captured throughout a day. The following report covers the features of our complete design and its three subsystems that combine to accomplish the requirements of the sun-tracking system. The primary functions of the three subsystems are as follows: the sun-tracking sensor will read photoresistor values that determine whether the solar panel's angle should be adjusted, the mechanical movement device will adjust the angle of the solar panel, and the electric circuit and control system will make the determination as to whether the solar panel should be shifted and by how much. Following the design overview is an evaluation of the final design through the scope of project requirements and constraints, as well as the associated tests used in assessing the overall system's performance.

Based on discussions with the Project Sponsor, two primary constraints were identified by the Sun-Tracking Solar Panel Team. The cost of designing, prototyping, testing, and building the product is limited to a $1200 budget provided by Trinity University. The time allotted for designing, prototyping, testing, and building of the product is limited to Fall 2021 and Spring 2022 semesters.

The final design is held to certain project requirements that will be discussed in future sections. The requirement that the solar panel system should be water-resistant through hurricane caliber rains was met with an IP-55 rated box. The requirement that the solar panel system should be windproof up to 60 mph was tested and partially met using a Fusion 360 wind simulation.When the actuators were fully extended, the system was unable to withstand 60 mph winds, though it was able to while flat and half extended. The requirement that the solar panel should be able to rest on a slanted residential roof with roof pitch ranging up to 9/12 (36.9) was met by building a makeshift roof and performing the weight test. The solar panel system was then rested on this roof. The requirement that the solar panel system should be more energy-efficient than a stationary solar panel was met. The financial requirement that the additional cost of the final product to the residential unit should be recovered within ten years of installation, however, was not met.

Looking forward, we would like to resolve the current issues preventing us from meeting our design requirements. For the wind simulation, the most likely way to resolve this would be to add a wind sensor to our design. When the wind sensor is reading above a certain value, the panel will retract to its flat state, as it is the most windproof of any tilt setting. In order to combat the financial issue we ran into, we must either harvest more energy, or lower the production cost of our system. We think harvesting more energy is the more viable option, and thus think that adding a second axis of tilt to our solar panel would be our best option.

# 1. Introduction

Our team set off to solve the problem of solar panels not maximizing the amount of energy they harvest in a day. Currently, the efficiency of solar panels is a relatively strong function of the light's angle of incidence, yet the majority of solar panels are installed in fixed positions. The fixed solar panel's orientation is typically chosen to maximize overall light energy collection; however, such fixed installations are clearly not optimal. Not only does the position of the sun (and the light's angle of incidence) change throughout the day, but the sun's trajectory also depends on the time of the year. This issue is more pronounced at latitudes nearer the poles, where the sun's path can be closer to the horizon. The project sponsor seeks a sun-tracking solar panel system that can be implemented for use on residential rooftops.

Our objective was to create a cost-efficient residential solar panel that had the potential to improve net energy collection by tracking the sun. The mechanism could ideally be able to adjust on at least one axis to maximize power output. It should. The specific project requirements were as follows:

1. The solar panel system should be water-resistant through hurricane caliber rains
2. The solar panel system should be windproof up to 60 mph.
3. The solar panel system should be able to rest on a slanted residential roof with roof pitch ranging up to 9/12 (36.9°).
4. The solar panel system should be more energy-efficient than a stationary solar panel.
5. The additional cost of the final product to the residential unit should be recovered within ten years of installation.

Based on initial discussions with our project sponsor, we identified two main constraints that would limit our project. The first was that the cost of designing, prototyping, testing, and building the product was limited to the $1200 budget provided by Trinity University. The second major constraint was that the time allotted for designing, prototyping, testing, and building of the product was limited to the Fall 2021 and Spring 2022 semesters.

While designing our prototype, we had to pay close attention to certain codes and standards that could potentially hinder our long-term ability to bring this product to market. The major code we looked to follow was OSHA 29 CFR 1910.269, *Electric power generation, transmission, and distribution.* The purpose of this code was to cover the operation and maintenance of electric power generation, control, transformation, transmission, and distribution lines and equipment.

In addition to codes, there were some other standards we also heavily considered while designing our prototype. The first of these came from the OSHA document *Assessing the Need for PPE (Discussion)*. Personal protective equipment (PPE), and more importantly taking precautions, was crucial throughout our project as we were dealing with potential electrical hazards as part of our solar panel system. Additionally, we used PPE to protect ourselves from the potential dangers associated with the use of the tools in the CSI Makerspace. Another standard of high importance was the *HOA Solar Guidelines.* Given that over a quarter of homes in the USA are part of an HOA, we would lose a large portion of our potential market if we didn't comply with this standard.

These codes and standards, along with the project objectives, design requirements, and constraints, were carefully considered as we designed our product. The most important objective was the energy efficient mechanical movement of our panel, which was achieved through the use of two linear actuators, and a wooden linkage mechanism. Linear actuators are relatively affordable up front, and are extremely energy efficient, meaning they will keep consumer operating costs low long into the future. To know when to move, the sun-tracking system utilizes two photoresistors separated by a vertical divider. This divider casts a shadow onto the other photoresistor when it is not perpendicular to the sun, causing the panel to adjust if it is anticipated to be more energy efficient than remaining stationary.

To ensure that the sun-tracking system was waterproof through heavy rains, the non-waterproof electrical components were put into an IP-55 rated waterproof box. To ensure the system does not move in heavy winds, we used metal joints at all connection points, ensuring a strong connection. Additionally, the actuators provide two points of contact on the roof, along with a third from the wood that the non-extending side of the solar panel resides on. To accomplish the requirements of energy efficiency, the linear actuators were chosen as they only draw power when moving. Thus, they have a low long-term cost to the user, while still enabling the energy-enhancing capabilities of moving a solar panel. In order to ensure the design could rest on a slanted roof, we added brackets to prevent our actuators and linkage mechanism from sagging with gravity, which could have caused errors with the linkage mechanism.

Another appeal of the linear actuator approach was that they have a relatively low up-front cost ($130 each) and were widely available for purchase. This allowed us to comply with our budget and stay well within the time constraint we were faced with. The OSHA code was particularly influential while wiring our circuit boards to the actuators, and hooking up our MPPT to the solar panel and battery. The OSHA code calling for PPE did not influence our overall design much, but rather guided our day-to-day practices to be more safe and accident averse. The HOA solar guidelines were a large factor specifically when thinking about the aesthetics of design. We could not have a design that was too bulky or tall, as HOAs do not want solar panels to be visible from the front yard. At the same time, however, we had the freedom to make our system look however we pleased as long as they weren't visible. We had many guidelines which we tried to accommodate throughout this project. Ultimately, we designed a system we felt balanced these in the best possible way.

# 2. Overview of the Final Design

## a. Complete System

As stated previously, the final design is composed of three individual subsystems: the sun tracking sensor, the mechanical movement device, and the electric circuit and control system. These systems come together to fulfill the primary function of maximizing the amount of sunlight captured throughout a day. As the photoresistors, functioning as part of the sun tracking sensor, read the amount of sunlight, the electric circuit and control system analyze the value read by the photoresistor. The circuit then determines whether the mechanical movement device needs to be activated to tilt the solar panel to continue maximizing the amount of sunlight captured throughout a day.

The complete system was designed with the following constraints in mind: the cost of designing, prototyping, testing, and building the product is limited to a $1200 budget provided by Trinity University, and the time allotted for designing, prototyping, testing, and building of the product is limited to Fall 2021 and Spring 2022 semesters. In addition, the following requirements were considered: the design should be water-resistant through hurricane caliber rains, windproof through up to 60 mph winds, more energy-efficient than a stationary solar panel, able to rest on a slanted residential roof with roof pitch ranging up to 9/12 (36.9°), and the final product to the residential unit should be recovered within ten years of installation.

We made several changes to the overall design since the submission of the Preliminary Design Report. First, we changed the design of the mechanical movement device. Originally, the linear actuators were situated on opposite sides of the solar panel in such a way that the panel would be able to tilt about 43° E and 43° W over the course of the day. During the first half of the day, one linear actuator would be extended, tilting the solar panel towards the sun according to the value read by the photoresistor. As the sun rose higher throughout the day, this actuator would gradually retract until the panel was parallel with the ground. From here, the second linear actuator would start to extend and would continue to tilt for the second half of the day. However, this design did not take into account the moment that would be imposed on the solar panel by the linear actuator's extension. This caused the solar panel to tilt, and thus the linkage mechanism did not properly raise the solar panel, and instead it put the system at risk of breaking. Therefore, we chose to rearrange the positions of the linear actuators and set them up so that they are on the same side of the solar panel. The range of motion that the solar panel can reach is thus halved as the panel is only able to track the sun for half of the day. For the second half of the day, the solar panel will be flat on the roof. This orientation can be seen in Figure 1 below.

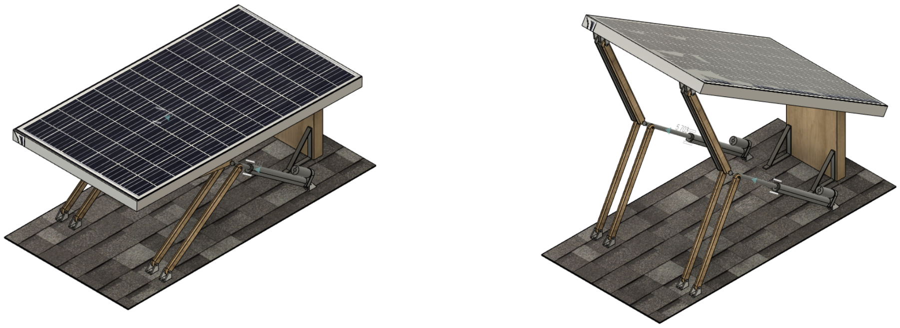

**Figure 1.** Left: Solar panel when the sun is directly above. Right: Solar panel when the sun is either in the east or west.

In making this change, the pattern in which the complete system is set up on the roof is most affected. The original idea was that one system would be able to track the sun for the majority of the day. Now, in order to limit the intermittence of energy generation, we recommend using two of the complete systems. One of the panels will be rotated 180° from the other. Though this configuration does not generate any additional energy, it would supply consumers with a more consistent energy source due to the expanded range of motion. Figure 2 below shows the orientation of the paired solar panels.

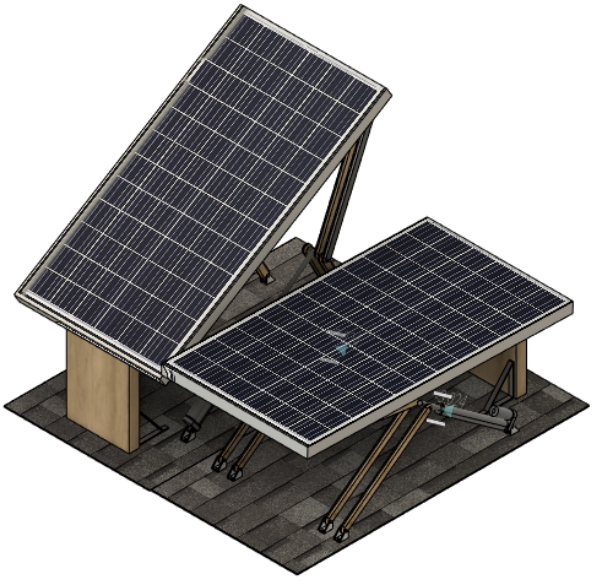

**Figure 2.** Model of the paired solar panel system used to collect consistent energy.

## b. Control System

The control system is split into two mechanisms, the sun-tracking sensor and the linear actuator controller. The sun-tracking sensor will effectively capture the sunlight incident to the solar panel and transform it into a programmable value in Arduino. The design of the sensor itself is also crucial and can be seen below in Figure 3. The blue circles represent the photoresistors, whose resistance varies depending on the intensity of sunlight incident upon them. The two photoresistors separated by a purposefully long extrusion so that as sunlight shines upon the top or bottom half a shadow is cast with the intention that the linear actuators will adjust themselves until the light shines on both halves thus maximizing the sunlight received by the solar panel.

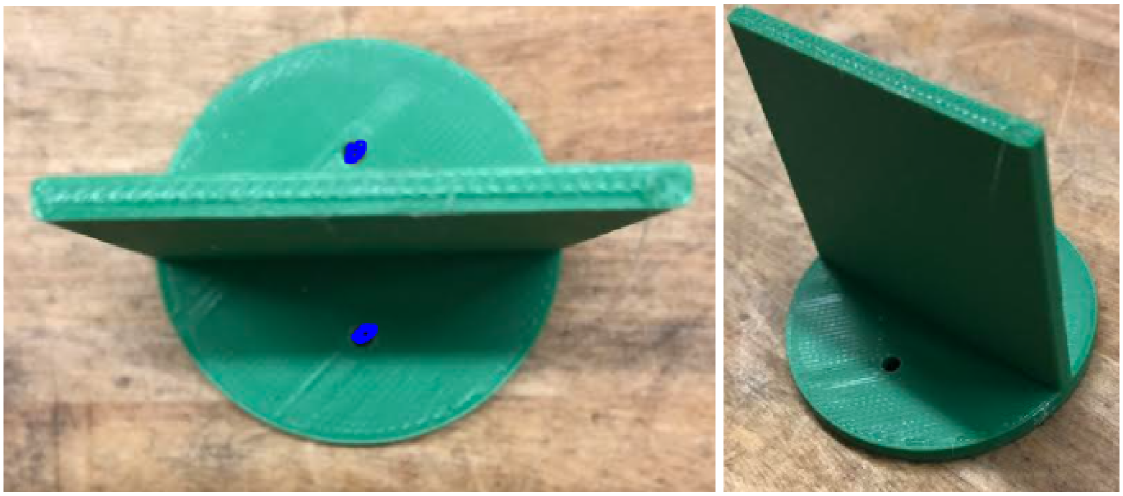

**Figure 3.** Sun-tracking sensor

The serial monitor within the Arduino Uno will read the resistance value of the photoresistors within the sensors. Arduino Uno is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins, 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header and a reset button. It contains everything needed to support the microcontroller. It can be powered by a USB cable plugged into a computer or laptop or by a 5V maximum DC battery. The operation voltage best fit the system we planned to build, which was a major factor in choosing to use it. A small set of resistors was used to step down the voltage of the 12V battery in order to provide the appropriate 5V to the Arduino Uno board.

A threshold can be found for the photoresistors by finding what resistance the photoresistors have when the acceptable amount of sunlight is incident upon them. From here, when the photoresistors read that threshold resistance or lower then the sunlight incident upon the sun-tracking sensor is optimal. However, if one half of the sensor reads a resistance above the defined threshold, then the solar panel should move appropriately to maximize total sunlight received. The sun-tracking sensor is small enough and light enough to be easily attached to the solar panel itself without obstructing any of the sunlight received by the solar panel.

The linear actuator controller is the subsystem that controls the movement and speed of the linear actuators. The linear actuator controller was constructed using IBT-2 motor drivers, a 12V battery source, an Arduino Uno, and the linear actuators by following the schematic in Figure 4.

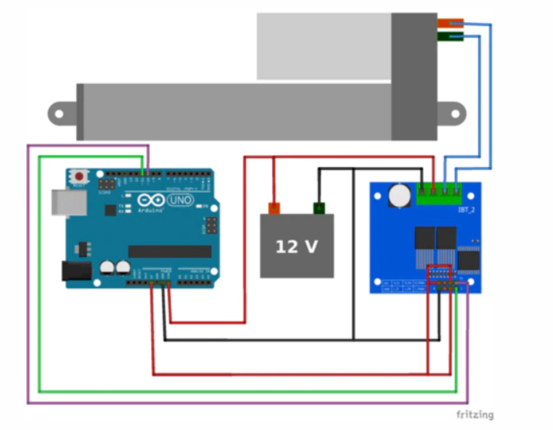

**Figure 4.** Linear actuator control system circuit diagram provided by Firgelli Automations.

The linear actuator control system circuit was combined with the sun-tracking sensor circuit as seen in Figure 5 below.

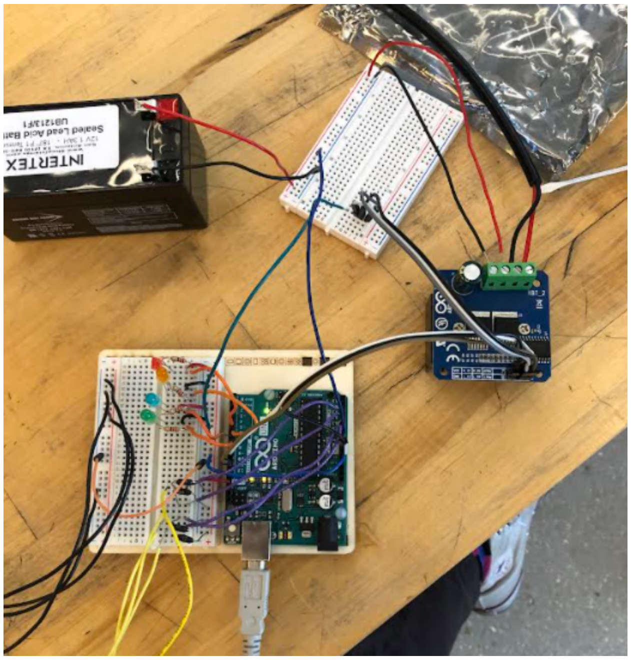

**Figure 5.** Linear actuator control system circuit merged with the sun-tracking sensor circuit.

Next, the code was combined so that as the sun-tracking sensor read a photoresistor value an LED would turn on and the linear actuator would extend or retract appropriately. The IBT-2 motor drivers were chosen to follow the schematic provided by Firgelli Automations in Figure 4 above. Firgelli Automations was the same company used to order our linear actuators. This way we knew that the motor drivers would be compatible with the linear actuators.

### c. Linkage Mechanism

The linkage mechanism has two components. One is the linear actuator which is the output device of our control system. For this design, we have chosen to use a classic rod linear actuator. These can lift, slide, push, or rotate another object as the piston extends and retracts to exert the force needed. The linear actuators used have their structural components made from aerospace-grade aluminum, allowing for a lightweight performance. These linear actuators are also IP54 rated, proving each unit to be dust and splash-resistant enough to withstand the weather. For added safety, internal limit switches deactivate the unit once the arm has reached maximum extension or retraction, protecting the device and the complete system. The operating temperature of the linear actuators range from -15 °F to 150 °F, which fits the temperatures that will be experienced by the solar panel users.

The other is a set of folding wooden rods which change the direction of force exerted by the linear actuator from lateral to vertical. This in turn is what lifts up the solar panel, allowing it to move with the sun. The extending side of the actuators connects to the wooden rods via a metal bolt. The connection between the actuators and the wooden rods allows the rods to rotate about a singular moving point. The base side of the linear actuators is connected to the roof. Each set of folding rods has two long and two short rods. The long rods connect to the solar panel on one side and the actuator on the other side. The short rods connect with the roof on one side and the actuator on the other side. Ideally if the wooden rods would be made out of steel instead of wood because wood will deteriorate more quickly especially when exposed to various weather conditions. However being conscious of our budget and time constraint we chose to work with wood.

**Figure 6.** Wooden rods of the linkage mechanism

**Figure 7.** Linear actuator and connectors

**Figure 8.** Connector

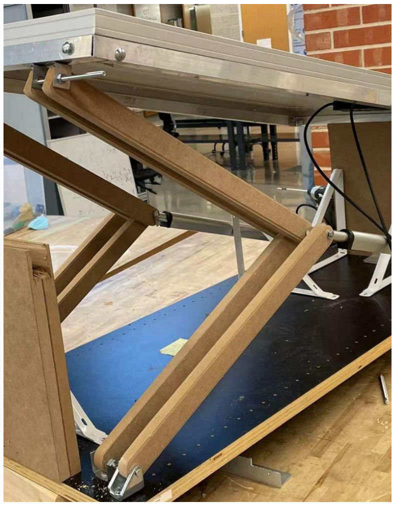

**Figure 9.** Linkage mechanism structure

When the control system sends a signal to the linear mechanism, the actuator extends the joint of the upper and lower rods causing them to straighten vertically. The pre-existing angle between wooden rods will help separate force into vertical components. This angle continues to widen, and the panel continues to tilt steeper as the actuator extends, eventually resulting in the two rods standing vertically at full extension.

# 3. Design Evaluation

## a. Water Resistance

Requirement addressed: The solar panel system should be water resistant through hurricane caliber rains.

### *i. Test Overview*

Water resistance test: The water resistance of the compartment holding all of the electrical components is essential. If water were to leak into the compartment, the design will fail due to the circuit shorting.

### *ii. Objectives*

The objective of the water resistance test was to ensure that water could not get inside the compartment holding the electrical components.

### *iii. Features Evaluated*

The water resistance test evaluated the ability of the compartment to prevent water from leaking through.

### *iv. Test Scope*

The water resistance test included exposing the water resistant compartment to water from all directions. The interior of the box was examined to determine if water was able to leak through.

### *i. Test Plan*

This test was conducted using a source of water and the IP-rated water resistant box large that was responsible for holding our electrical components. Since pressure was not being tested, the box was not submerged. Instead, it had water sprayed onto it from above and the sides to simulate rain. Tissue paper was placed inside the water resistant box to be able to easily see whether water has seeped through. Additionally, wires were placed from the box entrance to exit to simulate the wires that feed from our batteries to actuators.

### *ii. Acceptance Criteria*

The tissue paper inside the IP rated resistant box was examined to evaluate the success of the test. If the tissue paper remained dry, the test was deemed successful. If the tissue paper was found to be wet, then the water resistance was insufficient, and the test would be repeated with a higher grade box until successful.

### *iii. Test Results and Evaluation*

The water resistant box successfully passed the test plan. As we simulated rain by spraying it onto the outside of the container the tissue paper inside remained dry. This ensures that the IP rated water resistant box can safely hold the circuit and battery of our sun-tracking system.

## b. Wind Resistance

Requirement addressed: The solar panel system should be windproof up to 60 mph.

### *i. Test Overview*

Windproof Test: This test will prove that the sun-tracking solar panel system withstands winds of up to 60 mph. This will ensure that it can survive poor weather conditions and will not move on the residential rooftop.

### *ii. Objectives*

The objectives of the windproof test include:

1. The confirmation that the solar panel tracking system is stable on the roof and can withstand poor weather conditions of up to 60 mph.
2. To prove the solar panel system is safe for residential use.

### *iii. Features Evaluated*

The features of the windproof test include:

1. Measuring the force exerted on one side of the panel while stationary due to 60 mph wind.
2. Measuring the force exerted on one side of the panel while extending and contracting due to 60 mph wind.
3. Measuring the force exerted on one side of the panel while the actuators are at maximum extension due to 60 mph wind.

### *iv. Test Scope*

The force of the wind was tested on the entirety of the solar-tracking device. A model of the design was built in Fusion 360 and tested using Autodesk CFD.

### *v. Test Plan*

To perform the windproof test, Autodesk CFD was used. Wind was simulated in increments of 20 mph until 60 mph was reached. These increments were used to evaluate the changes in drag and lift. If the design could withstand 60 mph, then the wind would be further tested in increasing increments of 10 mph to determine the maximum wind speed the design could withstand. In this test, the drag force evaluated horizontal direction force caused by wind; the lift force evaluated the vertical direction force caused by wind.

### *vi. Acceptance Criteria*

The solar panel tracking system would be considered successful if it did not exceed drag forces of 150 N and lift forces of 100 N when exposed to 60 mph wind. If drag forces of 150 N and lift forces of 100 N are encountered at speeds of less than 40 mph, then the design will have to be reevaluated and retested.

## vii. Test Results and Evaluation

Computational fluid dynamics (CFD) simulations were performed at three different positions for our solar panel system: flat/resting, half way extended, and fully extended. For the duration of this testing, the complete system was tilting towards the eastward direction, while the wind came from the westward direction. A cube of air surrounded the complete system, allowing for the following boundary conditions to be used: the underside of the solar panel as it tilted was provided the constant wind, and the face facing the top of the solar panel as it tilted was given a pressure of 0 to let the wind flow out. In this section, the results for 60 and 70 mph winds are shown, with the remaining test result figures allocated to Appendix 5.2. These remaining figures include the results for 20 and 40 mph winds for each orientation and wind direction.

The following results are grouped by the orientation that the solar panel was tested. With the wind coming from the west, the wind had a greater chance of pushing the solar panel upwards, creating greater force. If the complete system could withstand the scenario that would create the most drag, then it was assumed that the complete system could withstand the scenarios at lower wind speeds that created less drag and lift.

### 1. Flat/Resting

When the solar panel was in the flat position, the solar panel remained stable at 20, 40, 60, and 70 mph. Figure 10 shows the planar view of the magnitude of velocity at 60 mph when the wind is approaching from the west. Figure 11 shows the convergence plot at 60 mph when the wind approaches from the west. It can be seen that at 60 mph, the complete system reached a steady state where the measured values approached a constant value over time. In this scenario, the complete system experienced a maximum drag of 101.18 N and maximum lift of 17.88 N. Both of these values passed the acceptance criteria.

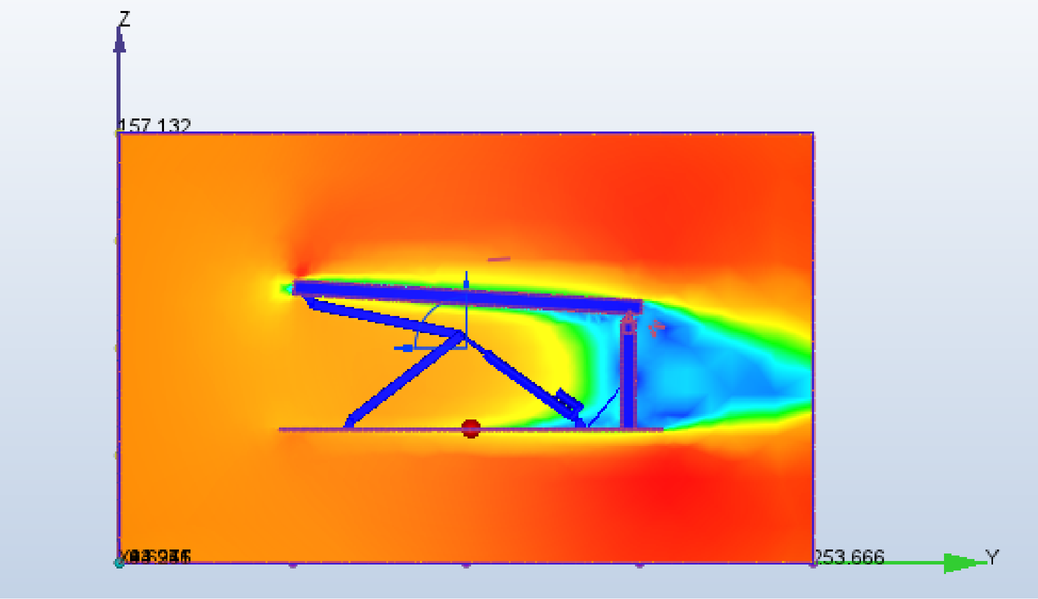

**Figure 10.** CFD simulation of 60 mph wind approaching the eastward oriented system from the west when the complete system is flat/resting.

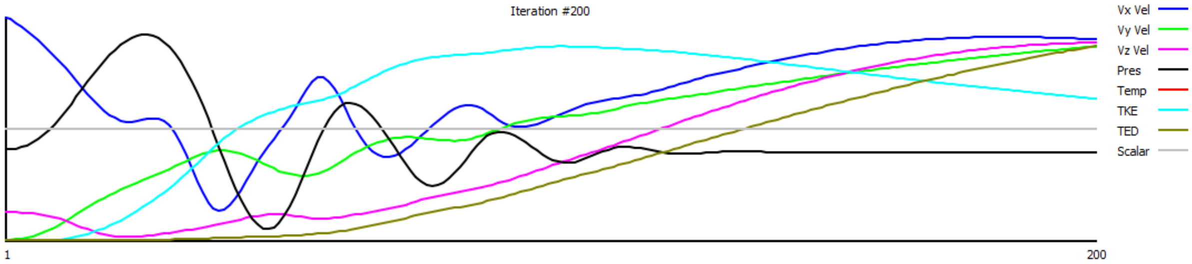

**Figure 11.** Convergence plot based on CFD simulation of 60 mph wind approaching the eastward oriented system from the west.

At 70 mph, the complete system reaches a steady state where the measured values reach a constant value over time. In this scenario, the complete system experiences a maximum drag of 157.28 N and maximum lift of 23.51 N. Though our criteria does not hold for 70 mph, the results of which can be seen in Figures 12 and 13, this information is still good to know, and can be improved upon for the future.

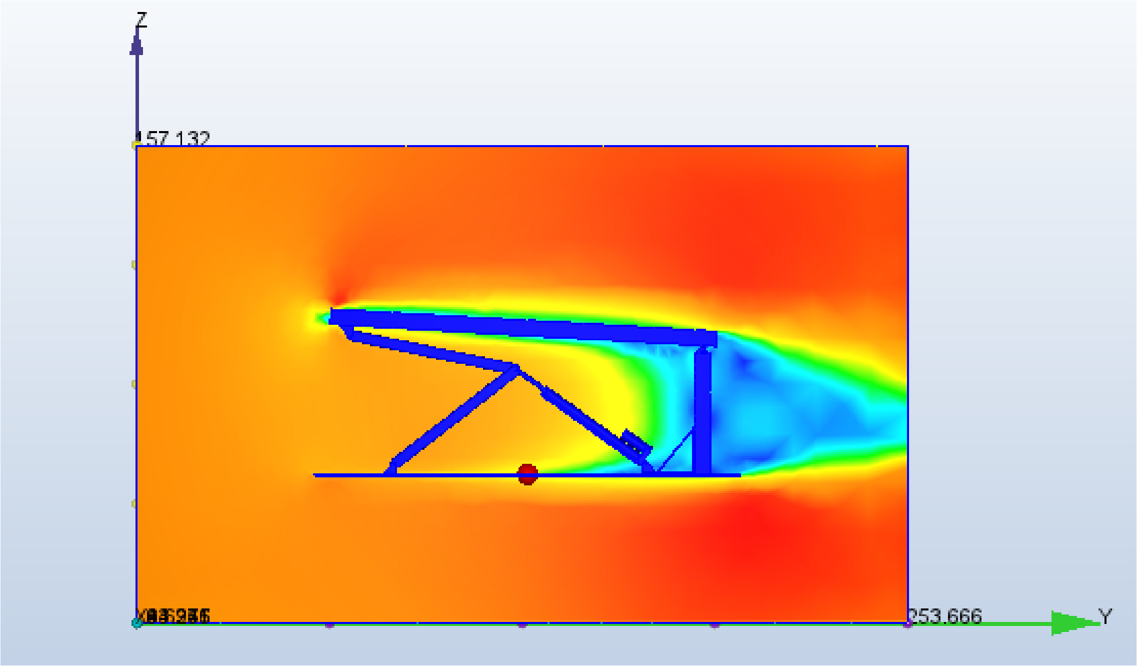

**Figure 12.** CFD simulation of 70 mph wind approaching the eastward oriented system from the west when the complete system is flat/resting.

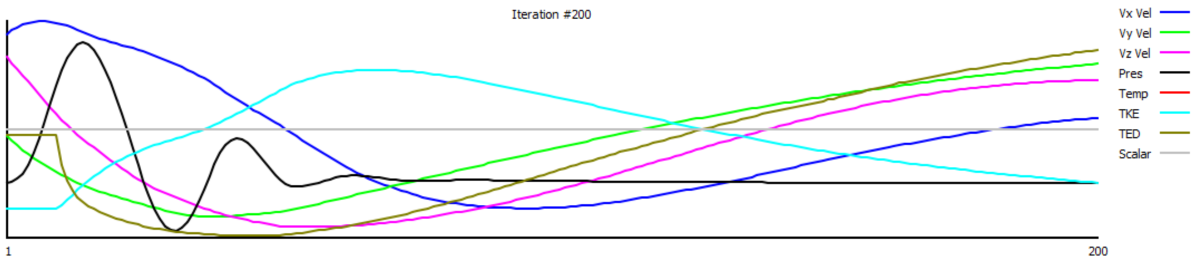

**Figure 13.** Convergence plot based on CFD simulation of 60 mph wind approaching the eastward oriented system from the west.

## 2. Half Extended

When the solar panel was half way up, the solar panel remained stable at 20, 40, 60, and 70 mph wind speeds. Figure 14 shows the planar view of the magnitude of velocity at 60 mph when the wind was approaching from the west. Figure 15 shows the convergence plot at 60 mph when the wind approaches from the west. At 60 mph, the complete system appeared to be in the process of reaching a steady state, as the measurements approached a constant value over time. In this scenario, the complete system experienced a maximum drag of 149.84 N and maximum lift of 95.32 N. These values were extremely close to the maximum limit for the testing. Though they did pass the criteria, it would be beneficial to find a more stable design.

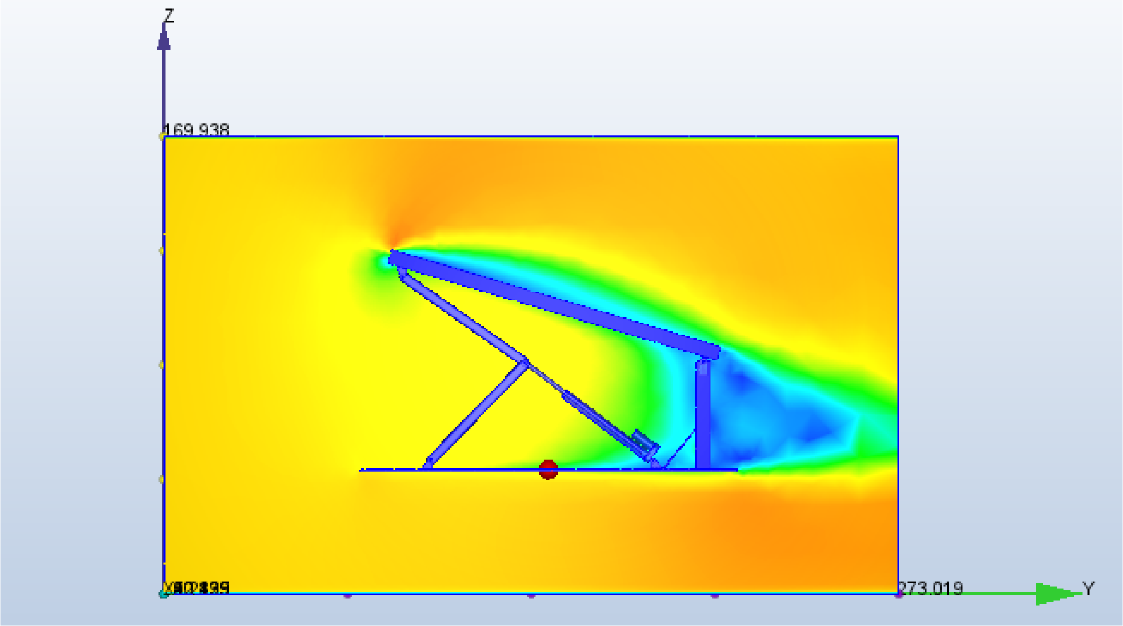

**Figure 14.** CFD simulation of 60 mph wind approaching the eastward oriented system from the west when the complete system is half-way up.

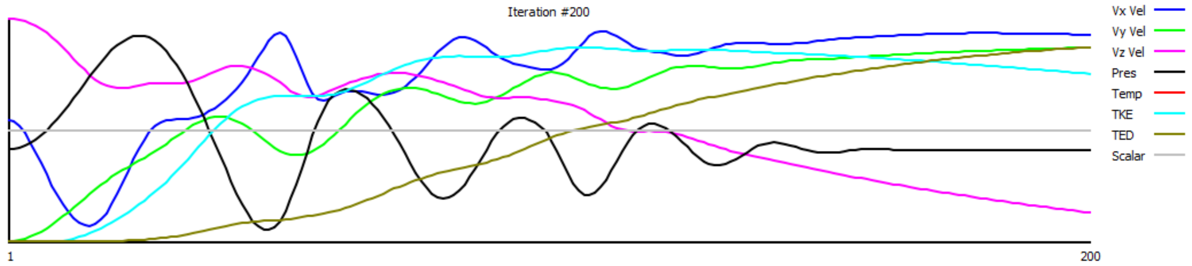

**Figure 15.** Convergence plot based on CFD simulation of 60 mph wind approaching the eastward oriented system from the west.

At 70 mph, the complete system experienced a maximum drag of 306.95 N and a maximum lift of 134.27 N. The results for these simulations are seen in Figures 16 and 17.

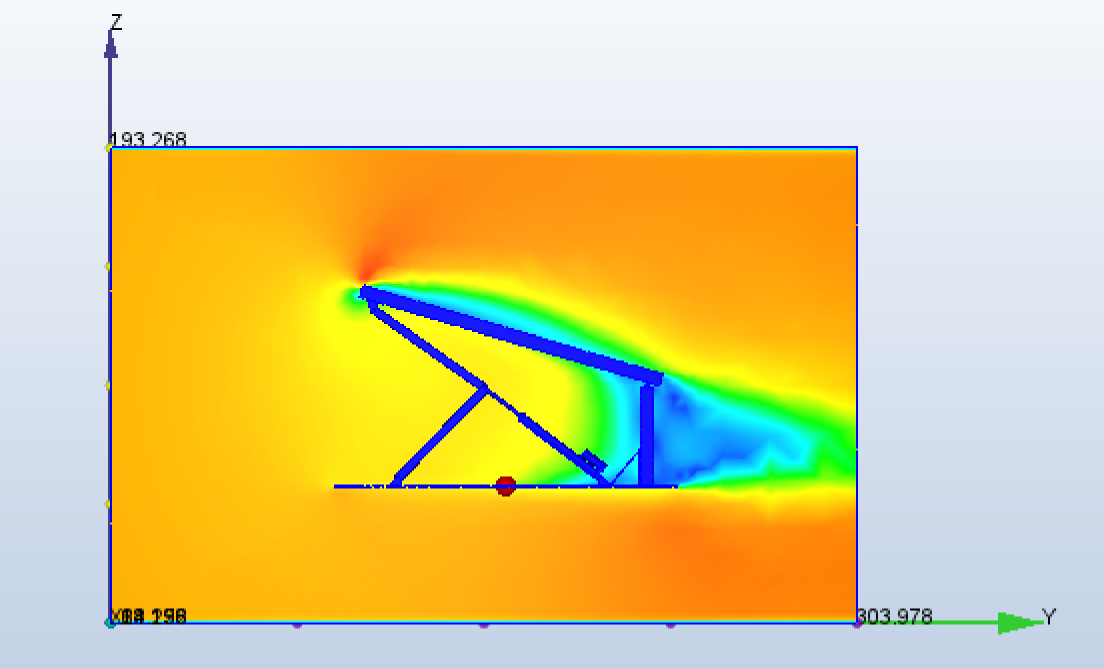

**Figure 16.** CFD simulation of 60 mph wind approaching the eastward oriented system from the west when the complete system is half-way up.

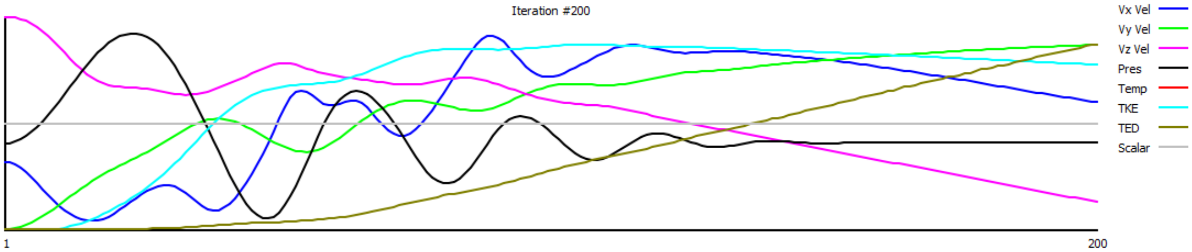

**Figure 17.** Convergence plot based on CFD simulation of 60 mph wind approaching the eastward oriented system from the west.

### *3. Fully Extended*

When the linear actuators were fully extended, the system remained stable at 20 and 40 mph. Figure 18 shows the planar view of the magnitude of velocity at 60 mph when the wind is approaching from the west. Figure 19 shows the convergence plot at 60 mph when the wind approaches from the west. At 60 mph, the complete system did not reach steady state, as some of the measured values did not approach a constant value over time. In this scenario, the complete system experienced a maximum drag of 300 N and maximum lift of 170 N. These values far exceeded those of our criteria, therefore, our complete system failed when the linkage mechanism was fully extended.

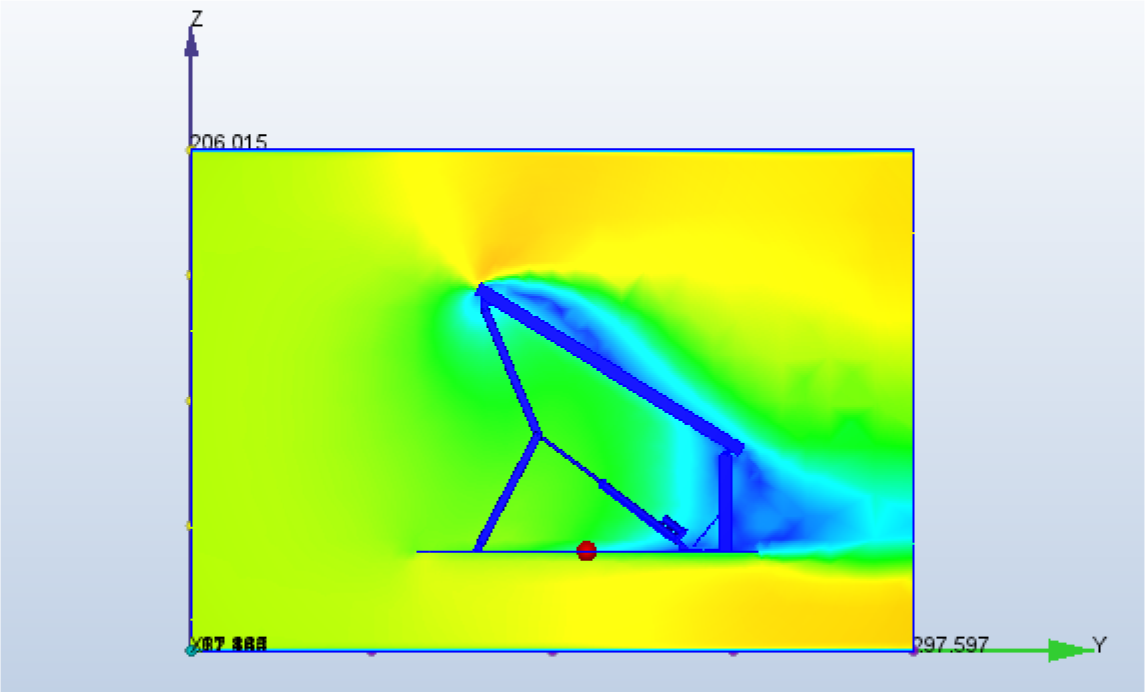

**Figure 18.** CFD simulation of 60 mph wind approaching the eastward oriented system from the west when the complete system is fully extended.

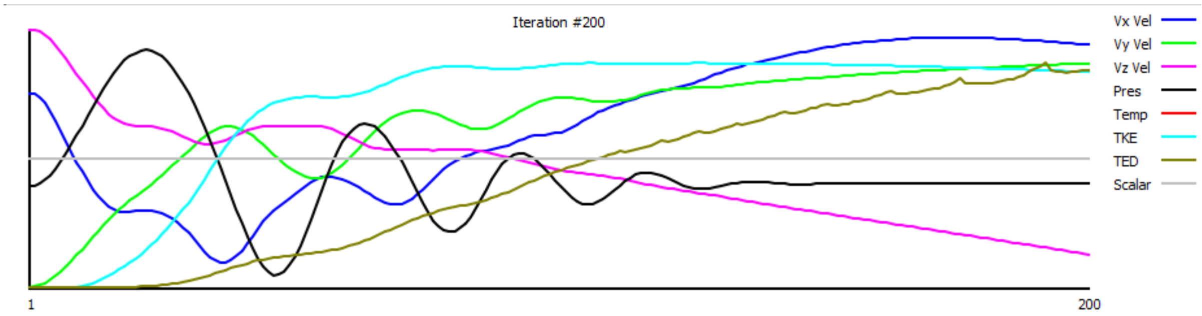

**Figure 19.** Convergence plot based on CFD simulation of 60 mph wind approaching the eastward oriented system from the west.

Though it was not required, the simulation was also performed to see what would happen to the fully extended system at 70 mph. This simulation seemed very similar to the simulation at 60 mph. The velocity magnitudes look nearly identical, however, the convergence plots show differences in how the measured values approach steady state. A 70 mph wind yielded worse results, which was expected, as seen in Figures 20 and 21. The drag force was 572.98 N and the lift force was 460.12 N.

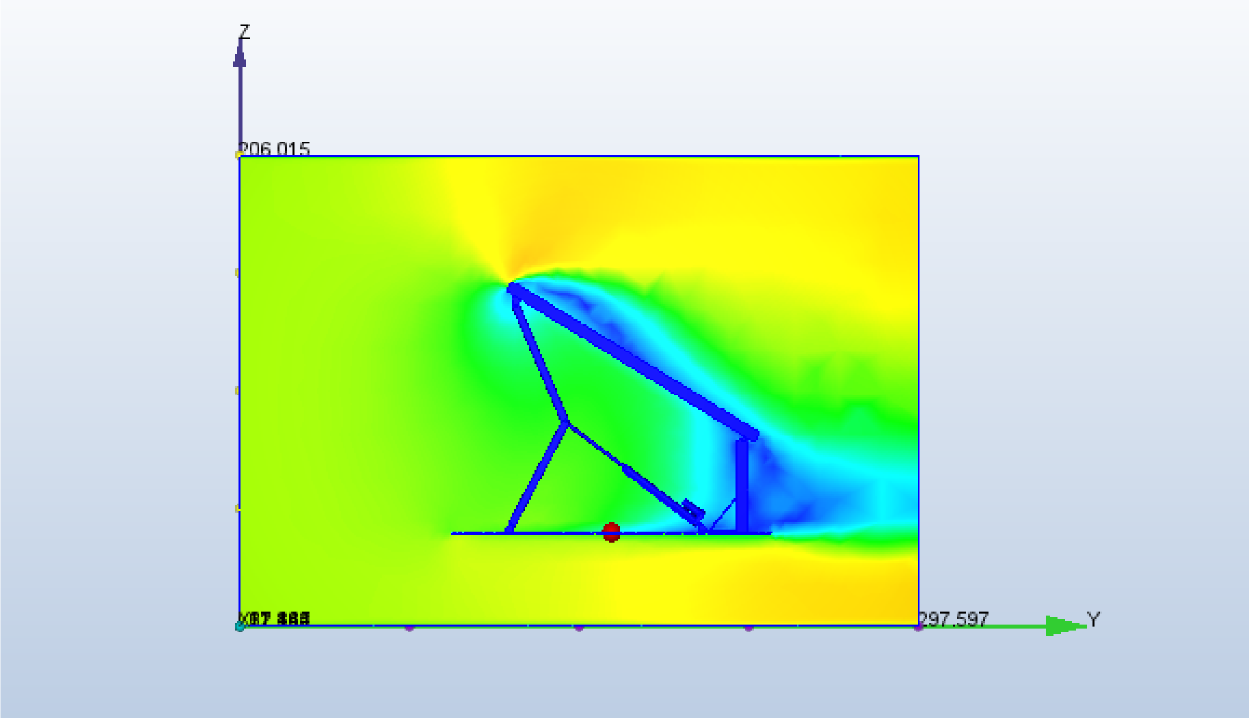

**Figure 20.** CFD simulation of 70 mph wind approaching the eastward oriented system from the west when the complete system is fully extended.

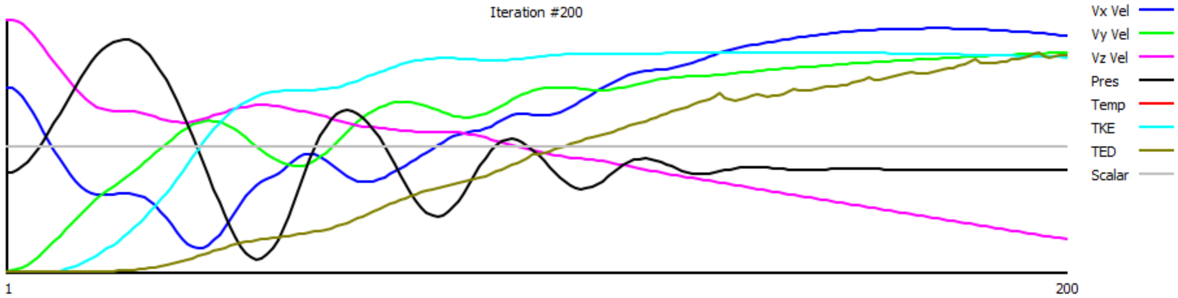

**Figure 21.** Convergence plot based on CFD simulation of 70 mph wind approaching the eastward oriented system from the west.

As these simulations were performed, there was a noticeable trend. When the solar panel was flat, the lift force would be significantly less than the drag force. While the drag force increased with the wind speed, the lift force didn't vary significantly. When the solar panel was half way up, the drag force was higher than the drag force of the flat orientation, as was the lift force. The lift force increased to about half of the value of the drag force at half extension, depending on the wind speed. Once the solar panel reached full extension, the lift force was about 85% of the drag force. This shows that as the actuators extend, the lift force increases as there is more exposed surface area of the solar panel for the wind to act on.

## c. Weight Test

Requirement addressed: The sun-tracking solar panel system should be able to rest on a slanted residential roof with roof pitch ranging from flat up to 9/12 (36.9°) to be installed on the roof.

### *i. Test Overview*

Weight Test: This test will prove that the sun-tracking solar panel system does not exceed the maximum weight capacity of a residential roof at any given location on the roof, or any tilt configuration of the roof.

### *ii. Objectives*

The objectives of the weight test included:

1. Confirming that the weight of the solar panel system was below 20 pounds per square foot.
2. Proving the solar panel system was safe for residential use.

### *iii. Features Evaluated*

The features of the weight test included:

1. Measuring the force exerted on one side of the panel while stationary.
2. Measuring the force exerted on the higher side of the panel while both actuators are at maximum extension.
3. Measuring the force exerted on the lower side of the panel while both actuators are at maximum extension.

### *iv. Test Scope*

The sun-tracking solar panel system's weight was tested using two identical slabs of wood. One represented the roof by itself (baseline weight) and the other represented the roof with the system on top. The slabs were placed flat with one half on a scale and the other half on a textbook at the same height. This allowed us to determine the weight that was acting on a given section of the roof.

### *v. Test Plan*

To perform the weight test the following instruments were needed:

1. A bare slab of wood (roof)
2. A slab of wood (roof) with a sun-tracking system mounted on top of it
3. A scale that can support our wooden roof

To conduct this test the system had to be moving properly so that the force exerted could be measured throughout the entirety of its range. A scale and a stack of books were set to the same height so that the slab of wood could be placed flat on top. The slab of wood without the solar panel mounted was placed flat on the scale and the weight was recorded. The weight detected by the scale throughout this test was approximated to be the force per square foot in the maximum stress areas of the panel system. This was because the majority of weight was beared on the two sides of the panel system, with approximately one square foot on each side bearing the brunt of the load.

Next, the slab of wood with the solar panel mounted was substituted in for this bare slab. The weight of this system was recorded. Then, the solar panel was tested at its maximum tilted setting. The weight was monitored as the actuators extended to full extension, and the force exerted was recorded. Then, the prototype was turned 180° and the force on the other side was measured. If the weight being borne by the scale never exceeded 20 pounds, the panel system was considered to have passed the weight test. Figure 22 shows the retracted solar panel system being weighed.

**Figure 22.** Solar panel system resting flat with one-half on the scale and the other half off.

## *vi. Acceptance Criteria*

The criteria that must be met to pass the test include:

1. The ability of the sun tracking system to exert less than 20 pounds of force per square foot while stationary.

2. The ability of the sun tracking system to exert less than 20 pounds of force per square foot on the higher side of the panel.

3. The ability of the sun tracking system to exert less than 20 pounds of force per square foot on the lower side of the panel.

### *vii. Test Results and Evaluation*

The weight test that we performed yielded positive results. We were able to test and pass all proposed criteria. The first test involved less than 20 pounds of force per square foot while the system was stationary. Our setup involved a panel that weighed 16.31 pounds and the mounting system (actuators and other parts) that weigh approximately 17.70 pounds. Given that we distributed this force across two 1-square-foot mounting areas, this amounted to approximately 17 pounds per square foot mount. Thus, our first criteria was met.

The second and third criteria tested was for when the sun tracking system was at maximum extension on the higher side of the panel. The tilt of the solar panel means that more force should be concentrated on the side that is lower to the roof. Given that our solar panel's maximum angle of tilt is approximately 43°, the solar panel itself exerted 10.75 pounds of force on the mount of the low side, and 5.56 pounds of force on the other mount. The mounting system still exerted the 17.70 pounds of total force, split evenly between the two mounts. This resulted in the low side mount carrying 19.60 pounds of force per square foot, and the high side carrying 14.40 pounds per square foot. Since these were both under 20 pounds per square foot mount, the system passed the second and third criteria for the weight test.

Overall, this was a positive test for the weight of our solar panel system, as it met all three criteria proposed and tested.

## d. Power Comparison Test

Requirement addressed: The solar panel system should be more energy-efficient than a stationary solar panel.

### *i. Test Overview*

Power comparison test: The power of the solar panel can be measured by multiplying current and voltage. We were constrained with only one solar panel, and thus it acted as both our control (always flat) solar panel, and our adjusting solar panel. To test this criteria, we manually adjusted our solar panel between flat and an optimized angle of incidence to the sun. We assumed that light intensity did not change between data collection for the two configurations as we took data for both configurations within one minute. Over the course of the day, readings of both solar panel configurations were taken every thirty minutes. Thus, we gathered data from a control solar panel and our adjusting solar panel. From this, we were able to make comparisons between fixed solar panels and a sun-tracking solar panel mechanism.

### *ii. Objectives*

The objectives associated with this test included:

- Measuring the power of a fixed solar panel and a sun-tracking solar panel.
- Modeling the power data.
- Comparing the total energy generated.

### *iii. Features Evaluated*

The features of the power comparison test included:

1. The voltage of the solar panel.
2. The current of the solar panel.

### *iv. Test Scope*

The sun-tracking solar panel system's power could be measured from the Maximum Power Point Tracking (MPPT) time data. The MPPT measured the current and the voltage of the solar panel. The fixed solar panel was resting on a 45° inclined south facing roof for the entire day. The rotating solar panel had the same initial alignment as the fixed solar panel, but could extend on one axis to optimize the angle of incidence with the sun.

### *iv. Test Plan*

To perform the power comparison test the following instruments were needed:

1. A solar panel
2. A wood slab (roof)
3. An MPPT

To perform this test, the solar panel was placed at a 45° angle facing south on the wood slab representing the roof. A closed loop was formed between the MPPT and battery for the solar panel system. Once the loop was formed, the MPPT could read the voltage and current being output by the solar panel. Every 30 minutes the voltage and the current were recorded. Immediately after recording these values for the fixed panel, the solar panel was tilted in such a way that the solar energy collected was maximized. The voltage and current data was then recorded for this configuration. We ensured that the time between data collection for the flat and optimized solar panel configurations was as low as possible.

### *v. Acceptance Criteria*

The criteria that must be met in order to pass the test include:

1. The overall power of the sun-tracking solar panel system is higher than the fixed position solar panel.

### *vi. Test Results and Evaluation*

The purpose of this test was to estimate power generation over the course of a day. Table 1 displays the time and the power generated from the 100W solar panel in a fixed and sun-tracking state. The maximum power generated from the sun-tracking solar panel system was 82W, compared to the 75W that the fixed panel generated. Effective generation time was roughly from 6:30 AM to 5:30 PM. While testing, the maximum power was reached at the same time of day. In a simulated environment, however, the sun-tracking solar panel arrived at its peak slightly earlier than the fixed solar panel.

To compare the rough data, we used modeling to smooth the peaks and calculate how much power was generated. Figure 23 shows four lines of power generation. The blue line represents the fixed solar panel, and the orange line represents the sun tracking solar panel. We tested our sun-tracking solar panel in operation for the entire day, while in reality it will only track for half of the day, and be flat for the other half. To account for this, we calculated our additional energy generated by setting the morning values of our sun-tracking solar panel equal to the flat solar panel values. We then summed this value with energy generated in the afternoon for the fixed and sun-tracking solar panels, respectively. We calculate this afternoon value by integrating the quadratic function of power and calculating the area difference between them. Summed with equal morning values, this yields a difference in energy of 2038360.2-1647944.52=390415.7 J. This is approximately 23.69% more energy generated than the fixed solar panel. Converting to kW-h, the extra energy that one sun-tracking solar panel can generate is 0.1084 kW-h.

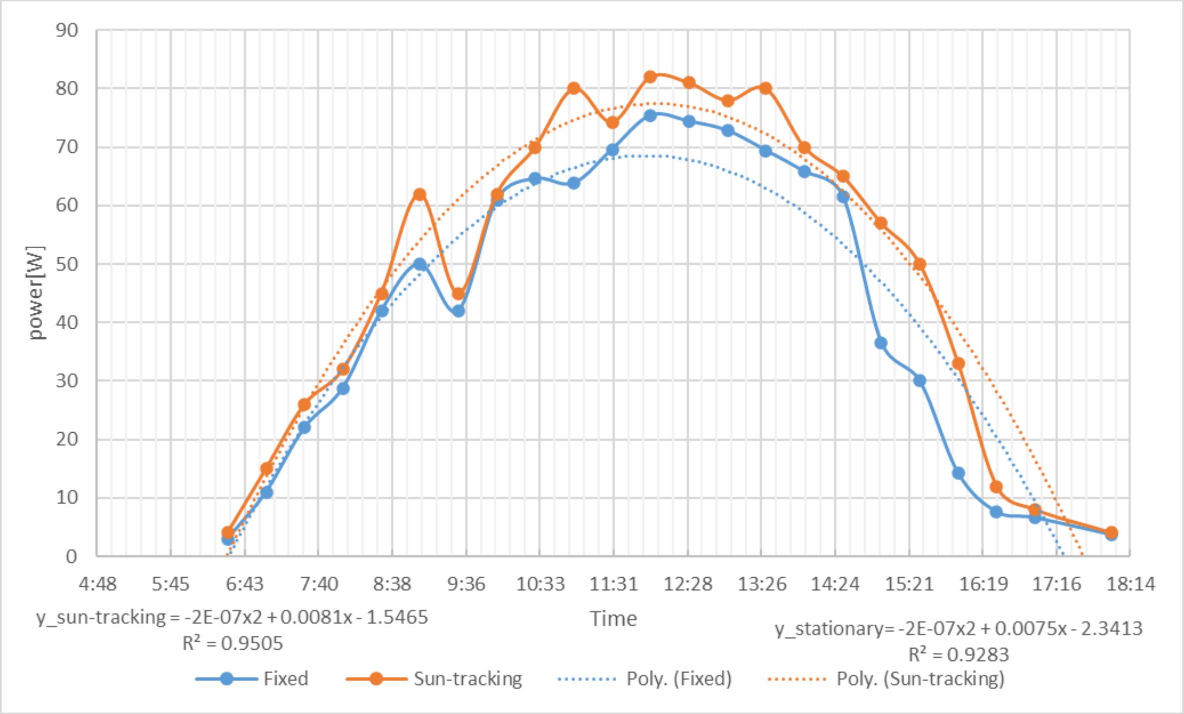

**Figure 23.** Power of data of fixed solar panel and sun tracking panel and molding.

1 kW-h of electricity in Texas typically costs 13 cents. Thus, we estimate each solar panel can save 1.401 cents per day. The data we collected has one standard deviation of uncertainty, meaning at least 68% of trials would produce similar results.

## e. Assumption of cost

Requirement addressed: The additional cost of the final product to the residential unit should be recovered within ten years of installation.

### ○ Evaluation

Since our data is specific to one day, we recognize that there will be variability throughout the year in ability to harvest energy. We estimate that two-thirds of the days in Texas will have a similar performance in power generation. For the remaining one-third of the days, we will assume they match the energy generation of a flat solar panel (no advantage). The economic value of extra electricity energy is 1.401 cents/day × (365days/year) × 10 years ÷ (100 cents/dollar) × ⅔ = $34.

The incremental cost of the sun-tracking system is around $400, which can support six 100-W solar panels tracking the sun during a day. Thus, each sun tracking solar panel costs $66.70. This means the net loss over 10 years to households would be $32.70 per sun-tracking solar panel.

## f. Remain Within $1200 Budget

Constraint addressed: We were tasked with a $1200 budget as supplied by the Trinity University Engineering Science Department.

### ○ Evaluation

We stayed under this budget as we only spent $660.26 out of the $1200 we were given.

## g. Time Constraint

Constraint addressed: We were tasked with accomplishing our project within the confines of the two semesters.

### ○ Evaluation

We stayed within this timeframe as we were able to build a prototype, test it, make modifications, then retest all within the allotted time.

## h. HOA Aesthetics Review

HOAs do not want any solar panels to be visible to folks driving by. Thus, our panels had to be low enough to the roof that they were not visible.

### ○ Evaluation

This was one of the harder criteria to evaluate, as it is tough to tell what the pitches of roofs will average. Overall, we think our panels will be able to remain out of sight on most deep-slanted roofs. For shallow roofs, our design may be visible to those walking, meaning we may not be able to install as many on this kind of roof.

# 4. Conclusions

## a. Current Project Status

The current prototype partially accomplishes the goals we set forth in our updated project proposal. We have created a cost-efficient solar panel for residential usage that shifts on one axis to help maximize electricity output. We have implemented controls so that it only shifts when the projected energy that will be gained from shifting exceeds the energy it requires to shift. The goal that we did not meet, however, was improving the energy collection by approximately 40% over a stationary solar panel. This lofty goal was not met, and our system instead improved energy collection by about 24% over a stationary solar panel. We still felt this value to be encouraging, as it was a noticeable improvement from a stationary panel.

Of the design requirements we set forth in our project proposal, we accomplished three out of the five. The first successful test pertained to water proofing our design. It met the criteria that the design should be waterproof through hurricane force rains. The next criteria we tested for was the windproof ability of our solar panel system. When the solar panel system was laying flat or half way extended, the simulations proved the system would remain stable at winds up to 60 mph. When the solar panel system was fully extended, however, the wind simulation could not prove complete stability at 60 mph. Though it was partially stable, we did not feel it provided a safe environment. Thus, the windproof design requirement of our solar panel system was not met. After this, the design requirement of being able to safely sit on a residential roof was achieved through the weight test. The final two design requirements pertained to the power generation and economical side of the project. We showed that the solar panel system was more energy-efficient than a stationary solar panel. The final design requirement we tested was that the additional cost of the final product should be recovered within ten years of installation. Despite the increased efficiency in energy collection, the additional cost of supplies left our system at a 10-year deficit of $32.70 per solar panel.

In addition to these design requirements, the objectives we set for our project were also met. The most prominent objective was creating a cost-efficient residential solar panel that had the potential to improve net energy by tracking the sun, which we did. We wanted our system to shift on at least one axis, which it does. The system was supposed to only shift when the additional energy gained by adjusting was greater than the energy required to shift the panel. Fortunately, our control system code incorporates a measure to address this scenario, which means that we successfully satisfied all objectives that we set out to achieve.

The most exciting part of our prototype is that it works. When deployed into a light setting, it is able to track the source of light as described in our project objectives. Fortunately, as mentioned previously, we were also able to achieve all design requirements. One area we were unable to achieve the goal we set was in our project proposal. We set a goal of achieving a 40% increase in energy collection, but came up short with our system instead improving energy collection by about 23.69% over a stationary solar panel.

## b. Next Steps and Recommendations

After finalizing our prototype for the semester there are some recommendations we would make for continuation of our design. The first suggestion is making the solar panel lower to the roof. This would allow the solar panel to be more stable and deal better with the effects of wind. Additionally, the solar panel being lower to the house would greatly increase the appeal of these panels to HOAs, as they will be less visible from the street. Given our current design the solar panel rests about a foot above the roof. This can cause leaves, animals, and other debris to sit directly below the panel and potentially interfere with the wiring. If we were unable to devise a solution that involves lowering the panels, we would suggest implementing some sort of guard around the current opening that helps prevent this buildup.

Another step that we foresee is pairing a tandem of solar panels rotated 180° from each other to help limit the intermittence of energy generation. Though this configuration does not generate any additional energy, it would supply consumers with a more consistent energy source throughout the day, which is valuable. For example, one of the two panels will be tilting from morning to mid-day, while the other is stationary, as shown in Figure 2. Once the originally moving panel is flat, the second panel will start rising and following the sun until night time. This allows for a full range of motion throughout the day, and thus a more consistent energy supply. Since we only had one complete system, we only tested the energy collected when it could rise in the afternoon. So, as a next step, we would duplicate the system, set it 180° from the original, and observe one of the two solar panels tracking all day.

Furthering this idea, another optimization we envision being implemented one day is a similar set of actuators on the other side of the solar panel. This would allow for an increase in sun-tracking ability and efficiency, as a singular panel could track the sun from morning until midday and midday until night, as opposed to just one of those time periods. This would maximize spatial efficiency of the panels. This was our initial goal for our project, but due to unanticipated difficulties, we were only able to implement the actuators on one side. Given more time, this would be one of the first things we would address to improve our design.

To achieve our goal of a 40% increase in energy collection, a second axis of rotation for the panel could be added, or a set of actuators on the opposite side of the current set could be implemented. Another area we came up short in was the wind test design requirement. Two of the three orientations tested worked, but a full extension of the actuators caused instability. To address this issue going forward, a wind sensor could be installed on our system, and the solar panel could retract to flat when it senses winds above a certain speed. Since the flat solar panel is able to withstand much higher wind speeds, this should resolve any possibility of instability when winds are high. Another potential solution would be to add more points of contact to the roof. This would allow for drag and lift forces to be distributed across more contact points on the design, thus reducing the amount of drag and lift acting on each point. The last requirement we failed to meet was the cost of the solar panel system paying itself off after 10 years. To combat this, we either need to harvest energy more efficiently or lower the product cost. We believe the best choice in this scenario would be to add another axis of rotation.

There were a few other minor optimization issues that we did not address but feel we should in the future. The first is to employ quieter actuators. Currently, the actuators are audible from a good distance away, which would not only be disruptive to neighbors and those passing by, but likely cause serious frustration to the people living with them on the roof. The second quick optimization would be to replace our current wooden linkage mechanism with aluminum. This would increase the longevity of our prototype due to wood's tendency to rot over time (especially in the elements) and reduce the potential of breaking due to repeated stresses. Replacing our actuators to be quieter, as well as substituting aluminum for our wooden linkage mechanism would be great steps for the future of our project. The third optimization is to design a support system to counteract the moment imposed on the solar panel by gravity. As roofs get steeper, the moment imposed on the system due to gravity will increase. By installing supports for the linkage mechanism, this would ensure we limit fatigue on the system and increase the product life span.

## c. Potential Pitfalls & Alternatives

One limitation of our testing was that we did not have the opportunity to evaluate how the complete system behaved for several days in a row. During the last month of the semester, the weather was very poor. Heavy rain and dark clouds did not allow for optimal data collection. When we were able to test our system, we determined that the system behaved as intended.

In regards to specific areas of the complete system, we have identified four areas of concern that should be addressed when considering the final model of the completed system. These include repairs, linear actuator durability, the legs of the linkage mechanism, and long-term stress on the roof.

In regard to the repairs, we did not test the simplicity or difficulty of repairs due to the time constraint. However, the design of the complete system is very modular. Therefore, should something malfunction, a complete disassembly is not required. The part raising concern can be taken out and replaced without affecting other parts of the system, meaning a cost and time-efficient repair. The linear actuators that we chose are meant to last for at least 25 years. The durability of a linear actuator does vary depending on the environment in which it is placed. However, due to the impressive IP54 rating of our linear actuators, we expect them to last at least 25 years. The legs of the linkage mechanism are currently made out of wood. This makes the legs susceptible to becoming waterlogged, rotting, and otherwise deforming. To help increase the durability of this linkage mechanism, an aluminum alloy would likely be used instead of wood, as they are very corrosion resistant and strong. The continuous load that is applied on the roof will likely take its toll on the long-term well-being of the structure. Once we saw that our solar panel system passed the weight test for safety, we did not think much about the weight of it. Though we have not researched it extensively, the integrity of the roof is a likely pitfall for houses with a lot of panels on their roof. Though this may be a hindrance, we could look into using a lighter material for our solar panel, or a lighter material for our actuators.

The last aspect of the complete system that needs further testing is the results of the wind simulation at 60 mph. The simulations were performed under the conditions that the wind will be going towards the underside of the solar panel. This is the situation in which the complete system will experience the most force from the wind. Due to this, the complete system experienced large amounts of force, especially when considering the scenario when the linkage mechanism was fully extended. In the future, an alternative to using a solid board to hold up one side of the solar panel could be splitting it up into 2 boards. With two boards, space can be left in between, which would allow for wind to be able to flow through and lessen the drag force. While there wouldn't be a large impact to the lift force, the opening at the other side of the system would allow for an escape for the wind.

# 5. Appendices

## i. References

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## ii. Results of Additional Wind Tests

### v. Flat/Resting

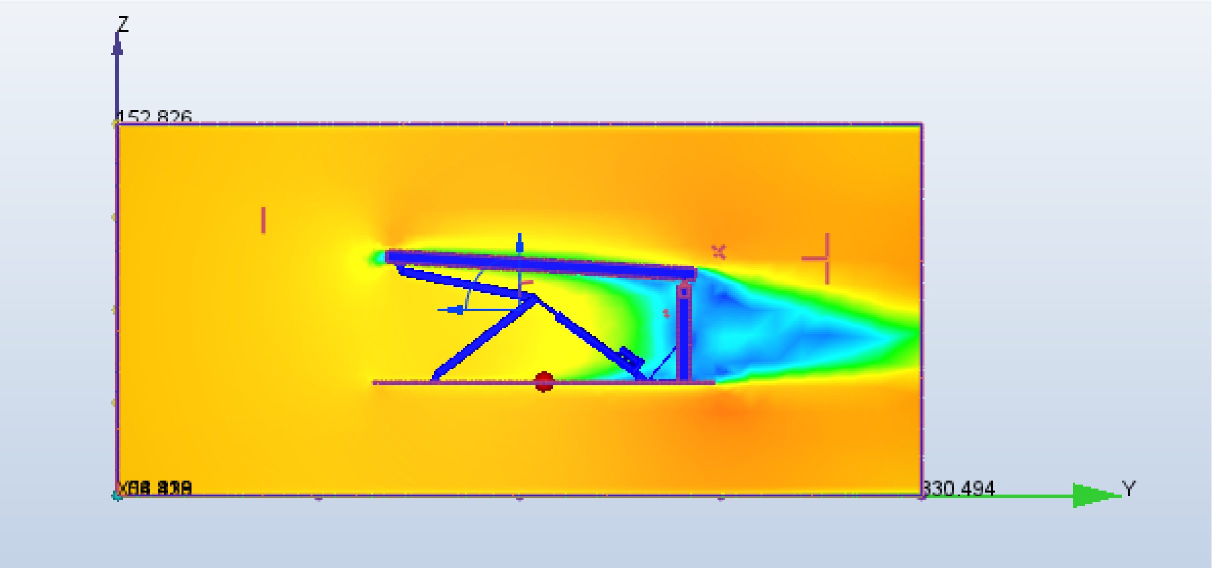


**Figure 5.2.1.1.** CFD simulation of 20 mph winds when the complete system is flat/resting. The drag is 17.60 N and the lift is 4.19N

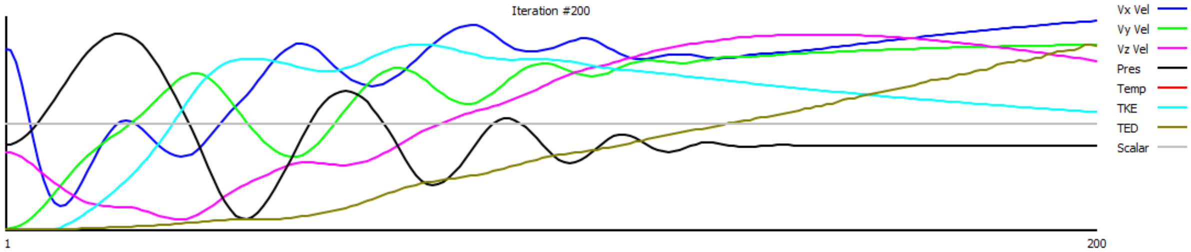


**Figure 5.2.1.2.** Convergence plot of 20 mph winds when the complete system is half-way up.

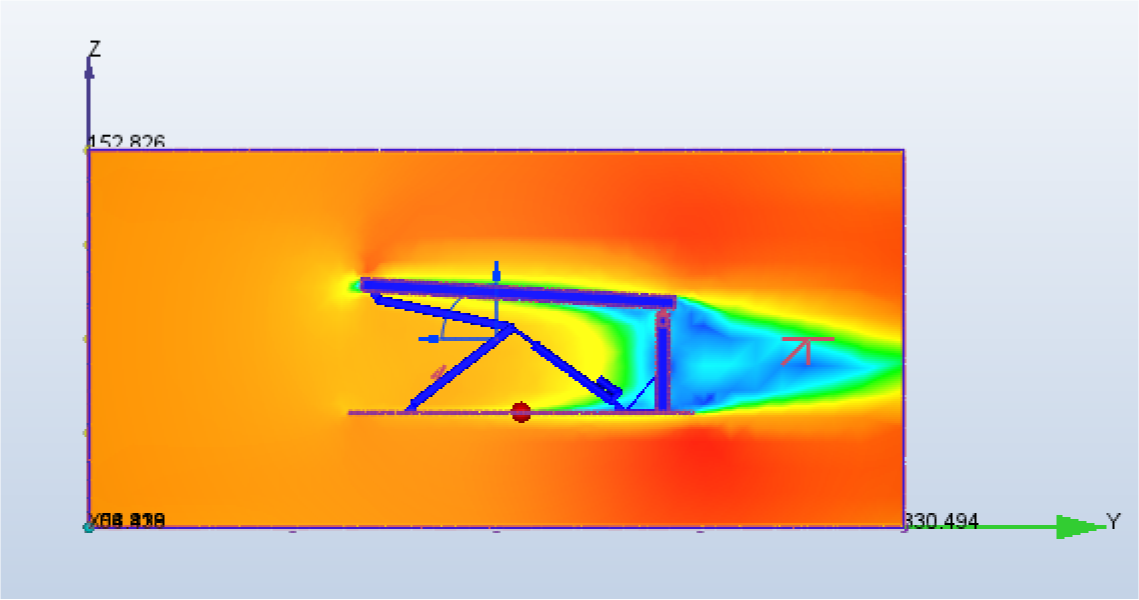


**Figure 5.2.1.3.** CFD simulation of 40 mph winds when the complete system is flat/resting. The drag is 60.09 N and the lift is 25.64 N

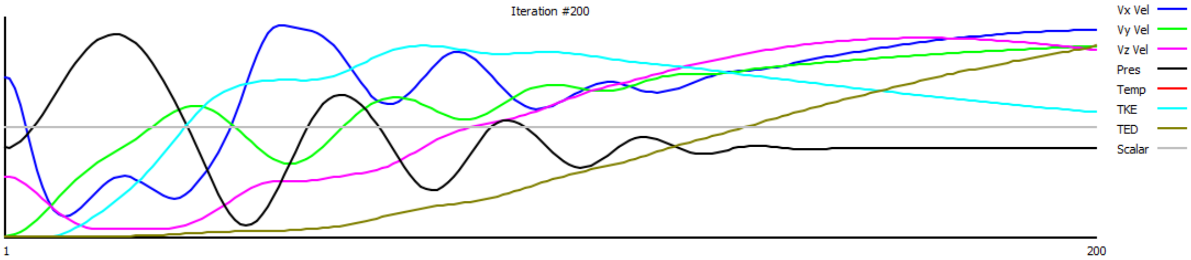


**Figure 5.2.1.4.** Convergence plot of 40 mph winds when the complete system is half-way up.

## vi. Half-Way Extended

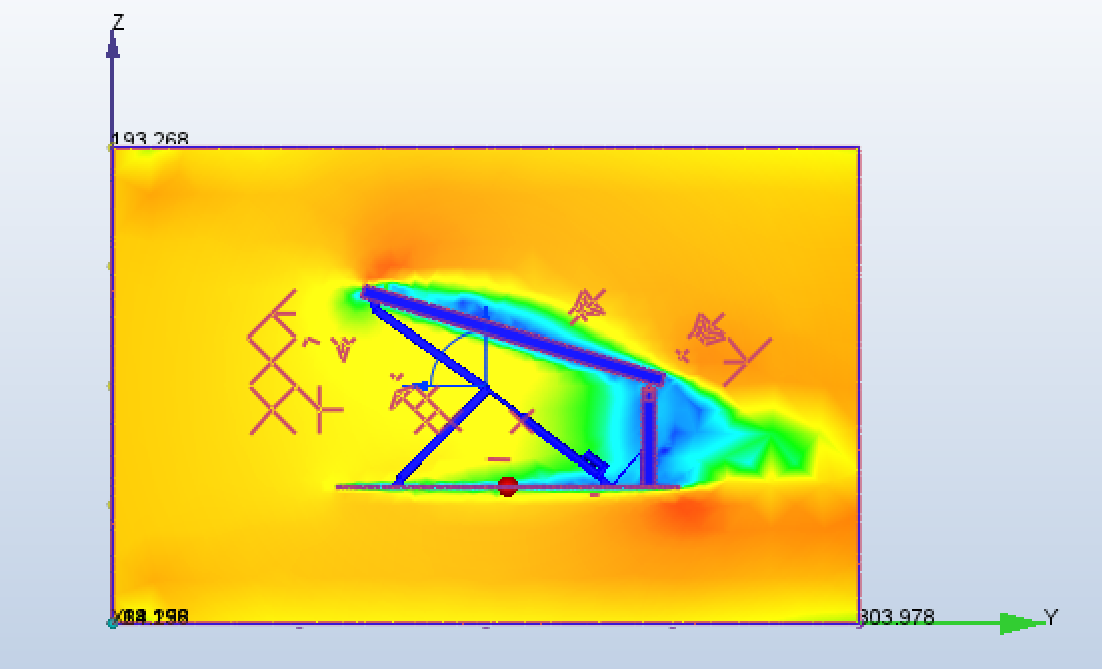


**Figure 5.2.2.1.** CFD simulation of 20 mph winds when the complete system is half-way up. The drag is 29.46 N and the lift is 21.15 N

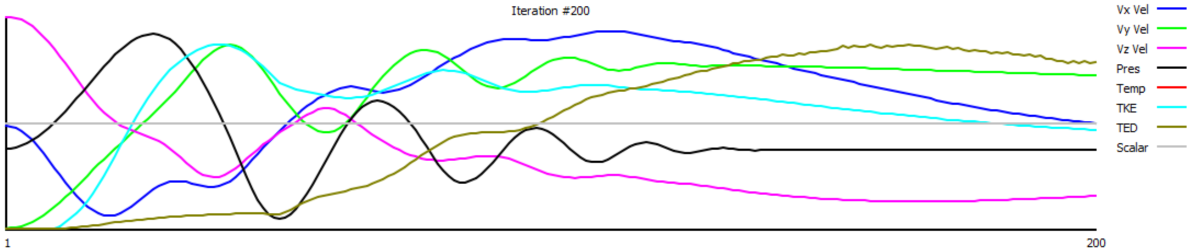


**Figure 5.2.2.2.** Convergence plot of 20 mph winds when the complete system is half-way up.

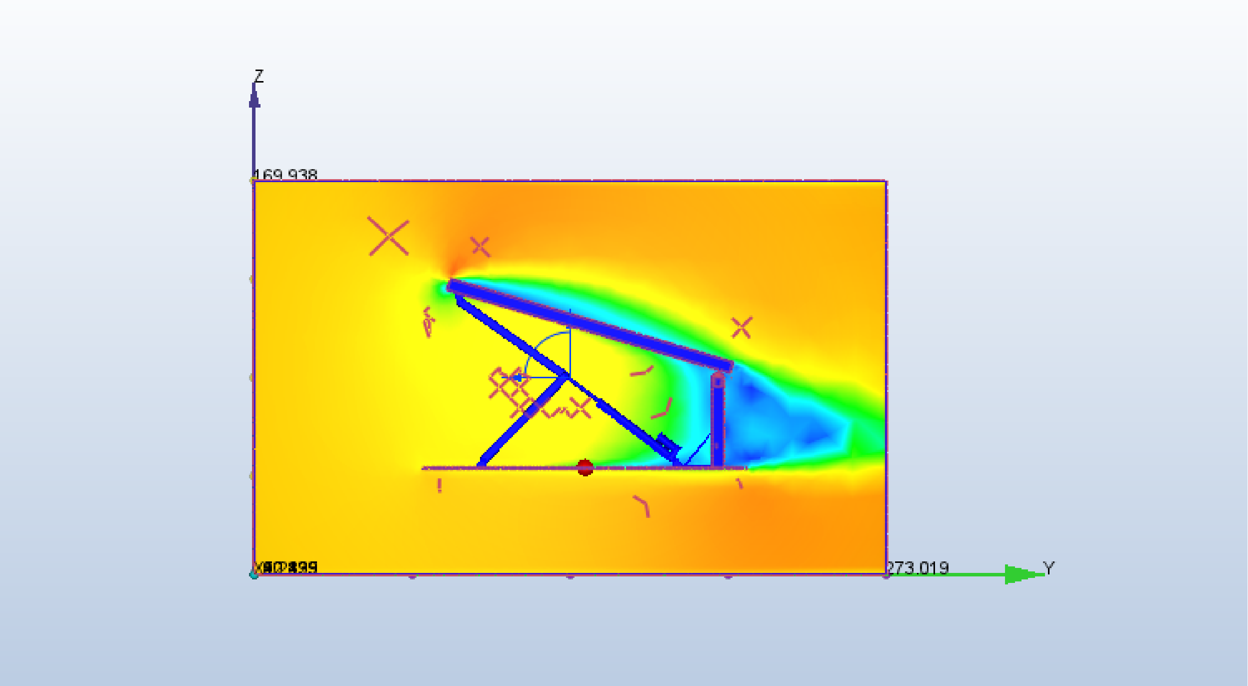


**Figure 5.2.2.3.** CFD simulation of 40 mph winds when the complete system is half-way up. The drag is 100.03 N and the lift is 65.39 N

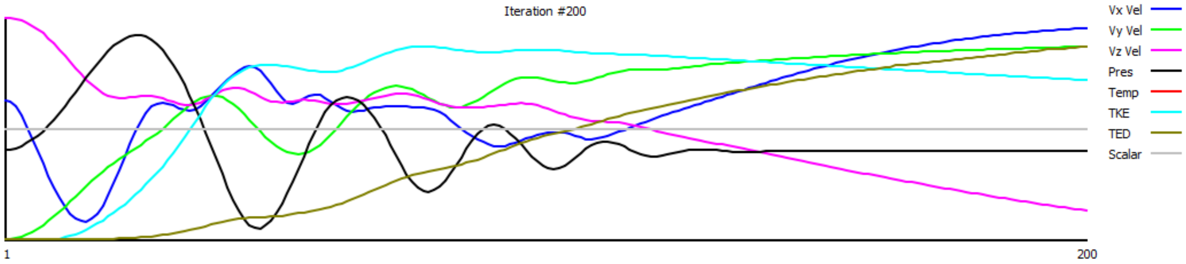


**Figure 5.2.2.4.** Convergence plot of 40 mph winds when the complete system is half-way up.

## vii. Fully Extended

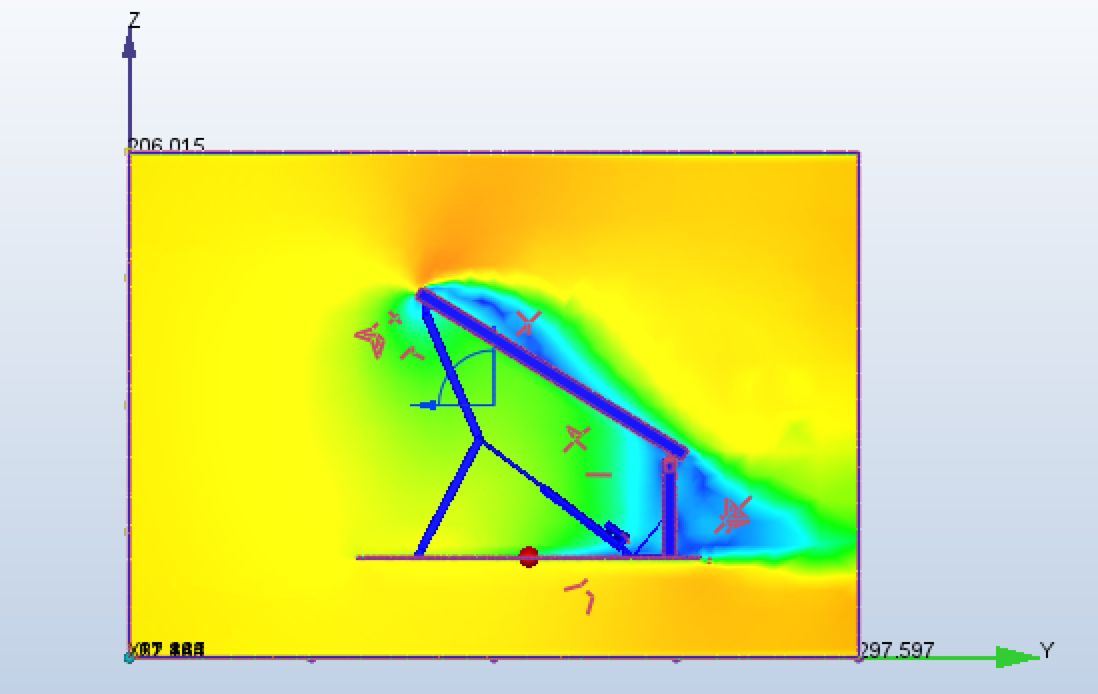


**Figure 5.2.3.1.** CFD simulation of 20 mph winds when the complete system is fully extended. The drag is 56.65 N and the lift is 43.83 N

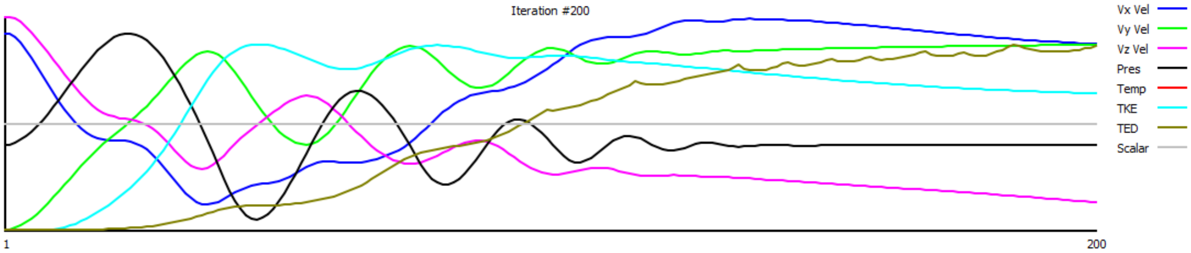


**Figure 5.2.3.2.** Convergence plot of 20 mph winds when the complete system is fully extended.

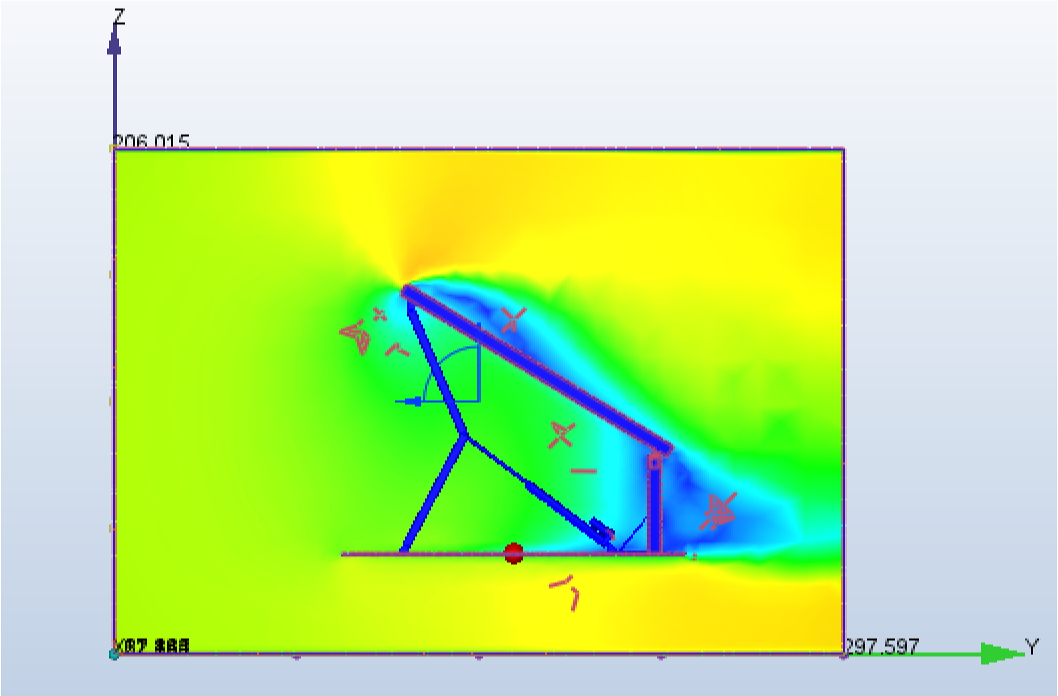


**Figure 5.2.3.3.** CFD simulation of 40 mph winds when the complete system is fully extended. The drag is 224.36 N and the lift is 170.12 N

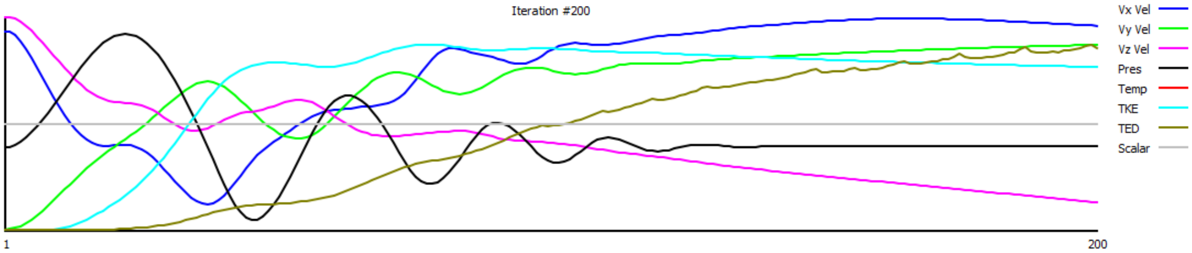
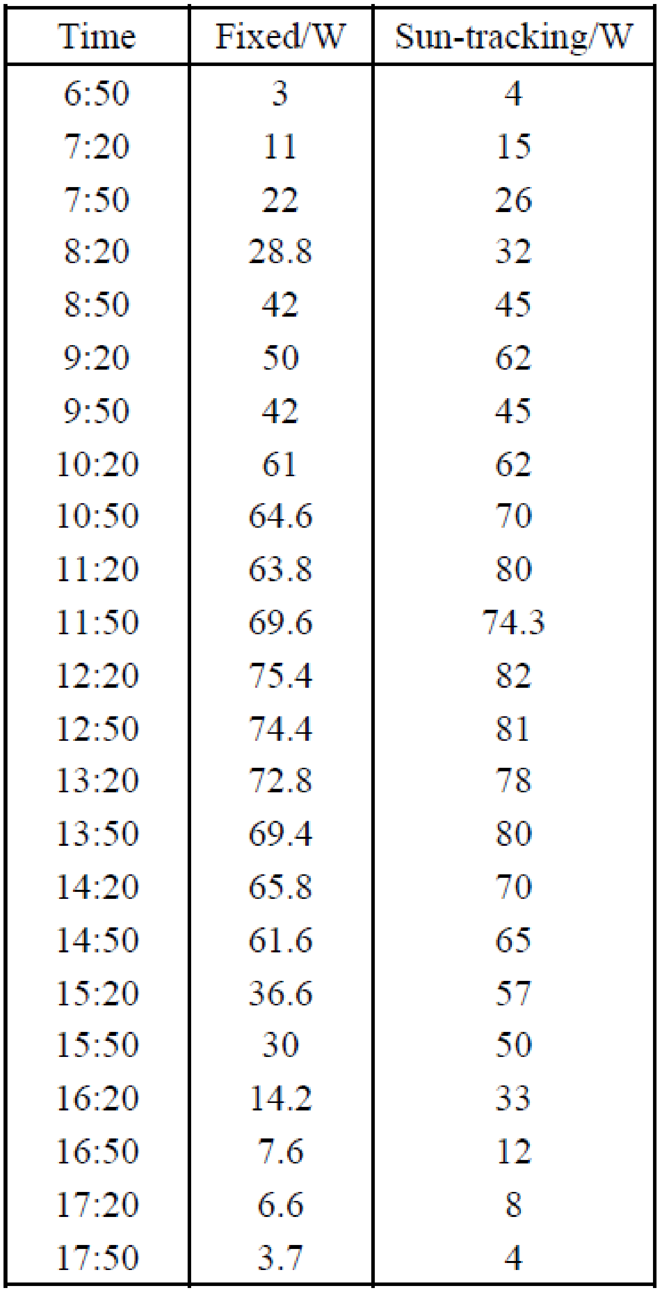


**Figure 5.2.3.4.** Convergence plot of 40 mph winds when the complete system is fully extended.

## iii. Power Consumption Test

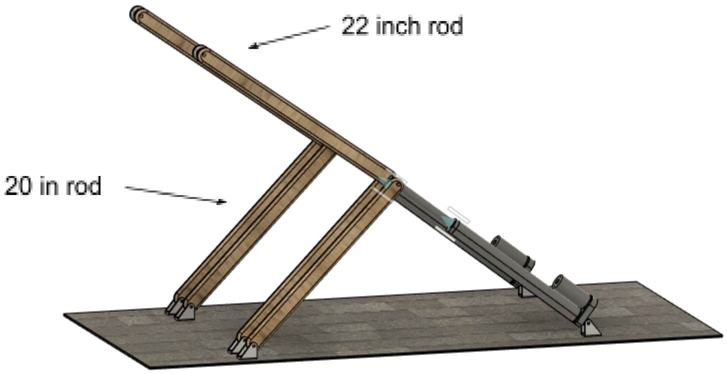
**Table 1.** Power generation by fixed solar panel and sun-tracking solar panel.



| Time | Fixed/W | Sun-tracking/W |
|---|---|---|
| 6:50 | 3 | 4 |
| 7:20 | 11 | 15 |
| 7:50 | 22 | 26 |
| 8:20 | 28.8 | 32 |
| 8:50 | 42 | 45 |
| 9:20 | 50 | 62 |
| 9:50 | 42 | 45 |
| 10:20 | 61 | 62 |
| 10:50 | 64.6 | 70 |
| 11:20 | 63.8 | 80 |
| 11:50 | 69.6 | 74.3 |
| 12:20 | 75.4 | 82 |
| 12:50 | 74.4 | 81 |
| 13:20 | 72.8 | 78 |
| 13:50 | 69.4 | 80 |
| 14:20 | 65.8 | 70 |
| 14:50 | 61.6 | 65 |
| 15:20 | 36.6 | 57 |
| 15:50 | 30 | 50 |
| 16:20 | 14.2 | 33 |
| 16:50 | 7.6 | 12 |
| 17:20 | 6.6 | 8 |
| 17:50 | 3.7 | 4 |

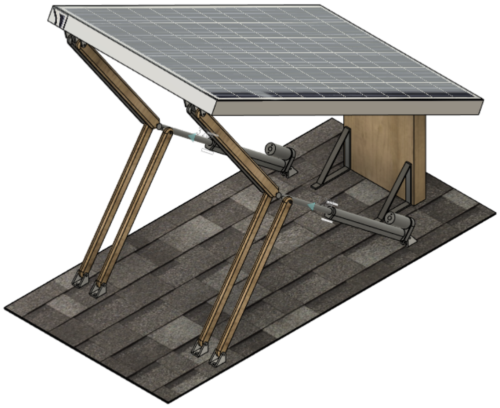
# iv. User Manual

1. **Purpose**
   The purpose of this procedure is to provide instructions for installing a tracking solar panel system on a residential roof.
2. Scope
   This protocol has been developed for homeowners looking to install solar panels and save more money than normally would be when using fixed solar panels.
3. References
4. Procedure
   a. Prior to installation:
      i. Before installing solar panels, ensure that the residential roof is in good shape. Solar panels are meant to work for many years, therefore, the roof should be solid. The roof should also be able to support the extra weight of the solar panels.
         1. In the event the roof is damaged, fix any damages before mounting the solar panels.
      ii. Consider the location of the house. Are there any areas of the roof block from the sun via trees or nearby buildings? The solar panels should be placed on the part of the roof that receives the most sunlight.
   b. Ensure that all of the materials needed to install the solar panel are immediately available. These materials include a drill, drill bit, tape measure, a ladder, and anything that came as a part of the solar panel package.
      i. Within the solar panel package (for one solar panel) should be four 22 inch links, four 20 inch links, two linear actuators, a board, four fixtures
   c. Ensure that the roof is tilted to at least an 18° to get the most sun exposure possible. Look for the best place to fix the stanchions. Stanchions support the panels so that they are not torn from the roof. They behave similarly to screws, therefore, they should be placed on the roof's rafters. Fix the stanchions to the room at a distance of 4 feet from each other.
      i. If not sure where the rafters are, use the house's blueprints to locate them
   d. Lift the shingles and put the flashing underneath them and then fasten the flashing onto the rafters using a bolt. A flashing is meant to keep water out of the house once a hole has been drilled into it. Apart from the flashing, the bolts also have a seal that help avoid any leaking.
   e. Place the screws into the holes created and tighten them. Then use bots to fix the fixtures to the stanchions. An impact driver will ensure that everything is fastened properly.
   f. Attach the linkage mechanism and the linear actuators to the fixtures according to the diagram referenced below.



g. Attach the board to the fixtures according to the diagram referenced below.

h. Ensure that the copper wires are on the inverter kits. These connections should go in and out of the solar arrays. Pull the wires from the panels to an electrical meter and out to an electrical sub-panel. Run the wires to the power inverter kits through the rail, which has a trunk.
i. Mount the panel to the linkage mechanism and the board as referenced below.



j. Shut off the power supply to the house before connecting the solar system to it. Connect the solar inverter to the system. A solar inverter is what converts solar energy from DC to AC energy that the household uses.
    i. If the inverter is outdoors, avoid placing it in direct sunlight.
k. Connect the solar inverter to the battery. The battery will be useful on the days when the solar panels are not producing enough energy, for example on cloudy days. Connect the solar inverter to the fuse board. The fuse board will protect the user in case of an electrical emergency.