SOLAR FARM UTILIZING A BATTERY ENERGY STORAGE SYSTEM

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ABSTRACT

Solar Farm Utilizing a Battery Energy Storage System

Hannah Nicole Bonderov

According to the US Energy and Information Administration, between 2022-2023 60% of planned new electricity generation consists of solar farms with a battery energy storage system [1]. The demand for these paired systems has increased since batteries can be charged during the day with the energy captured from the solar farm then released to the customer in the evening during peak energy demand. This achieves peak load shaving which reduces the cost of electricity for the customer and is ecologically friendly.

This thesis aims to create an efficient solar farm with a battery energy storage system for a farmer in California that achieves peak load shaving. Full cell modules and half-cell modules were explored to determine the type that best suits this project. The half-cell modules were best suited because of the increased efficiency. Six different solar farm designs were created, four fixed tilt designs and two single axis tracking designs. Two types of software, System Advisor Model (SAM) and REopt, were compared to determine which would be most useful in simulating these designs. It was concluded that System Advisor Model (SAM) would be the most accurate to simulate the six designs and produce metrics such as the annual energy production, capacity factor, DC to AC ratio, and levelized cost of energy. The final design, design 6, a 2-string single axis tracking design produced the best metrics that met the project requirements and a battery energy storage system was sized for the design.

ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Majid Poshtan. His guidance, thoughtfulness, and expertise made this project possible. Furthermore, it is his flexibility in advising during the ongoing global COVID-19 pandemic that allowed this work to be completed; I thank him for his willingness to work with me and his adaptability to the many unusual difficulties that the pandemic placed on this project.

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Anthony Margulis and Hetav Gore worked with me on early stages of the project. As part of their own senior projects, they worked with me in determining software simulator suitability for this thesis. I would like to extend my gratitude to them for their contributions.

I would like to thank Dr. Ahmad Nafisi and Dr. Ali Dehghan Banadaki for their time and their consideration of this thesis, as well as for their input and insights on the project. Real growth in science and engineering is made possible through collaboration, and I appreciate my committee members’ dedication to my growth as a student of science and engineering.

I would like to thank my family and my friends for their infinite love and support in this process. Working on a thesis takes an amount of time and energy that is difficult to encapsulate with words. My parents recognize that, and they were always there for me whenever I needed them. I cannot possibly thank them enough. My friends at Cal Poly

were my family away from home. They made the best of the everyday aspects of being students, and they helped me to retain focus on why I was doing a project like this. I will always be grateful for that.

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1. INTRODUCTION

A farmer from California is inquiring to convert part of their land from growing agriculture to a solar farm with an energy storage system. The requested design specifications are shown in table 1. Figures 1-4 show the site boundary measurements taken from google earth. A model of the property is shown in figure 5. Six designs will be evaluated to determine which is the most fit for this location.

Table 1: Project Requirements

Design Requirements	**Engineering Specification**	**Justification**
1	Inverter with an AC output of 208V	There is a 208V transformer near the location.
2	Efficient Solar Module	Maximizing the solar modules efficiency increases the overall energy production of the design.
3	Efficient Inverter	Maximizing the inverter efficiency increases the overall energy production of the design.
4	DC to AC ratio between 1.3-1.6	A DC to AC ratio in this range causes slight clipping losses but can have financial benefits [2].
5	No module shading between 10am-2pm on the winter solstice, December 21st	Shading drastically reduces the energy production of the module. To increase energy production, solar module shading of the design should be minimal. [3]
6	Final design includes a battery energy storage system to achieve peak load shaving	Achieving peak load shaving utilizing a battery can reduce the cost of electricity and reduce carbon emission [4].
7	Capacity Factor of at least 24.6%	According to [5], average solar PV capacity factor in 2021 was 24.6% [5].

Table 1: Project Requirements Cont.

8	Energy Yield	The highest energy yield will benefit both the owner and the customers while reducing carbon emissions [4].
9	Minimum Levelized Cost of Energy	According to [6], minimizing the levelized cost of energy may provide financial benefits [6].
10	REopt or System Advisor Model (SAM) to simulate the design	Each potential design will need to be simulated using the most appropriate software between REopt and SAM.

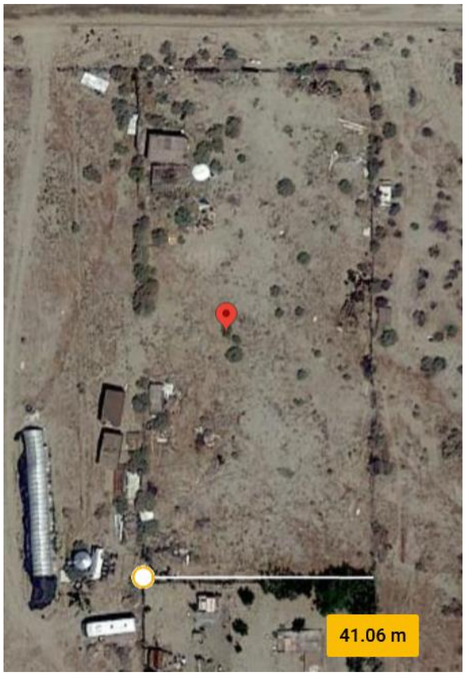


Figure 1: Google Earth Measurement of South Side Property Boundary

Figure 2: Google Earth Measurement of West Side Property Boundary

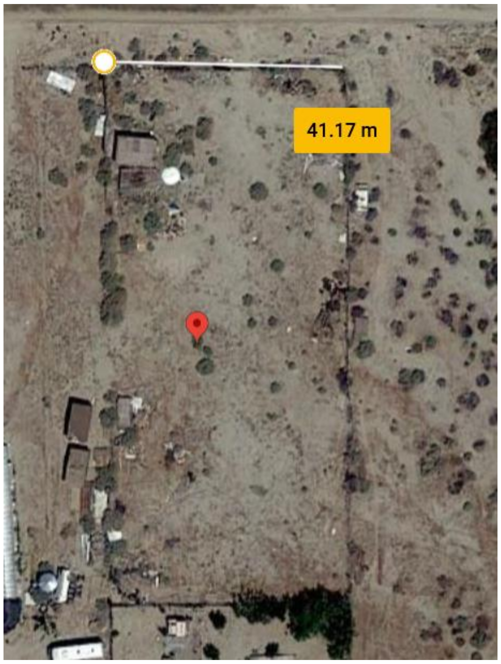


Figure 3: Google Earth Measurement of North Side Property Boundary

Figure 4: Google Earth Measurement of East Side Property Boundary

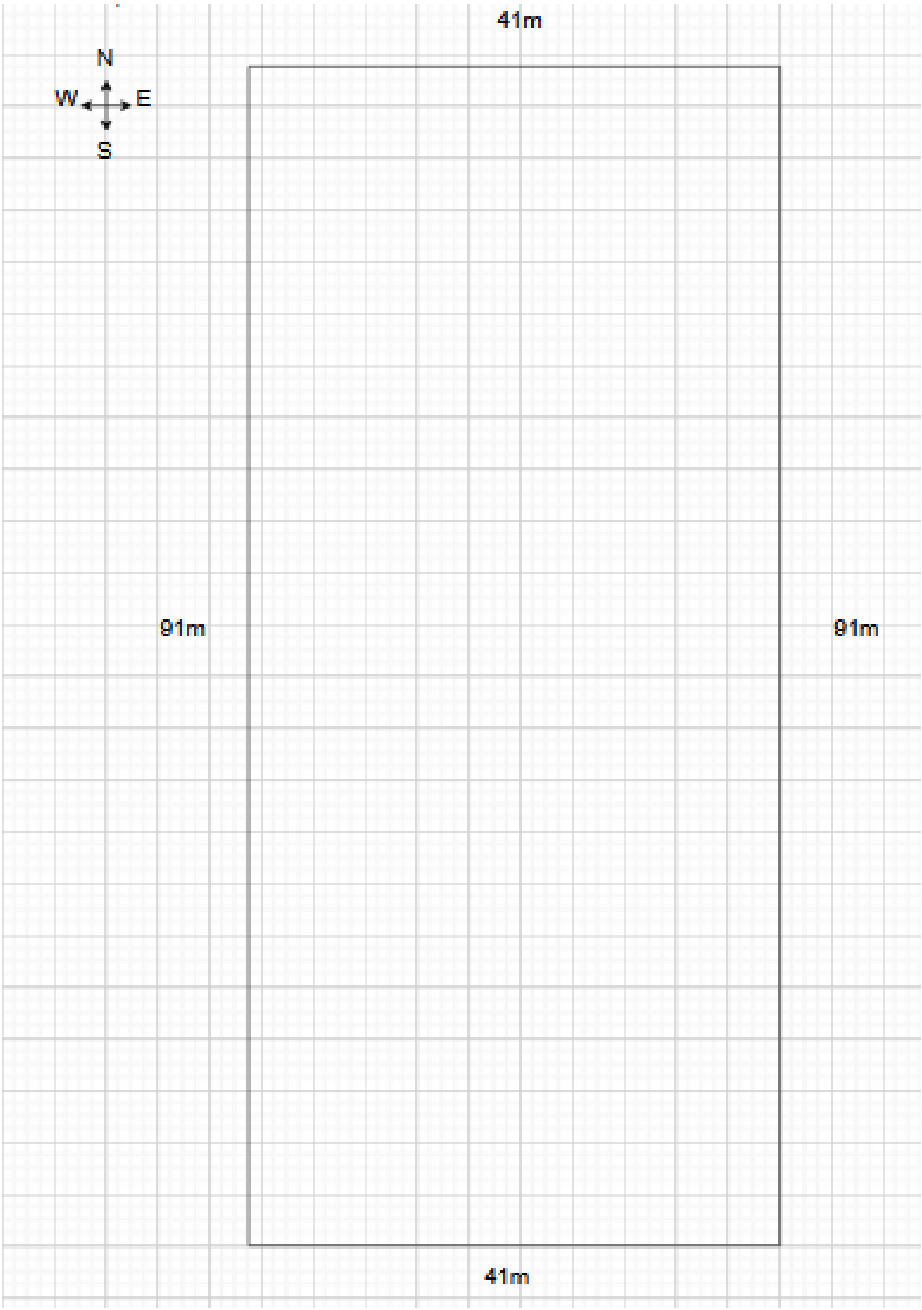


Figure 5: Model of Property Based off Google Earth Measurements

It should be noted that in figure 5 above, each small square represents 1 meter. No decimals are considered in later design layouts. All decimals will be rounded up to overcompensate and ensure the design does not exceed property boundaries. Next discussed will be how solar modules operate and why it is important to prevent shading.

2. SOLAR MODULE ANALYSIS

2.1 IV Curves and PV Curves [3]

Figure 6 shows the IV (current vs. voltage) curve and the PV curve (power vs. voltage) of a solar module. When solar modules operate at the maximum power point, the maximum amount of energy is captured. To find the maximum power point, first the IV (current vs. voltage) curve of the module needs to be determined. Many inverters have the capability to find the maximum power point using a tracker [3].

There are also other important module electrical data that can be determined from the IV curve and is identified in figure 6 below. The open circuit voltage (V_{OC}) occurs when there is no current and the voltage is at the maximum. The short circuit current (I_{SC}) occurs when there is no voltage, and the current is at the maximum. The maximum power point (M_{pp}) is the voltage and current point (V_{mpp}, I_{mpp}) at which the maximum power is captured. The PV (power vs. voltage) curve can then be calculated by multiplying the current and voltage points from the IV curve. The maximum power point is the maximum value on this curve, identified as M_{PP} in figure 6 bellow.

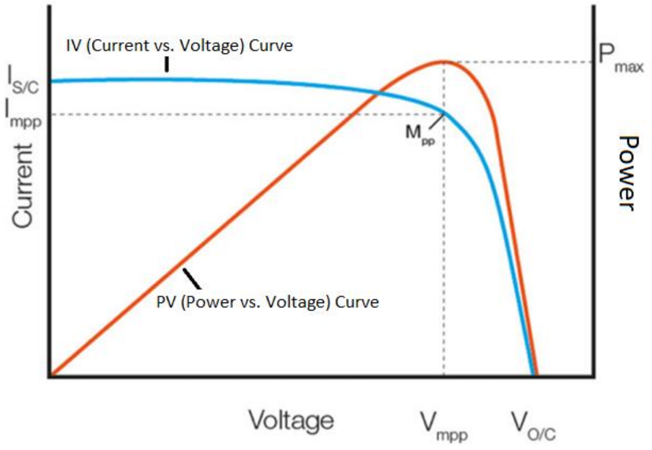


Figure 6: IV Curve and PV Curve for a Solar Module with Bypass Diodes and No Shade [7]

2.2 Bypass Diodes [8]

Solar modules have three bypass diodes, connected to the cells in different orientations depending on the module type to help prevent shading issues. It is possible shading can cause permanent damage to the module and fire without working bypass diodes. Therefore, bypass diodes serve an important purpose when one cell or multiple cells are shaded. If one cell or part of the solar module is shaded, that shaded strings current will be bypassed by the bypass diode as shown in figure 10. This means having three bypass diodes still allows for some energy production even if part of the solar module is shaded. It should be noted that when a cell is shaded and a bypass diode is turned on, the IV curve of that module changes from having one global maximum power point to having a local maximum and a global maximum as shown in figure 7 bellow. Therefore, it is necessary the inverter have a global maximum power point tracker [8].

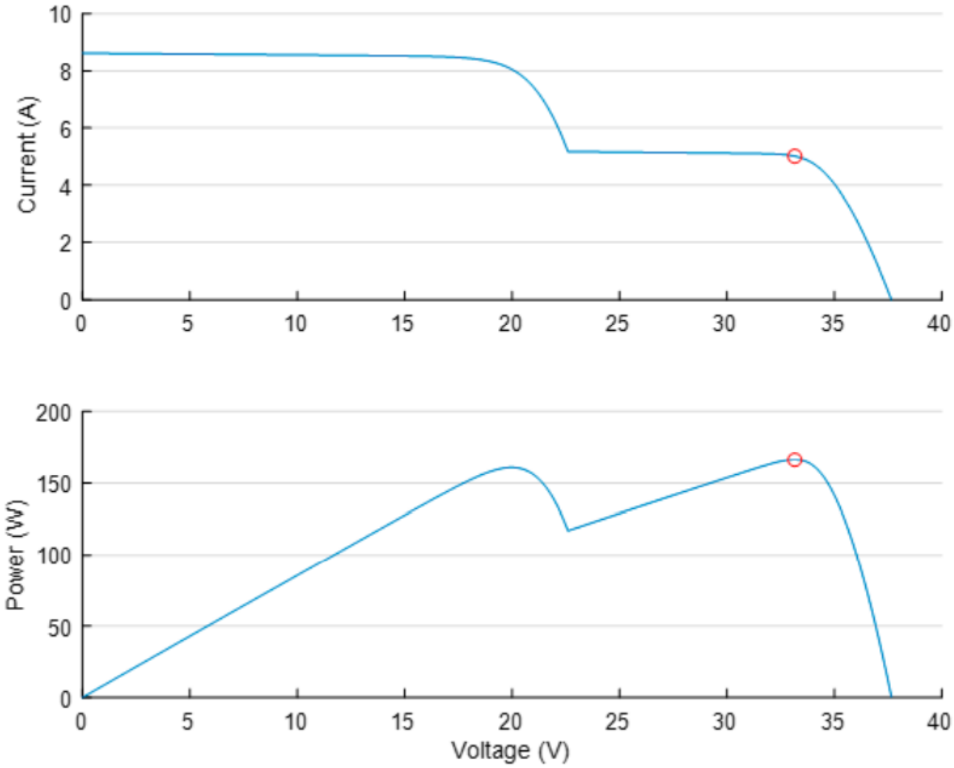


Figure 7: IV Curve (Top) and PV Curve (Bottom) when One Bypass Diode is Activated [8]

If there was only one bypass diode in between the positive and negative terminal of the module and a single cell or part of the module was shaded, then the entire module would be bypassed and there would be no energy production from that module.

When there are no bypass diodes and one cell is shaded, that shaded cell is reversed bias, meaning it becomes a load and heat is dissipated in the shaded cells. The IV curve of a shaded cell/reversed bias cell is shown in figure 8 bellow [8].

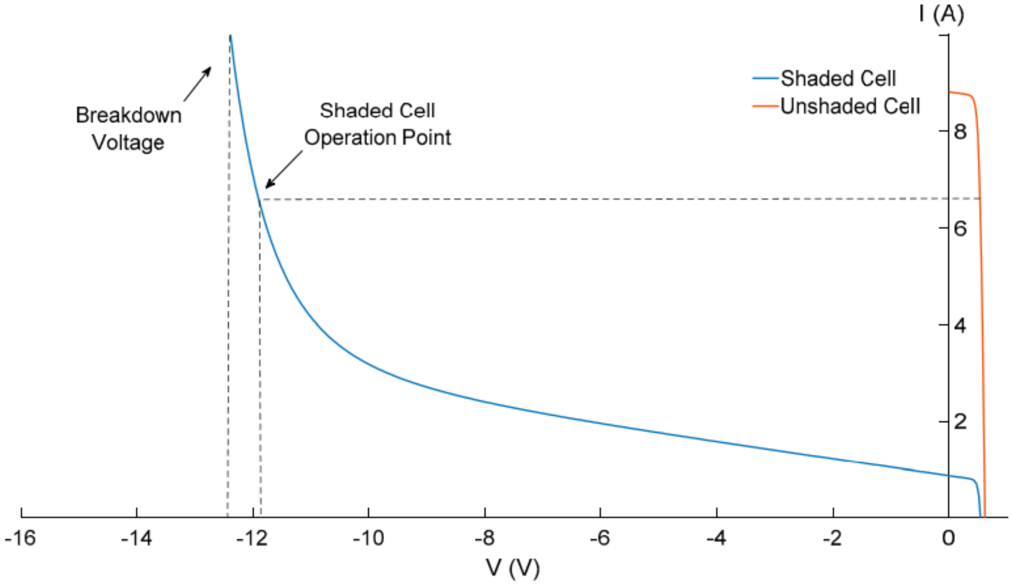


Figure 8: IV Curve of a Shaded Cell (Reversed Bias) and Unshaded Cell (Forward Bias) [8]

Power production also drastically decreases when there are no bypass diodes, and a single cell or multiple cells are shaded. Figure 9 shows the change in IV curves and PV curves for a nonshaded module and a partially shaded module [8].

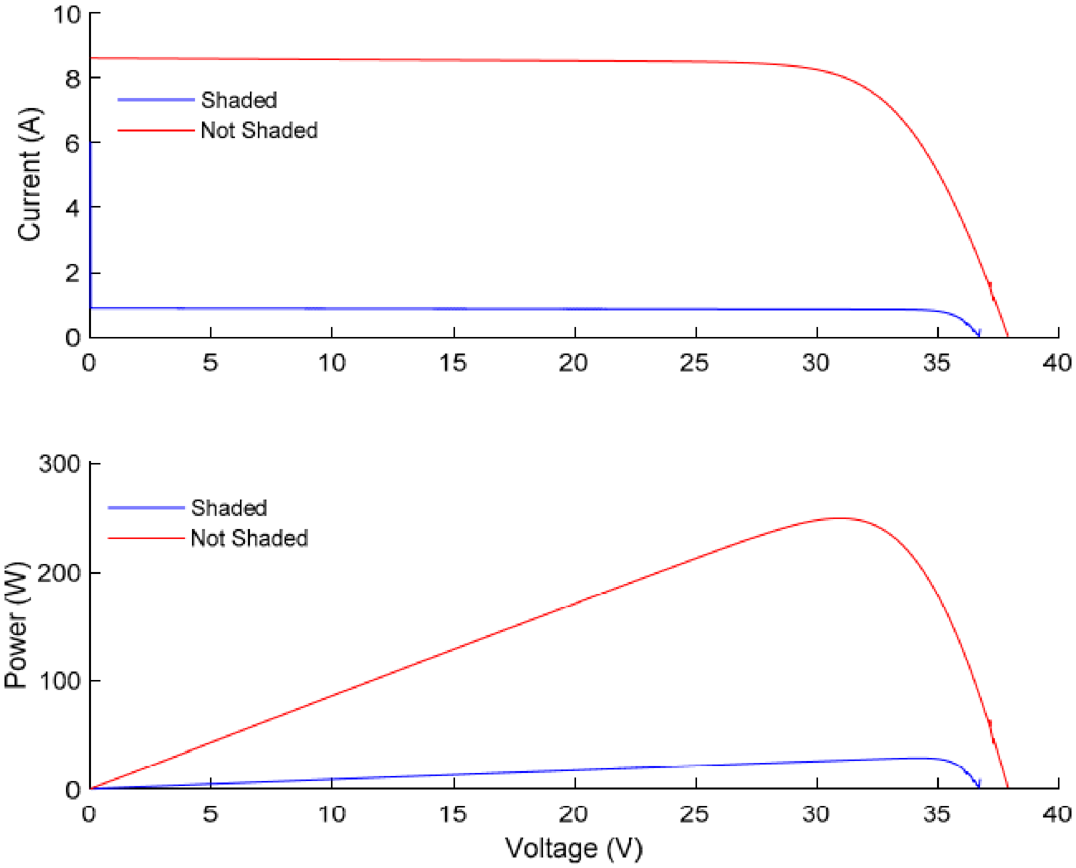


Figure 9: No Bypass Diodes on Modules [8]

For a module with working bypass diodes and no shaded cells, the IV curve and maximum power curve is shown in figure 6 [7]. Solar modules can be further classified by either a full cell module, half-cell module, and bifacial module. Full cell modules and half-cell modules will be discussed next.

2.3 Full Cells [8]

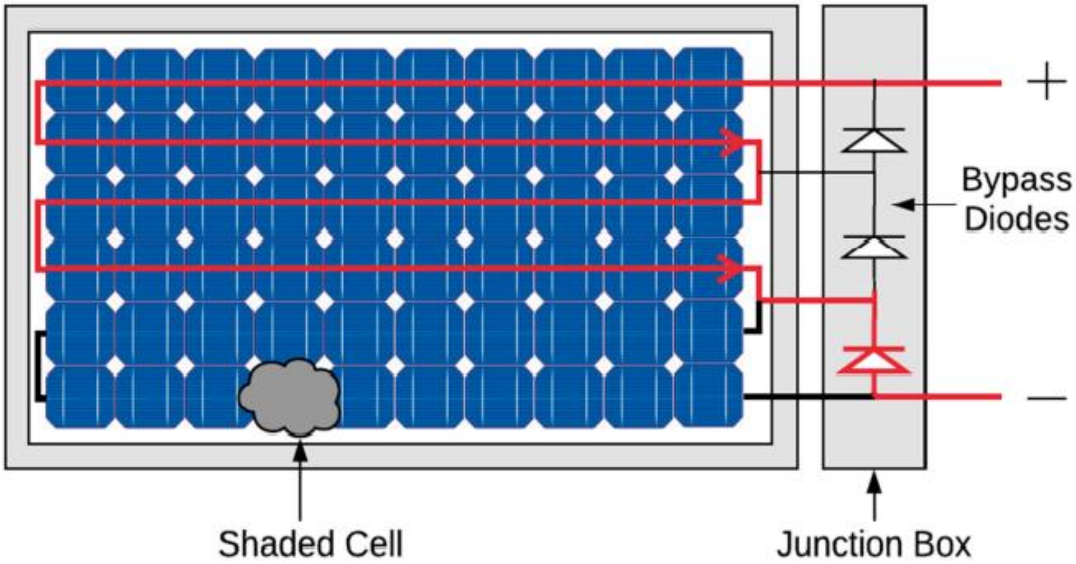


Figure 10: Full Cell Module (60 Cells) [8]

A full cell module is shown in figure 10 above. This type of module can have a varying range of cells, but some typical modules have 32, 36, 60, 72, or 96 cells in series with three bypass diodes. A 60-cell module is shown in figure 10. The three bypass diodes are connected to make three strings of cells on the module [9]. Typically, each cell has a voltage of approximately 0.5V which for a 60-cell module produces an overall voltage of approximately 30V [10].

2.4 Half Cells [10]

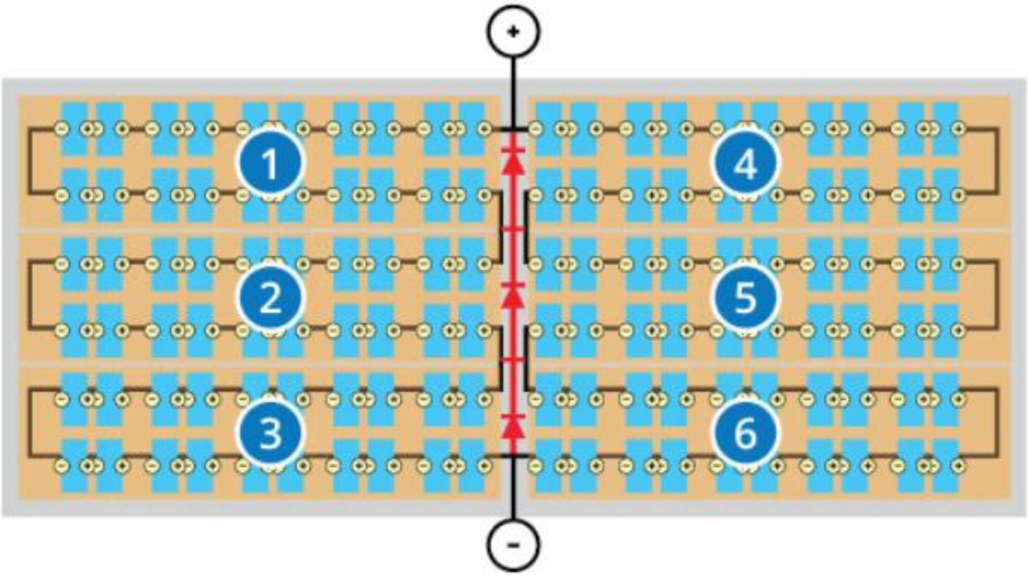


Figure 11: Half Cell Module Showing Bypass Diodes [9]

Half-cell modules are made from full cells that have been cut in half by a laser. In the half cell modules, the bypass diodes are connected such that there are six strings instead of three. Figure 11 shows a 120-half-cell module that was created from 60 full cells. The current through each cell is halved compared to a full cell module, but there are twice as many cells. The module in figure 11 creates an overall voltage of approximately 60V. This is because each cell still has an approximate voltage of 0.5V and there are 60 cells on left side as well as the right side. Each side creates a voltage of approximately 30V and the two sides are connected in parallel, creating an overall voltage of approximately 60V [10].

This type of module offers many advantages including higher efficiency by reducing shading losses and power losses related to decreased current and resistance. For example, figure 12 shows a possible path for current to flow when two cells are shaded.

At this point, only 2/3rds of the panel are in operation, similar to a full cell module with one cell shaded. Figure 12 also shows the module operating at the local maximum power point instead of the global maximum. Figure 13 shows another possible path for current to flow when two cells are shaded when the module is operating at the global maximum power point. When operating at this maximum power point, current can flow through 5/6 strings instead of 4/6 at the local maximum. Because of this, the half-cell module can produce more power than a full cell module with two cells shaded, making it more efficient. The half-cell module also has reduced resistive power losses when compared to a full cell module because only half the total current is flowing through each cell. This can be understood by looking at equation 1 below. Since the current is reduced in half cell modules by half, this decreases the resistive losses by a factor of four [10].

$$P = I^2R \tag{1}$$

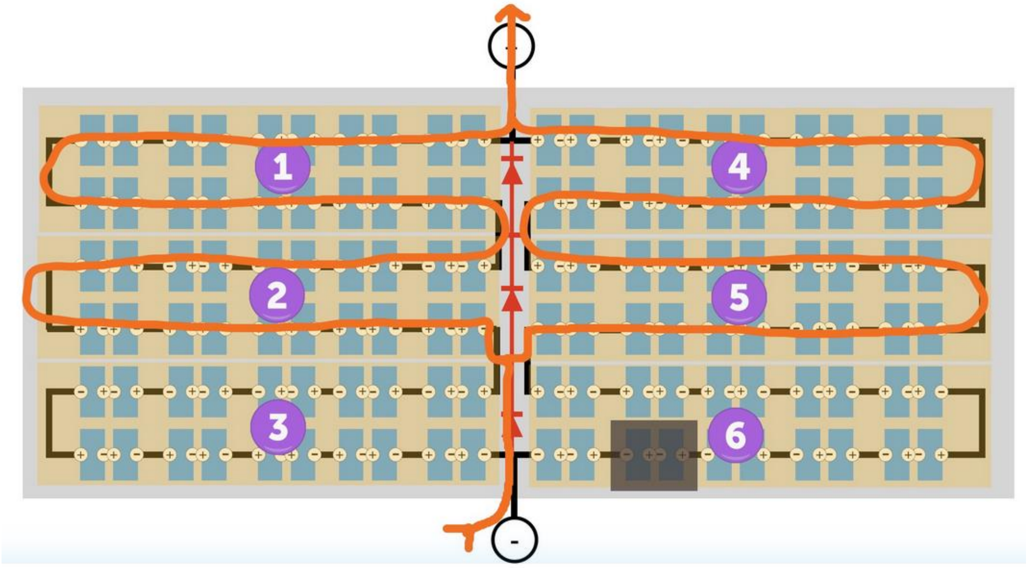


Figure 12: A Possible Path for Current to Flow when 2 Cells are Shaded [10]

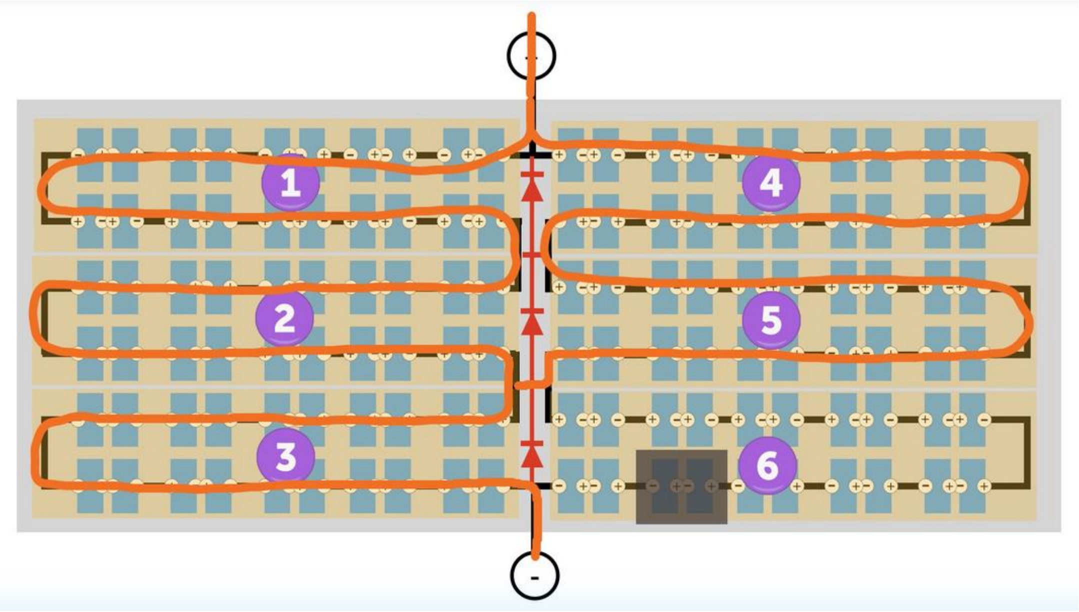


Figure 13: Possible Path for Current to Flow when 2 Cells are Shaded [10]

3. PEAK LOAD SHAVING [4]

An example peak load curve is shown below in figure 14. This curve shows the amount of power used versus time. The peaks indicate more people have started to use electricity; therefore, the power demand increases. The highest peak shows the capacity the power plant must have to meet the demand.

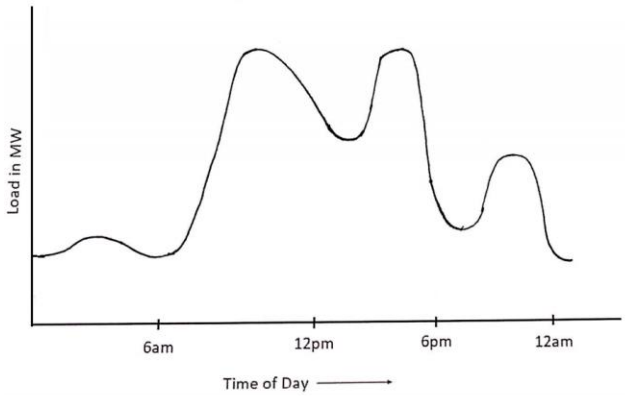


Figure 14: Example Load Peak Curve [4]

[4] examines three different ways to shave the high peaks in a peak load curve. This includes adding an energy storage system (ESS), adding electric vehicles (EV) to the grid, and demand side management (DSM). It is stated peak load shaving can benefit the grid operators, the customer, and can reduce the amount of carbon dioxide released into the atmosphere. Currently to meet the peak electricity demand, some power plants use fossil fuel generators. This can increase the amount of CO2 released into the atmosphere as well as increase the cost for the utility company and the customer because the cost of maintaining and running the power plant for only a couple hours each day is high. This expense then gets passed along to the customer who pays more for electricity during the peak time periods [4].

To ensure a high power quality in the power system, the supply of electricity and the demand of electricity needs to be balanced. If the demand of electricity is higher than the supply, then this could cause instability, voltage fluctuations, possible blackouts, and a low power quality.

To measure how efficiently the electricity generated is being used, load factor is calculated. Load factor helps show the variability in load/demand and is the ratio of average real power demand over the peak real power demand as shown below.

$$\text{Load Factor [\%]} = (P_{AVG} / P_{PEAK}) \times 100\% \tag{2}$$

A higher load factor indicates the power plant is economically feasible. The higher the load factor, the cheaper the energy. To increase the load factor, the real peak power on the peak load curve needs to be reduced using peak load shaving. This also reduces the power lost in the system since when the peak load demand is decreased, the current in the system is also decreased, reducing the overall power lost in the system and making it more efficient.

Incorporating renewable energy sources such as wind and solar is then explored and shows that when added to the system, the peak load during the day can be reduced and the highest peak is shifted to the evening [4].

Adding a battery energy storage system (BESS) is then evaluated to help shave the highest peaks on the peak load curve. As time goes on, the electricity demand is increasing. This is because our individual electricity consumption increases and because the population is increasing. By looking at figure 15 below, if the BESS is charged during low demand times, the BESS can help shave the highest demand peaks by discharging during high demand times. This can decrease the cost for the end user since they are using less electricity during the high peak times when the price is the most expensive. This also reduces CO2 emissions since a battery is providing the extra electricity instead of a fossil fuel burning generator [4].

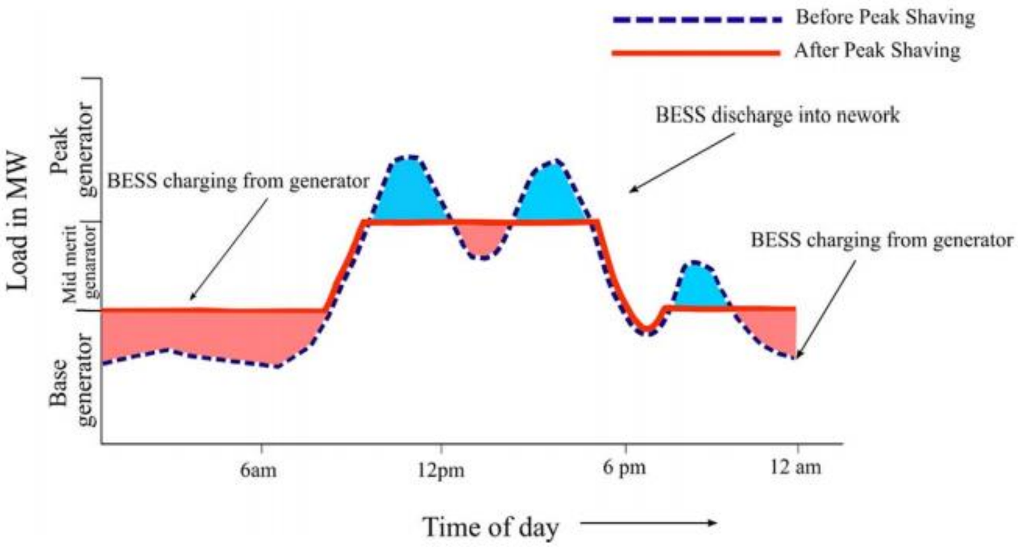


Figure 15: Demonstrates Shaving the Load Curve with a BESS [4]

4. DC TO AC RATIO AND CLIPPING LOSSES [2]

Solar modules operate on direct current (DC) power while inverters convert that DC power to alternating current (AC) power. This facilitates the addition of DC power from the modules threw the inverter to the AC electrical grid. Both the modules and the inverters have a maximum threshold in which it can produce and convert. The DC to AC ratio of a design is the amount of power produced by the modules over the maximum amount of power the inverter can convert from DC to AC. According to [2], having a DC to AC ratio between 1.3 to 1.6 could provide some financial benefits since the maximum amount of energy produced per day would remain higher for a longer period. The downsides would be an increase of clipping losses and the inverter would be working at maximum power for a longer amount of time which could reduce the inverters lifetime. This can be seen in figure 16 below. [2] concludes that a DC to AC ratio of maximum 1.6 will not drastically reduce an inverters lifetime which is why a maximum DC to AC ratio of 1.6 was placed on all 6 designs.

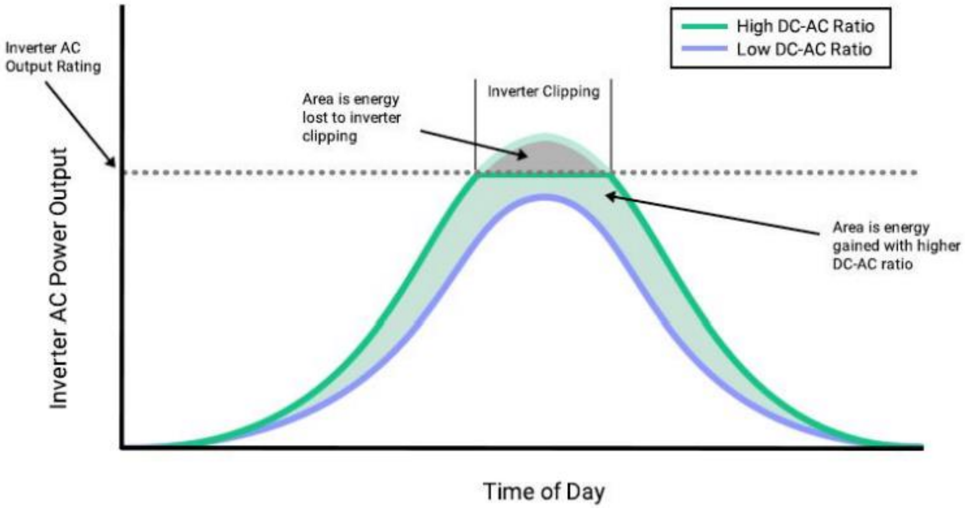


Figure 16: Difference in AC Power Output Between a High vs. Low DC to AC Ratio [2]

5. SOFTWARE - SYSTEM ADVISOR MODEL (SAM) AND REOPT

REopt and System Advisor Model (SAM) were compared to determine which software would be most suitable for simulating the solar farm designs. The software screenshots with explanation are included in appendix section G and H. It should be noted that when each software was simulating the same design, the outputs did not match. Further evaluations showed REopt was not responding to changes in the inputs such as the critical load and grid outage duration, making it unfit for this project. Therefore, System Advisor Model (SAM) was used to simulate all designs.

6. MODULE ORIENTATION

6.1 Direction of Tilt [11]

When located in the northern hemisphere the solar modules should face south for the maximum energy production during the middle of the day. The solar modules should face more towards the southwest if maximum energy production is required in the afternoon during peak energy demand. Since this project design will have an energy storage system, batteries, and the property is symmetrical with a compass, meaning the four sides of the property boundary are in line with north, south, east, and west, the solar modules will be tilted towards the south [11].

6.2 Optimal Degree of Tilt

Optimal module tilt angle is achieved when the tilt of the solar panels is equal to the latitude in degrees of the location of the module [11]. Conversions for latitude will be done here to convert the notation of degrees, minutes, seconds taken from google earth to decimal degrees.

Location Latitude = 34° 34’ 20’’ N

Conversion calculation of Latitude to degree (without minutes and seconds):

Conversion Factors: 1° = 60’ (minutes) 1’ (minute) = 60’’ (seconds)

34’ x (1° / 60’) = 0.5667°

20’’ x (1° / 60’’) x (1° / 60’) = 0.0056°

Location Latitude in degrees: 34° + 0.567°+ 0.0056° = 34.5723° N

New Location Latitude: 34.5723° N

Therefore, the tilt of all fixed modules will be 34.5723° towards the South. In Simulations this will be rounded to 34.6°.

6.3 Module and Inverter Specifications:

The module and inverter used for all designs in this project were chosen based off efficiency ranking in System Advisory Model (SAM) and available online information as shown in the appendix section A and B. It was also required the inverter have a 208V AC voltage to ensure proper connection at the property. Necessary information for the top efficiency modules and inverters listed in the appendix were unavailable so adjustments were made until the required specifications could be located, such as the open circuit voltage, short circuit current, etc. It is important to note the inverter has a battery attachment capability. Specifications below are from the datasheets.

Table 2: Module REC Solar REC405AA [12]

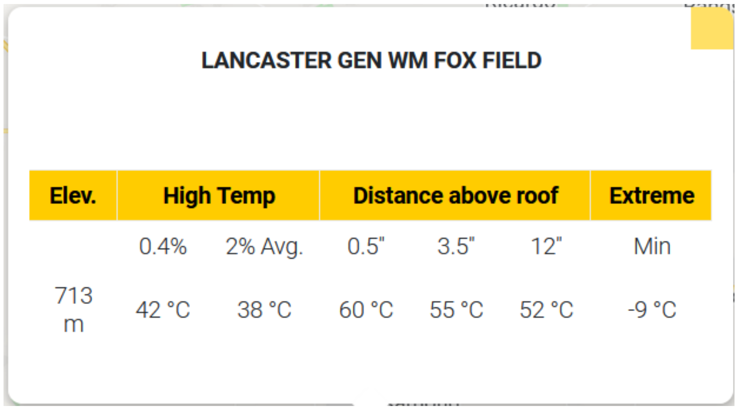
Cell Type	Half Cell
Open Circuit Voltage Voc [Vdc]	48.9
Nominal Efficiency [%]	21.9
Maximum Power [Wdc]	405
Temperature Coefficient [%/°C]	-0.24
Short Circuit Current Isc [Adc]	10.14
Module Dimensions [m]	1.821 x 1.016 x 0.03

Table 3: Inverter Delta Electronics E8-TL-US [208V]

Nominal AC Voltage [V]	208
Maximum DC Voltage [V]	480
Maximum AC Power [Wac]	5000
Efficiency [%]	98
Inverter Dimensions [m]	0.425 x 0.590 x 0.150
Maximum Power Point Trackers	3
Compatible Battery Pack Size [kWh per Inverter]	5-30

6.4 Property Weather Statistics

Figure 17 below shows the weather statistics for Lancaster, CA. This is a city close to Palmdale, CA and was used because Palmdale, CA was not an option in the weather statistics search. The lowest temperature in the area is -9°C as shown in figure 17. This lowest temperature is used later in the module string size calculation.



LANCASTER GEN WM FOX FIELD

Elev.	High Temp		Distance above roof			Extreme
	0.4%	2% Avg.	0.5"	3.5"	12"	Min
713 m	42 °C	38 °C	60 °C	55 °C	52 °C	-9 °C

Figure 17: Weather Report for the Closest City to the Property [13]

6.5 Module String Size Calculation [14]

Equations for Calculating Maximum String Size:

$$\text{Module } V_{OCMAX} = V_{OC} \times [1 + (T_{MIN} - T_{STC}) \times (T_{kVoc}/100)] \qquad (3)$$

Where Module V_{OCMAX}, is the maximum open circuit voltage, V_{OC} is the open circuit voltage, T_{MIN} is the lowest temperature at the location in Celsius, T_{STC} is the standard test condition temperature (25°C), and T_{kVoc} is the temperature coefficient.

$$\text{Maximum String Size} = (\text{Lowest Component Vmax} / \text{Module } V_{OCMAX}) \qquad (4)$$

Where Lowest Component Vmax is the lowest maximum voltage for either device, Module V_{OCMAX} is the maximum open circuit voltage (calculated in equation 2), and the Maximum String Size is how long the string can be before exceeding the maximum voltage.

Calculations for Maximum String Size:

Module V_{OCMAX} = 48.9V x [1 + (-9 – 25) x (-0.240/100)]

Module V_{OCMAX} = 52.89V

Maximum String Size = (480V/52.89V)

Maximum String Size = 9.08

Round down to 8 modules per string to ensure the maximum voltage of the inverter is never exceeded. All numbers in this calculation came from the module data sheet, inverter datasheet, and figure 17. In the first iteration of calculating maximum string size and design of a few different module layouts on the land, a string of 9 modules was used. This first iteration calculation and possible design layouts is shown in the appendix section C. Later the decision was made to round down to 8 for better over voltage protection.

7. SUN POSITION EXPLANTATION AND EQUATIONS [15]

7.1 Solar Declination Equation

The solar dedication of the earth describes the tilt of the earth. More specifically it's the angle between the plane of the earth's equator and the center of the sun. The angle varies between -23.45° and +23.45° [14].

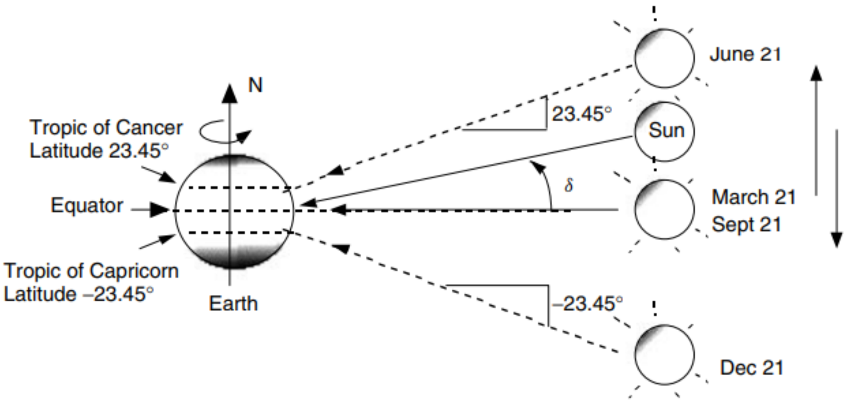


Figure 18: Displays the Solar Declination [15]

$$\delta = 23.45 \times \sin[(360/365)(n - 81)] \quad (5)$$

Where δ is the solar declination and n is the day of the year (out of 365).

7.2 Hour Angle of the Sun

The hour angle of the sun describes the difference from noon in terms of a 360° rotation in one day [14].

$$H = 15(12 - T) \quad (6)$$

Where H is the hour angle and T is the time of day on a 24-hour clock.

7.3 Altitude Angle of the Sun

The altitude angle of the sun describes the angle from the horizon up to the sun [15].

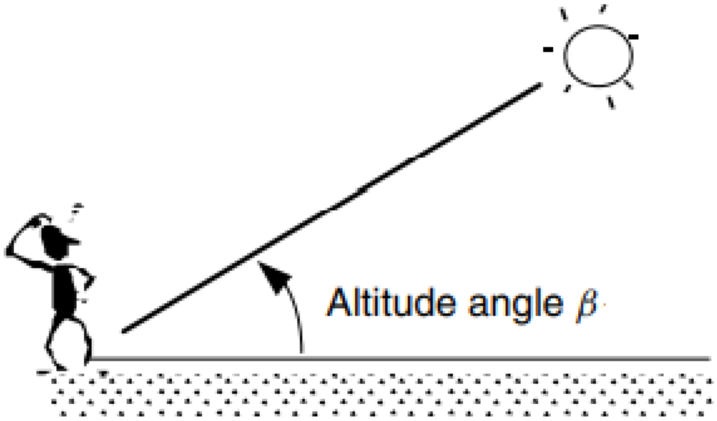


Figure 19: Depiction of the Sun's Altitude Angle [15]

$$\beta = \sin^{-1}[\sin(\delta)\sin(L) + \cos(\delta)\cos(L)\cos(H)] \qquad (7)$$

Where β is the suns altitude angle at a certain time, δ is the Solar Declination, L is the Latitude, and H is the Hour Angle at a certain time.

7.4 Azimuth Angle of the Sun

The azimuth angle of the sun describes the angle the sun is away from south. For this project a reference direction of south will be 0°. If the sun is east of south, this will be designated as a positive azimuth angle. If the sun is west of south, this will be designated as a negative azimuth angle [15].

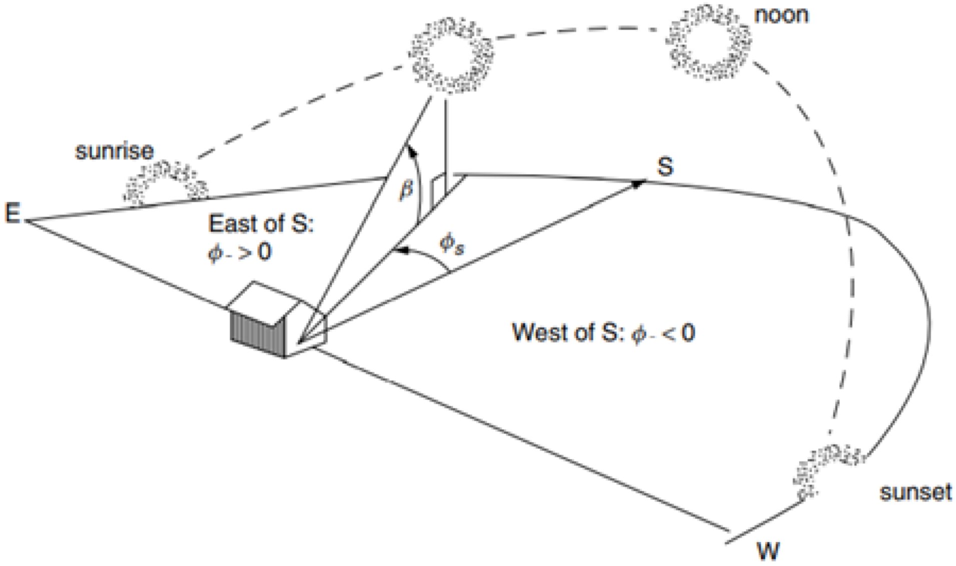


Figure 20: Depiction of the Sun's Azimuth Angle [15]

$$\Phi = \sin^{-1}[(\cos(\delta)\sin(H)) / \cos(\beta)] \qquad (8)$$

Where Φ is the suns azimuth angle at a certain time, δ is the Solar Declination, H is the Hour Angle at a certain time, and β is the suns altitude angle at a certain time.

7.5 Altitude vs. Azimuth Plot for Location

Figure 21 below shows the altitude versus azimuth plot of the sun for the entire year at the location of the design. MATLAB code is included in appendix section F.

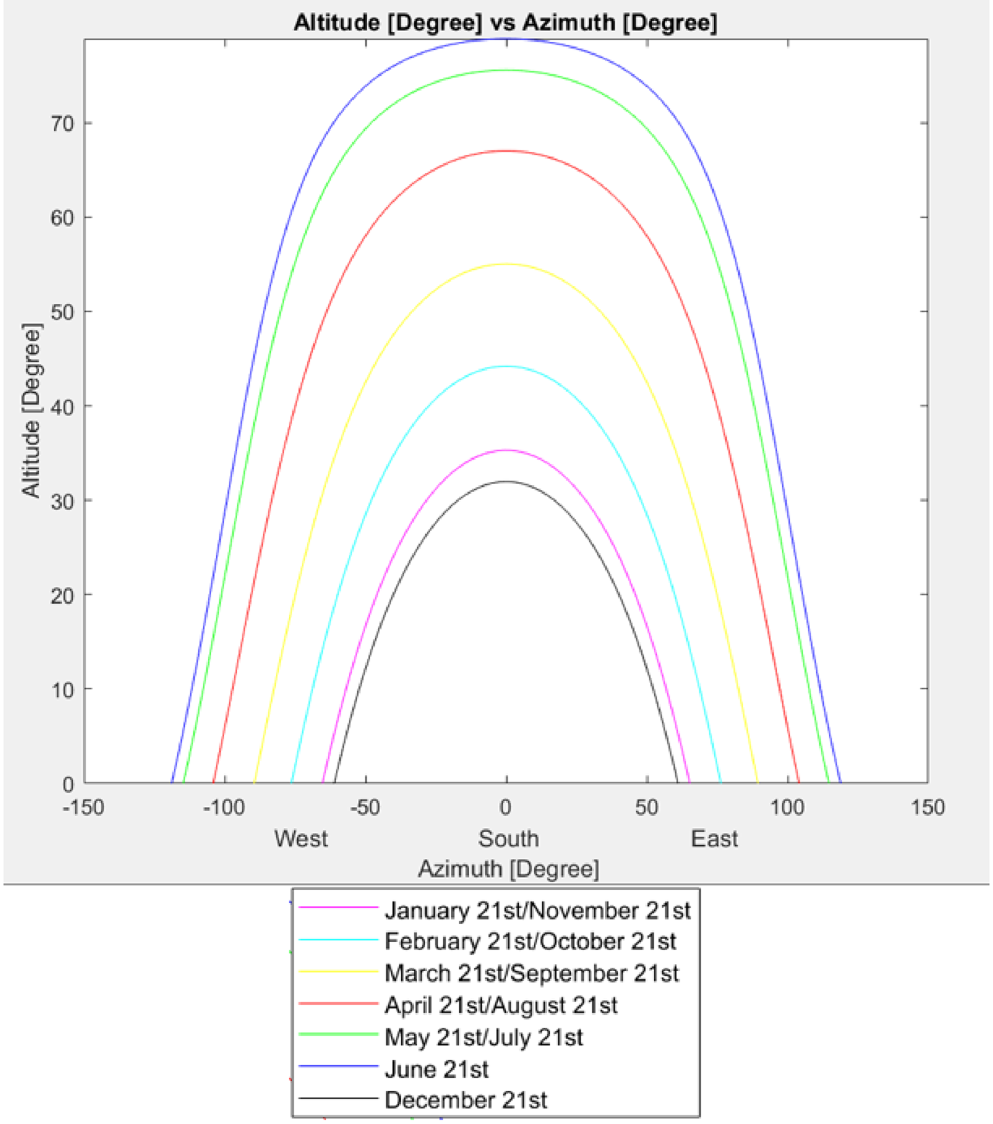


Figure 21: Altitude vs. Azimuth Plot

8. DESIGN INTRODUCTIONS

It is important to space the solar module rows far enough apart to prevent shading on the solar modules since shading can drastically reduce power production. Unfortunately, at some point during the morning and afternoon, shading cannot be prevented since the sun will be so low in the sky. According to the United States Environmental Protection Agency, sun ray intensity is the strongest during the hours of 10am and 4pm [16]. After preliminary testing and calculations, ensuring no shading between 10am-4pm spaced the rows so far apart it would drastically limit the number of solar modules on the property. Therefore, no shading hours were reduced to 10am-2pm.

To calculate how far apart the rows of solar modules need to be placed to prevent shading during the hours of 10am-2pm, the worst-case scenario needs to be considered. The worst-case scenario occurs on the winter solstice, December 21st. This the worst-case scenario because the sun is the lowest in the sky on this date.

The suns solar declination, hour angle, altitude, and azimuth will be calculated at the hours of 10am and 2pm on December 21st. Then the height of the solar array will be calculated. Using that information, the shadow length will be calculated to determine the required interrow spacing of the solar panels. Since the sun rises and falls symmetrically around 12pm (noon) the shadow length at 10am and 2pm will be the same, although calculations were done at both times for each design for confirmation. According to [17], the solar modules should be placed off the ground anywhere between a couple inches to a couple feet. Therefore, the fixed tilt solar modules will be placed off the ground 14 inches (0.3556m) to promote air flow and clear any brush. The single axis tacking designs will be placed 19.685 inches (0.5m) off the ground also to promote air flow, clear any brush, and account for any additional mounting requirements.

The first test calculation did not take into consideration the solar array would be lifted off the ground. These test calculations are shown in appendix section D. Appendix section E shows the calculations for no shading on the winter solstice between the hours of 10am to 4pm for designs 1 and 2.

9. EXAMPLE SHADING CALULCATIONS - ALL FIXED TILT [18]

To calculate how far apart the module rows need to be, it is necessary to look at the position of the sun on the winter solstice, December 21st, at the hours of 10am and 2pm, which is the time shading should be prevented [16]. To do the calculation there are two triangles that need to be looked at to determine the shadow length.

Triangle one is shown as yellow in figure 22. In this triangle the height of the solar array can be calculated and so can the altitude angle of the sun at a certain time on a certain day. Then using trigonometry, Length X can be solved for using tangent as shown in equation 9. Figure 22 shows the second triangle in red. In this triangle, Length X is known and the azimuth angle can be calculated. With that information, the shadow length can be calculated using cosine as shown in equation 10. Then the arrays should be place further apart than the shadow length. This method was used when calculating the interrow spacing in designs 1, 2, 3, and 4.

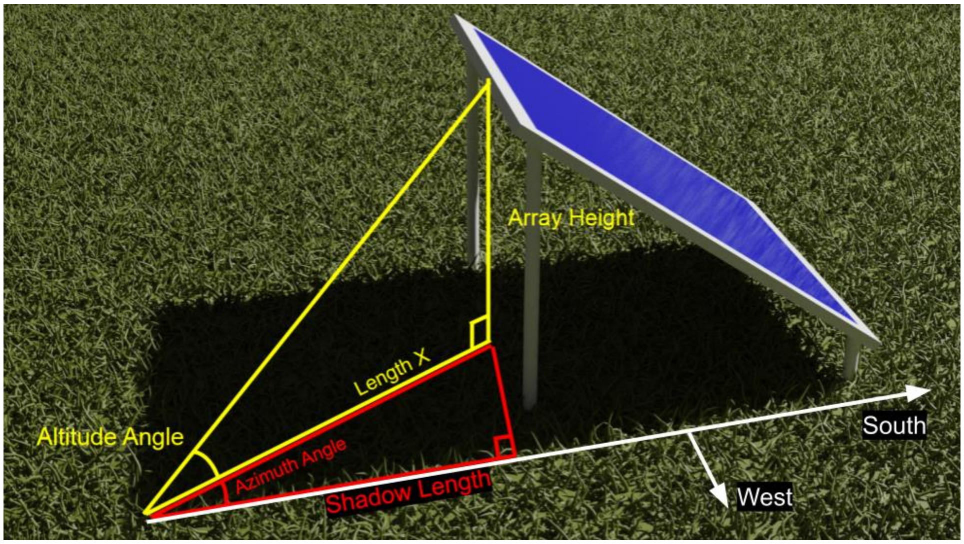


Figure 22: Calculating Shadow Length of South Facing Fixed Tilt Modules [18]

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X (9)

Length X = Array Height / Tan(Altitude Angle)

Part 2: Red Triangle

cos(Azimuth Angle) = Shadow Length / Length X (10)

Shadow Length = Length X x cos(Azimuth Angle)

10. SUN POSITION CALCULATIONS USED FOR ALL 6 DESIGNS [15]

Shading calculations will be done for all 6 designs to prevent shading between rows on the winter solstice between the hours of 10am and 2pm. First the solar declination, hour angle, altitude angle, and azimuth angle will be calculated for both the hours of 10am and 2pm on December 21st. The solar declination will only be calculated once as it is the same for each time. These calculations are used in all 6 designs.

10.1 Calculation of Solar Declination on December 21st:

$\delta = 23.45 \times \sin[(360/365)(n - 81)]$

Where δ is the solar declination and n is the day of the year (out of 365)

$\delta = 23.45 \times \sin[(360/365)(355 - 81)]$

$\delta = -23.45°$

10.2 Calculation of Hour Angle at 10am on December 21st:

$H = 15(12 - T)$

Where H is the hour angle and T is the time of day on a 24-hour clock

$H = 15(12 - 10)$

$H = 30°$ at 10am December 21st

10.3 Calculation of Suns Altitude at 10am on December 21st:

$\beta = \sin^{-1}[\sin(\delta)\sin(L) + \cos(\delta)\cos(L)\cos(H)]$

Where β is the suns altitude angle at 10am, δ is the Solar Declination, L is the Latitude, and H is the Hour Angle at 10am.

$\beta = \sin^{-1}[\sin(-23.45°)\sin(34.5723°) + \cos(-23.45°)\cos(34.5723°) \cos(30°)]$

$\beta = 25.37°$

10.4 Calculation of Suns Azimuth at 10am on December 21st:

$\Phi = \sin^{-1}[(\cos (\delta)\sin(H)) / \cos(\beta)]$

Where Φ is the suns azimuth angle at 10am, δ is the Solar Declination, H is the Hour Angle at 10am, and β is the suns altitude angle at 10am.

$\Phi = \sin^{-1}[(\cos (-23.45°)\sin(30°)) / \cos(25.37°)]$

$\Phi = 30.51°$

10.5 Calculation of Hour Angle at 2pm on December 21st:

$H = 15(12 – T)$

Where H is the hour angle and T is the time of day on a 24-hour clock

$H = 15(12 – 14)$

$H = -30°$ at 2pm December 21st

10.6 Calculation of Suns Altitude at 2pm on December 21st :

$\beta = \sin^{-1}[\sin(\delta)\sin(L) + \cos(\delta)\cos(L)\cos(H)]$

Where β is the suns altitude angle at 2pm, δ is the Solar Declination, L is the Latitude, and H is the Hour Angle at 2pm.

$\beta = \sin^{-1}[\sin(-23.45°)\sin(34.5723°) + \cos(-23.45°)\cos(34.5723°)\cos(-30°)]$

$\beta = 25.37°$

10.7 Calculation of Suns Azimuth at 2pm on December 21st:

$\Phi = \sin^{-1}[(\cos(\delta)\sin(H)) / \cos(\beta)]$

Where Φ is the suns azimuth angle at 2pm, δ is the Solar Declination, H is the Hour Angle at 2pm, and β is the suns altitude angle at 2pm.

$\Phi = \sin^{-1}[(\cos(-23.45°)\sin(-30°)) / \cos(25.37°)]$

$\Phi = -30.51°$

11. DESIGN 1 (3 STRING) – FIXED TILT

Design 1 utilizes all 3 maximum power point trackers on the inverter as shown below in figure 23.

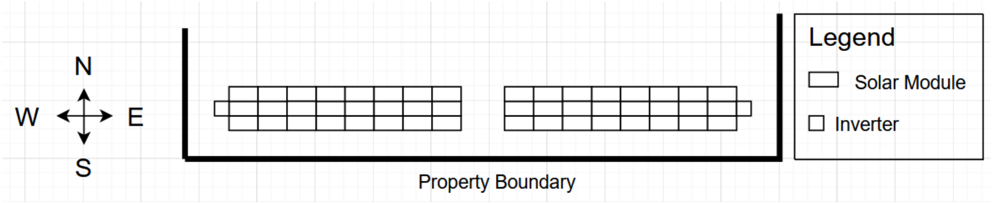


Figure 23: Design 1 - First Row of Solar Farm, Modules Tilted Towards the South

Interrow spacing/shading calculation will be done for the design in figure 23 and will prevent shading on the winter solstice between the hours of 10am and 2pm. The solar declination, hour angle, altitude angle, and azimuth angle has already been calculated in chapter 10.

11.1 Calculation of Height and Length of Solar Module Array

Figure 23 shows one row of design 1 with 3 strings and 8 modules per string. The solar modules will be tilted at an angle of 34.5723° South and the hypotenuse length is known as shown below in figure 24. The hypotenuse has a length of three solar modules. Since the modules are in the landscape orientation and the length of one solar module is 1.016m, the length of three solar modules is 3.048m. With this information, the angle of tilt, and the length of the hypotenuse, the height and length can be determined from trigonometric calculations. Figure 25 shows the height and length labeled in the figure.

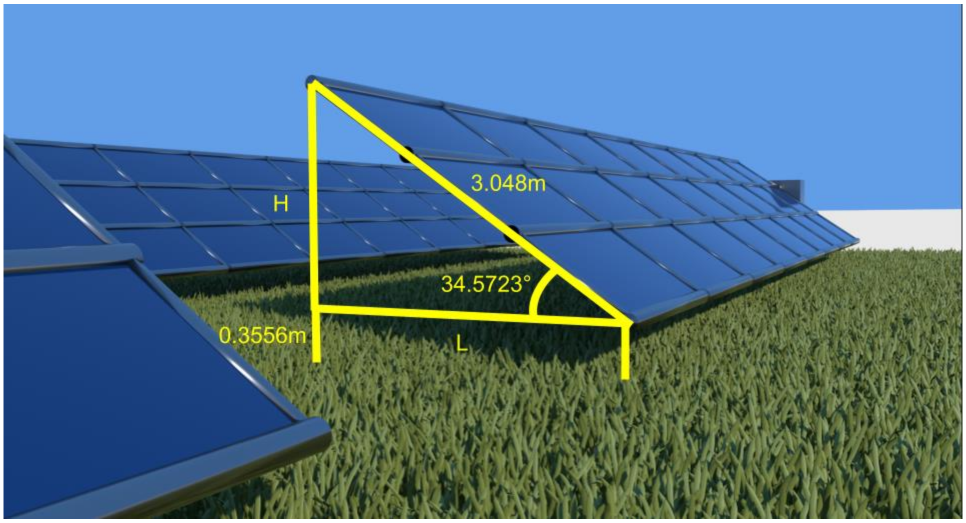


Figure 24: Design 1 - Depiction of the Height and Length of the Array

Calculation of Height:

$\sin(34.5723°) = H / 3.048m$

$H = 3.048m \times \sin(34.5723°)$

$H = 1.73m$

Because the solar modules are lifted off the ground by 0.3556 meters, this needs to be added to the calculated height measurement to determine the total height.

Total Height = 1.73m + 0.3556m = 2.09m

Calculation of Length:

$\cos(34.5723°) = L / 3.048m$

$L = 3.048 \times \cos(34.5723°)$

$L = 2.51m$

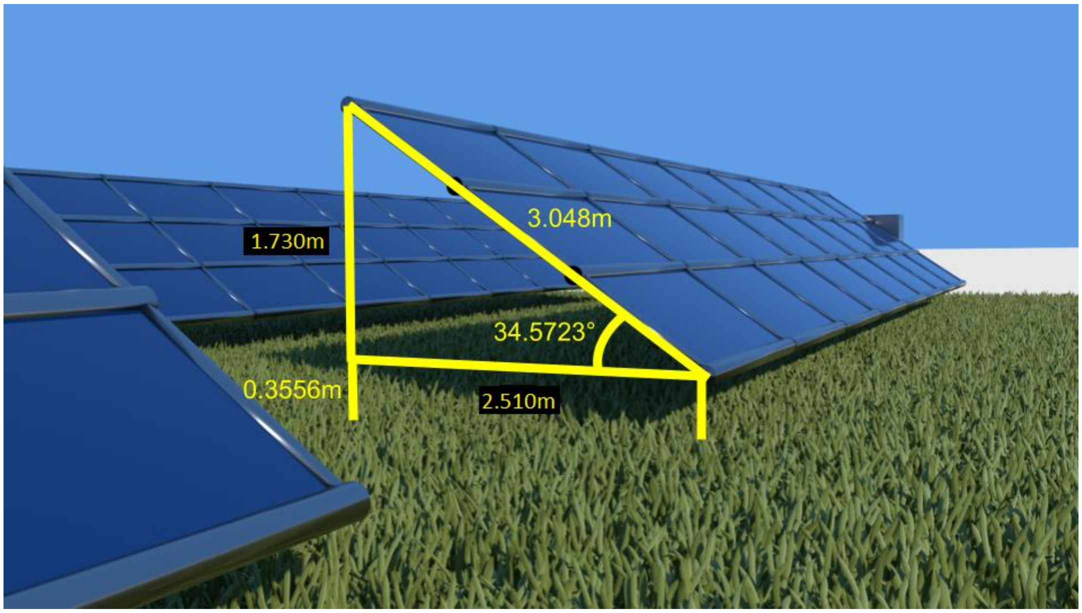


Figure 25: Design 1 - Displays the Height and Length of the Array

11.2 Calculation of Interrow Spacing at 10am December 21st [18]:

Reference chapter 9 for depictions of the yellow and red triangles.

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 2.09m / Tan(25.37°)

Length X = 4.41m

Part 2: Red Triangle

Cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = 4.41m x Cos(Azimuth Angle)

Shadow Length = 4.41m x Cos(30.51°)

Shadow Length = 3.80m

11.3 Calculation of Interrow Spacing at 2pm December 21st [18]:

Reference chapter 9 for depictions of the yellow and red triangles

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 2.09m / Tan(25.37°)

Length X = 4.41m

Part 2: Red Triangle

cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = Length X x cos(Azimuth Angle)

Shadow Length = 4.41m x cos(-30.51°)

Shadow Length = 3.80m

The shadow length at 10am and 2pm is 3.80m. To prevent shading, the arrays will be placed 4 meters apart as shown in figure 26 and 27 below. It is important to note the array length and the module length is shorter than is shown in figure 26 since the modules are at an angle. Therefore figure 26 overcompensates the space the modules will take up. Figure 27 is a 3D visual aid to help show what the solar panels would look like on the property. Simulations results are shown in chapter 18.

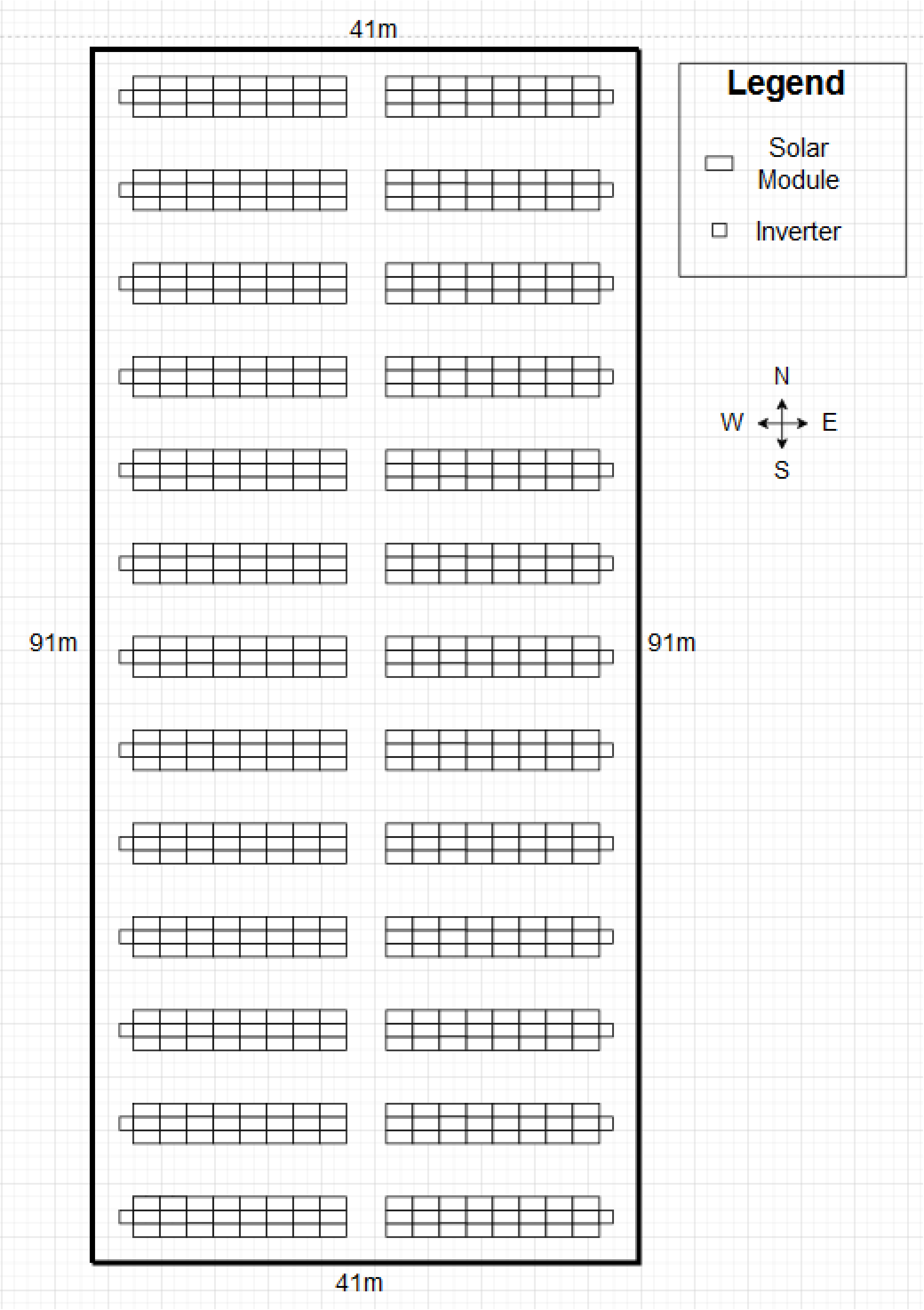


Figure 26: Design 1 - Modules Tilted South at Angle of 34.6°, 26 Inverters, 624 Modules

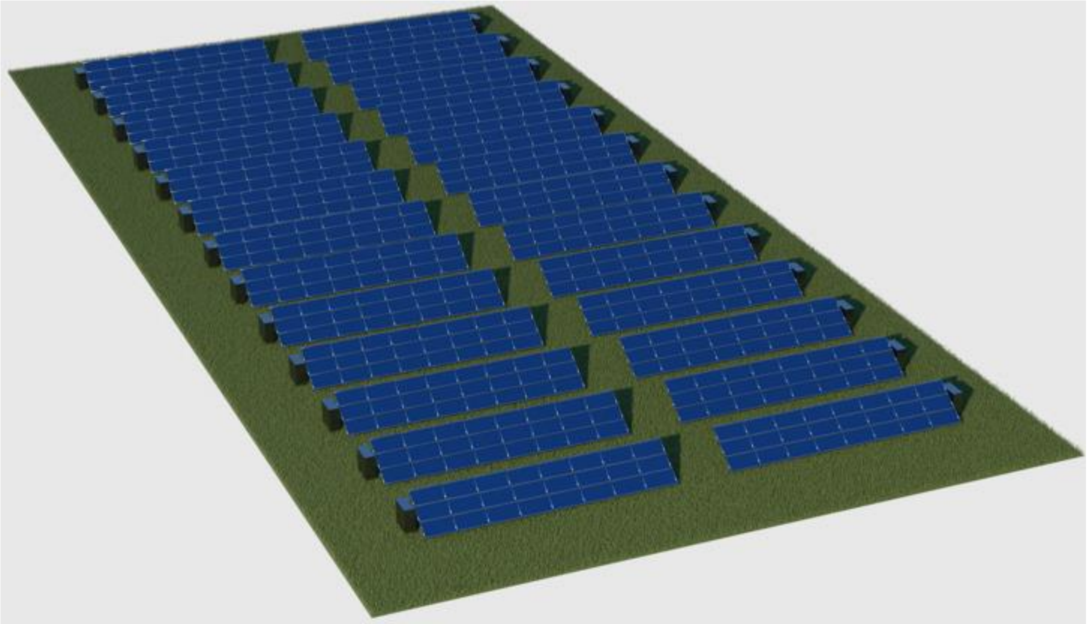


Figure 27: Design 1 – 3D Model of Modules Tilted 34.6° South, 26 Inverters, 624 Modules

12. DESIGN 2 (3 STRING) - FIXED TILT

Design 2 utilizes all 3 maximum power point trackers on the inverter as shown below in figure 28.

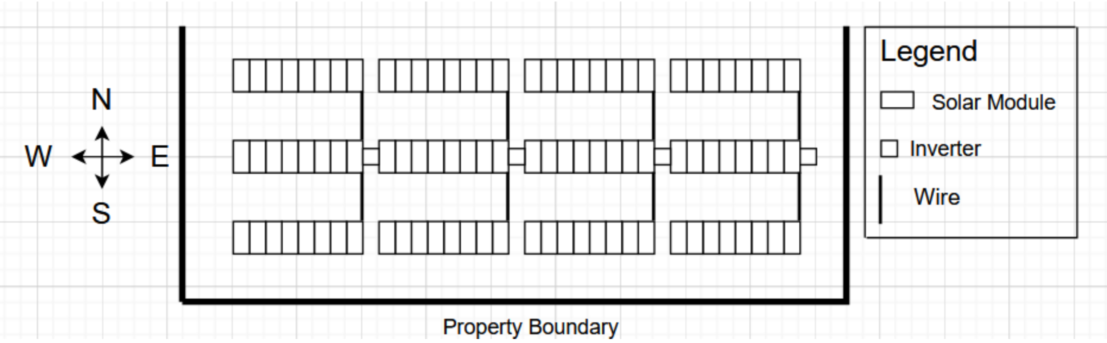


Figure 28: Design 2 - First Row Strings of Solar Farm, Modules Tilted Towards the South

Interrow spacing/shading calculation will be done for the design in figure 28 and will prevent shading on the winter solstice between the hours of 10am and 2pm. The solar declination, hour angle, altitude angle, and azimuth angle has already been calculated in chapter 10.

12.1 Calculation of Height and Length of Solar Module Array

The solar modules will be tilted at an angle of 34.5723° and the hypotenuse length is known as shown below in figure 29. The hypotenuse has a length of one solar module. Since the modules are in the portrait orientation, the length of one solar module is 1.821m. With this information, the angle of tilt and the length of the hypotenuse, the height and length can be determined from trigonometric calculations. Figure 30 shows the height and length labeled in the figure.

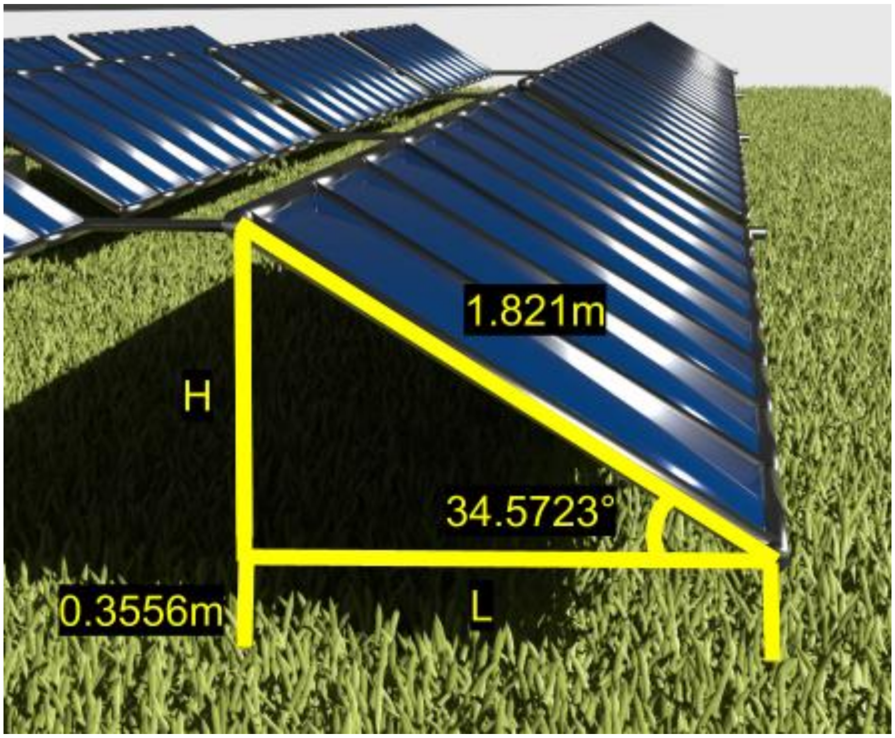


Figure 29: Design 2 - Depiction of the Height and Length of the Array

Calculation of Height:

sin(34.5723°) = H / 1.821m

H = 1.821m x sin(34.5723°)

H = 1.03m

Because the solar modules are lifted off the ground by 0.3556 meters, this needs to be added to the calculated height measurement to determine the total height.

Total Height = 1.03m + 0.3556m = 1.39m

Calculation of Length:

cos(34.5723°) = L / 1.821m

L = 1.821 x cos(34.5723°)

L = 1.50m

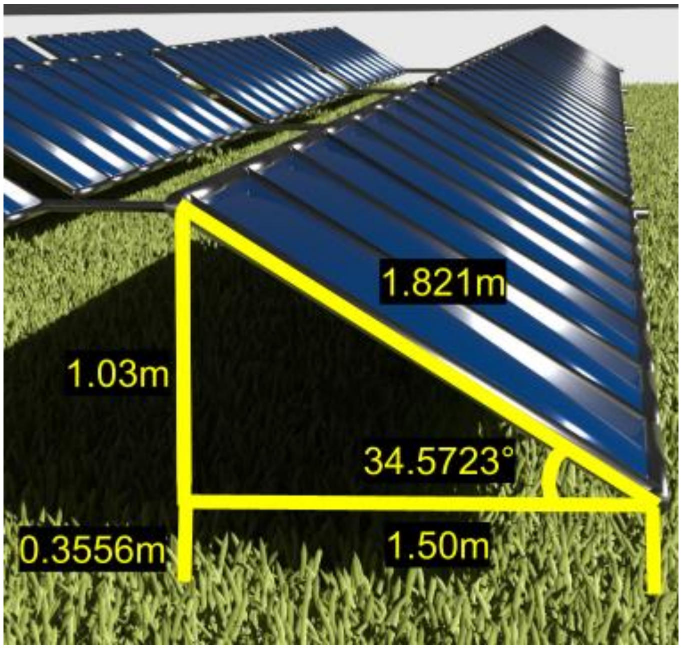


Figure 30: Design 2 - Displays the Height and Length of the Array

12.2 Calculation of Interrow Spacing at 10am December 21st [18]:

Reference chapter 9 for depictions of the yellow and red triangles.

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 1.39m / Tan(25.37°)

Length X = 2.93m

Part 2: Red Triangle

Cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = 2.93m x Cos(Azimuth Angle)

Shadow Length = 2.93m x Cos(30.51°)

Shadow Length = 2.52m

12.3 Calculation of Interrow Spacing at 2pm December 21st [18]:

Reference chapter 9 for depictions of the yellow and red triangles.

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 1.39m / Tan(25.37°)

Length X = 2.93m

Part 2: Red Triangle

cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = Length X x cos(Azimuth Angle)

Shadow Length = 2.93m x cos(-30.51°)

Shadow Length = 2.52m

The shadow length at 10am and 2pm is the same at 2.52m. To prevent shading the arrays will be placed 3 meters apart as shown in figure 31 and 32. It is important to note the array length and the module length is shorter than is shown in figure 31. Therefore figure 31 overcompensates the space the modules will take up. Figure 31 is a visual aid to help show what the solar panels would look like on the property.

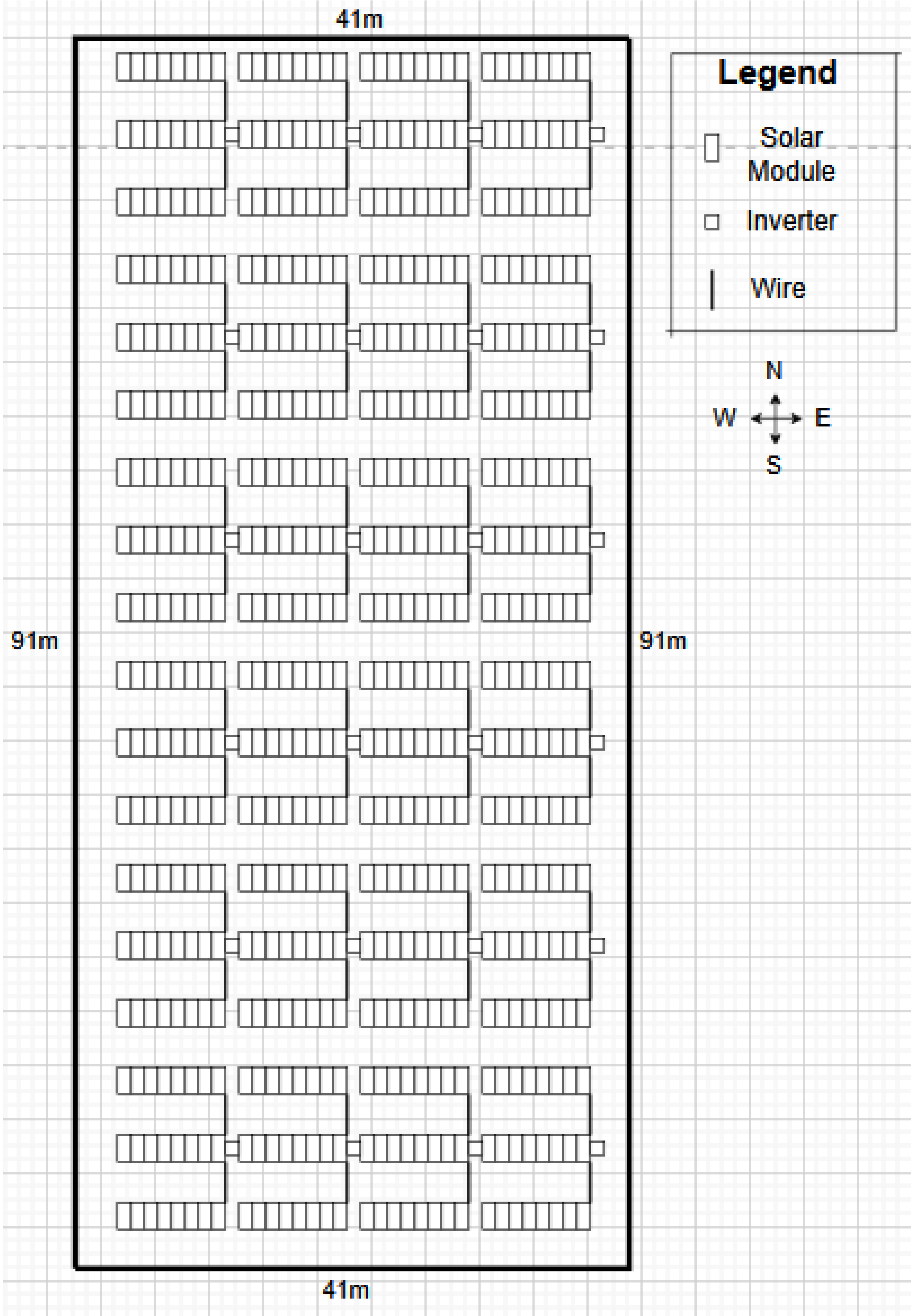


Figure 31: Design 2 - Modules Tilted South at Angle of 34.6°, 24 Inverters, 576 Modules

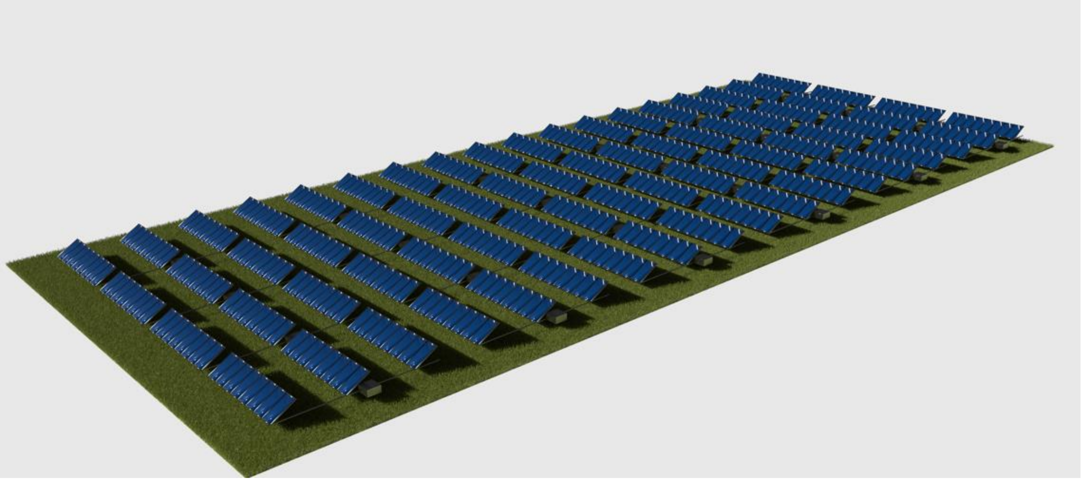


Figure 32: Design 2- 3D Model of Modules Tilted 34.6° South, 24 Inverters, 576 Modules

13. DESIGN 3 (2 STRING) – FIXED TILT

Design 3 only utilizes 2 maximum power point trackers on the inverter as shown below in figure 33. Two string designs were included to evaluate the difference between 3 string simulation results and 2 string simulation results.

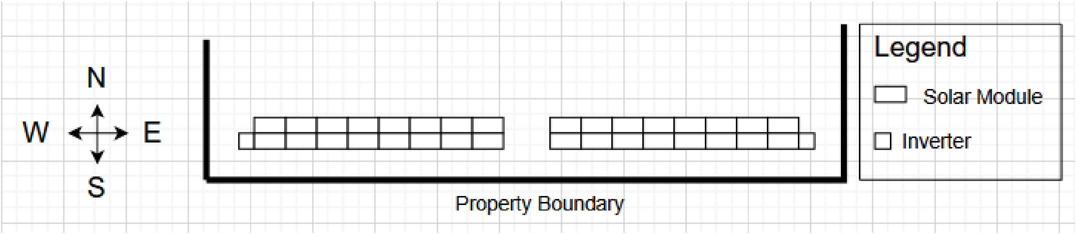


Figure 33: Design 3 - First Row of Solar Farm, Modules Tilted Towards the South

Interrow spacing/shading calculation will be done for the design in figure 33 and will prevent shading on the winter solstice between the hours of 10am and 2pm. The solar declination, hour angle, altitude angle, and azimuth angle has already been calculated in chapter 10.

13.1 Calculation of Height and Length of Solar Module Array

The solar modules will be tilted at an angle of 34.5723° south and the hypotenuse length is known as shown below in figure 34. The solar modules are in the landscape orientation. Therefore, the hypotenuse has a length of two solar modules at 2.023m. With this information, the angle of tilt and the length of the hypotenuse, the height and length can be determined from trigonometric calculations. Figure 35 shows the height and length labeled in the figure.

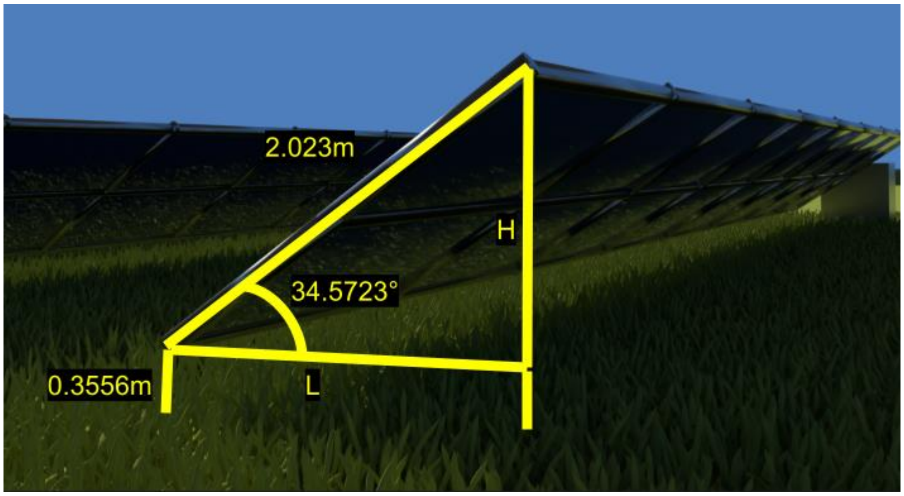


Figure 34: Design 3 - Depiction of the Height and Length of the Array

Calculation of Height:

sin(34.5723°) = H / 2.023m

H = 2.023m x sin(34.5723°)

H = 1.148m

Because the solar modules are lifted off the ground by 0.3556 meters, this needs to be added to the calculated height measurement to determine the total height.

Total Height = 1.148m + 0.3556m = 1.5m

Calculation of Length:

cos(34.5723°) = L / 2.023m

L = 2.023 x cos(34.5723°)

L = 1.67m

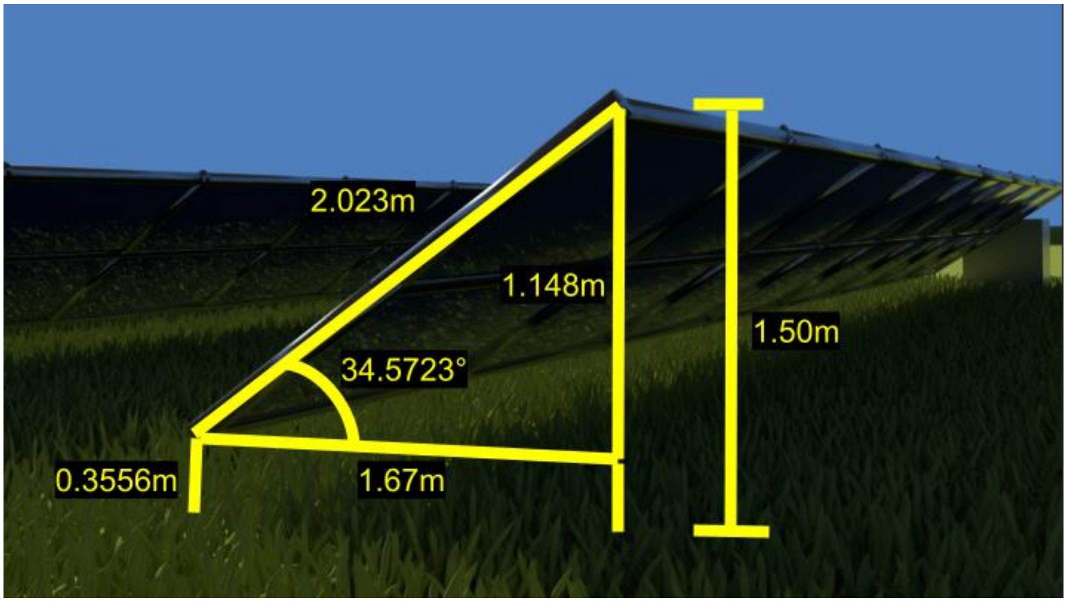


Figure 35: Design 3 - Displays the Height and Length of the Array

13.2 Calculation of Interrow Spacing at 10am December 21st [18]:

Reference chapter 9 for depictions of the yellow and red triangles.

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 1.50m / Tan(25.37°)

Length X = 3.16m

Part 2: Red Triangle

Cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = 3.16m x Cos(Azimuth Angle)

Shadow Length = 3.16m x Cos(30.51°)

Shadow Length = 2.72m

13.3 Calculation of Interrow Spacing at 2pm December 21st [18]:

Reference chapter 9 for depictions of the yellow and red triangles.

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 1.50m / Tan(25.37°)

Length X = 3.16m

Part 2: Red Triangle

cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = Length X x cos(Azimuth Angle)

Shadow Length = 3.16m x cos(-30.51°)

Shadow Length = 2.72m

The shadow length at 10am and 2pm is the same at 2.72m. To prevent shading the arrays will be placed 3 meters apart as shown in figure 36 and 37. It is important to note the array length and the module length is shorter than is shown in figure 36. Therefore figure 36 overcompensates the space the modules will take up. Figure 37 is a 3D visual aid to help show what the solar panels would look like on the property.

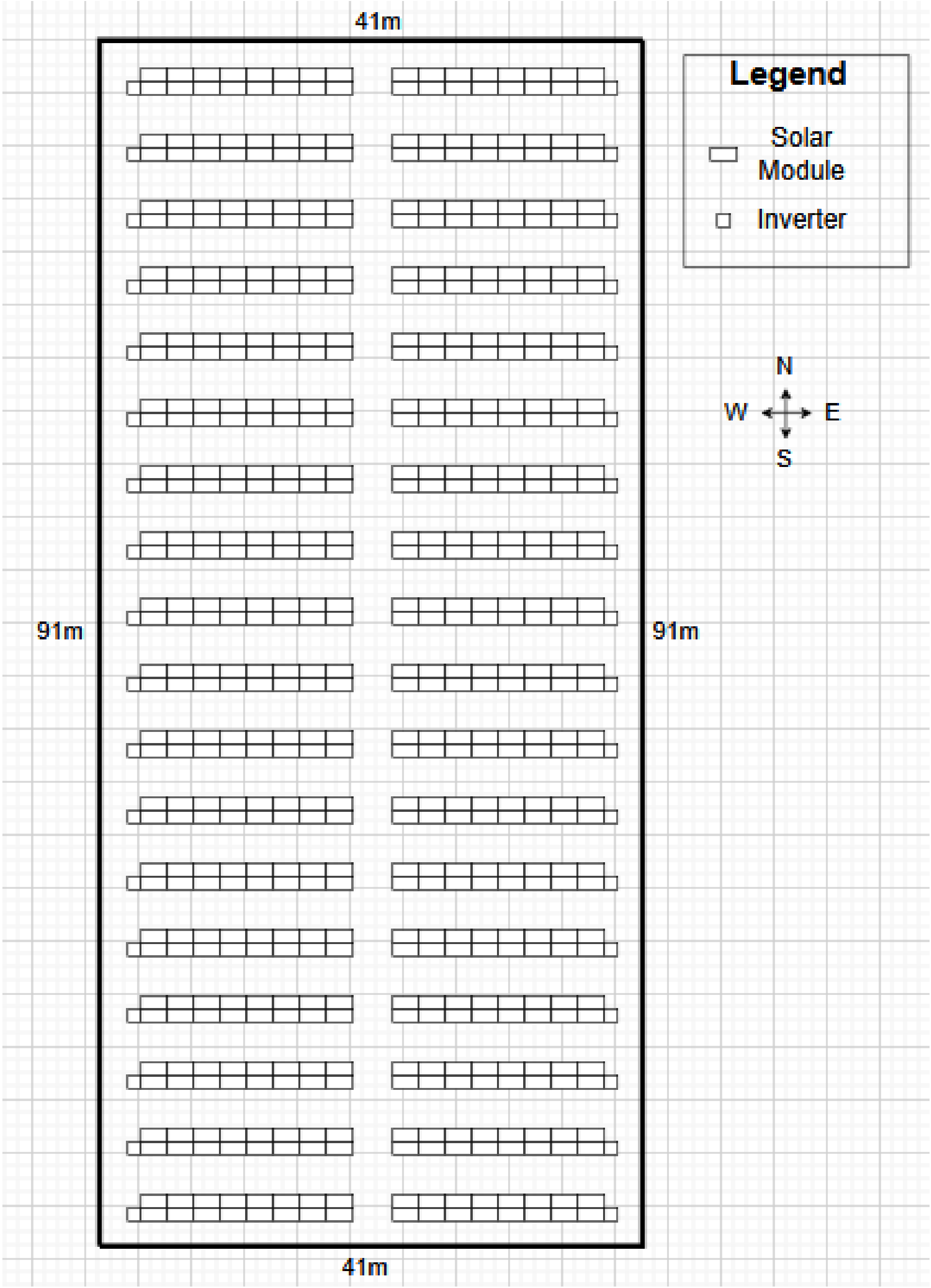


Figure 36: Design 3 - Modules Tilted South at Angle of 34.6°, 36 Inverters, 576 Modules

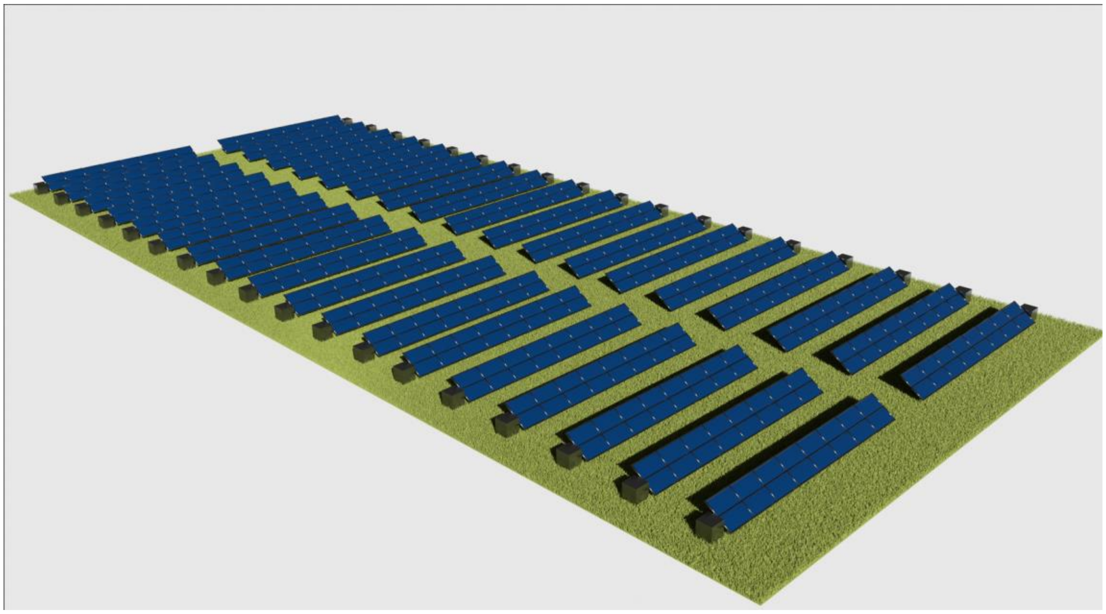


Figure 37: Design 3- 3D Model of Modules Tilted 34.6° South, 36 Inverters, 576 Modules

14. DESIGN 4 (2 STRING) – FIXED TILT

Design 4 only utilizes 2 maximum power point trackers on the inverter as shown below in figure 38. Two string designs were included to evaluate the difference between 3 string simulation results and 2 string simulation results.

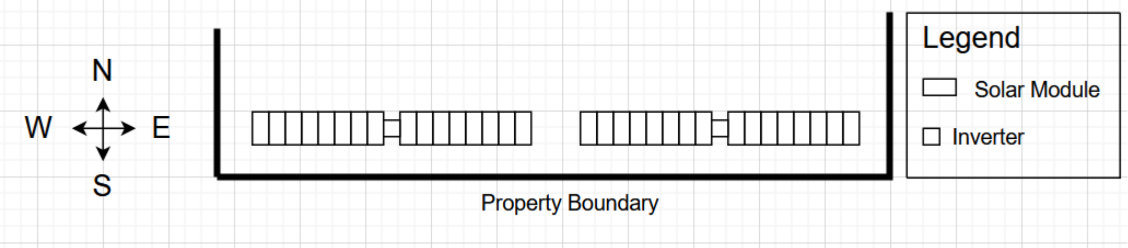


Figure 38: Design 4 - First Row of Solar Farm, Modules Tilted Towards the South

Interrow spacing/shading calculation will be done for the design in figure 38 and will prevent shading on the winter solstice between the hours of 10am and 2pm. The solar declination, hour angle, altitude angle, and azimuth angle has already been calculated in chapter 10.

14.1 Calculation of Height and Length of Solar Module Array

The solar modules will be tilted at an angle of 34.5723° south and the hypotenuse length is known as shown below in figure 39. The hypotenuse has a length of the longer side of the solar modules at 1.821m. With this information, the angle of tilt and the length of the hypotenuse, the height and length can be determined from trigonometric calculations. Figure 40 shows the height and length labeled in the figure.

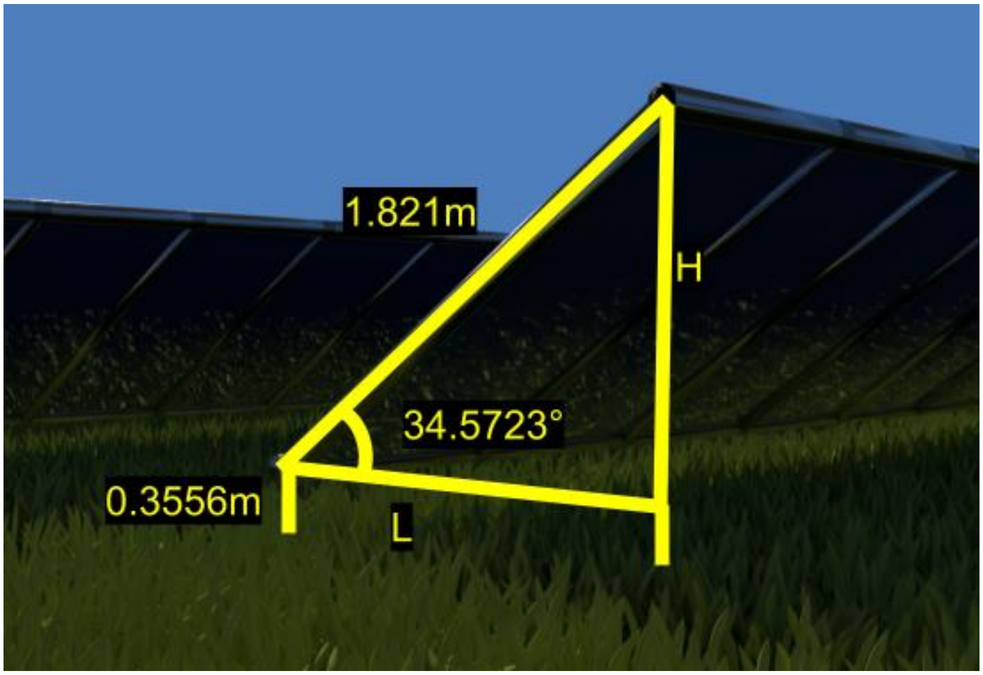


Figure 39: Design 4 - Depiction of the Height and Length of the Array

Calculation of Height:

sin(34.5723°) = H / 1.821m

H = 1.821m x sin(34.5723°)

H = 1.03m

Because the solar modules are lifted off the ground by 0.3556 meters, this needs to be added to the calculated height measurement to determine the total height.

Total Height = 1.03m + 0.3556m = 1.39m

Calculation of Length:

cos(34.5723°) = L / 1.821m

L = 1.821 x cos(34.5723°)

L = 1.5m

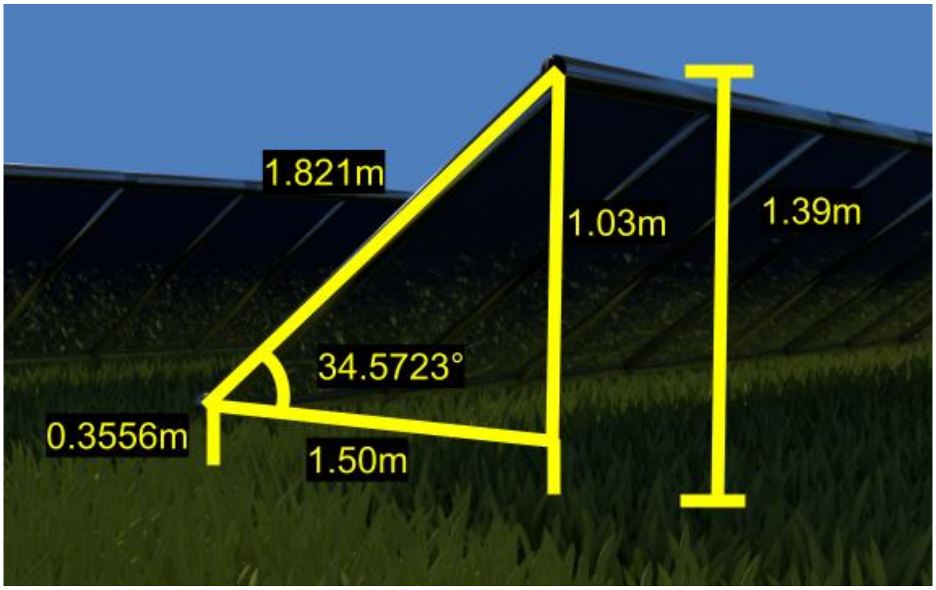


Figure 40: Design 4 - Displays the Height and Length of the Array

14.2 Calculation of Interrow Spacing at 10am December 21st [18]:

Reference chapter 9 for depictions of the yellow and red triangles.

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 1.39m / Tan(25.37°)

Length X = 2.93m

Part 2: Red Triangle

Cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = 2.93m x Cos(Azimuth Angle)

Shadow Length = 2.93m x Cos(30.51°)

Shadow Length = 2.5m

14.3 Calculation of Interrow Spacing at 2pm December 21st [18]:

Reference chapter 9 for depictions of the yellow and red triangles.

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 1.39m / Tan(25.37°)

Length X = 2.93m

Part 2: Red Triangle

cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = Length X x cos(Azimuth Angle)

Shadow Length = 2.93m x cos(-30.51°)

Shadow Length = 2.52m

The shadow length at 10am and 2pm is the same at 2.5m. To prevent shading the arrays will be placed 2.5 meters apart as shown in figure 41 and 42. It is important to note the array length and the module length is shorter than is shown in figure 41. Therefore figure 41 overcompensates the space the modules will take up. Figure 42 is a 3D visual aid to help show what the solar panels would look like on the property.

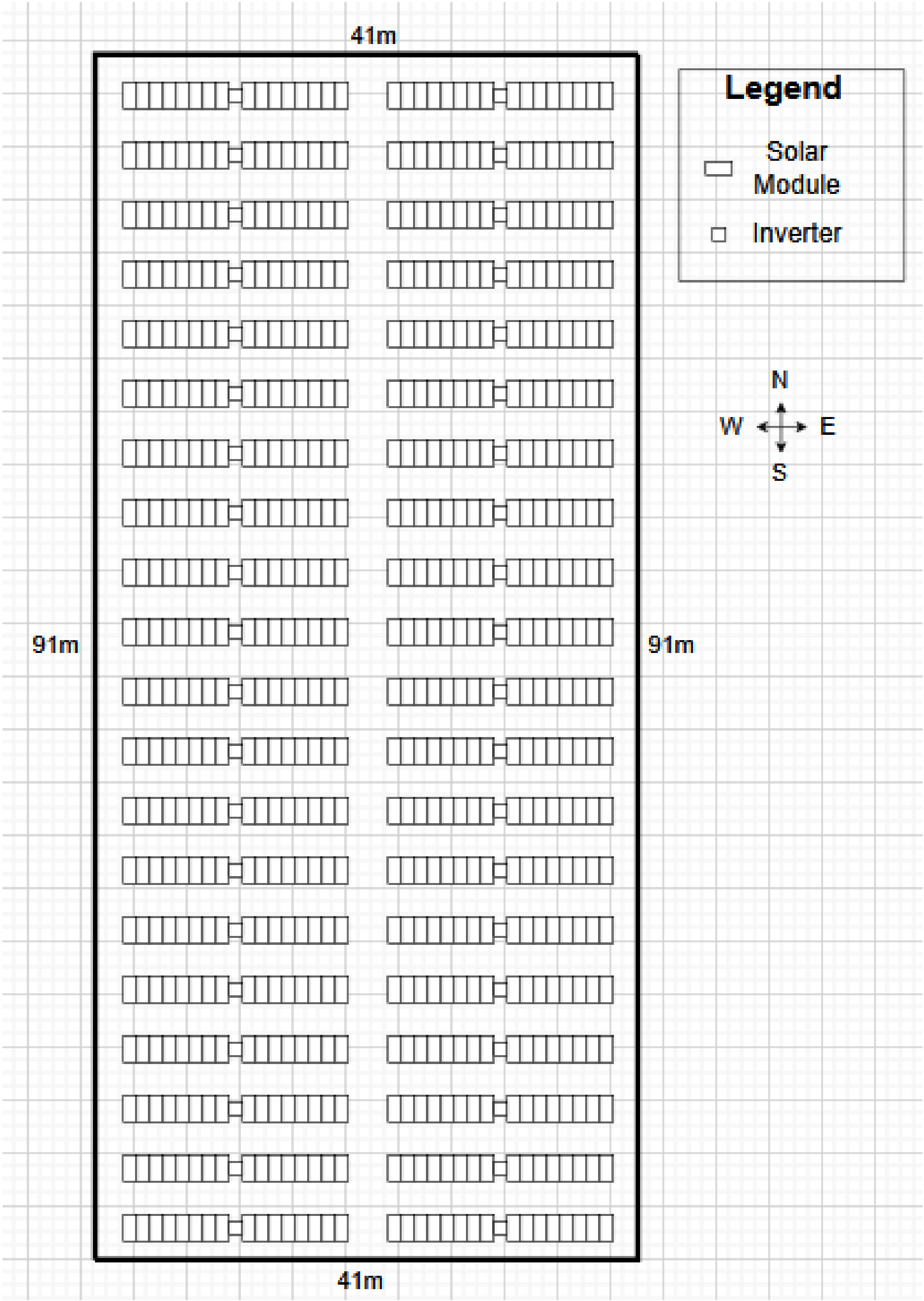


Figure 41: Design 4 - Modules Tilted South at Angle of 34.6°, 40 Inverters, 640 Modules

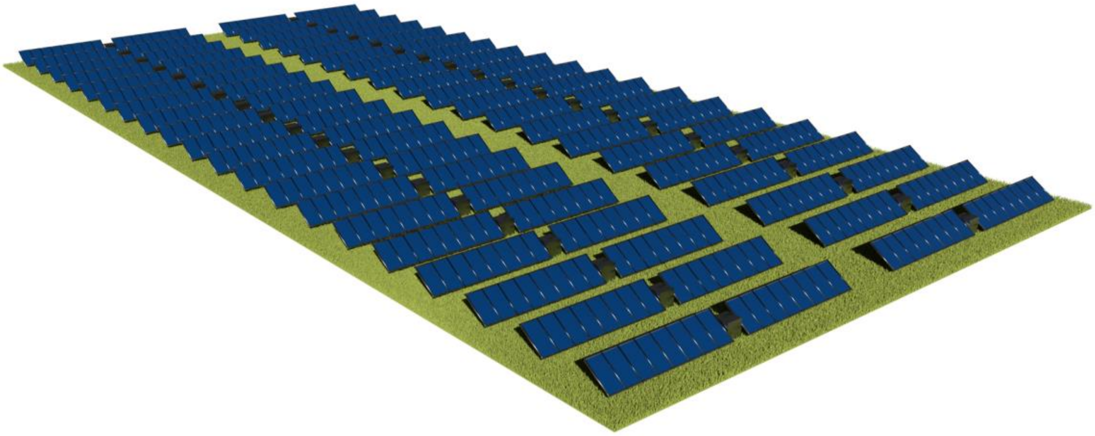


Figure 42: Design 4 - 3D Model of Modules Tilted 34.6° South, 40 Inverters, 640 Modules

15. SINGLE AXIS TRACKING - OPTIMAL TILT ANGLE [19]

To calculate the interrow spacing of single axis tilt solar modules, backtracking needs to be considered. Backtracking is when the tilt of the solar modules changes from the optimal tilt angle to account for shading on other solar modules in a different row. To ensure the solar modules are oriented at the optimal tilt angle between the hours of 10am to 2pm, the optimal tilt angle for 10am and 2pm needs to be calculated on the winter solstice, December 21st. The modules will be oriented on a north south axis to ensure the modules are facing more east in the morning and more west in the afternoon. This optimal tilt angle equation is used in designs 5 and 6.

15.1 Optimal Tilt Angle Derivation [19]

To calculate the optimal tilt angle, first, two vectors on the plane of the solar module needs to be defined as shown in figure 44. Tau (τ) in this derivation is the tilt angle of the module. It is positive in the morning when the modules are tilted toward the east and negative in the evening when the modules are tilted toward the west. Tau is shown in figure 43 [19].

$V1 = [-1 \; 0 \; 0]$

$V2 = [0 \; -\cos(\tau) \; \sin(\tau)]$

Using V1 and V2, a vector normal to the module is calculated by crossing V1 and V2.

$$n = V1 \times V2 \qquad (11)$$

$$n = V1 \times V2 = [(0 \times \sin(\tau) - 0 \times -\cos(\tau)) \quad (0 \times 0 - -1 \times \sin(\tau)) \quad (-1 \times -\cos(\tau) - 0 \times 0)]$$

$$n = V1 \times V2 = [0 \quad -\sin(\tau) \quad \cos(\tau)]$$

$$n = [0 \quad -\sin(\tau) \quad \cos(\tau)]$$

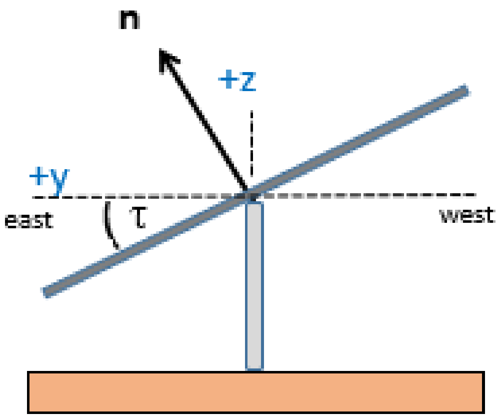


Figure 43: Displays the Tilt Angle Tau τ [19]

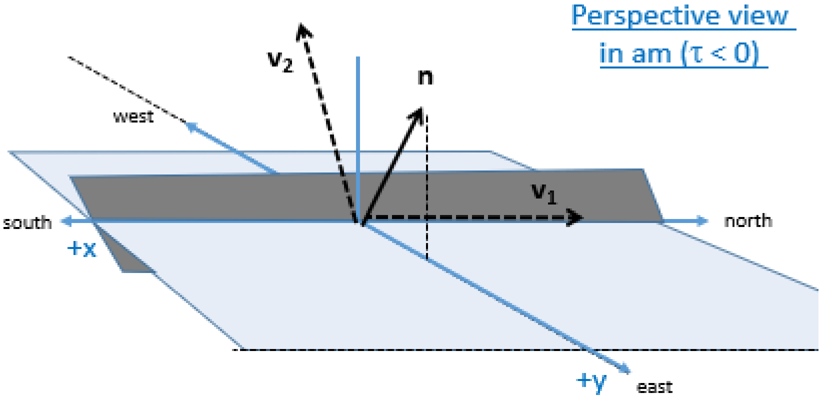


Figure 44: Displays V1, V2, and the Normal Vector [19]

Next a vector pointing toward the sun needs to be determined. This can be done using functions of the sun's altitude angle β and the suns azimuth angle Φ. This vector takes into consideration the location, time of day, and day of the year.

$v_S = [\cos(\beta)\cos(\Phi) \quad \cos(\beta)\sin(\Phi) \quad \sin(\beta)]$

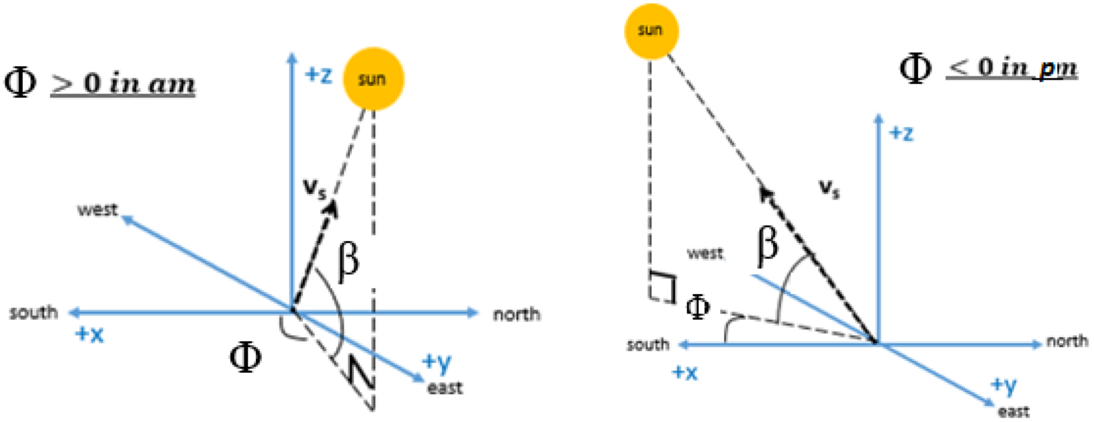


Figure 45: Displays the Vector that is in the Direction of the Sun [19]

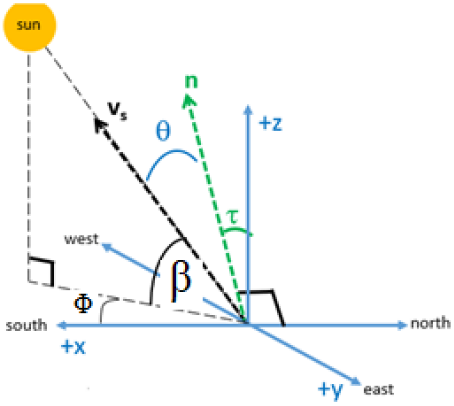


Figure 46: Shows the Relationship Between Each Angle [19]

The next step is to calculate the dot product between vector v_S and vector n as shown below in equation 12. The dot product of v_S and n is also equal to cos(θ) as shown in figure 46.

$$v_S \text{ dot } n = \cos(\theta) = \cos(\beta)\cos(\Phi) \times 0 + \cos(\beta)\sin(\Phi) \times -\sin(\tau) + \sin(\beta) \times \cos(\tau) \qquad (12)$$

$$v_S \text{ dot } n = \cos(\theta) = -\cos(\beta)\sin(\Phi)\sin(\tau) + \sin(\beta)\cos(\tau)$$

Next is to take the derivative of v_S dot n with respect to tau τ.

$$d(\cos(\theta))/d\tau = -\cos(\beta)\sin(\Phi)\cos(\tau) - \sin(\beta)\sin(\tau)$$

Then set it equal to zero. This is because cosine is at its maximum at 0.

$-\cos(\beta)\sin(\Phi)\cos(\tau) - \sin(\beta)\sin(\tau) = 0$

Then solve for tau τ to find the equation for optimal tilt angle.

$-\cos(\beta)\sin(\Phi)\cos(\tau) = \sin(\beta)\sin(\tau)$

$-\cos(\beta)\sin(\Phi) = \sin(\beta)(\sin(\tau) / \cos(\tau))$

$-\cos(\beta)\sin(\Phi) = \sin(\beta)\tan(\tau)$

$\tan(\tau) = -(\cos(\beta)\sin(\Phi)) / \sin(\beta)$

$\tan(\tau) = - \sin(\Phi) / \tan(\beta)$

$$\tau = \arctan(- \sin(\Phi) / \tan(\beta)) \tag{13}$$

Where tau is the optimal tilt angle of the solar modules in degrees

The equation above for tau, τ, calculates the optimal tilt angle for the solar modules.

The calculations for the optimal tilt angle at 10am and 2pm on December 21st are shown below and are the same for designs 5 and 6.

Solar Declination on December 21st : $\delta = -23.45^\circ$

Hour Angle at 10am on December 21st: $H = 30^\circ$ at 10am December 21st

Suns altitude at 10am on December 21st: $\beta = 25.37^\circ$

Suns Azimuth at 10am on December 21st: $\Phi = 30.51^\circ$

15.2 Modules optimal tilt angle at 10am on December 21st:

τ = arctan(- sin(Φ) / tan(β))

Where τ is the optimal tilt angle at 10am, β is the suns altitude at 10am, and Φ is the suns azimuth at 10am.

τ = arctan(- sin(30.51°) / tan(25.37°))

τ = -46.95°

Solar Declination on December 21st	δ = -23.45°
Hour Angle at 2pm on December 21st:	H = -30° at 2pm December 21st
Suns altitude at 2pm on December 21st :	β = 25.37°
Suns Azimuth at 2pm on December 21st:	Φ = -30.51°

15.3 Calculation of the modules optimal tilt angle at 2pm on December 21st:

τ = arctan(- sin(Φ) / tan(β))

Where τ is the optimal tilt angle at 2pm, β is the suns altitude at 2pm, and Φ is the suns azimuth at 2pm.

τ = arctan(- sin(-30.51°) / tan(25.37°))

τ = 46.95°

The next step is calculating the shadow length for designs 5 and 6 when the solar module is tilted a 46.95° facing east and facing west. Then the modules can be placed into a design layout to determine how many inverters and modules will fit on the property and a simulation can be ran.

16. EXAMPLE SHADING CALCS – SINGLE AXIS TRACKING [18]

To determine how far apart the modules should be placed for single axis tracking the shadow length needs to be calculated at the hours of 10am when the module is facing east and at 2pm when the module is facing west. Since the sun rises and falls symmetrically around 12pm noon, the shadow lengths will be the same. Figure 47 shows a single module facing east with a tilt of 46.95°. To complete the calculation there are two triangles that need to be looked at to determine the shadow length. Triangle one is shown as yellow in figure 47. In this triangle the height of the solar array can be calculated and so can the altitude angle of the sun at a certain time on a certain day. Then using trigonometry, Length X can be solved for using tangent as shown in equation 14. Figure 47 shows the second triangle in red. In this triangle, Length X is known, and the azimuth angle can be calculated. With that information, the shadow length can be calculated using sine as shown in equation 15. Then the arrays should be place further apart than the shadow length. This method was used when calculating the interrow spacing in designs 5 and 6.

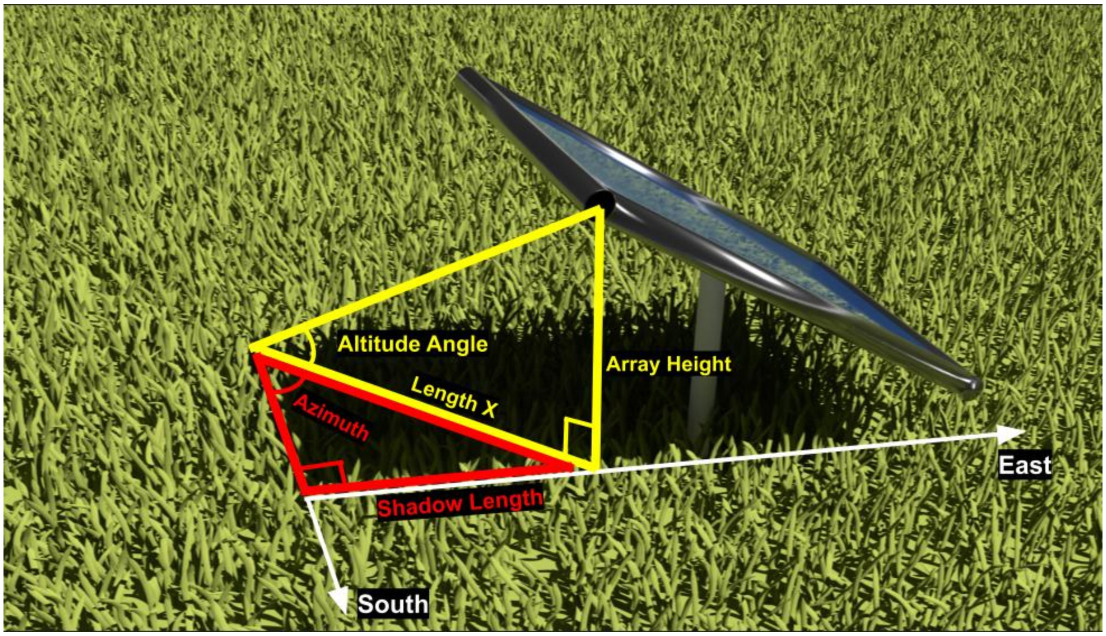


Figure 47: Triangles for Calculating Shadow Length of Single Axis Tracking Modules [18]

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X (14)

Length X = Array Height / Tan(Altitude Angle)

Part 2: Red Triangle

Sin(Azimuth Angle) = Shadow Length / Length X (15)

Shadow Length = Length X x Sin(Azimuth Angle)

17. DESIGN 5 & DESIGN 6 - SINGLE AXIS TRACKING

Figure 48 shows the base format of design 5 which has 3 strings of modules per inverter. Figure 49 shows the base format of design 6 which has 2 strings of modules per inverter. Because the only difference between these designs is the number of strings connected to the inverter, the shadow length calculation will be the same for both designs.

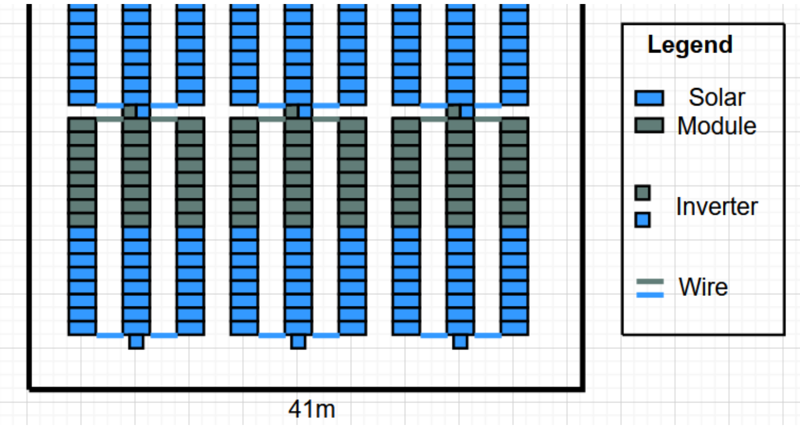


Figure 48: Design 5 (3 String) – Base Design Layout

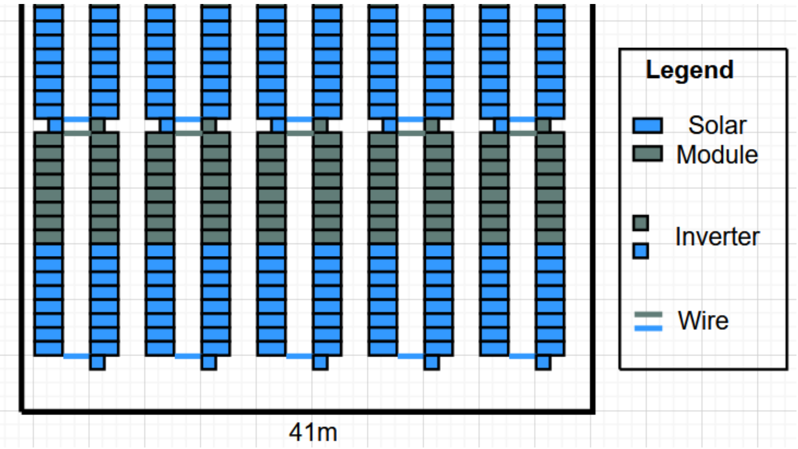


Figure 49: Design 6 (2 String) - Base Design Layout

17.1 Calculation of Height and Length of Solar Module Array:

For both the designs of the single axis tracking modules, the modules will be in single rows as shown in figure 50. Figure 50 shows the height and length measurements that need to be calculated. The solar modules will have a height of 0.5m off the ground to promote airflow, clear any brush, and allow for any extra mounting requirements [17].

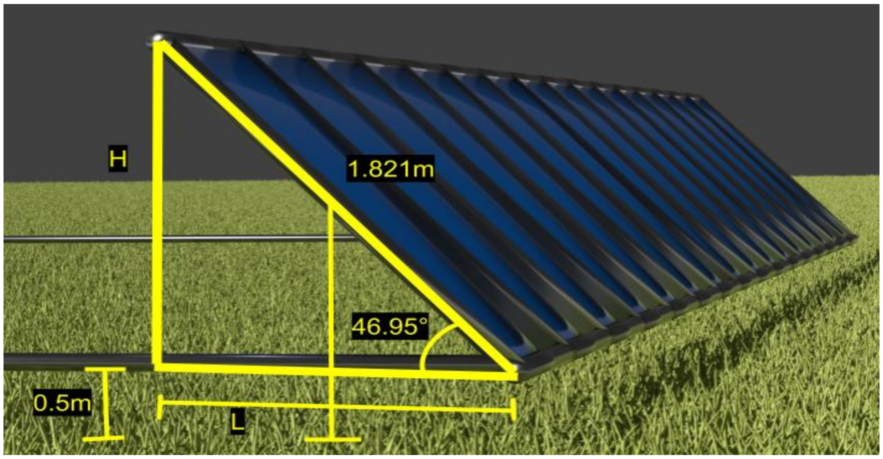


Figure 50: Design 5 & 6 - Height and Length of the Array

Calculation of Height:

Sin(46.95°) = H / 1.821m

H = 1.821m x Sin(46.95°)

H = 1.33m

Total Height = 1.33m + 0.5m

Total Height = 1.83m

Calculation of Length:

Cos(46.95°) = L / 1.821m

L = 1.821m x Cos(46.95°)

L = 1.24m

Figure 51 shows the height and length measurements in these designs. Because the modules are lifted 0.5m, the total height of the modules is 1.83m.

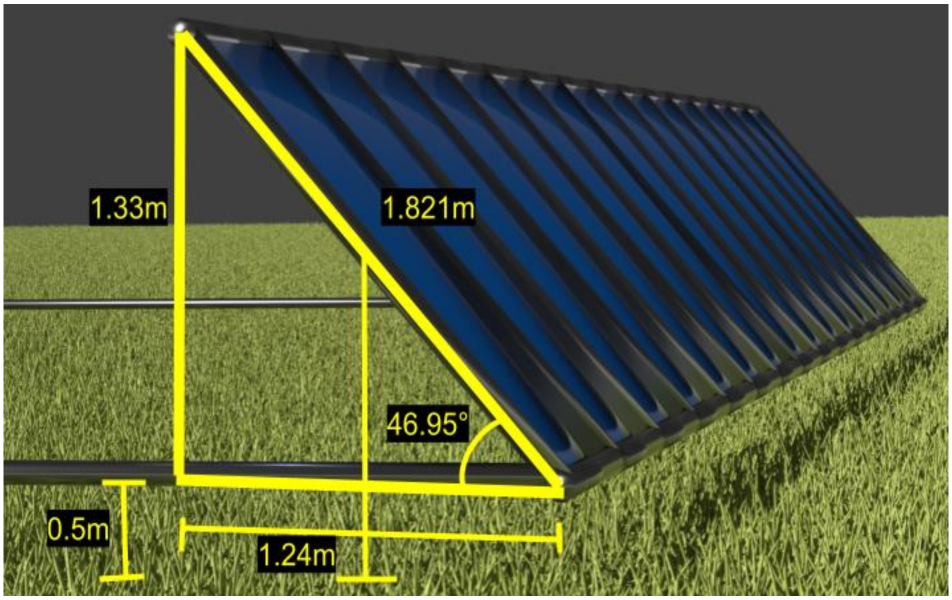


Figure 51: Design 5 & 6 - Height and Length of the Array

17.2 Calculation of Interrow Spacing at 10am December 21st [18]:

Reference chapter 16 for depictions of the yellow and red triangles.

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 1.83m / Tan(25.37°)

Length X = 3.86m

Part 2: Red Triangle

Sin(Azimuth Angle) = Shadow Length / Length X

Shadow Length = 3.86m x Sin(Azimuth Angle)

Shadow Length = 3.86m x Sin(30.51°)

Shadow Length = 1.96m

17.3 Calculation of Interrow Spacing at 2pm December 21st [18]:

Reference chapter 16 for depictions of the yellow and red triangles.

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 1.83m / Tan(25.37°)

Length X = 3.86m

Part 2: Red Triangle

Sin(Azimuth Angle) = Shadow Length / Length X

Shadow Length = Length X x Sin(Azimuth Angle)

Shadow Length = 3.86m x Sin(30.51°)

Shadow Length = 1.96m

The shadow length at 10am and 2pm is the same at 1.96m. To prevent shading the arrays for these two designs will be placed 2 meters apart as shown in figure 52 and figure 54. It is important to note the array length and the module length is shorter than is shown. Therefore figure 52 and figure 54 overcompensates the space the modules will take up. Figures 53 and 55 show a 3D visual aid to help show what the solar panels would look like on the property.

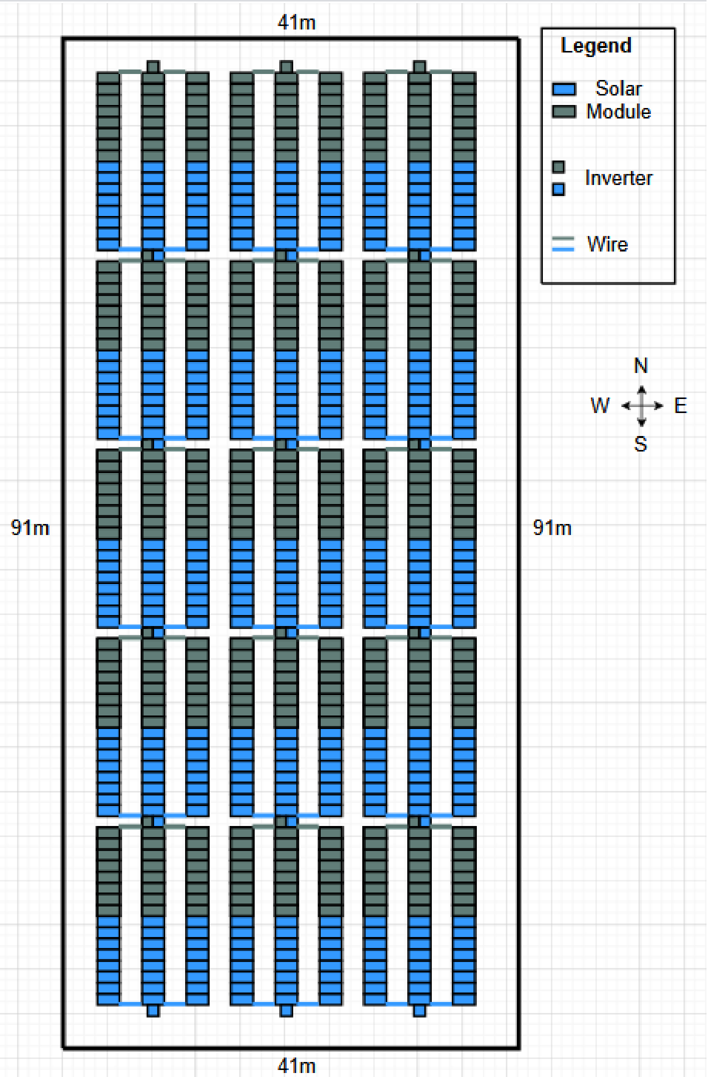


Figure 52: Design 5 – Module Layout, 30 Inverters, 720 Modules

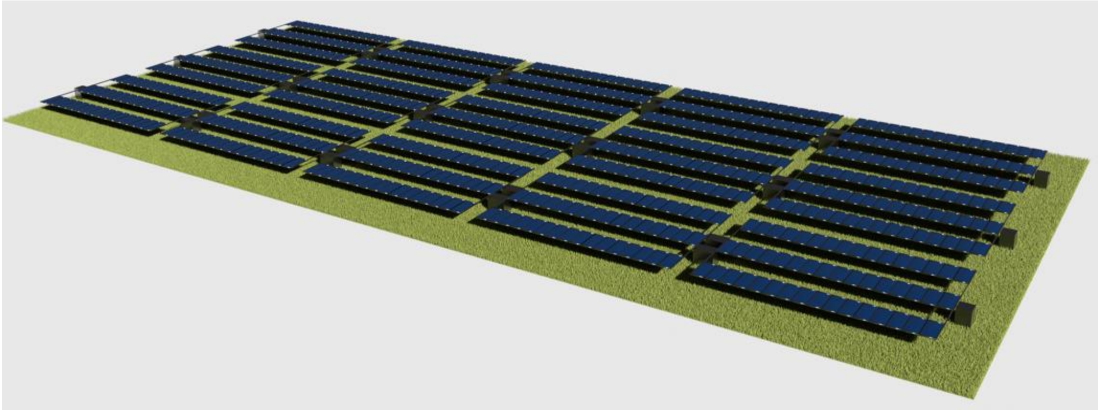


Figure 53: Design 5 - 3D Module Visual Aid, 30 Inverters, 720 Modules

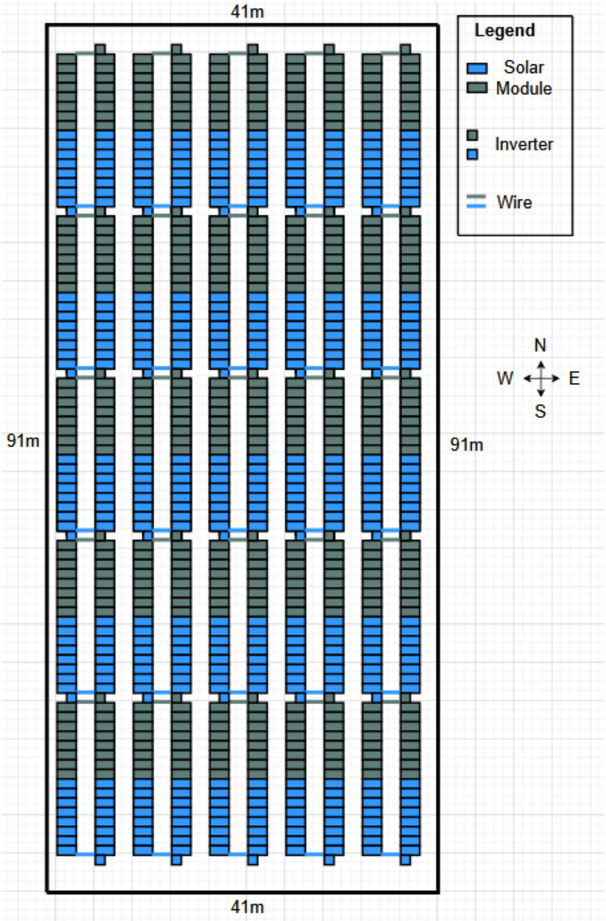


Figure 54: Design 6 – Module Layout, 50 Inverters, 800 Modules

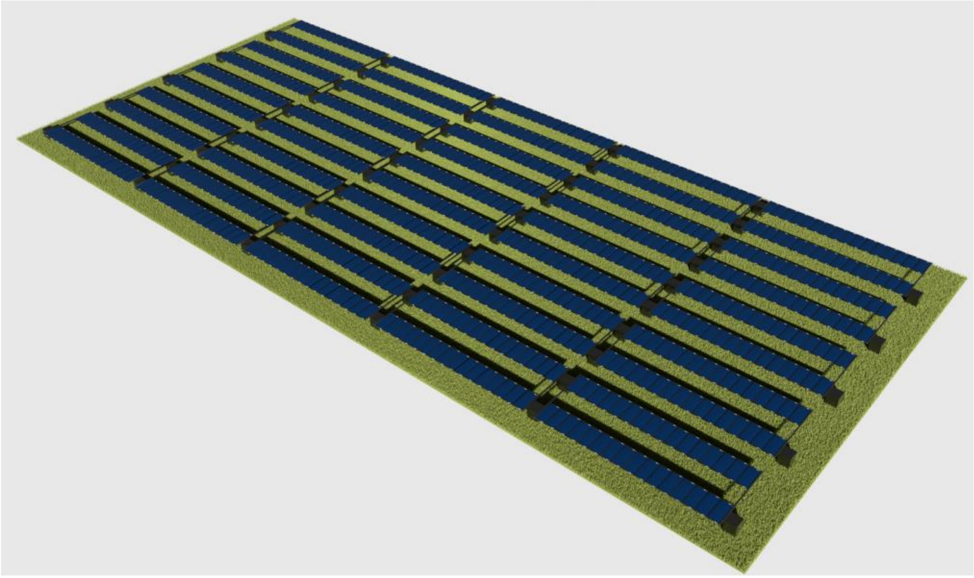


Figure 55: Design 6 - 3D Module Visual Aid, 50 Inverters, 800 Modules

18. DESIGN SIMULATION RESULTS AND COMPARISON

All designs will be compared based on the project requirements in chapter 1. The location input for all design simulations was Palmdale, California. For all fixed tilt designs a tilt angle of 34.6° towards the south was inputted. Module simulation inputs and inverter simulation inputs are shown below in tables 4 and 5.

Table 4: Module Simulation Inputs Used for All Design Simulations

	Simulation Inputs
Module Area [m^2]	1.85
Nominal Operating Cell Temperature [°C]	44
Maximum Power Point Voltage (V_{mp}) [V]	42.4
Maximum Power Point Current (I_{mp}) [A]	9.56
Open Circuit Voltage (V_{oc}) [V]	48.9
Short Circuit Current (I_{sc}) [A]	10.14
Temperature Coefficient of V_{oc} [%/°C]	-0.24
Temperature Coefficient of I_{sc} [%/°C]	0.04
Temp. Coefficient of Max. Power Point [%/°C]	-0.26
Number of Cells in Series	132

Table 5: Inverter Simulation Inputs Used for All Design Simulations

Maximum AC Output Power [Wac]	5000
Weighted Efficiency	97.5%
Nominal AC Voltage [Vac]	208
Maximum DC Voltage [Vdc]	480
Maximum DC Current [Adc]	12
Minimum MPPT DC Voltage [Vdc]	50
Nominal DC Voltage [V]	120
Maximum MPPT DC Voltage [Vdc]	480

Table 6 below shows the individual design simulation inputs which include the number of modules and inverter in each design as well as if the modules are fixed or single axis tracking.

Table 6: Individual Design Simulation Inputs

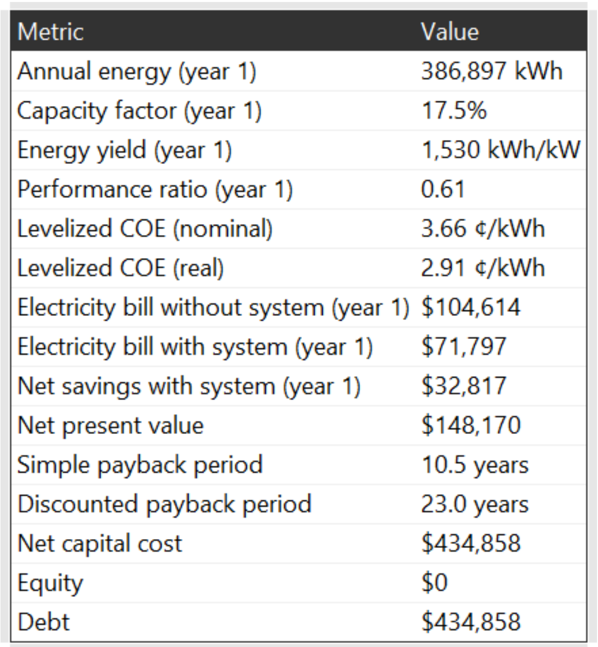
	Design 1 3 Strings Fixed Tilt	**Design 2 3 Strings Fixed Tilt**	**Design 3 2 Strings Fixed Tilt**	**Design 4 2 strings Fixed Tilt**	**Design 5 – 3 Strings Single Axis Tracking**	**Design 6 – 2 Strings Single Axis Tracking**
Modules	624	576	576	640	720	800
Inverters	26	24	36	40	30	50
Tracking and Orientation	Fixed at 34.6° South	Fixed at 34.6° South	Fixed at 34.6° South	Fixed at 34.6° South	1 Axis Backtracking	1 Axis Backtracking

SAM provides default values for losses such as soiling, module mismatch, diodes and connections, DC wiring, tracking error, nameplate, DC power optimizer, and AC wiring. These default losses are show below in table 7.

Table 7: SAM Default Percentage Losses

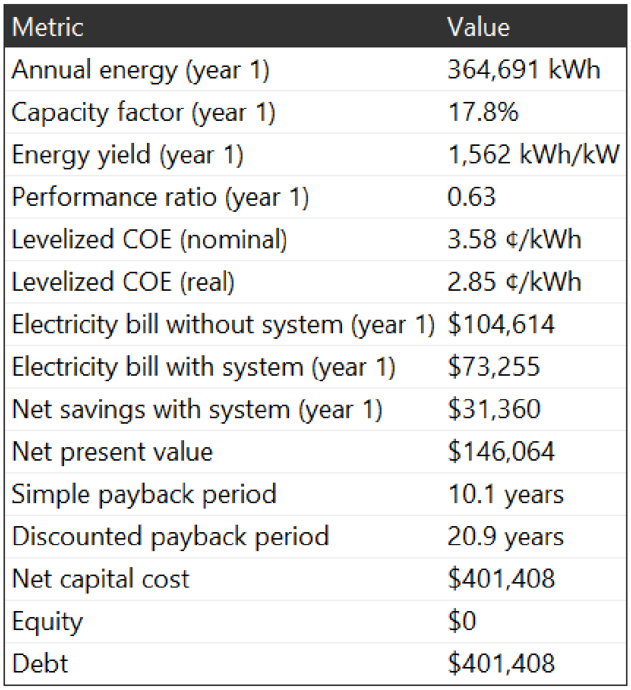
[%]	**Design 1– 3 Strings Fixed Tilt**	**Design 2 – 3 Strings Fixed Tilt**	**Design 3 – 2 Strings Fixed Tilt**	**Design 4 – 2 Strings Fixed Tilt**	**Design 5 – 3 Strings Single Axis Tracking**	**Design 6 – 2 Strings Single Axis Tracking**
Soiling	5	5	5	5	5	5
Module Mismatch	2	2	2	2	2	2
Diodes and Connections	0.5	0.5	0.5	0.5	0.5	0.5
DC Wiring	2	2	2	2	2	2
Tracking Error	0	0	0	0	0	0
Nameplate	0	0	0	0	0	0
DC Power Optimizer	0	0	0	0	0	0
AC Wiring	1	1	1	1	1	1

Figures 56-61 display each designs simulation result metric and the value. In table 9, these metrics are compared to each to determine the most suitable design.



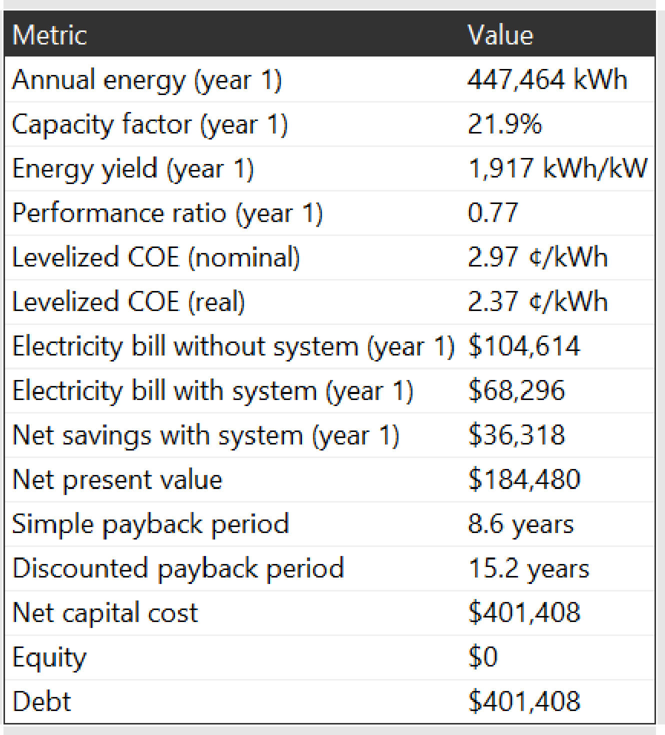
Metric	Value
Annual energy (year 1)	386,897 kWh
Capacity factor (year 1)	17.5%
Energy yield (year 1)	1,530 kWh/kW
Performance ratio (year 1)	0.61
Levelized COE (nominal)	3.66 ¢/kWh
Levelized COE (real)	2.91 ¢/kWh
Electricity bill without system (year 1)	$104,614
Electricity bill with system (year 1)	$71,797
Net savings with system (year 1)	$32,817
Net present value	$148,170
Simple payback period	10.5 years
Discounted payback period	23.0 years
Net capital cost	$434,858
Equity	$0
Debt	$434,858

Figure 56: Design 1 (3 String) - Fixed Tilt Simulation Results



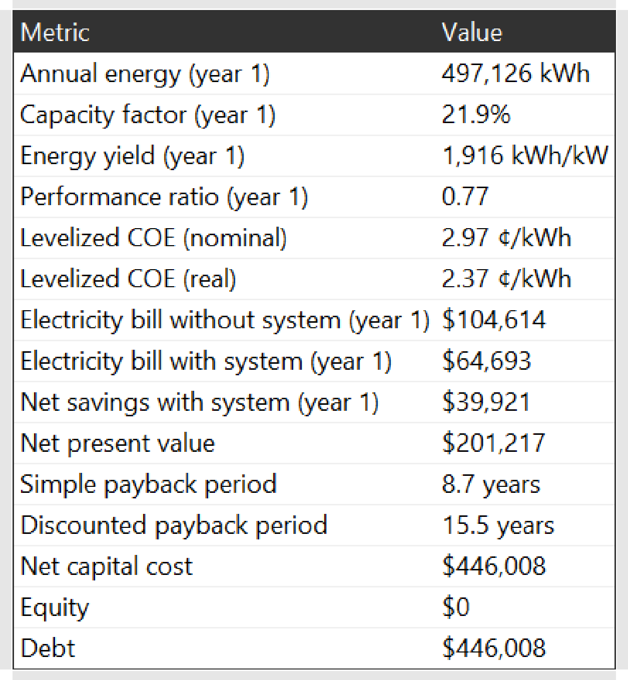
Metric	Value
Annual energy (year 1)	364,691 kWh
Capacity factor (year 1)	17.8%
Energy yield (year 1)	1,562 kWh/kW
Performance ratio (year 1)	0.63
Levelized COE (nominal)	3.58 ¢/kWh
Levelized COE (real)	2.85 ¢/kWh
Electricity bill without system (year 1)	$104,614
Electricity bill with system (year 1)	$73,255
Net savings with system (year 1)	$31,360
Net present value	$146,064
Simple payback period	10.1 years
Discounted payback period	20.9 years
Net capital cost	$401,408
Equity	$0
Debt	$401,408

Figure 57: Design 2 (3 String) - Fixed Tilt Simulation Results



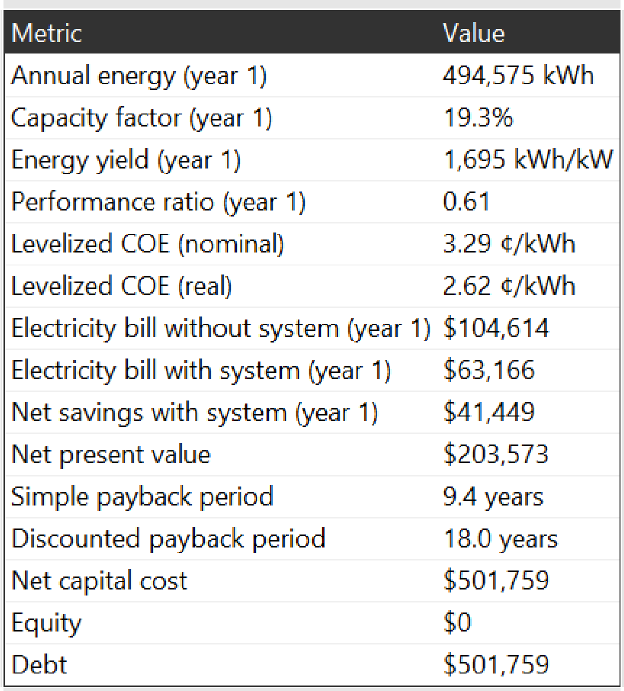
Metric	Value
Annual energy (year 1)	447,464 kWh
Capacity factor (year 1)	21.9%
Energy yield (year 1)	1,917 kWh/kW
Performance ratio (year 1)	0.77
Levelized COE (nominal)	2.97 ¢/kWh
Levelized COE (real)	2.37 ¢/kWh
Electricity bill without system (year 1)	$104,614
Electricity bill with system (year 1)	$68,296
Net savings with system (year 1)	$36,318
Net present value	$184,480
Simple payback period	8.6 years
Discounted payback period	15.2 years
Net capital cost	$401,408
Equity	$0
Debt	$401,408

Figure 58: Design 3 (2 String) - Fixed Tilt Simulation Results



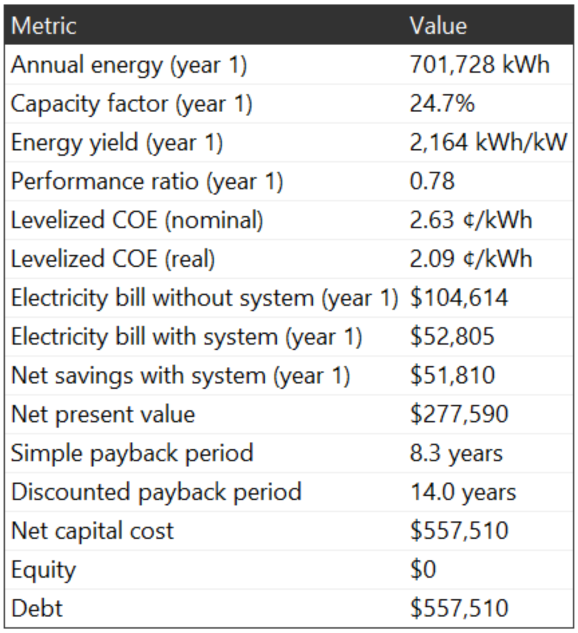
Metric	Value
Annual energy (year 1)	497,126 kWh
Capacity factor (year 1)	21.9%
Energy yield (year 1)	1,916 kWh/kW
Performance ratio (year 1)	0.77
Levelized COE (nominal)	2.97 ¢/kWh
Levelized COE (real)	2.37 ¢/kWh
Electricity bill without system (year 1)	$104,614
Electricity bill with system (year 1)	$64,693
Net savings with system (year 1)	$39,921
Net present value	$201,217
Simple payback period	8.7 years
Discounted payback period	15.5 years
Net capital cost	$446,008
Equity	$0
Debt	$446,008

Figure 59: Design 4 (2 String) - Fixed Tilt Simulation Results



Metric	Value
Annual energy (year 1)	494,575 kWh
Capacity factor (year 1)	19.3%
Energy yield (year 1)	1,695 kWh/kW
Performance ratio (year 1)	0.61
Levelized COE (nominal)	3.29 ¢/kWh
Levelized COE (real)	2.62 ¢/kWh
Electricity bill without system (year 1)	$104,614
Electricity bill with system (year 1)	$63,166
Net savings with system (year 1)	$41,449
Net present value	$203,573
Simple payback period	9.4 years
Discounted payback period	18.0 years
Net capital cost	$501,759
Equity	$0
Debt	$501,759

Figure 60: Design 5 (3 String) - Single Axis Tracking Simulation Results



Metric	Value
Annual energy (year 1)	701,728 kWh
Capacity factor (year 1)	24.7%
Energy yield (year 1)	2,164 kWh/kW
Performance ratio (year 1)	0.78
Levelized COE (nominal)	2.63 ¢/kWh
Levelized COE (real)	2.09 ¢/kWh
Electricity bill without system (year 1)	$104,614
Electricity bill with system (year 1)	$52,805
Net savings with system (year 1)	$51,810
Net present value	$277,590
Simple payback period	8.3 years
Discounted payback period	14.0 years
Net capital cost	$557,510
Equity	$0
Debt	$557,510

Figure 61: Design 6 (2 String) - Single Axis Tracking

Table 8 bellow shows the simulation result for the losses in each design, excluding the power clipping losses which is shown in table 9. Losses shown in table 8 shows very similar losses for all designs. Therefore, these losses were not considered when determining the most suitable design according to project requirements. Losses for inverter MPPT clipping, DC availability and curtailment, inverter power consumption, AC availability and curtailment, snow, tracking error, nameplate, DC power optimizer, and transformer losses all resulted in a 0% loss.

Table 8: Design Percentage Losses from Simulation

[%]	Design 1– 3 Strings Fixed Tilt	Design 2 – 3 Strings Fixed Tilt	Design 3 – 2 Strings Fixed Tilt	Design 4 – 2 Strings Fixed Tilt	Design 5 – 3 Strings Single Axis Tracking	Design 6 – 2 Strings Single Axis Tracking
Shading	2.57	0	2.56	2.57	2.033	2.044
Reflection	2.512	2.752	2.513	2.512	1.892	1.89
Module Deviation From STC	5.546	4.842	5.541	5.546	4.923	4.923
Inverter Nighttime Consumption	0.023	0.022	0.033	0.033	0.021	0.029
Inverter Efficiency	3.019	3.041	2.554	2.554	3.002	2.537

From looking at table 9, design 6 has the most suitable design characteristics according to the project requirements. The next best deign would be design 4 followed by design 3. Design 3, 4, and 6 have a DC to AC ratio in an acceptable range between 1.3 to 1.6, while designs 1, 2, and 5 exceed the maximum DC to AC ratio for this project. A high DC to AC ratio will increase the inverters power clipping losses which is why designs 1, 2, and 5, have an increased amount of power clipping losses. The high DC to AC ratio in designs 1, 2 and 5 are because the modules are producing more power than the inverter can convert. This comes from a mismatch in module to inverter sizing for those designs.

Only design 6 has a capacity factor that meets an acceptable range of more than 24.6%. Design 6 also produces the most energy, has the highest nameplate DC capacity, highest energy yield, and lowest levelized cost of energy. Design 6 does have the highest cost, but cost was not a limiting factor in this analysis. Therefore, a battery energy storage system will be added to design 6.

Table 9: Design Simulation Comparison

	Design 1– 3 Strings Fixed Tilt	**Design 2 – 3 Strings Fixed Tilt**	**Design 3 – 2 Strings Fixed Tilt**	**Design 4 – 2 Strings Fixed Tilt**	**Design 5 – 3 Strings Single Axis Tracking**	**Design 6 – 2 Strings Single Axis Tracking**
DC to AC Ratio	1.95	1.95	1.3	1.3	1.95	1.3
Inverter Power Clipping	17.18	17.788	2.106	2.105	16.716	1.448
Capacity Factor [%]	17.5	17.8	21.9	21.9	19.3	24.7
Levelized Cost of Energy [cents/kWh]	2.91	2.85	2.37	2.37	2.62	2.09
Annual Energy Production [kWh]	386,897	364,691	447,464	497,126	494,575	701,728
Net Capital Cost [$]	434,858	401,408	401,408	446,008	501,759	557,510

19. BATTERY ANALYSIS [20]

The simulation results from SAM list the predicted hourly power production for 25 years. Looking at the first year of this data for design 6 (2 string) single axis tracking the design shows the maximum energy producing day is June 21st and the minimum energy producing day is December 21st. To properly size the battery, the worst-case scenario will be considered, which would be the day the most energy is produced, June 21st, since the largest energy storage system will be needed to compensate for that day. Each inverter has a maximum compatible battery pack size of 30kWh per inverter and there are 50 inverters in this design, therefore there will be a maximum capacity of 1500kWh battery storage for the design. Table 10 bellow shows the battery requirements from the inverter datasheet. A battery energy storage system was also designed for design 5 and is shown in appendix section I.

Table 10: Battery Requirements from Inverter Datasheet

Compatible Battery Pack Size	5-30kWh
Rated I/O Power	5000W
Peak I/O Power	6000W
Acceptable Input Voltage Range	350V – 480V
Rated I/O Current	15A
Peak I/O Current (30s)	18A
Cycle Efficiency Charging to Discharging (PCS Only)	Peak > 95%
Fuse Rating	30A
Battery Terminal	Screw Type

Table 11: Hourly kW on June 21st SAM Simulation Design 6

Time of Day	Predicted Power Production [kW]
6am	35.07
7am	135.27
8am	233.80
9am	247.50
10am	247.50
11am	247.50
12pm	246.58
1pm	246.25
2pm	246.34
3pm	247
4pm	247.38
5pm	216.20
6pm	114.97
7pm	21.78

Table 12: Hourly kW on December 21st SAM Simulation Design 6

Time of Day	Predicted Power Production [kW]
8am	19.57
9am	107.89
10am	178.84
11am	164.93
12pm	121.94
1pm	157.27
2pm	169.57
3pm	168.50
4pm	79.73
5pm	4.18

Maximum Capacity: 1500kWh

Peak Load Shaving on Year 1 June 21st (9am-2pm): 1,481.67kWh

Peak Load Shaving on Year 1 December 21st (8am-5pm): 1,172,42kWh

From looking at the data above, on June 21st charging the batteries between the hours of 9am to 2pm would need a battery energy storage system capable of storing 1,481.67kWh, which would be just under the maximum capacity of the battery energy storage system. Therefore, the maximum 1500kWh should be installed for this design.

20. CONCLUSION

The goal of this thesis was to design an efficient solar farm with a battery energy storage system for a farmer in California. Six different designs were created and compared, including four fixed tilt designs and two single axis tracking designs. Shading calculations were done to prevent shading between the hours of 10am and 2pm on December 21st. These calculations used the module angle of tilt, height of the array, altitude angle, and azimuth angle. When comparing the simulation of these designs using System Advisor Model (SAM), design 6 (2 string) single axis tracking had the best outputs that met the project requirements. This included the highest energy production, DC to AC ratio and capacity factor in an acceptable range, and lowest levelized cost of energy. Therefore, a battery energy storage system was sized and added to design 6 (2 string) single axis tracking design. Future work for this project would include adding a rapid shut down (RSD) device, defining the DC and AC cables, determining a wire size, adding a switchyard, and picking out an available battery for the energy storage system [21]. In addition, designs 1, 2, and 5 could possibly be improved by changing the inverter to a more appropriate size for the amount of power produced by the modules, thus reducing the DC to AC ratio and clipping losses for those designs. More future work would include an in-depth analysis of the economic side of the designs, such as when the design would become profitable.

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APPENDICES

A. Module Efficiency in SAM

Table 13: Modules in SAM Ordered by Efficiency.

Module Name	Efficiency [%]
Seraphim Energy Group Inc. SEG-445-BMA-BG	23.8032
Seraphim Energy Group Inc. SEG-440-BMA-BG	23.5338
Seraphim Energy Group Inc. SEG-435-BMA-BG	23.2782
Seraphim Energy Group Inc. SEG-430-BMA-BG	23.0116
SunPower SPR-A425-COM SunPower SPR-A425-COM-MLSD	22.8867
REC Solar REC385AA	22.7901
LG Electronics Inc. LG380A1C-V5 LG Electronics Inc. LG380Q1C-V5	22.7759
Seraphim Energy Group Inc. SEG-425-BMA-BG	22.7465
SunPower SPR-X22-370 SunPower SPR-X22-370-D-AC SunPower SPR-X22-370-E-AC	22.7065
SunPower SPR-X22-370-COM SunPower SPR-X22-370-COM-MLSD	22.6973
SunPower SPR-A460-COM	22.6420
SunPower SPR-A420-COM SunPower SPR-A420-COM-MLSD	22.5882
REC Solar REC380AA	22.4993
LG Electronics Inc. LG375A1C-V5	22.4759
SunPower SPR-A425 SunPower SPR-A425-G-AC SunPower SPR-A425-MLSD	22.4727
Seraphim Energy Group Inc. SEG-420-BMA-BG	22.4612
LG Electronics Inc. LG375Q1C-V5	22.4319
SunPower SPR-A415-COM SunPower SPR-A415-COM-MLSD	22.3394
SunPower SPR-A420	22.2545

SunPower SPR-A420-G-AC SunPower SPR-A420-MLSD	
SunPower SPR-X22-480-COM	22.2370
REC Solar REC375AA	22.2327
LG Electronics Inc. LG370Q1K-V5	22.2086
LG Electronics Inc. LG370A1C-A5 LG Electronics Inc. LG370A1C-V5	22.1778
LG Electronics Inc. LG370Q1C-A5	22.1381
LG Electronics Inc. LG370Q1C-V5	22.1344
Silfab Solar Inc. SIL-420NT	22.1184
SunPower SPR-A450-COM	22.1084
SunPower SPR-A410-COM SunPower SPR-A410-COM-MLSD	22.0906
SunPower SPR-X22-360-E-AC	22.0837
SunPower SPR-X22-360 SunPower SPR-X22-360-COM-MLSD	22.0809
SunPower SPR-X22-360-C-AC SunPower SPR-X22-360-COM SunPower SPR-X22-360-D-AC	22.0701
SunPower SPR-X22-475-COM	22.0395
SunPower SPR-A415 SunPower SPR-A415-G-AC SunPower SPR-A415-MLSD	22.0364
SunPower SPR-X22-359	22.0321
Hanwha Q CELL Q PEAK DUO BLK ML-G9+ 400	22.0147
Intregrated Solar Technology STS-105MB4U	22.0115
Silfab Solar Inc. SLA320BC	21.9603
Hanwha Q CELL Q PEAK DUO XL-G9 470 Hanwha Q CELL Q PEAK DUO XL-G9.2 470 Hanwha Q CELL Q PEAK DUO XL-G9.3 470	21.9575
LONGi Green Energy Technology Co.Ltd. LR4-72HPH-465M	21.9436
Silfab Solar Inc. SIL-430HU	21.9138
REC Solar REC370AA	21.9089
LG Electronics Inc. LG365A1K-V5	21.8749

LG Electronics Inc. LG365Q1K-V5	
LG Electronics Inc. LG365A1C-A5 LG Electronics Inc. LG365A1C-V5	21.8662
LG Electronics Inc. LG365Q1C-A5	21.8644
Silfab Solar Inc. SIL-415NT	21.8495
REC Solar REC450AA 72 REC Solar REC450AA 72 XV	21.8464
LG Electronics Inc. LG365Q1C-V5	21.8233
Hanwha Q CELL Q PEAK DUO XL-G9 465 Hanwha Q CELL Q PEAK DUO XL-G9.2 465 Hanwha Q CELL Q PEAK DUO XL-G9.3 465	21.7551
SunPower SPR-X21-A470-COM	21.7471
SunPower SPR-X22-A470-COM	21.7270
Hanwha Q CELL Q PEAK DUO ML-G9+ 395	21.7174
REC Solar REC365AA	21.7143
SunPower SPR-A410 SunPower SPR-A410-G-AC SunPower SPR-A410-MLSD	21.7123
LONGi Green Energy Technology Co.Ltd. LR4-72HPH-460M	21.7010
Silfab Solar Inc. SIL-425HU	21.6605
LG Electronics Inc. LG360Q1K-A5	21.6581
Canadian Solar Inc. CS1U-430MS	21.6484
SANYO ELECTRIC CO LTD PANASONIC GROUP VBHN345SA17	21.6360
REC Solar REC445AA 72 REC Solar REC445AA 72 XV	21.6155
Silfab Solar Inc. SLA315BC	21.5938
SunPower SPR-A405-COM SunPower SPR-A405-COM-MLSD	21.5931
REC Solar REC365AA Black	21.5858
Silfab Solar Inc. SIL-410NT	21.5821
LG Electronics Inc. LG360A1K-V5 LG Electronics Inc. LG360Q1K-V5	21.5805
LG Electronics Inc. LG360A1C-A5	21.5722
Caterpillar Inc. PVC455MB03H LONGi Green Energy Technology Co.Ltd. LR4-72HBD-455M	21.5492

SunPower SPR-X21-255	21.5448
SunPower SPR-A400-COM	21.5434
LG Electronics Inc. LG360Q1C-V5	21.5299
LG Electronics Inc. LG355N1C-V5 LG Electronics Inc. LG355N1W-V5	21.5282
Chint Solar (Zhejiang) Co. Ltd CHSM72M-HC-430	21.5257
LG Electronics Inc. LG360Q1C-A5	21.5117
Hanwha Q CELL Q PEAK DUO XL-G9+ 460 Hanwha Q CELL Q PEAK DUO XL-G9.2 460 Hanwha Q CELL Q PEAK DUO XL-G9.3 460	21.5058
SunPower SPR-A405 SunPower SPR-A405-G-AC SunPower SPR-A405-MLSD	21.4963
Caterpillar Inc. PVC455MP03H LONGi Green Energy Technology Co.Ltd. LR4-72HPH-455M	21.4794
SunPower SPR-X21-350-BLK-E-AC	21.4787
LONGi Green Energy Technology Co.Ltd. LR4-60HPH-380M	21.4698
SunPower SPR-X21-350-BLK SunPower SPR-X21-350-BLK-D-AC	21.4611
Silfab Solar Inc. SIL-420NU	21.4413
REC Solar REC360AA	21.4307
Silfab Solar Inc. SIL-420HU	21.4296
Hanwha Q CELL Q PEAK DUO BLK ML-G9 390 Hanwha Q CELL Q PEAK DUO BLK ML-G9+ 390	21.4220
Seraphim Energy Group Inc. SEG-400-6MA-HV	21.3979
LG Electronics Inc. LG370M1C-N5 LG Electronics Inc. LG370N1C-N5 LG Electronics Inc. LG370N1W-N5	21.3972
Canadian Solar Inc. CS1U-425MS	21.3942
SunPower SPR-A400 SunPower SPR-A400-G-AC SunPower SPR-A400-MLSD	21.3882
Canadian Solar Inc. CS3U-410MS	21.3725

LG Electronics Inc. LG355Q1K-A5	21.3657
REC Solar REC440AA 72 REC Solar REC440AA 72 XV	21.3636
SunPower SPR-A395-MLSD	
Caterpillar Inc. PVC450MB03H LONGi Green Energy Technology Co.Ltd. LR4-72HBD-450M	21.3279
Silfab Solar Inc. SIL-405NT	21.3163
REC Solar REC360AA Black	21.3038
Aptos Solar Technology LLC DNA-144-BF23-415W Prism Solar TechnologiesInc. BHC72-415	21.2885
LG Electronics Inc. LG355A1C-A5	21.2801
Chint Solar (Zhejiang) Co. Ltd CHSM72M-HC-425	21.2784
LG Electronics Inc. LG335Q1K-V5	21.2733
Hanwha Q CELL Q PEAK DUO L-G7 415 Hanwha Q CELL Q PEAK DUO L-G7.2 415 Hanwha Q CELL Q PEAK DUO L-G7.3 415	21.2731
LG Electronics Inc. LG425N2W-V5	21.2712
Silfab Solar Inc. SLA310BC	21.2688
SANYO ELECTRIC CO LTD PANASONIC GROUP VBHN340SA17	21.2681
Hanwha Q CELL Q PEAK DUO XL-G9 455 Hanwha Q CELL Q PEAK DUO XL-G9.2 455 Hanwha Q CELL Q PEAK DUO XL-G9.3 455	21.2579
LG Electronics Inc. LG335Q1C-A5	21.2419
LG Electronics Inc. LG350N1C-V5 LG Electronics Inc. LG350N1W-V5	21.2395
Caterpillar Inc. PVC450MP03H LONGi Green Energy Technology Co.Ltd. LR4-72HPH-450M	21.2394
LG Electronics Inc. LG355Q1C-V5	21.2383
Solaria Corporation Solaria PowerXT-420R-PM	21.2364
Silfab Solar Inc. SIL-345BL	21.2233
Chint Solar (Zhejiang) Co. Ltd CHSM60M-HC-380	21.2204
Silfab Solar Inc. SIL-345HL	21.1902
LONGi Green Energy Technology Co.Ltd. LR4-60HPH-375M	21.1901
Silfab Solar Inc. SIL-415NU	21.1806
Silfab Solar Inc. SIL-415HU	21.1791

Silfab Solar Inc. SIL-345NL	21.1717
SunPower SPR-X21-345-COM-MLSD	21.1623
SunPower SPR-X21-345 SunPower SPR-X21-345-C-AC SunPower SPR-X21-345-COM SunPower SPR-X21-345-D-AC SunPower SPR-X21-345-E-AC SunPower SPR-X22-345-BLK	21.1494
REC Solar REC355AA	21.1488
Canadian Solar Inc. CS1U-420MS	21.1414
LG Electronics Inc. LG365M1C-N5 LG Electronics Inc. LG365N1C-N5 LG Electronics Inc. LG365N1W-N5	21.1358
REC Solar REC435AA 72 REC Solar REC435AA 72 XV	21.1352
Seraphim Energy Group Inc. SEG-395-6MA-HV	21.1319
Hanwha Q CELL Q PEAK DUO BLK ML-G9 385 Hanwha Q CELL Q PEAK DUO BLK ML-G9+ 385 Hanwha Q CELL Q PEAK DUO ML-G9+ 385	21.1286
REC Solar REC340TP3M REC Solar REC340TP3M Black	21.1002
LG Electronics Inc. LG365N1C-L5 LG Electronics Inc. LG365N1W-L5	21.0984
Canadian Solar Inc. CS3U-405MS	21.0979
LG Electronics Inc. LG350Q1K-A5	21.0968
Caterpillar Inc. PVC445MB03H LONGi Green Energy Technology Co.Ltd. LR4-72HBD-445M	21.0882
Silfab Solar Inc. SIL-400NT	21.0521
Aptos Solar Technology LLC DNA-144-BF23-410W Prism Solar TechnologiesInc. BHC72-410	21.0494
SunPower SPR-343J-WHT-D	21.0440

SunPower SPR-343NJ-WHT-D SunPower SPR-343NX-BLK-D SunPower SPR-343NX-WHT-D	
Hanwha Q CELL Q PEAK DUO L-G7 410 Hanwha Q CELL Q PEAK DUO L-G7.2 410 Hanwha Q CELL Q PEAK DUO L-G7.3 410	21.0359
REC Solar REC355AA Black	21.0237
Aptos Solar Technology LLC DNA-144-MF23-410W [Wht]	21.0137
Chint Solar (Zhejiang) Co. Ltd CHSM72M-HC-420	21.0124
LG Electronics Inc. LG420N2W-V5	21.0079
Caterpillar Inc. PVC445MP03H LONGi Green Energy Technology Co.Ltd. LR472HPH-445M	21.0007
LG Electronics Inc. LG350Q1K-V5	20.9830
Chint Solar (Zhejiang) Co. Ltd CHSM60M-HC-375	20.9632
Canadian Solar Inc. CS3K-335MS	20.9544
Canadian Solar Inc. CS3L-375P	20.9508
LG Electronics Inc. LG345N1C-V5 LG Electronics Inc. LG345N1W-V5	20.9353
LG Electronics Inc. LG345N1C-A5 LG Electronics Inc. LG345N1W-A5	20.9315
Caterpillar Inc. PVC370MP03HA	20.9211
Canadian Solar Inc. CS1U-415MS	20.8899
Canadian Solar Inc. CS1H-340MS	20.8798
China Sunergy (Nanjing) Co.Ltd.CSUN405-72MH5 China Sunergy (Nanjing) Co.Ltd.CSUN405-72MH5BB China Sunergy (Nanjing) Co.Ltd.CSUN405-72MH5BW China Sunergy (Nanjing) Co.Ltd.CSUN405-72MM5 China Sunergy (Nanjing) Co.Ltd.CSUN405-72MM5BB China Sunergy (Nanjing) Co.Ltd.CSUN405-72MM5BW	20.8771
LG Electronics Inc. LG345N1C-Z5	20.8683
Aptos Solar Technology LLC DNA-120-MF23-340W [Wht]	20.8585
Caterpillar Inc. PVC440MB03H	20.8498

Canadian Solar Inc. CS3U-400MS	20.8463
Hansol Technics Co.Ltd. HS435UE-JH2	20.8249
Hansol Technics Co.Ltd. HS335UB-JH2 [Wht]	20.8202
Aptos Solar Technology LLC DNA-144-MF23-405W [Wht] CertainTeed CT405HC00-04 CertainTeed CT405HC11-04	20.7944
LG Electronics Inc. LG345Q1K-A5	20.7718
Caterpillar Inc. PVC440MP03H	20.7633
Chint Solar (Zhejiang) Co. Ltd CHSM72M-HC-415	20.7553
Chint Solar (Zhejiang) Co. Ltd CHSM72M(DG)/F-BH-450	20.7425
Hansol Technics Co.Ltd. HS400UD-JH2	20.7417
Boviet Solar Technology Co.Ltd. BVM6612M-455S-H-HC	20.7289
Canadian Solar Inc. CS1K-340MS	20.7176
LG Electronics Inc. LG345Q1K-V5	20.7162
Aptos Solar Technology LLC DNA-120-BF23-340W	20.7132
AXITEC AC-410MH/144S AXITEC AC-410MH/144V	20.6953
Boviet Solar Technology Co.Ltd. BVM6612M-400-H Boviet Solar Technology Co.Ltd. BVM6612M-W5-400-H	20.6802
Chint Solar (Zhejiang) Co. Ltd CHSM60M-HC-370	20.6849
Canadian Solar Inc. CS3L-370P	20.6765
Canadian Solar Inc. CS3K-330MS	20.6413
Canadian Solar Inc. CS1U-410MS	20.6399
Boviet Solar Technology Co.Ltd. BVM6612M-410L-H	20.6367
Canadian Solar Inc. CS3K-330P	20.6366
China Sunergy (Nanjing) Co.Ltd.CSUN400-72MH5 China Sunergy (Nanjing) Co.Ltd.CSUN400-72MH5BB China Sunergy (Nanjing) Co.Ltd.CSUN400-72MH5BW China Sunergy (Nanjing) Co.Ltd.CSUN400-72MM5 China Sunergy (Nanjing) Co.Ltd.CSUN400-72MM5BB China Sunergy (Nanjing) Co.Ltd.CSUN400-72MM5BW	20.6288
LG Electronics Inc. LG345Q1C-A5	20.6283
LG Electronics Inc. LG345Q1C-V5	20.6249
Caterpillar Inc. PVC365MP03HA	20.6243
Caterpillar Inc. PVC435MB03H	20.6127
Canadian Solar Inc. CS3W-445PB-AG	20.6063

Canadian Solar Inc. CS1H-335MS	20.5874
Canadian Solar Inc. CS3U-395P	20.5854
Canadian Solar Inc. CS3U-395MS	20.5749
Boviet Solar Technology Co.Ltd. BVM6610M-W5-335-H	20.5688
Canadian Solar Inc. CS3U-405MB-AG	20.5624
Aptos Solar Technology LLC DNA-120-MF23-335W [Wht]	20.5301
Chint Solar (Zhejiang) Co. Ltd CHSM72M(DG)/F-BH-445	20.5283
Caterpillar Inc. PVC435MP03H	20.5272
Aptos Solar Technology LLC DNA-144-MF23-400W [Wht]	20.5255
Boviet Solar Technology Co.Ltd. BVM6612M-450S-H-HC	20.5113
AXITEC AC-340MH/120S AXITEC AC-340MH/120V	20.4815
AXITEC AC-405MH/144S AXITEC AC-405MH/144V	20.4793
Aptos Solar Technology LLC DNA-144-BF23-405W	20.4655
Canadian Solar Inc. CS1K-335MS	20.4615
Boviet Solar Technology Co.Ltd. BVM6612M-455S-H-HC-BF Boviet Solar Technology Co.Ltd. BVM6612M-455S-H-HC-BF-DG	20.4500
Boviet Solar Technology Co.Ltd. BVM6612M-410L-H-BF	20.4313
AU Optronics PM096B00333	20.4245
Boviet Solar Technology Co.Ltd. BVM6612M-395-H Boviet Solar Technology Co.Ltd. BVM6612M-W5-395-H	20.4124
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS 6P-315W	20.3977
Caterpillar Inc. PVC430MB03H	20.3962
Canadian Solar Inc. CS1U-405MS	20.3914
Aptos Solar Technology LLC DNA-144-MF23-410W [Blk]	20.3864
Boviet Solar Technology Co.Ltd. BVM6612M-405L-H	20.3728
Caterpiller Inc. PVC360MP03HA	20.3492
Canadian Solar Inc. CS3K-325MS	20.3303
Boviet Solar Technology Co.Ltd. BVM6612M-410L-H-BF-DG	20.3302
Canadian Solar Inc. CS3U-390MS	20.3263
Canadian Solar Inc. CS3K-325P	20.3253
Canadian Solar Inc. CS3U-400MB-AG	20.3172
Canadian Solar Inc. CS3U-390P	20.3150
Boviet Solar Technology Co.Ltd. BVM6612M-445S-H-HC	20.2815
Aptos Solar Technology LLC DNA-144-MF23-395W [Wht]	20.2792
Canadian Solar Inc. CS1H-330MS	20.2748
Canadian Solar Inc. CS6K-320P	20.2616

Boviet Solar Technology Co.Ltd. BVM6610M-330-H Boviet Solar Technology Co.Ltd. BVM6610M-W5-330-H	20.2614
AU Optronics PM096B00330	20.2568
Boviet Solar Technology Co.Ltd. BVM6612M-450S-H-HC-BF Boviet Solar Technology Co.Ltd. BVM6612M-450S-H-HC-BF-DG	20.2353
Boviet Solar Technology Co.Ltd. BVM6612M-410L-H-HC	20.2300
Aptos Solar Technology LLC DNA-120-MF23-330 [Wht]	20.2244
AXITEC AC-400MH/144S AXITEC AC-400MH/144V	20.2145
Aptos Solar Technology LLC DNA-144-BF23-400W	20.2020
Aptos Solar Technology LLC DNA-120-BF23-335W	20.1808
Aptos Solar Technology LLC DNA-144-MF23-405W [Blk]	20.1736
Boviet Solar Technology Co.Ltd. BVM6612M-405L-H-BF	20.1700
Boviet Solar Technology Co.Ltd. BVM6612M-400L-H	20.1606
AXITEC AC-335MH/120S AXITEC AC-335MH/120V	20.1591
Boviet Solar Technology Co.Ltd. BVM6612M-390-H Boviet Solar Technology Co.Ltd. BVM6612M-W5-390-H	20.1462
Canadian Solar Inc. CS1K-330MS	20.1415
Aptos Solar Technology LLC DNA-120-MF23-340W [Blk]	20.1179
Boviet Solar Technology Co.Ltd. BVM6610M-335L-H	20.0761
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS 6P-310W	20.0751
Boviet Solar Technology Co.Ltd. BVM6612M-405L-H-BF-DG	20.0702
AU Optronics PM096B00327	20.0555
Boviet Solar Technology Co.Ltd. BVM6612M-440S-H-HC	20.0531
Boviet Solar Technology Co.Ltd. BVM6612M-410L-H-HC-BF Boviet Solar Technology Co.Ltd. BVM6612M-410L-H-HC-BF-DG	20.0327
Aptos Solar Technology LLC DNA-144-MF23-390W [Wht]	20.0135
Boviet Solar Technology Co.Ltd. BVM6612M-445S-H-HC-BF Boviet Solar Technology Co.Ltd. BVM6612M-445S-H-HC-BF-DG	20.0087
Auxin Solar AXN6M610T325	19.9792
AXITEC AC-395MH/144S AXITEC AC-395MH/144V	19.9719

Boviet Solar Technology Co.Ltd. BVM6610M-325-H Boviet Solar Technology Co.Ltd. BVM6610M-W5-325-H	19.9561
AU Optronics PM096B00325	19.9214
Aptos Solar Technology LLC DNA-120-MF23-325W [Wht]	19.9209
Bluesun Solar Energy Tech Co.LtdBSM385M-72	19.8721
Aptos Solar Technology LLC DNA-120-BF23-330W	19.8600
AXITEC AC-330MH/120S AXITEC AC-330MH/120V	19.8589
Auxin Solar AXN6M610T385	19.8519
Aptos Solar Technology LLC DNA-120-MF23-335W [Blk]	19.8012
AU Optronics PM096B00323	19.7872
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS 6P-305W	19.7636
AXITEC AC-390MH/144S AXITEC AC-390MH/144V	19.7103
Auxin Solar AXN6M610T320	19.6665
AU Optronics PM096B00320 Boviet Solar Technology Co.Ltd. BVM6610M-320-H Boviet Solar Technology Co.Ltd. BVM6610M-W5-320-H	19.6531
Bluesun Solar Energy Tech Co.LtdBSM320M-60	19.6507
Bluesun Solar Energy Tech Co.LtdBSM380M-72	19.6289
Ap Aptos Solar Technology LLC DNA-120-MF23-320W [Wht]	19.6178
Andalay Solar TW-250-1-AC2-D-B Andalay Solar TW-250-1-DC4-0-B	19.5998
Aptos Solar Technology LLC DNA-120-BF23-325W	19.5808
AXITEC AC-325MH/120S AXITEC AC-325MH/120V	19.5609
AU Optronics PM096B00318	19.5189
Aptos Solar Technology LLC DNA-120-MF23-330W [Blk]	19.5064
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS 6P-300W	19.4071
Auxin Solar AXN6M610T315	19.3562
AU Optronics PM096B00315	19.3177
Aptos Solar Technology LLC DNA-120-BF23-320W	19.2831
Aptos Solar Technology LLC DNA-120-MF23-325W [Blk]	19.2137
Andalay Solar TW-245-1-DC4-0-B	19.1917

Andalay Solar TW-245-1-AC2-D-B	
AU Optronics PM096B00313	19.1485
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS 6P-295W	19.0986
Advanced Power API-M370	19.0800
Anhui Rinengzhongtian Semiconductor Development Co.Ltd QJM370-72	19.0663
AU Optronics PM096B00310	19.0159
Aleo Solar P19Y310 Aleo Solar S19Y310 Aleo Solar S59Y310	18.9081
Advanced Power API-M365	18.8114
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS 6P-290W	18.7915
Aleo Solar P19Y305 Aleo Solar S19Y305 Aleo Solar S59Y305 Aleo Solar S79Y305	18.5763
Advanced Power API-M360	18.5439
Advanced Power API-M355	18.3251
Aleo Solar P19Y300 Aleo Solar P19Y300 Aleo Solar S59Y300 Aleo Solar S79Y300	18.2870
Advanced Power API-M350	18.0593
Aleo Solar P19Y295 Aleo Solar S19Y295 Aleo Solar S59Y295 Aleo Solar S79Y295	17.9456
Ablytek 6MN6A290	17.8252
Advanced Power API-M345	17.7748
Advanced Power API-M340	17.6891
Aleo Solar P19Y290 Aleo Solar S19y290	17.6217

Aleo Solar S59y290 Aleo Solar S79Y290	
Ablytek 6MN6A285	17.5188
Aleo Solar P19Y285 Aleo Solar S19y285 Aleo Solar S59y285 Aleo Solar S79y285	17.3360
Advanced Power API-P335	17.3270
Advanced Power API-M335	17.2763
Ablytek 6MN6A280	17.2151
Aleo Solar S59y280 Aleo Solar S79y280	17.0337
Aleo Solar S19y280	17.0213
Advanced Power API-P330	17.0085
Advanced Power API-M330	17.0039
Ablytek 6MN6A275	16.914
Aleo Solar S19y275	16.7989
Advanced Power API-P325	16.7572
Aleo Solar P19Y275 Aleo Solar P79y275	16.7141
Ablytek 6MN6A270	16.6345
Alfasolar Alfasolar M6L60-265	16.5817
Aleo Solar S19Y270	16.5313
Advanced Power API-P320	16.5077
American Solar Wholesale ASW-315P	16.2749
Alfasolar Alfasolar M6L60-260	16.2664
Advanced Power API-P315	16.2393
Advanced Power API-M315	16.1485
Aleo Solar P18Y265	16.1441
American Solar Wholesale ASW-310P	16.0328
Alfasolar Alfasolar M6L60-255	15.9531
Advanced Power API-M310	15.9038
Advanced Power API-P310	15.9018
Advanced Power API-M260	15.8791
Aleo Solar P18y260	15.7976
American Solar Wholesale ASW-305P	15.7728
Advanced Power API-P305	15.6837
Alfasolar Alfasolar P6L60-250	15.6437

Alfasolar Alfasolar M6L60-250	15.6417
Advanced Power API-M305	15.6403
Advanced Power API-M255	15.5989
Advanced Power API-P255	15.5681
Advanced Power API-P300	15.5389
American Solar Wholesale ASW-300M	15.5147
American Solar Wholesale ASW-300P	15.5119
Aleo Solar P18y255	15.5053
Advanced Power API-M300	15.3769
American Value SM260-5M	15.3750
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M27-225W Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M27-B-225W	15.3536
Alfasolar Alfasolar M6L60-245	15.3323
Alfasolar Alfasolar P6L60-245	15.3265
American Solar Wholesale ASW-250M	15.2972
Advanced Power API-P250	15.2952
Advanced Power API-M250	15.2626
American Solar Wholesale ASW-295M American Solar Wholesale ASW-295P	15.2544
Aleo Solar P18y250	15.1961
Advanced Power API-P295	15.1758
Advanced Power API-M295	15.1322
American Value SM255-5M	15.0828
Advanced Power API-P245	15.0623
Alfasolar Alfasolar M6L60-240	15.0248
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M27-220W Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M27-B-220W	15.0205
Alfasolar Alfasolar P6L60-240	15.0124
Advanced Power API-P290	15.0102
American Solar Wholesale ASW-245M	15.0071
American Solar Wholesale ASW-290M American Solar Wholesale ASW-290P	14.9960
American Solar Wholesale ASW-245P	14.9929
Advanced Power API-M245	14.9615
Apls Technology ATI-M660-240	14.9402
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-5M-190W	14.8825

Advanced Power API-M290	14.8687
A10Green Technology A10J-M60-240 Ablytek 6PN6A240-A0	14.8114
American Value SM250-5M	14.7833
American Solar Wholesale ASW-285M American Solar Wholesale ASW-285P	14.7372
Advanced Power API-P240	14.7293
Alfasolar Alfasolar P6L60-235	14.7015
American Solar Wholesale ASW-240M-60 American Solar Wholesale ASW-240P	14.6835
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M27-215W Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M27-B-215W	14.6711
Advanced Power API-M240	14.6476
Advanced Power API-M285	14.6240
Advanced Power API-P285	14.6142
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M24-190W Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6P24-190W	14.5977
Apls Technology ATI-M660-235	14.5968
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-5M36-185W	14.5133
American Solar Wholesale ASW-185M	14.4973
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-5M-185W	14.4938
American Solar Wholesale ASW-280M	14.4863
American Value SM245-5M	14.4742
A10Green Technology A10J-M60-235 Ablytek 6PN6A235-A0	14.4709
American Solar Wholesale ASW-280P	14.4693
American Solar Wholesale ASW-235P	14.3918
American Solar Wholesale ASW-235M	14.3868
Apls Technology ATI-S572-185	14.3787
Alfasolar Alfasolar P6L60-230	14.3753
Advanced Power API-P280	14.3605
Advanced Power API-M280	14.3586
Advanced Power API-P235	14.3473

Advanced Power API-M235	14.3459
Aavid Solar ASMS-235M	14.328
Apls Technology ATI-M660-230	14.2937
AccuSolar Power ASP610-B230	14.287
Advanced Renewable Energy AREi-230W-M6-G	14.2574
American Solar Wholesale ASW-275M	14.2174
A10Green Technology A10J-S72-185 Ablytek 5MN6C185-A0	14.2078
American Value SM240-5M	14.1971
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M24-185W Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6P24-185W	14.1954
Aavid Solar ASMS-185M	14.1952
Advanced Solar Hydro Wind Power API156P-230	14.1764
A10Green Technology A10J-M60-230 Ablytek 6PN6A230-A0	14.1705
Advanced Power API-M275 Advanced Power API-P275	14.0995
Advanced Solar Hydro Wind Power API-180 Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-5M-180W Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-5M35-180W	14.0985
American Solar Wholesale ASW-180M	14.0888
American Solar Wholesale ASW-230M	14.0838
American Solar Wholesale ASW-230P	14.0754
Alfasolar Alfasolar P6L60-225	14.0708
Aavid Thermalloy ASMP-180M	14.0558
Advanced Power API-M230	14.0491
Aavid Solar ASMS-230M	14.0426
Apls Technology ATI-S572-180	13.9804
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6P30-225W	13.9766
Apls Technology ATI-M660-225	13.9743
American Solar Wholesale ASW-270P	13.9587
Advanced Renewable Energy AREi-225W-M6-G	13.9312
Aavid Solar ASMS-270P	13.9134
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd	13.8562

AS-6M30-225W	
A10Green Technology A10J-M60-225 Ablytek 6PN6A225-A0	13.8538
A10Green Technology A10J-S72-180 Ablytek 5MN6C180-A0	13.8406
Advanced Power API-P270	13.8363
Aavid Solar ASMS-180M	13.8355
Advanced Power API-M270	13.8084
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M24-180W Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6P24-18-W	13.7986
American Solar Wholesale ASW-225M	13.7697
Alfasolar Alfasolar P6L60-220	13.7693
American Solar Wholesale ASW-225P	13.7508
Advanced Power API-M225	13.7363
Advanced Power API-P225	13.7343
Advanced Solar Hydro Wind Power API-175 Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-5M-175W Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-5M36-175W	13.7271
Aavid Solar ASMS-225M	13.7195
American Solar Wholesale ASW-175M	13.7088
American Solar Wholesale ASW-265M	13.7011
Aavid Thermalloy ASMP-175	13.6767
Apls Technology ATI-M660-220	13.6569
Advanced Renewable Energy AREi-220W-M6-G	13.6183
Apls Technology ATI-S572-175	13.6046
Advanced Solar Hydro Wind Power API156P-220	13.5856
Advanced Power API-M265	13.5807
Advanced Power API-P265	13.5780
American Solar Wholesale ASW-270M	13.5771
A10Green Technology A10J-M60-220 Ablytek 6PN6A220-A0	13.5392
A2Peak Power POWER ON P220-6x10	13.4708
A10Green Technology A10J-S72-175 Ablytek 5MN6C175-A0	13.4686

Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6P30-220W	13.4637
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M30-220W	13.4528
American Solar Wholesale ASW-220P	13.4495
Aavid Solar ASMS-220P	13.4451
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M24-175W Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6P24-175W	13.4444
American Solar Wholesale ASW-260P	13.4280
Advanced Power API-P220	13.4234
American Solar Wholesale ASW-260M	13.4022
Advanced Power API-P260	13.3333
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-5M-170W Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-5M36-170W	13.3235
Advanced Renewable Energy AREi-215W-M6-G	13.2986
Advanced Solar Hydro Wind Power API-170	13.2955
American Solar Wholesale ASW-215P	13.1492
Advanced Power API-P215	13.1239
Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6M24-170W Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-6P24-17W	13.0575
Advanced Renewable Energy AREi-210W-M6-G	13.0188
Advanced Solar Hydro Wind Power API156P-210	12.9518
Advanced Solar Hydro Wind Power API-165 Amerisolar-Worldwide Energy and Manufacturing USA Co.Ltd AS-5M36-165W	12.9429
American Solar Wholesale ASW-250P	12.9224
Advanced Power API-P210	12.8295
Aavid Solar ASMS-165P	12.6710
Advanced Solar Hydro Wind Power API-160	12.5520
Advanced Solar Hydro Wind Power API156P-200	12.3405
Advanced Solar Hydro Wind Power API-150	11.7338
Advanced Solar Power (Hangzhou) ASP-S1-80	11.1090

B. Inverters in SAM Ordered by Efficiency

Only inverters with an AC output of 120V and 208V are listed based off property connection voltages.

Table 14: 208 Vac Inverters in SAM Ordered by Efficiency.

208 Vac Inverters	**Efficiency [%]**
SolarEdge Technologies Ltd : SE3800H-US	98.903
SolarEdge Technologies Ltd : SE6000H-US	98.799
SolarEdge Technologies Ltd : SE5000H-US	98.653
SolarEdge Technologies Ltd : SE10000H-US SolarEdge Technologies Ltd : SE11400H-US	98.638
SMA America: SB6000TL-US SMA America: SB6000TL-US-12	98.049
SMA America: SB7000TL-US SMA America: SB7000TL-US-12	97.980
SMA America: SB8000TL-US-12	97.889
Delta Electronics: E4-TL-US(AC)	97.884
Delta Electronics: E8-TL-US(AC)	97.867
LG Electronics Inc : A005KEEN261	97.797
Delta Electronics: E6-TL-US(AC)	97.795
SMA America: SB9000TL-US SMA America: SB9000TL-US-12	97.754
NGETEAM POWER TECHNOLOGY S A : Ingecon Sun 3.3 TL U M 208 Vac	97.626
SMA America: SB10000TL-US SMA America: SB10000TL-US-12	97.622
NGETEAM POWER TECHNOLOGY S A : Ingecon Sun 2.8 TL U M 208 Vac	97.529
NGETEAM POWER TECHNOLOGY S A : Ingecon Sun 5 TL U M 208 Vac	97.507
Delta Electronics: E8-TL-US	97.447
Delta Electronics: M8-TL-US	97.446
Delta Electronics: M5-TL-US	97.439
SolarEdge Technologies Ltd : SE3000	97.404

SolarEdge Technologies Ltd : SE3000x	
Delta Electronics: M10-TL-US	97.377
Delta Electronics: SOLIVIA 5.2 NA G4 TL Yaskawa Solectria Solar: PVI 5200TL	97.369
Trina Energy Storage Solutions (Jiangsu) Co – Ltd: TB8000SHU	97.354
Generac Power Systems: X11402	97.352
Delta Electronics: SOLIVIA 6.6 NA G4 TL Delta Electronics: SOLIVIA 7.6 NA G4 TL Yaskawa Solectria Solar: PVI 6600TL Yaskawa Solectria Solar: PVI 7600TL	97.341
Pika Energy: X11402 Pika Energy: X11403	97.336
HiQ Solar: TS208-5k75	97.335
SolarEdge Technologies Ltd : SE7600A-US	97.334
Delta Electronics: SOLIVIA 3.8 NA G4 TL Yaskawa Solectria Solar: PVI 3800TL	97.330
Samil Power: SolarRiver5000TL-US SMA America: SB6000TL-US	97.324
Fronius International GmbH: Fronius Primo 8.2-1 Fronius USA: Fronius Primo 8.2-1	97.310
Delta Electronics: E4-TL-US	97.309
Fronius International GmbH: Fronius Primo 7.6-1 Fronius USA: Fronius Primo 7.6-1	97.279
Trina Energy Storage Solutions (Jiangsu) Co – Ltd: TB6000SHU	97.291
SolarEdge Technologies Ltd : SE10000A-US	97.260
Delta Electronics: M10-4-TL-US	97.257
Delta Electronics: M6-TL-US	97.239
Delta Electronics: E6-TL-US	97.238
SMA America: SB20000HFUS-30	97.231
Enphase Energy Inc : IQ7X-96-x-ACM-US	97.209

Enphase Energy Inc : IQ7X-96-x-US Enphase Energy Inc : IQ7XS-96-y-ACM-z SunPower: SPR-E19-320-BLK-E-AC SunPower: SPR-E20-325-BLK-E-AC	
Delta Electronics: RPI H7U	97.204
Enphase Energy Inc : IQ7X-96-x-ACM-US-y-z-& Enphase Energy Inc : IQ7X-96-x-US-& Enphase Energy Inc : IQ7XS-96-x-ACM-US-y-z-& Enphase Energy Inc : IQ7XS-96-x-US-&	97.181
SunPower: SPR-E19-320-E-AC SunPower: SPR-E20-327-E-AC SunPower: SPR-X20-327-BLK-E-AC SunPower: SPR-X20-327-E-AC SunPower: SPR-X21-335-BLK-E-AC SunPower: SPR-X21-335-E-AC SunPower: SPR-X21-345-E-AC SunPower: SPR-X21-350-BLK-E-AC SunPower: SPR-X22-360-E-AC SunPower: SPR-X22-370-E-AC	97.172
Beijing Kinglong New Energy Technology: Sunteams 4000 HiSEL Power: HiSEL-K 4000	97.158
Shenzhen Growatt New Energy Technology Co – Ltd: Growatt 8000MTLP-US	97.156
AE Solar Energy: AE3.8	97.121
Advanced Solar Photonics: PV240	97.120

Chint Power Systems America: CPS SCE4KTL-O US Eaton: PV238 Eaton: PV240	
AE Solar Energy: AE7.0 Advanced Solar Photonics: PV270	97.115
Advanced Solar Photonics: PV250 Chint Power Systems America: CPS SCE5KTL-O US Eaton: PV250	97.079
AE Solar Energy: AE5.0	97.072
Enphase Energy Inc : IQ7-60-x-ACM-US Enphase Energy Inc : IQ7-60-x-US Jinko Solar Co – Ltd : JKMS300M-60BL-EP Jinko Solar Co – Ltd : JKMS305M-60BL-EP Jinko Solar Co – Ltd : JKMS305M-60L-EP Jinko Solar Co – Ltd : JKMS310M-60BL-EP Jinko Solar Co – Ltd : JKMS310M-60L-EP Jinko Solar Co – Ltd : JKMS315M-60BL-EP Jinko Solar Co – Ltd : JKMS315M-60L-EP Jinko Solar Co – Ltd : JKMS320M-60BL-EP Jinko Solar Co – Ltd : JKMS320M-60L-EP Jinko Solar Co – Ltd : JKMS325M-60BL-EP	97.044

Jinko Solar Co – Ltd : JKMS325M-60L-EP Jinko Solar Co – Ltd : JKMS330M-60L-EP	
Generac Power Systems: XVT114G03	97.031
Enphase Energy Inc : IQ7-60-x-ACM-US-y-z-& Enphase Energy Inc : IQ7-60-x-ACM-US-& Enphase Energy Inc : XACM-IQ7-LR6-60PB-300M Enphase Energy Inc : XACM-IQ7-LR6-60PB-305M Jinko Solar Co – Ltd : JKMS300M-60BL-EP	97.027
Advanced Solar Photonics: PV260 Eaton: PV260	97.020
Chint Power Systems America: CPS SCE6KTL-O US	97.018
Fronius International GmbH: Fronius Primo 15.0-1 Fronius USA: Fronius Primo 15.0-1	97.010
AE Solar Energy: AE6.0	97.008

Table 15: 120 Vac Inverters in SAM.

120 Vac Inverters	**Efficiency [%]**
Exeltech: XLGT18A60 Exeltech: XLGT18A60-01	96.378
Petra Systems: 103.10400.0001	95.867
Helios USA: 6TA Solarbine: S6T AC	94.408
Exeltech: AC2-1-2-6-5-XX Exeltech: AC2-1-B-6-5-XX Exeltech: AC2-1-C-6-5-XX Exeltech: AC2-1-L-6-5-XX Exeltech: AM24-1-B-6-0-00	94.401
Concept by US: Power Station PS247-05-180	93.997
Concept by US: Power Station PS247-10-180	93.767
Schneider Electric Solar Inc. : XW Pro 6848 NA	93.588
Petra Solar: 103.10866.500x	92.870
PV Powered: PVP2000	92.747
SMA America: SWR1800U SMA America: SWR1800U-SBD Schuco USA: SWR1800U Schuco USA: SWR1800U-SBD	91.832
Sonnetek: Sonnetek 2000 Sysgration: Soleil 2000-120	91.640
SMA America: SB700U SMA America: SB700U-SBD Schuco USA: SB700U Schuco USA: SB700U-SBD	91.582
Apparent Inc : SG424U CA - 120VAC – 60Hz	91.555
Apparent Inc : SG424-120V	91.540

CFM Equipment Distributors: Green Power 1100 E-Village Solar: EVS1100EVR GE Energy: GEPVe-1100NA-120 iPower: SHO-1.1 Home Director: HD-SUN-INV1100-EVR Mohr Power: MPS1100EVR PV Powered: PVP1100EVR	90.929
OutBack Power Technologies – Inc : VFXR3524A	90.730
OutBack Power Technologies – Inc : FXR3048A	90.681
OutBack Power Technologies – Inc : VFXR3648A	90.671
Xslent Energy Technologies: XPX A1000	88.643

C. Layout of Solar Panels for Fixed Tilt String Size of 9 Modules

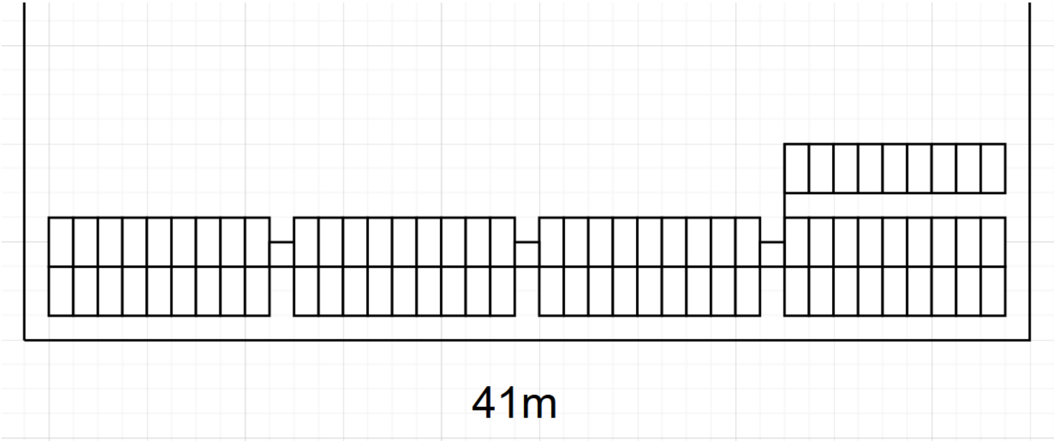


Figure 62: Possible Design with a String of 9 Modules, 12 ft Hypotenuse Length

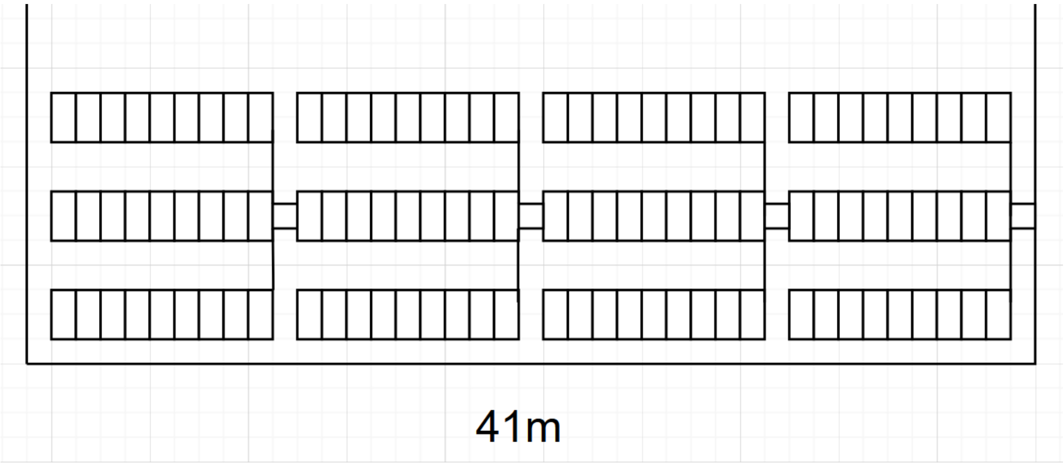


Figure 63: Possible Design with a String of 9 Modules, 6 ft Hypotenuse Length

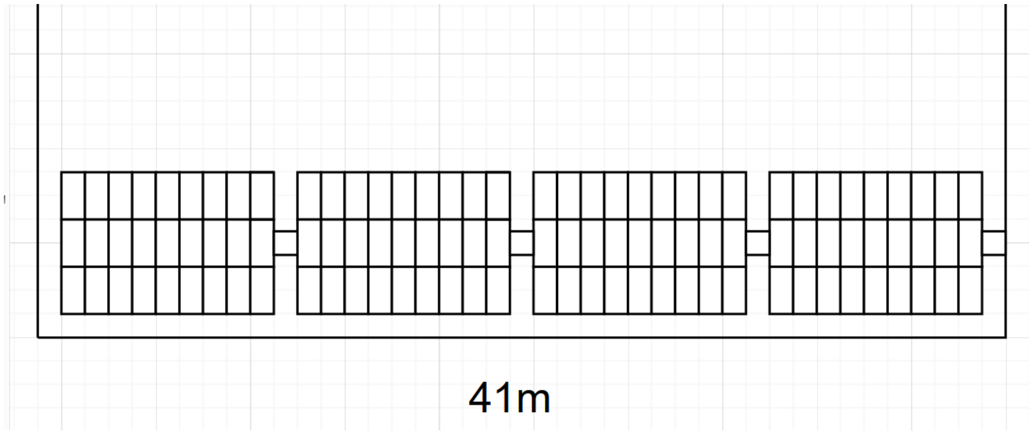


Figure 64: Possible Design with a String of 9 Modules, 18 ft Hypotenuse Length

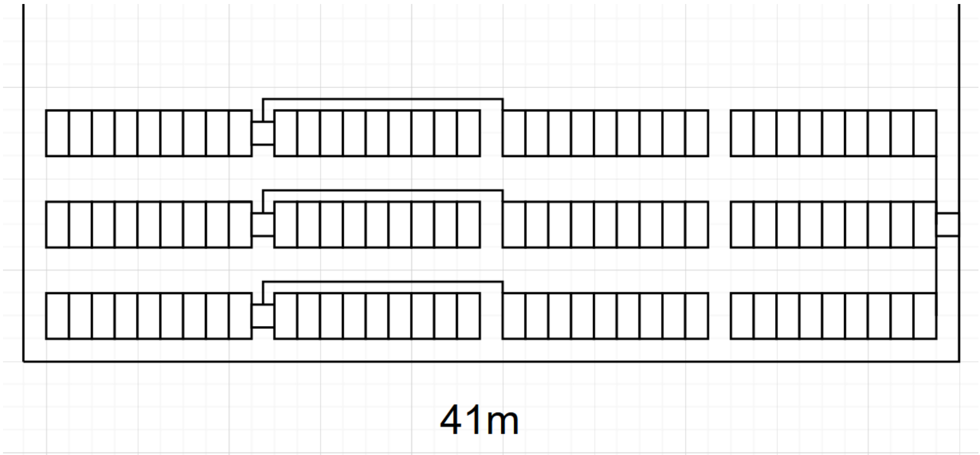


Figure 65: Possible Design with a String of 9 Modules,~6 ft Hypotenuse Length

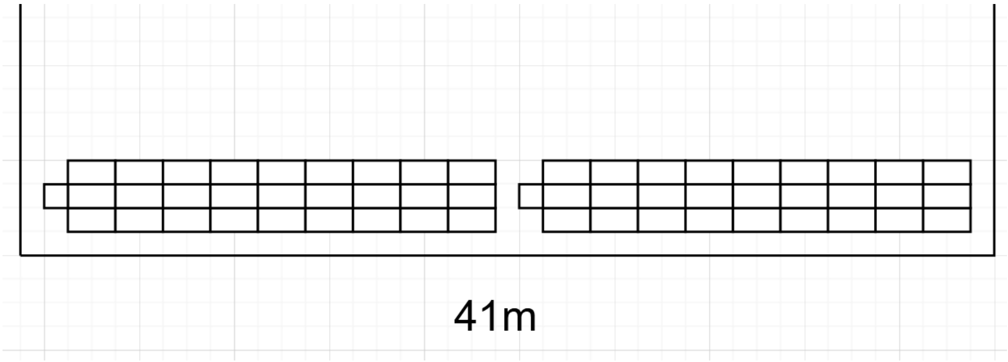


Figure 66: Possible Design with a String of 9 Modules,~9 ft Hypotenuse Length

D. Interrow Spacing Calc. Fixed Tilt Design 1 and 2 with Solar Array on Ground [18]

This section shows the calculations and simulation completed for fixed tilt design 1 and 2 and DOES NOT consider the fact that the solar array will need to be elevated off the ground.

Calculation of December 21st Day Number in the Year:

n = December 21st Day Number in the Year

n = Number of Days in January + Number of Days in February + Number of Days in March + Number of Days in April + Number of Days in May + Number of Days in June + Number of Days in July + Number of Days in August + Number of Days in September + Number of Days in October + Number of Days in November + 21 Days in December

n = 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31 + 30 + 31 + 30 + 21 = 355 days

Calculation of Solar Declination on December 21st:

$\delta = 23.45 \times \sin[(360/365)(355 - 81)]$

$\delta = -23.45°$

Calculation of Hour Angle at 10am on December 21st:

$H = 15(12 - 10)$

H = 30° at 10am December 21st

Calculation of Hour Angle at 4pm on December 21st:

$H = 15(12 - 16)$

H = -60° at 4pm December 21st

Calculation of Suns altitude at 10am on December 21st:

$\beta = \sin^{-1}[\sin(-23.45°)\sin(34.5723°) + \cos(-23.45°)\cos(34.5723°)\cos(30°)]$

$\beta = 25.37°$

Calculation of Suns altitude at 4pm on December 21st:

$\beta = \sin^{-1}[\sin(-23.45°)\sin(34.5723°) + \cos(-23.45°)\cos(34.5723°)\cos(-60°)]$

$\beta = 8.74°$

Calculation of Suns Azimuth on December 21st at 10am:

$\Phi = \sin^{-1}[(\cos(-23.45°)\sin(30°)) / \cos(25.37°)]$

$\Phi = 30.51°$

Calculation of Suns Azimuth on December 21st at 4pm:

$\Phi = \sin^{-1}[(\cos(-23.45°)\sin(-60°)) / \cos(8.74°)]$

$\Phi = -53.50°$

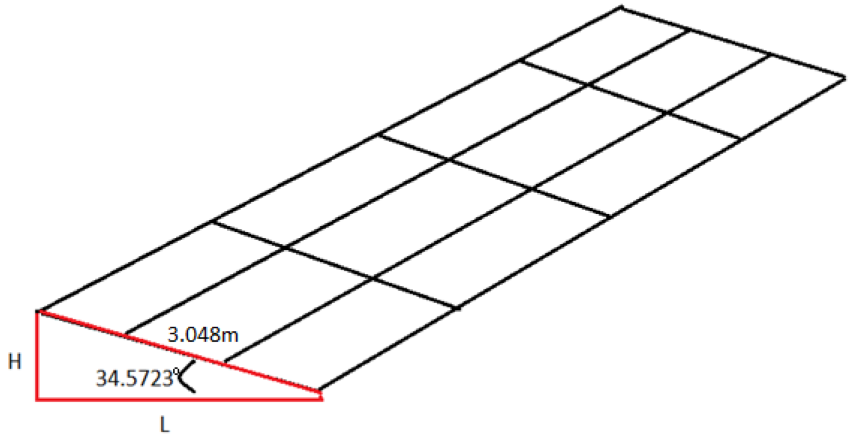


Figure 67: Height and Length. Does Not Consider the Array will Be Off the Ground

Calculation of Height:

sin(34.5723°) = H / 3.048m

H = 3.048m x sin(34.5723°)

H = 1.73m

Calculation of Length:

cos(34.5723°) = L / 3.048m

L = 3.048 x cos(34.5723°)

L = 2.51m

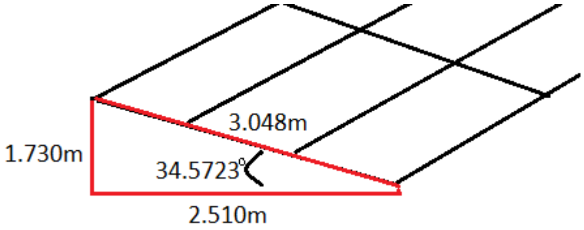


Figure 68: Height and Length. Does Not Consider Array Will Be Off the Ground.

Calculation of Interrow Spacing at 10am December 21st [18]:

Part 1: First Triangle

Tan(Altitude Angle at 10am) = Height of solar panel / Distance1

Distance1 = Height of solar panel / Tan(Altitude Angle at 10am)

Distance1 = 1.73m / Tan(25.37°)

Distance1 = 3.65m

Part 2: Second Triangle

Cos(azimuth) = Distance2 / Distance1

Distance2 = 3.648m x Cos(azimuth)

Distance2 = 3.648m x Cos(30.51°)

Distance2 = 3.14m

Calculation of Interrow Spacing at 4pm December 21st [18]:

Part 1: First Triangle

Tan(Altitude Angle at 4pm) = Height of solar panel / Distance1

Distance1 = Height of solar panel / Tan(Altitude Angle at 4pm)

Distance1 = 1.73m / Tan(8.74°)

Distance1 = 11.25m

Part 2: Second Triangle

cos(azimuth) = Distance2 / Distance1

Distance2 = Distance1 x cos(azimuth)

Distance2 = 11.253m x cos(53.50°)

Distance2 = 6.69m

The shadow length at 10am is 3.14m while the shadow length at 4pm is 6.69m. The shadow length at 4pm presents a longer shadow, therefore the module rows will be placed 7m apart as shown in figure 69. It is important to note this overcompensates the space the modules will take up as the length of the solar modules is shorter than is shown in the figure below.

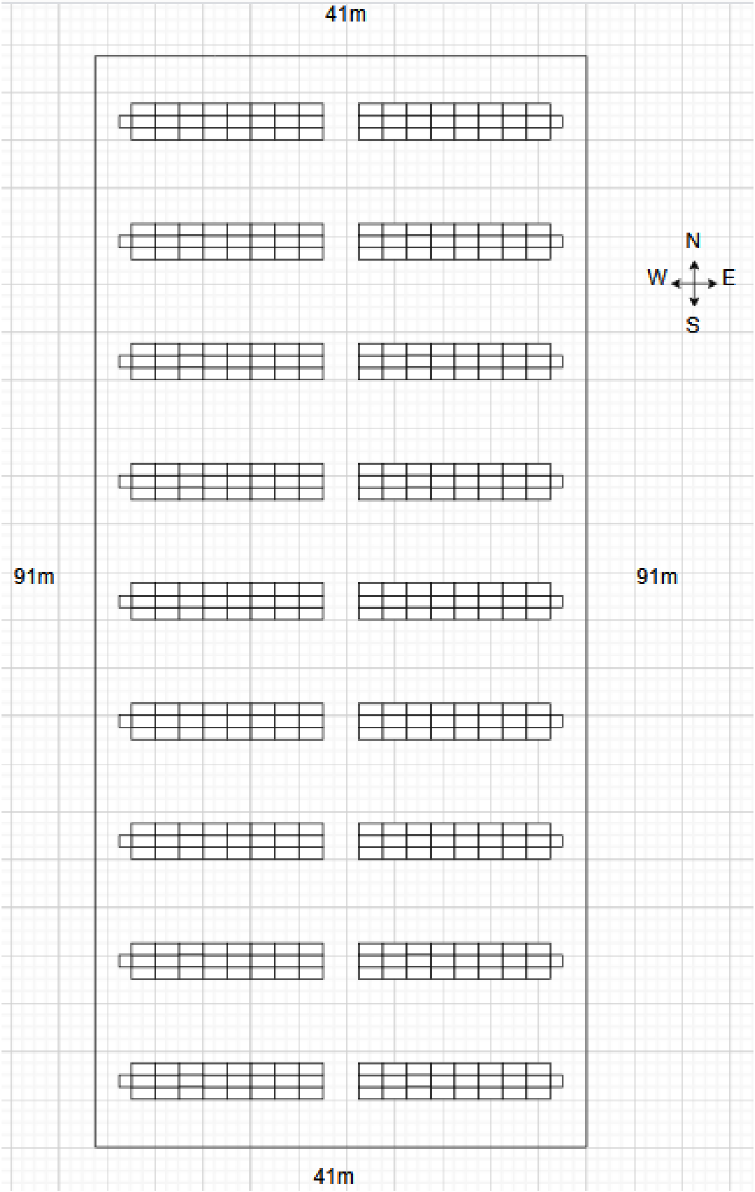


Figure 69: Modules Tilted 34.6° South, 18 Inverters, 432 Modules. Modules on Ground

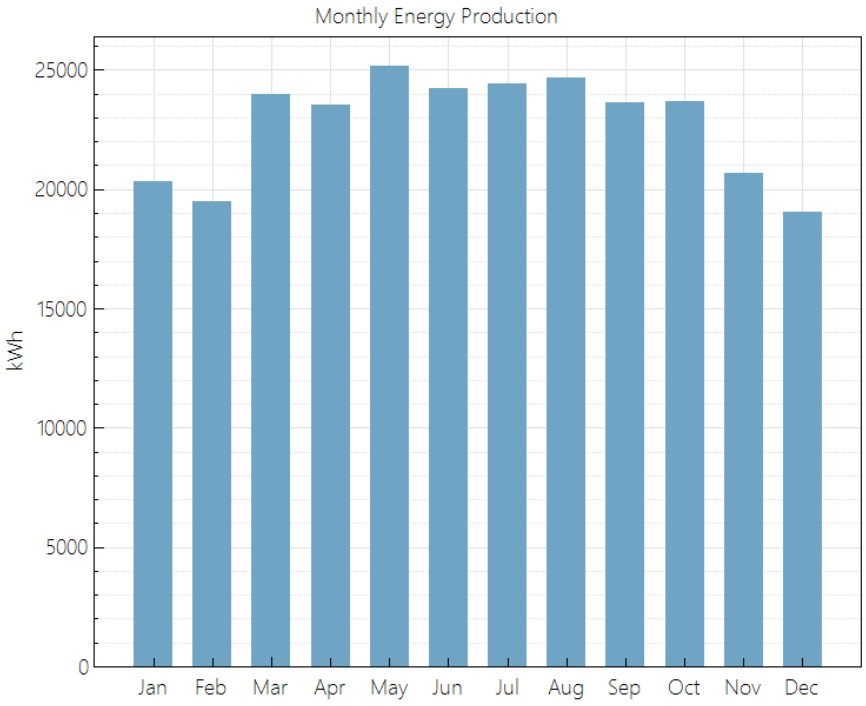
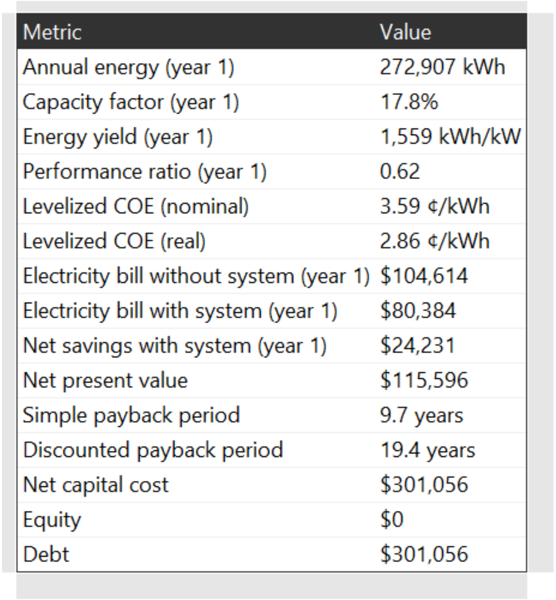


Figure 70: How Many kW Produced Each Month with Fixed Tilt Design 1 (3 String)



Metric	Value
Annual energy (year 1)	272,907 kWh
Capacity factor (year 1)	17.8%
Energy yield (year 1)	1,559 kWh/kW
Performance ratio (year 1)	0.62
Levelized COE (nominal)	3.59 ¢/kWh
Levelized COE (real)	2.86 ¢/kWh
Electricity bill without system (year 1)	$104,614
Electricity bill with system (year 1)	$80,384
Net savings with system (year 1)	$24,231
Net present value	$115,596
Simple payback period	9.7 years
Discounted payback period	19.4 years
Net capital cost	$301,056
Equity	$0
Debt	$301,056

Figure 71: Shows Simulation Metrics of Fixed Tilt Design 1 (3 String)

Fixed Tilt Design 2 Calculations

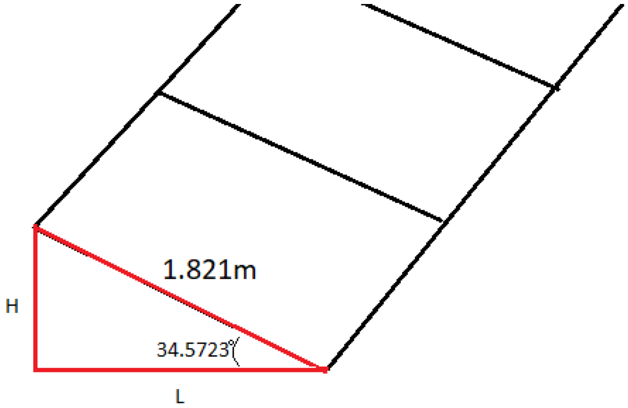


Figure 72: Design 2 (3 String) - Height and Length of the Array, Array on Ground

Calculation of Height:

sin(34.5723°) = H / 1.821m

H = 1.821m x sin(34.5723°)

H = 1.03m

Calculation of Length:

cos(34.5723°) = L / 1.821m

L = 1.821 x cos(34.5723°)

L = 1.50m

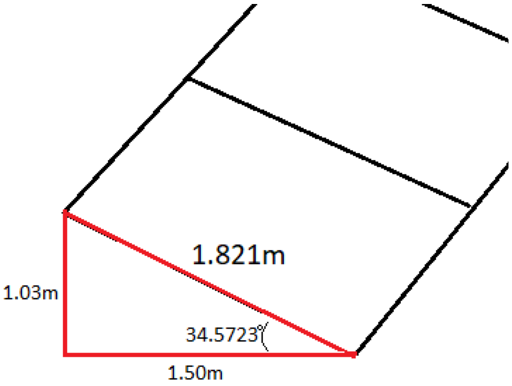


Figure 73: Design 2 (3 String) - Height and Length of the Array, Array on Ground

Calculation of Interrow Spacing at 10am December 21st [18]:

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 1.03m / Tan(25.37°)

Length X = 2.17m

Part 2: Red Triangle

Cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = 2.17m x Cos(Azimuth Angle)

Shadow Length = 2.17m x Cos(30.51°)

Shadow Length = 1.87m

Calculation of Interrow Spacing at 4pm December 21st [18]:

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Height of solar panel / Tan(Altitude Angle)

Length X = 1.03m / Tan(8.74°)

Length X = 6.70m

Part 2: Red Triangle

cos(azimuth) = Shadow Length / Length X

Shadow Length = Length X x cos(Azimuth Angle)

Shadow Length = 6.70m x cos(53.50°)

Shadow Length = 3.99m

The shadow length at 10am is 1.87m while the shadow length at 4pm is 3.99m. The shadow length at 4pm presents a longer shadow, therefore the module rows will be placed 4m apart as shown in figure 74. It is important to note this overcompensates the space the modules will take up as the length of the solar modules is shorter than is shown in the figure below.

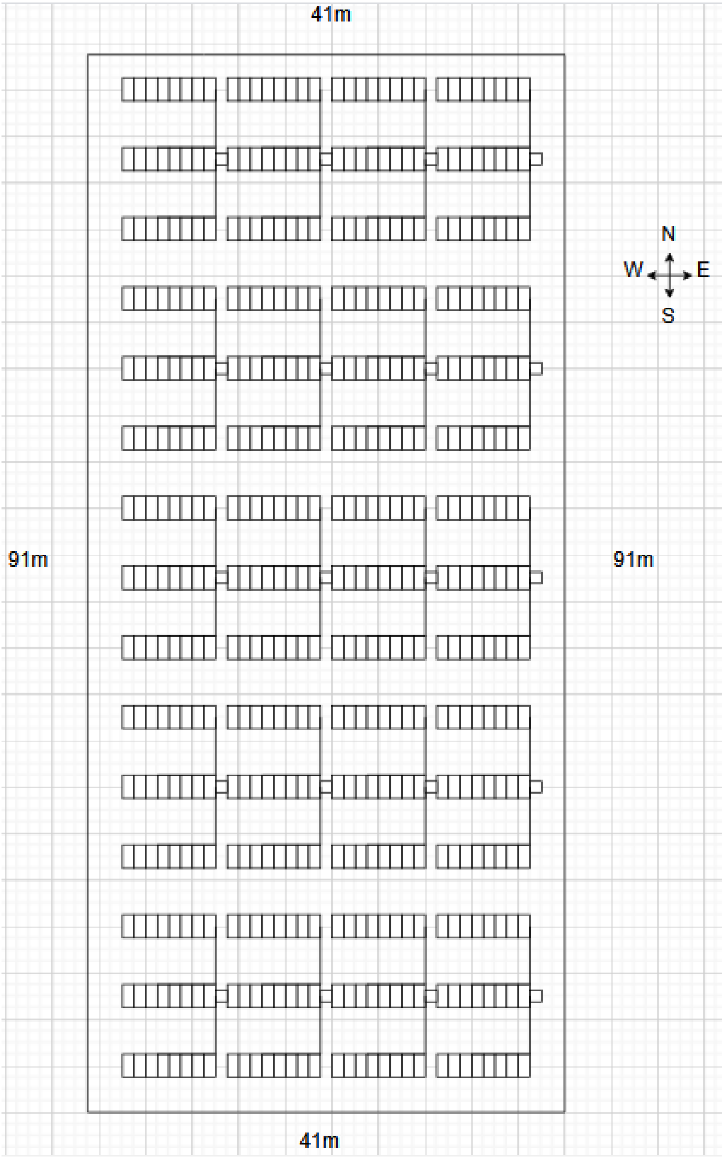


Figure 74: Modules Tilted South, Angle 34.6°, 20 Inverters, 480 Mods., Array on Ground

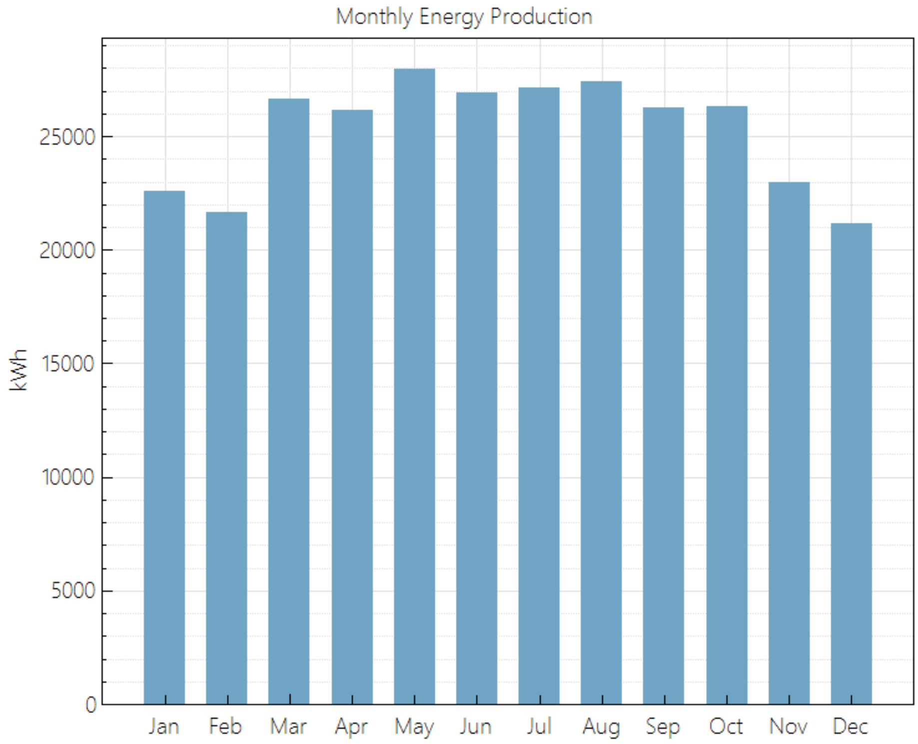
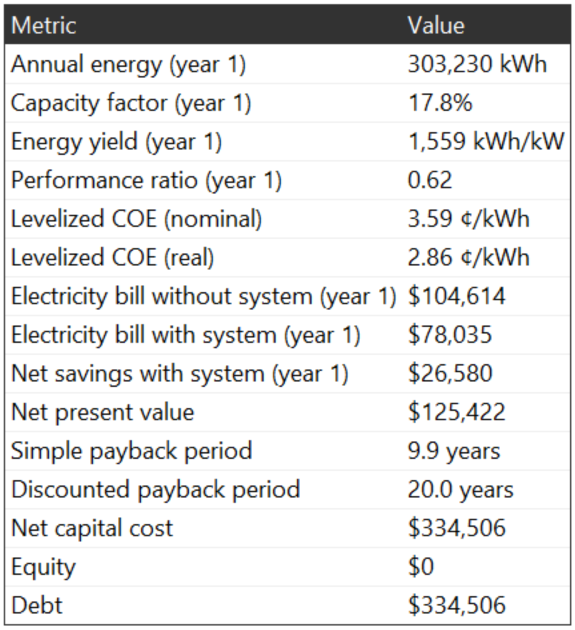


Figure 75: Design 2 (3 String) - How many kW Produced Monthly with the Fixed Tilt



Metric	Value
Annual energy (year 1)	303,230 kWh
Capacity factor (year 1)	17.8%
Energy yield (year 1)	1,559 kWh/kW
Performance ratio (year 1)	0.62
Levelized COE (nominal)	3.59 ¢/kWh
Levelized COE (real)	2.86 ¢/kWh
Electricity bill without system (year 1)	$104,614
Electricity bill with system (year 1)	$78,035
Net savings with system (year 1)	$26,580
Net present value	$125,422
Simple payback period	9.9 years
Discounted payback period	20.0 years
Net capital cost	$334,506
Equity	$0
Debt	$334,506

Figure 76: Design 2 (3 String) - Shows Simulation Metrics of Fixed Tilt

E. Interrow Spacing Fixed Tilt Design 1 and 2: 10am-4pm No Shading

This section displays the calculations done to prevent shading during the hours of 10am and 4pm on the winter solstice and does consider the that the array will be lifted off the ground by 14 inches or 0.3556 meters [17].

Interrow Spacing Design 1 –No shading 10am – 4pm [18]

Calculation of Solar Declination on December 21st:

$\delta = 23.45 \times \sin[(360/365)(n - 81)]$

Where δ is the solar declination and n is the day of the year (out of 365)

$\delta = 23.45 \times \sin[(360/365)(355 - 81)]$

$\delta = -23.45°$

Calculation of Hour Angle at 10am on December 21st:

$H = 15(12 - T)$

Where H is the hour angle and T is the time of day on a 24 hour clock

$H = 15(12 - 10)$

$H = 30°$ at 10am December 21st

Calculation of Hour Angle at 4pm on December 21st:

$H = 15(12 - T)$

Where H is the hour angle and T is the time of day on a 24 hour clock

$H = 15(12 - 16)$

$H = -60°$ at 4pm December 21st

Calculation of Suns altitude at 10am on December 21st:

$\beta = \sin^{-1}[\sin(\delta)\sin(L) + \cos(\delta)\cos(L)\cos(H)]$

Where β is the suns altitude angle at 10am, δ is the Solar Declination, L is the Latitude, and H is the Hour Angle at 10am.

$\beta = \sin^{-1}[\sin(-23.45°)\sin(34.5723°) + \cos(-23.45°)\cos(34.5723°) \cos(30°)]$

$\beta = 25.37°$

Calculation of Suns altitude at 4pm on December 21st:

$\beta = \sin^{-1}[\sin(\delta)\sin(L) + \cos(\delta)\cos(L)\cos(H)]$

Where β is the suns altitude angle at 4pm, δ is the Solar Declination, L is the Latitude, and H is the Hour Angle at 4pm.

$\beta = \sin^{-1}[\sin(-23.45°)\sin(34.5723°) + \cos(-23.45°)\cos(34.5723°) \cos(-60°)]$

$\beta = 8.74°$

Calculation of Suns Azimuth on December 21st at 10am:

$\Phi = \sin^{-1}[(\cos (\delta)\sin(H)) / \cos(\beta)]$

Where Φ is the suns azimuth angle at 10am, δ is the Solar Declination, H is the Hour Angle at 10am, and β is the suns altitude angle at 10am.

$\Phi = \sin^{-1}[(\cos (-23.45°)\sin(30°)) / \cos(25.37°)]$

$\Phi = 30.51°$

Calculation of Suns Azimuth on December 21st at 4pm:

$\Phi = \sin^{-1}[(\cos(\delta)\sin(H)) / \cos(\beta)]$

Where Φ is the suns azimuth angle at 4pm, δ is the Solar Declination, H is the Hour Angle at 4pm, and β is the suns altitude angle at 4pm.

$\Phi = \sin^{-1}[(\cos(-23.45°)\sin(-60°)) / \cos(8.74°)]$

$\Phi = -53.50°$

Calculation of Height and Length of Solar Module Array

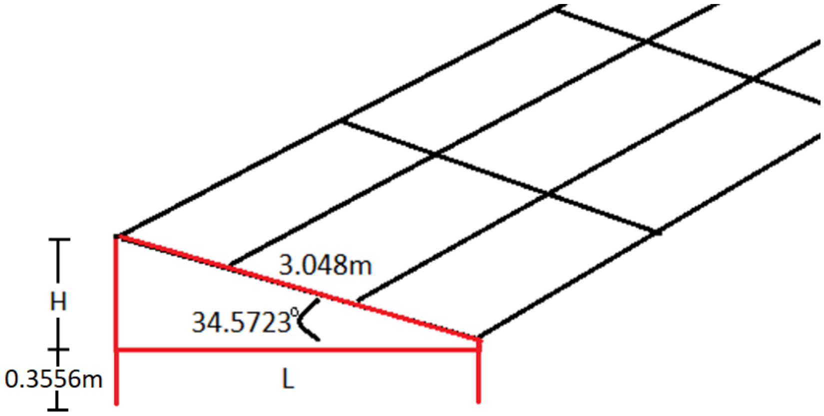


Figure 77: Design 1 (3 String) - Height and Length of the Array

Calculation of Height:

$\sin(34.5723°) = H / 3.048m$

$H = 3.048m \times \sin(34.5723°)$

$H = 1.73m$

Because the solar modules are lifted off the ground by 0.3556 meters, this needs to be added to the calculated height measurement to determine the total height.

Total Height = 1.73m + 0.3556m = 2.09m

Calculation of Length:

cos(34.5723°) = L / 3.048m

L = 3.048 x cos(34.5723°)

L = 2.51m

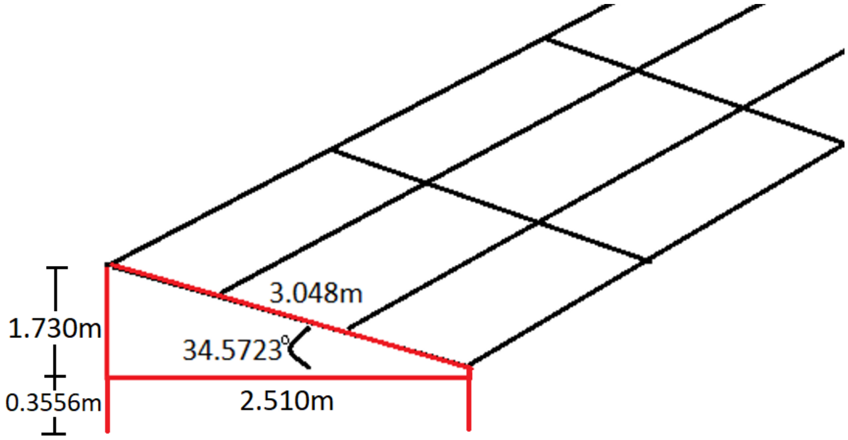


Figure 78: Design 1 (3 String) - Height and Length of the Array Labeled

Interrow Spacing at 10am December 21st [18]:

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 2.09m / Tan(25.37°)

Length X = 4.41m

Part 2: Red Triangle

Cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = 4.41m x Cos(Azimuth Angle)

Shadow Length = 4.41m x Cos(30.51°)

Shadow Length = 3.80m

Interrow Spacing at 4pm December 21st [18]:

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 2.09m / Tan(8.74°)

Length X = 13.60m

Part 2: Red Triangle

cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = Length X x cos(Azimuth Angle)

Shadow Length = 13.60m x cos(53.50°)

Shadow Length = 8.09m

The shadow length at 10am is 3.80m while the shadow length at 4pm is 8.09m. Therefore, the modules would need to be spaced out by over 8 meters. After the calculation, the decision was made to reduce the time period from 10am to 4pm no shading to 10am to 2pm no shading.

Interrow Spacing Design 2 – Modules off the Ground, 10am – 4pm [18]

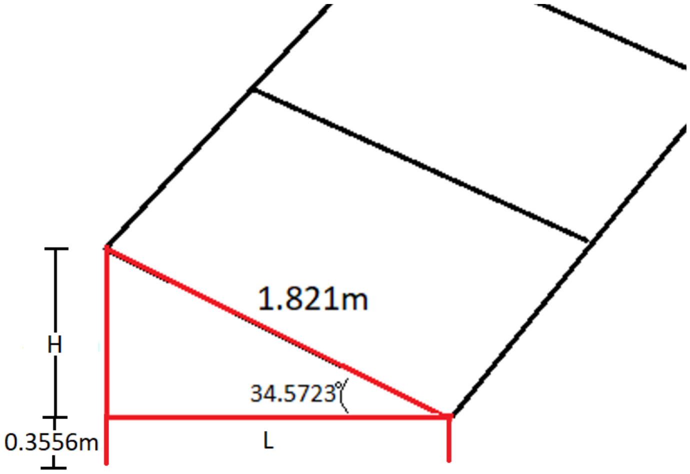


Figure 79: Design 2 (3 String) - Height and Length of the Array

Calculation of Height:

sin(34.5723°) = H / 1.821m

H = 1.821m x sin(34.5723°)

H = 1.03m

Because the solar modules are lifted off the ground by 0.3556 meters, this needs to be added to the calculated height measurement to determine the total height [17].

Total Height = 1.03m + 0.3556m = 1.39m

Calculation of Length:

cos(34.5723°) = L / 1.821m

L = 1.821 x cos(34.5723°)

L = 1.50m

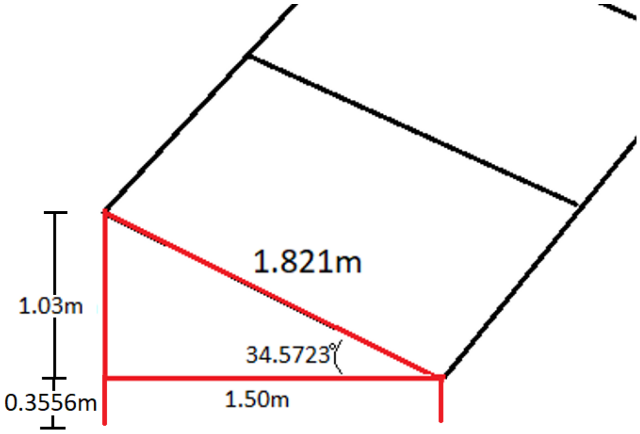


Figure 80: Design 2 (3 String) - Height and Length of the Array Labeled

<u>Interrow Spacing at 10am December 21st [18]:</u>

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 1.39m / Tan(25.37°)

Length X = 2.93m

Part 2: Red Triangle

Cos(Azimuth Angle) = Shadow Length/ Length X

Shadow Length = 2.93m x Cos(Azimuth Angle)

Shadow Length = 2.93m x Cos(30.51°)

Shadow Length = 2.52m

Interrow Spacing at 4pm December 21st [18]:

Part 1: Yellow Triangle

Tan(Altitude Angle) = Array Height / Length X

Length X = Array Height / Tan(Altitude Angle)

Length X = 1.39m / Tan(8.74°)

Length X = 9.04m

Part 2: Red Triangle

cos(Azimuth Angle) = Shadow Length / Length X

Shadow Length = Length X x cos(Azimuth Angle)

Shadow Length = 9.04m x cos(53.50°)

Shadow Length = 5.37m

The shadow length at 10am is 2.52m while the shadow length at 4pm is 5.37m. Therefore, the modules would need to be spaced out by over 5.37 meters. After the calculation, the decision was made to reduce the time period from 10am to 4pm no shading to 10am to 2pm no shading.

F. MATLAB Code for Altitude vs. Azimuth

```
% Thesis: Year Round Altitude vs Azimuth Graph Palmdale Location
% California
Latitude = 34.5723; % North

% Defining Day Numbers for each Month
Jan21_Day_Num = 21;
Feb21_Day_Num = 52;
Mar21_Day_Num = 80;
April21_Day_Num = 111;
May21_Day_Num = 141;
June21_Summer_Solstice_Day_Num = 172;
July21_Day_Num = 202;
Aug21_Day_Num = 233;
Sep21_Day_Num = 264;
Oct21_Day_Num = 294;
Nov21_Day_Num = 325;
Dec21_Winter_Solstice_Day_Num = 355;

% Calculating Solar Declination for all 12 Months
Jan21_Solar_Declination = 23.45 * sind((360/365) * (Jan21_Day_Num - 81));
Feb21_Solar_Declination = 23.45 * sind((360/365) * (Feb21_Day_Num - 81));
Mar21_Solar_Declination = 23.45 * sind((360/365) * (Mar21_Day_Num - 81));
April21_Solar_Declination = 23.45 * sind((360/365) * (April21_Day_Num - 81));
May21_Solar_Declination = 23.45 * sind((360/365) * (May21_Day_Num - 81));
June21_Summer_Solstice_Solar_Declination = 23.45 * sind((360/365) *
(June21_Summer_Solstice_Day_Num - 81));
July21_Solar_Declination = 23.45 * sind((360/365) * (July21_Day_Num - 81));
Aug21_Solar_Declination = 23.45 * sind((360/365) * (Aug21_Day_Num - 81));
Sep21_Solar_Declination = 23.45 * sind((360/365) * (Sep21_Day_Num - 81));
Oct21_Solar_Declination = 23.45 * sind((360/365) * (Oct21_Day_Num - 81));
Nov21_Solar_Declination = 23.45 * sind((360/365) * (Nov21_Day_Num - 81));
Dec21_Winter_Solstice_Solar_Declination = 23.45 * sind((360/365) *
(Dec21_Winter_Solstice_Day_Num - 81));

% Hour Angles for each day
Minutes_Per_Day = [0:1440];
Hours = Minutes_Per_Day / 60;
Hour_Angle = 15 * (12 - Hours);

% Altitude Angle Calculation for each month on the 21st day
Altitude_Angle_Jan21 =
asind(sind(Jan21_Solar_Declination)*sind(Latitude)+cosd(Jan21_Solar_Declinatio
n)*cosd(Latitude)*cosd(Hour_Angle));
Altitude_Angle_Feb21 =
asind(sind(Feb21_Solar_Declination)*sind(Latitude)+cosd(Feb21_Solar_Declinatio
n)*cosd(Latitude)*cosd(Hour_Angle));
Altitude_Angle_Mar21 =
asind(sind(Mar21_Solar_Declination)*sind(Latitude)+cosd(Mar21_Solar_Declinatio
n)*cosd(Latitude)*cosd(Hour_Angle));
Altitude_Angle_April21 =
asind(sind(April21_Solar_Declination)*sind(Latitude)+cosd(April21_Solar_Declin
ation)*cosd(Latitude)*cosd(Hour_Angle));
```

```
Altitude_Angle_May21 =
asind(sind(May21_Solar_Declination)*sind(Latitude)+cosd(May21_Solar_Declinatio
n)*cosd(Latitude)*cosd(Hour_Angle));
Altitude_Angle_June21 =
asind(sind(June21_Summer_Solstice_Solar_Declination)*sind(Latitude)+cosd(June2
1_Summer_Solstice_Solar_Declination)*cosd(Latitude)*cosd(Hour_Angle));
Altitude_Angle_July21 =
asind(sind(July21_Solar_Declination)*sind(Latitude)+cosd(July21_Solar_Declinat
ion)*cosd(Latitude)*cosd(Hour_Angle));
Altitude_Angle_Aug21 =
asind(sind(Aug21_Solar_Declination)*sind(Latitude)+cosd(Aug21_Solar_Declinatio
n)*cosd(Latitude)*cosd(Hour_Angle));
Altitude_Angle_Sep21 =
asind(sind(Sep21_Solar_Declination)*sind(Latitude)+cosd(Sep21_Solar_Declinatio
n)*cosd(Latitude)*cosd(Hour_Angle));
Altitude_Angle_Oct21 =
asind(sind(Oct21_Solar_Declination)*sind(Latitude)+cosd(Oct21_Solar_Declinatio
n)*cosd(Latitude)*cosd(Hour_Angle));
Altitude_Angle_Nov21 =
asind(sind(Nov21_Solar_Declination)*sind(Latitude)+cosd(Nov21_Solar_Declinatio
n)*cosd(Latitude)*cosd(Hour_Angle));
Altitude_Angle_Dec21 =
asind(sind(Dec21_Winter_Solstice_Solar_Declination)*sind(Latitude)+cosd(Dec21_
Winter_Solstice_Solar_Declination)*cosd(Latitude)*cosd(Hour_Angle));

% Azimuth Angle Calculation for each month on the 21st day
Azimuth_Angle_Jan21 = asind((cosd(Jan21_Solar_Declination).* sind(Hour_Angle))
./ cosd(Altitude_Angle_Jan21));
Azimuth_Angle_Feb21 = asind((cosd(Feb21_Solar_Declination).* sind(Hour_Angle))
./ cosd(Altitude_Angle_Feb21));
Azimuth_Angle_Mar21 = asind((cosd(Mar21_Solar_Declination).* sind(Hour_Angle))
./ cosd(Altitude_Angle_Mar21));
Azimuth_Angle_April21 = asind((cosd(April21_Solar_Declination).*
sind(Hour_Angle)) ./ cosd(Altitude_Angle_April21));
Azimuth_Angle_May21 = asind((cosd(May21_Solar_Declination).* sind(Hour_Angle))
./ cosd(Altitude_Angle_May21));
Azimuth_Angle_June21 = asind((cosd(June21_Summer_Solstice_Solar_Declination).*
sind(Hour_Angle)) ./ cosd(Altitude_Angle_June21));
Azimuth_Angle_July21 = asind((cosd(July21_Solar_Declination).*
sind(Hour_Angle)) ./ cosd(Altitude_Angle_July21));
Azimuth_Angle_Aug21 = asind((cosd(Aug21_Solar_Declination).* sind(Hour_Angle))
./ cosd(Altitude_Angle_Aug21));
Azimuth_Angle_Sep21 = asind((cosd(Sep21_Solar_Declination).* sind(Hour_Angle))
./ cosd(Altitude_Angle_Sep21));
Azimuth_Angle_Oct21 = asind((cosd(Oct21_Solar_Declination).* sind(Hour_Angle))
./ cosd(Altitude_Angle_Oct21));
Azimuth_Angle_Nov21 = asind((cosd(Nov21_Solar_Declination).* sind(Hour_Angle))
./ cosd(Altitude_Angle_Nov21));
Azimuth_Angle_Dec21 = asind((cosd(Dec21_Winter_Solstice_Solar_Declination).*
sind(Hour_Angle)) ./ cosd(Altitude_Angle_Dec21));


% Azimuth Angle Correction for June
for i = 1:length(Hour_Angle)
```

```
    if cosd(Hour_Angle(i)) >=
(tand(June21_Summer_Solstice_Solar_Declination))/(tand(Latitude))
        Azimuth_Angle_June21(i) =
asind((cosd(June21_Summer_Solstice_Solar_Declination).*sind(Hour_Angle(i)))./(
cosd(Altitude_Angle_June21(i))));
    else
        if Azimuth_Angle_June21(i) > 0
            Azimuth_Angle_June21(i) = 180-
asind((cosd(June21_Summer_Solstice_Solar_Declination).*sind(Hour_Angle(i)))./(
cosd(Altitude_Angle_June21(i))));
        else
            Azimuth_Angle_June21(i) = -180-
asind((cosd(June21_Summer_Solstice_Solar_Declination).*sind(Hour_Angle(i)))./(
cosd(Altitude_Angle_June21(i))));
        end
    end
end

% Azimuth Angle Correction for July
for i = 1:length(Hour_Angle)
    if cosd(Hour_Angle(i)) >=
(tand(July21_Solar_Declination))/(tand(Latitude))
        Azimuth_Angle_July21(i) =
asind((cosd(July21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_An
gle_July21(i))));
    else
        if Azimuth_Angle_July21(i) > 0
            Azimuth_Angle_July21(i) = 180-
asind((cosd(July21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_An
gle_July21(i))));
        else
            Azimuth_Angle_July21(i) = -180-
asind((cosd(July21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_An
gle_July21(i))));
        end
    end
end

% Azimuth Angle Correction for May
for i = 1:length(Hour_Angle)
    if cosd(Hour_Angle(i)) >= (tand(May21_Solar_Declination))/(tand(Latitude))
        Azimuth_Angle_May21(i) =
asind((cosd(May21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_Ang
le_May21(i))));
    else
        if Azimuth_Angle_May21(i) > 0
            Azimuth_Angle_May21(i) = 180-
asind((cosd(May21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_Ang
le_May21(i))));
        else
            Azimuth_Angle_May21(i) = -180-
asind((cosd(May21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_Ang
le_May21(i))));
        end
    end
```

```
end

% Azimuth Angle Correction for April
for i = 1:length(Hour_Angle)
    if cosd(Hour_Angle(i)) >=
(tand(April21_Solar_Declination))/(tand(Latitude))
        Azimuth_Angle_April21(i) =
asind((cosd(April21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_A
ngle_April21(i))));
    else
        if Azimuth_Angle_April21(i) > 0
            Azimuth_Angle_April21(i) = 180-
asind((cosd(April21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_A
ngle_April21(i))));
        else
            Azimuth_Angle_April21(i) = -180-
asind((cosd(April21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_A
ngle_April21(i))));
        end
    end
end

% Azimuth Angle Correction for August
for i = 1:length(Hour_Angle)
    if cosd(Hour_Angle(i)) >= (tand(Aug21_Solar_Declination))/(tand(Latitude))
        Azimuth_Angle_Aug21(i) =
asind((cosd(Aug21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_Ang
le_Aug21(i))));
    else
        if Azimuth_Angle_Aug21(i) > 0
            Azimuth_Angle_Aug21(i) = 180-
asind((cosd(Aug21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_Ang
le_Aug21(i))));
        else
            Azimuth_Angle_Aug21(i) = -180-
asind((cosd(Aug21_Solar_Declination).*sind(Hour_Angle(i)))./(cosd(Altitude_Ang
le_Aug21(i))));
        end
    end
end

%Ploting the Figure
figure(1)
plot(Azimuth_Angle_Jan21,Altitude_Angle_Jan21, 'm');
hold on;
plot(Azimuth_Angle_Feb21,Altitude_Angle_Feb21,'c')
hold on;
plot(Azimuth_Angle_Mar21,Altitude_Angle_Mar21,'y')
hold on;
plot(Azimuth_Angle_April21,Altitude_Angle_April21, 'r');
hold on;
plot(Azimuth_Angle_May21,Altitude_Angle_May21,'g')
hold on;
plot(Azimuth_Angle_June21,Altitude_Angle_June21,'b')
hold on;
```

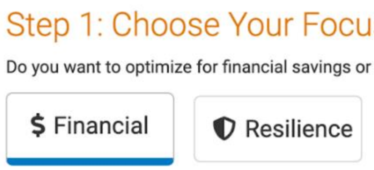
```
plot(Azimuth_Angle_Dec21,Altitude_Angle_Dec21,'k')
hold on;


ylim([0,inf])


title("Altitude [Degree] vs Azimuth [Degree]")
xlabel({"West                      South                          East"; "
Azimuth [Degree]"})
ylabel("Altitude [Degree]")
```

G. REopt Software Screenshots and Explanation

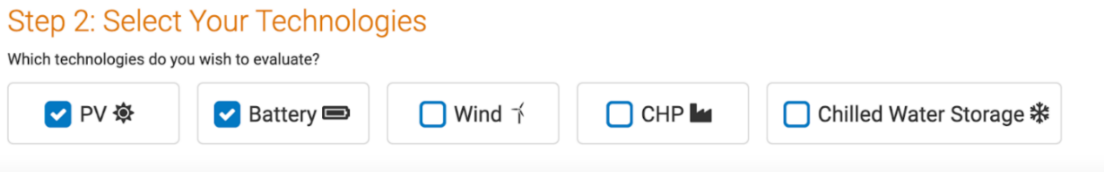
Table 16: REopt Screenshot Explanation



Step 1: Choose Your Focus

Do you want to optimize for financial savings or energy resilience?

The first option is either Financial or Resilience. Both options provide minimization of the present value of all future energy costs over the analysis period and may include a combination of many different distributed energy sources. The difference between the two is that financial does not optimize for a grid outage while resilience setting does.

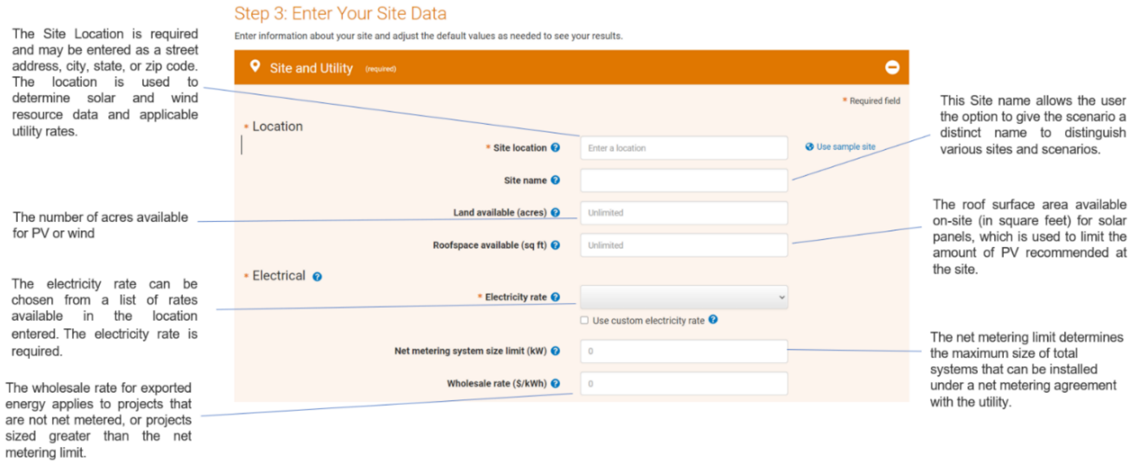


Step 2: Select Your Technologies

Which technologies do you wish to evaluate?

☑ PV
☑ Battery
☐ Wind
☐ CHP
☐ Chilled Water Storage

The second option is where you can choose which technologies you would like to have in your system. Based on which technology you choose other options can show up later.



Step 3: Enter Your Site Data

Enter information about your site and adjust the default values as needed to see your results.

* Site location: Enter a location
Use sample site
Site name:
Land available (acres): Unlimited
Roofspace available (sq ft): Unlimited

* Electricity rate:
☐ Use custom electricity rate
Net metering system size limit (kW): 0
Wholesale rate ($/kWh): 0

The Site Location is required and may be entered as a street address, city, state, or zip code. The location is used to determine solar and wind resource data and applicable utility rates.

The number of acres available for PV or wind

The electricity rate can be chosen from a list of rates available in the location entered. The electricity rate is required.

The wholesale rate for exported energy applies to projects that are not net metered, or projects sized greater than the net metering limit.

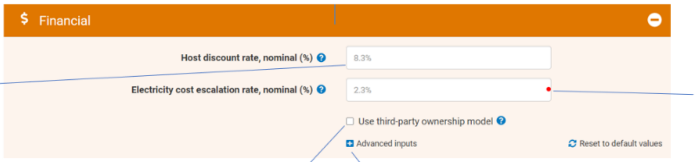
This Site name allows the user the option to give the scenario a distinct name to distinguish various sites and scenarios.

The roof surface area available on-site (in square feet) for solar panels, which is used to limit the amount of PV recommended at the site.

The net metering limit determines the maximum size of total systems that can be installed under a net metering agreement with the utility.

Table 16: REopt Screenshot Explanation Cont.

The rate at which the host discounts the future value of all future costs and savings.



Host discount rate, nominal (%): 8.3%

Electricity cost escalation rate, nominal (%): 2.3%

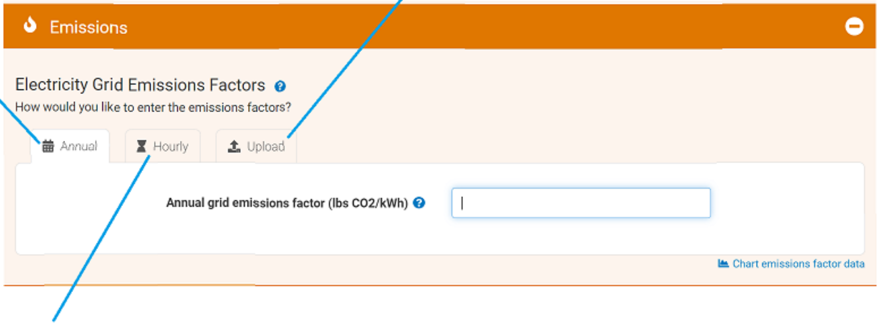
The expected annual escalation rate for the price of electricity provided by the utility over the financial life of the system.

A third-party ownership model evaluates the case where an entity other than the site owner, or host, owns and operates an energy system that is located at the site and sells energy services to the host. The host is interested in reducing their utility costs.

Clicking on Advanced inputs expands the Financial tab to additional inputs. The "Analysis period (years) 4" input is the financial life of the project in years. The "Host effective tax rate (%)" input is the percent of income that goes to tax for the system host. The "O&M cost escalation rate (%)" is the nominal expected annual rate of inflation over the financial life of the system.

If the user chooses to upload their own electricity grid emissions factor data, the file should have a grid emissions factor data point for each hour of the year.

If the user chooses to input annual emissions factor data, input the data in pounds of CO2 emitted per kilowatt hour per year [Annual lbs CO2/kWh]



Electricity Grid Emissions Factors

How would you like to enter the emissions factors?

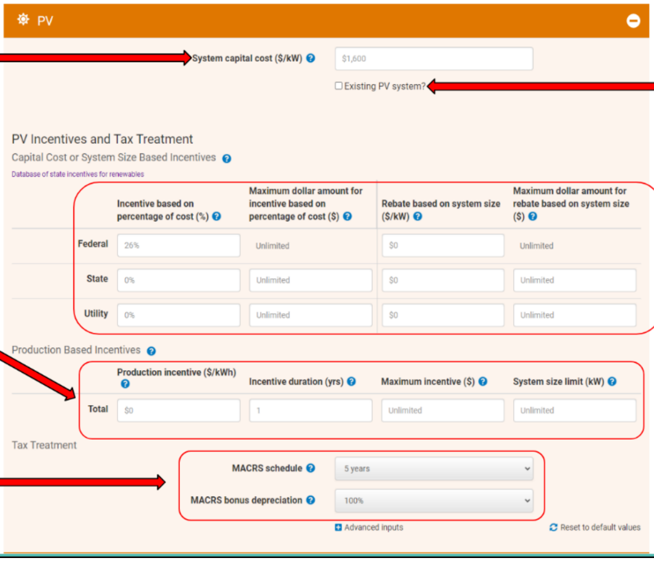
Annual grid emissions factor (lbs CO2/kWh): |

If the user chooses hourly grid emissions, the user can import emissions data from the US EPA AVERT tool.

Default value is $1,600. Based on 2020 Annual Technology Baseline and Standard Scenarios. NREL, 2020. https://atb.nrel.gov/ (Range $1400 - $1830)

Production-based incentives, or PBI, are entered as a dollar value of the incentive per kWh produced. The number of years the PBI is available and the maximum incentive amount are available fields.

The Modified Accelerated Cost Recovery System (MACRS) is the current tax depreciation system in the US. The capitalized cost of property is recovered over a specified life by annual deductions for depreciation.



System capital cost ($/kW): $1,600

PV Incentives and Tax Treatment

Capital Cost or System Size Based Incentives

	Incentive based on percentage of cost (%)	Maximum dollar amount for incentive based on percentage of cost ($)	Rebate based on system size ($/kW)	Maximum dollar amount for rebate based on system size ($)
Federal	26%	Unlimited	$0	Unlimited
State	0%	Unlimited	$0	Unlimited
Utility	0%	Unlimited	$0	Unlimited

Production Based Incentives

	Production incentive ($/kWh)	Incentive duration (yrs)	Maximum incentive ($)	System size limit (kW)
Total	$0	1	Unlimited	Unlimited

Tax Treatment

MACRS schedule: 5 years

MACRS bonus depreciation: 100%

If the site has an existing PV system, enter its size in kW. O&M costs are still associated but not capital

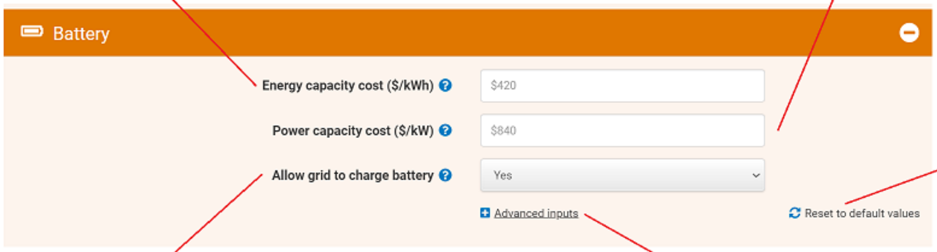
Incentives are available at the federal, state, and local level. A federal 26% investment tax credit is available, regardless of size making it default.

This site provides searchable specifics about incentives based on location. http://www.dsireusa.org/ http://programs.dsireusa.org/system/program/detail/658

Table 16: REopt Screenshot Explanation Cont.

The cost of the energy components for the battery system. For example, the cost of the battery pack. The energy metric for this field is dollars per kilowatt hour [$/kWh]. Default value of $420.

The cost of the power components for the battery system. For example the cost of the inverter and balance system (BOS). The power metric for this field is dollars per kilowatt [$/kW]. Default value of $840.



Battery

Energy capacity cost ($/kWh): $420

Power capacity cost ($/kW): $840

Allow grid to charge battery: Yes

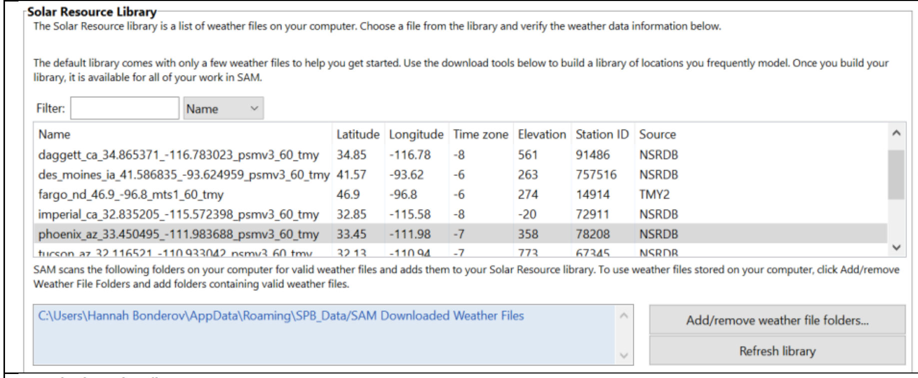
Option to reset values to the default value.

Yes or No option that will either allow the grid to charge the battery or will only allow the renewable energy system, such as PV and wind turbines, to charge the battery.

Allows for more advanced battery characterization, such as battery replacement costs, battery characteristics, battery incentives, and tax treatment, but not required additional values.

H. System Advisor Model Software Screenshots

Table 17: Location and Resource Section



Solar Resource Library

The Solar Resource library is a list of weather files on your computer. Choose a file from the library and verify the weather data information below.

The default library comes with only a few weather files to help you get started. Use the download tools below to build a library of locations you frequently model. Once you build your library, it is available for all of your work in SAM.

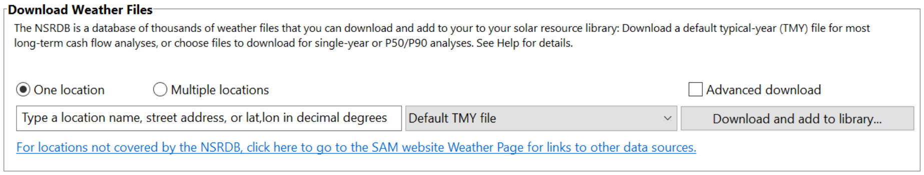
Filter: Name

Name	Latitude	Longitude	Time zone	Elevation	Station ID	Source
daggett_ca_34.865371_-116.783023_psmv3_60_tmy	34.85	-116.78	-8	561	91486	NSRDB
des_moines_ia_41.586835_-93.624959_psmv3_60_tmy	41.57	-93.62	-6	263	757516	NSRDB
fargo_nd_46.9_-96.8_mts1_60_tmy	46.9	-96.8	-6	274	14914	TMY2
imperial_ca_32.835205_-115.572398_psmv3_60_tmy	32.85	-115.58	-8	-20	72911	NSRDB
phoenix_az_33.450495_-111.983688_psmv3_60_tmy	33.45	-111.98	-7	358	78208	NSRDB
tucson_az_32.116521_-110.933042_psmv3_60_tmy	32.13	-110.94	-7	773	67345	NSRDB

SAM scans the following folders on your computer for valid weather files and adds them to your Solar Resource library. To use weather files stored on your computer, click Add/remove Weather File Folders and add folders containing valid weather files.

C:\Users\Hannah Bonderov\AppData\Roaming\SPB_Data/SAM Downloaded Weather Files

Pick the location of the system. Solar Resource data is determined based on location. If your location does not appear in the section, used the download weather files section below to add a new location.



Download Weather Files

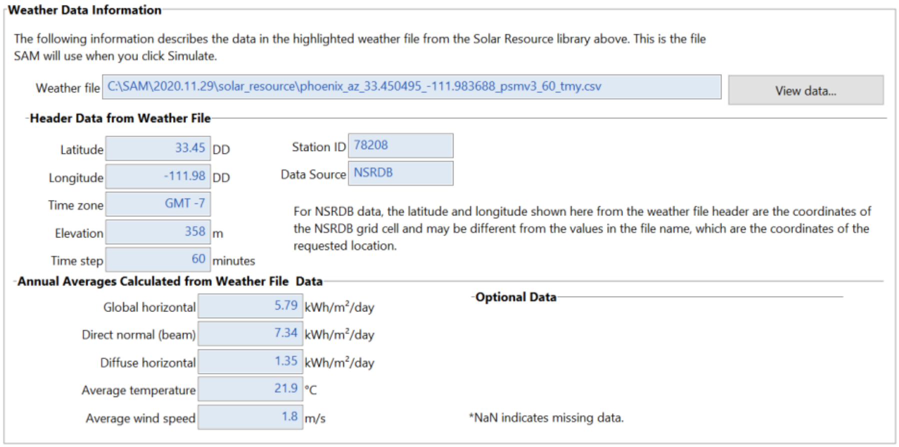
The NSRDB is a database of thousands of weather files that you can download and add to your to your solar resource library: Download a default typical-year (TMY) file for most long-term cash flow analyses, or choose files to download for single-year or P50/P90 analyses. See Help for details.

● One location ○ Multiple locations ☐ Advanced download

Type a location name, street address, or lat,lon in decimal degrees | Default TMY file

For locations not covered by the NSRDB, click here to go to the SAM website Weather Page for links to other data sources.

Use the Download Weather Files section to add a new location



Weather Data Information

The following information describes the data in the highlighted weather file from the Solar Resource library above. This is the file SAM will use when you click Simulate.

Weather file C:\SAM\2020.11.29\solar_resource\phoenix_az_33.450495_-111.983688_psmv3_60_tmy.csv

Header Data from Weather File

Latitude 33.45 DD
Longitude -111.98 DD
Time zone GMT -7
Elevation 358 m
Time step 60 minutes
Station ID 78208
Data Source NSRDB

For NSRDB data, the latitude and longitude shown here from the weather file header are the coordinates of the NSRDB grid cell and may be different from the values in the file name, which are the coordinates of the requested location.

Annual Averages Calculated from Weather File Data

Global horizontal 5.79 kWh/m²/day
Direct normal (beam) 7.34 kWh/m²/day
Diffuse horizontal 1.35 kWh/m²/day
Average temperature 21.9 °C
Average wind speed 1.8 m/s

Optional Data

*NaN indicates missing data.

All the information highlighted in blue gets automatically inputed depending on the location choosen.

Table 18: System Design

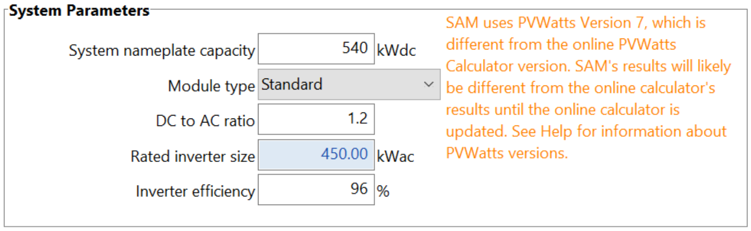
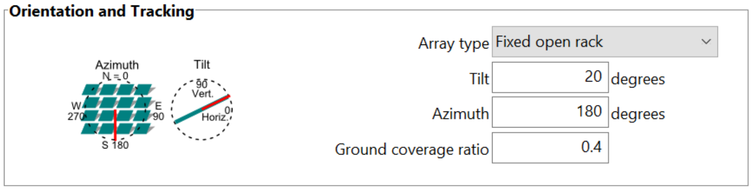
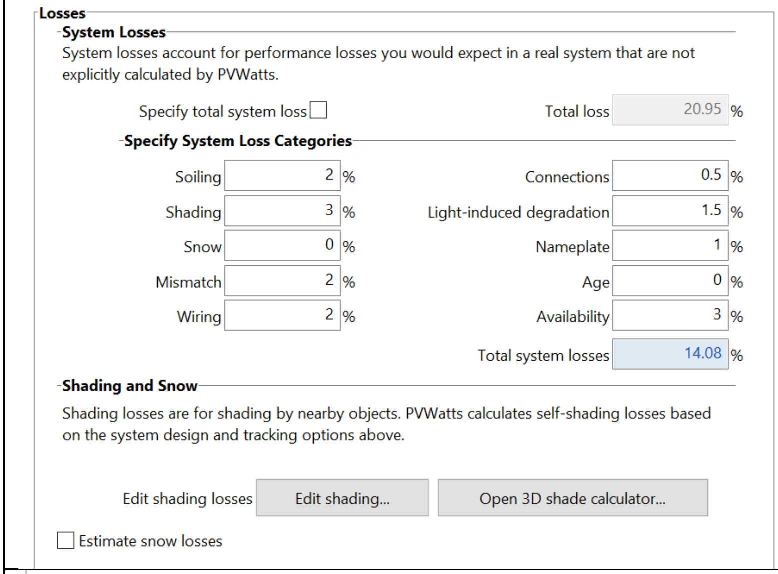
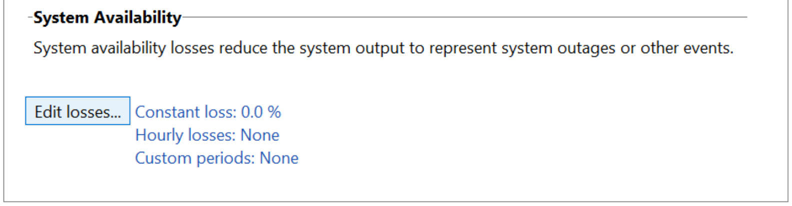
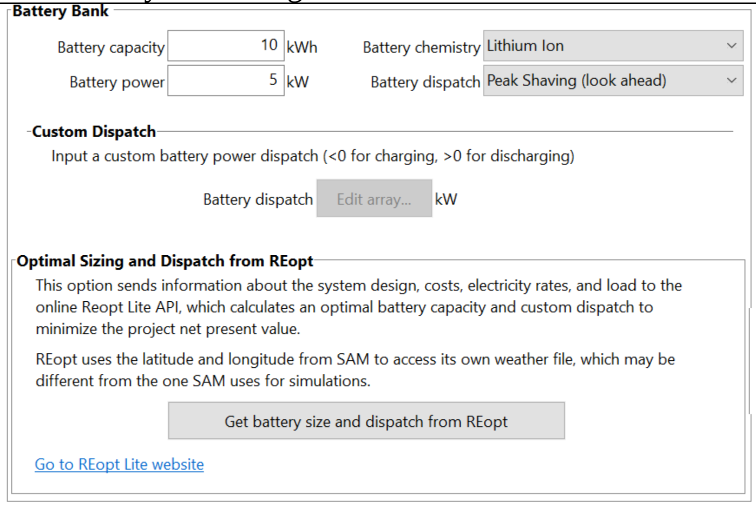
 **System Parameters** System nameplate capacity 540 kWdc Module type Standard DC to AC ratio 1.2 Rated inverter size 450.00 kWac Inverter efficiency 96 % SAM uses PVWatts Version 7, which is different from the online PVWatts Calculator version. SAM's results will likely be different from the online calculator's results until the online calculator is updated. See Help for information about PVWatts versions.	In this section input the system nameplate capacity, module type, DC to AC ratio, and inverter efficiency. The rated inverted size is automatically determined by the other inputs
 **Orientation and Tracking** Array type Fixed open rack Tilt 20 degrees Azimuth 180 degrees Ground coverage ratio 0.4	Input the array type, module tilt, azimuth, and the ground coverage ratio in this section
 **Losses** **System Losses** System losses account for performance losses you would expect in a real system that are not explicitly calculated by PVWatts. Specify total system loss ☐ Total loss 20.95 % **Specify System Loss Categories** Soiling 2 % Shading 3 % Snow 0 % Mismatch 2 % Wiring 2 % Connections 0.5 % Light-induced degradation 1.5 % Nameplate 1 % Age 0 % Availability 3 % Total system losses 14.08 % **Shading and Snow** Shading losses are for shading by nearby objects. PVWatts calculates self-shading losses based on the system design and tracking options above. Edit shading losses [Edit shading...] [Open 3D shade calculator...] ☐ Estimate snow losses	This section allows the user to input seperate system losses for soiling (dirt on panels), shading, snow, mismatch, wiring, connections, light-induced degradation, nameplate, age, and availability. Then the total system losses are automatically calculated. Use this section to simulate a more accurate model of the shading that may occur.
 **System Availability** System availability losses reduce the system output to represent system outages or other events. [Edit losses...] Constant loss: 0.0 % Hourly losses: None Custom periods: None	Use this section to simulate more detailed system losses.

Table 18: System Design Cont.



Battery capacity 10 kWh
Battery power 5 kW
Battery chemistry Lithium Ion
Battery dispatch Peak Shaving (look ahead)

Input a custom battery power dispatch (<0 for charging, >0 for discharging)

Battery dispatch kW

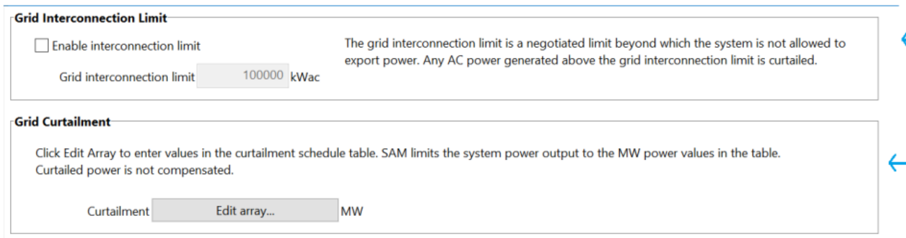
This option sends information about the system design, costs, electricity rates, and load to the online Reopt Lite API, which calculates an optimal battery capacity and custom dispatch to minimize the project net present value.

REopt uses the latitude and longitude from SAM to access its own weather file, which may be different from the one SAM uses for simulations.

Input the battery capacity and battery power in this section.

To optimize the battery, use this section which connects to the REopt Lite API.

Table 19: Grid Limits



☐ Enable interconnection limit

Grid interconnection limit 100000 kWac

The grid interconnection limit is a negotiated limit beyond which the system is not allowed to export power. Any AC power generated above the grid interconnection limit is curtailed.

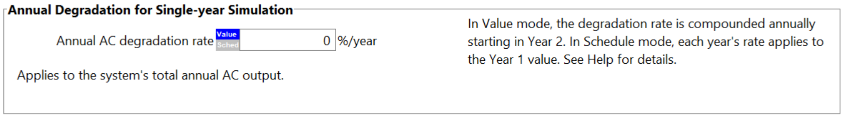
Click Edit Array to enter values in the curtailment schedule table. SAM limits the system power output to the MW power values in the table. Curtailed power is not compensated.

Curtailment MW

Choose if the system has a interconnection limit.

To edit the grid curtailment array, use this section.

Table 20: Lifetime and Degradation



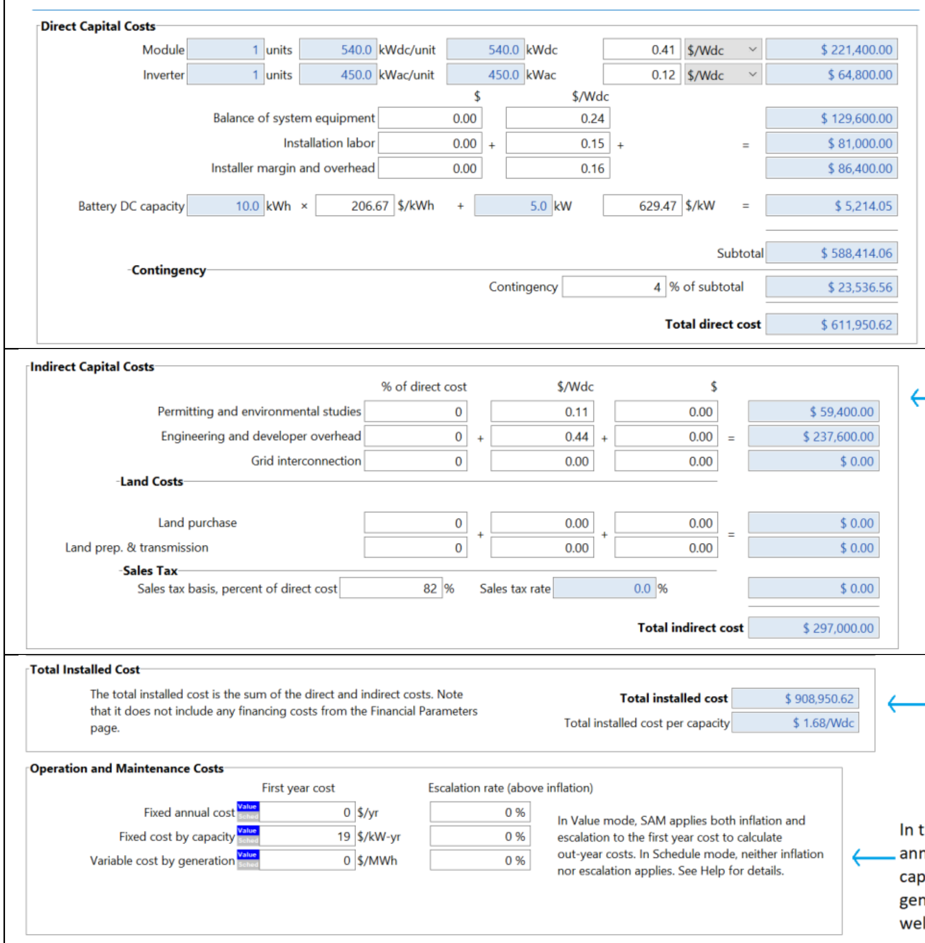
Annual AC degradation rate 0 %/year

Applies to the system's total annual AC output.

In Value mode, the degradation rate is compounded annually starting in Year 2. In Schedule mode, each year's rate applies to the Year 1 value. See Help for details.

Input the annual degradation in this section. Annual degradation is how much efficiency the system loses every year.

Table 21: System Costs



Direct Capital Costs

Module	1	units	540.0	kWdc/unit	540.0	kWdc	0.41	$/Wdc	$ 221,400.00
Inverter	1	units	450.0	kWac/unit	450.0	kWac	0.12	$/Wdc	$ 64,800.00

	$		$/Wdc			
Balance of system equipment	0.00		0.24			$ 129,600.00
Installation labor	0.00	+	0.15	+	=	$ 81,000.00
Installer margin and overhead	0.00		0.16			$ 86,400.00

Battery DC capacity 10.0 kWh × 206.67 $/kWh + 5.0 kW 629.47 $/kW = $ 5,214.05

Subtotal $ 588,414.06

Contingency

Contingency 4 % of subtotal $ 23,536.56

Total direct cost $ 611,950.62

Input the capitals costs, including module and inverter dollars per watt DC cost. The user can also input the cost of the balance of system equipment, installation labor, installer margin of overhead, and other battery costs

Indirect Capital Costs

	% of direct cost		$/Wdc		$		
Permitting and environmental studies	0		0.11		0.00		$ 59,400.00
Engineering and developer overhead	0	+	0.44	+	0.00	=	$ 237,600.00
Grid interconnection	0		0.00		0.00		$ 0.00
Land Costs							
Land purchase	0	+	0.00	+	0.00	=	$ 0.00
Land prep. & transmission	0		0.00		0.00		$ 0.00

Sales Tax

Sales tax basis, percent of direct cost 82 % Sales tax rate 0.0 % $ 0.00

Total indirect cost $ 297,000.00

Input system indirect capital costs in this section. These parameters include the permitting and enviromental studies, engineering and developer overhead, grid interconnection, land costs, and sales tax.

Total Installed Cost

The total installed cost is the sum of the direct and indirect costs. Note that it does not include any financing costs from the Financial Parameters page.

Total installed cost $ 908,950.62

Total installed cost per capacity $ 1.68/Wdc

After the capital costs and indirect capital costs are inputed, the total installed cost and the cost per capacity is automatically calculated

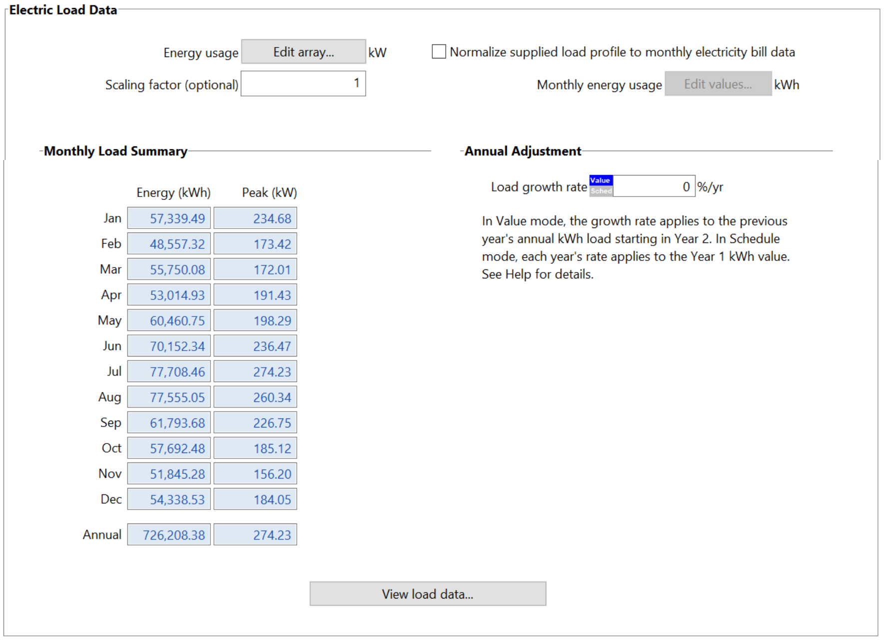
Operation and Maintenance Costs

	First year cost		Escalation rate (above inflation)
Fixed annual cost	0	$/yr	0 %
Fixed cost by capacity	19	$/kW-yr	0 %
Variable cost by generation	0	$/MWh	0 %

In Value mode, SAM applies both inflation and escalation to the first year cost to calculate out-year costs. In Schedule mode, neither inflation nor escalation applies. See Help for details.

In this section input the fixed annual cost, fixed cost by capacity, and variable cost by generation for the first year as well as an escalation rate.

Table 22: Electric Load



Electric Load Data

Energy usage: Edit array... kW

Scaling factor (optional): 1

☐ Normalize supplied load profile to monthly electricity bill data

Monthly energy usage: Edit values... kWh

Monthly Load Summary

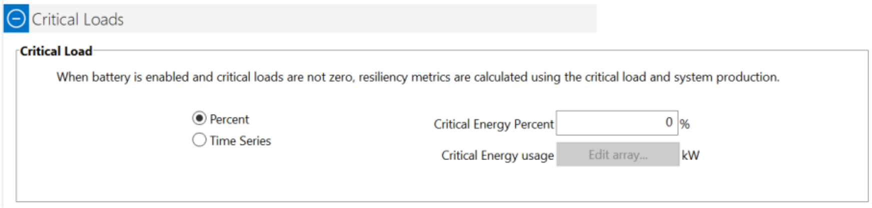
	Energy (kWh)	Peak (kW)
Jan	57,339.49	234.68
Feb	48,557.32	173.42
Mar	55,750.08	172.01
Apr	53,014.93	191.43
May	60,460.75	198.29
Jun	70,152.34	236.47
Jul	77,708.46	274.23
Aug	77,555.05	260.34
Sep	61,793.68	226.75
Oct	57,692.48	185.12
Nov	51,845.28	156.20
Dec	54,338.53	184.05
Annual	726,208.38	274.23

Annual Adjustment

Load growth rate: 0 %/yr

In Value mode, the growth rate applies to the previous year's annual kWh load starting in Year 2. In Schedule mode, each year's rate applies to the Year 1 kWh value. See Help for details.

In this section the load data is automatically generated depending on the input in the past sections. The user can edit this load data by clicking 'Edit array.' The user can also input a value for the load growth rate to simulate an increasing energy demand with time.



Critical Loads

Critical Load

When battery is enabled and critical loads are not zero, resiliency metrics are calculated using the critical load and system production.

● Percent
○ Time Series

Critical Energy Percent: 0 %

Critical Energy usage: Edit array... kW

Input the critical load as a percent of total energy in this section. Use the time series selection to simulate a more detailed critical load.

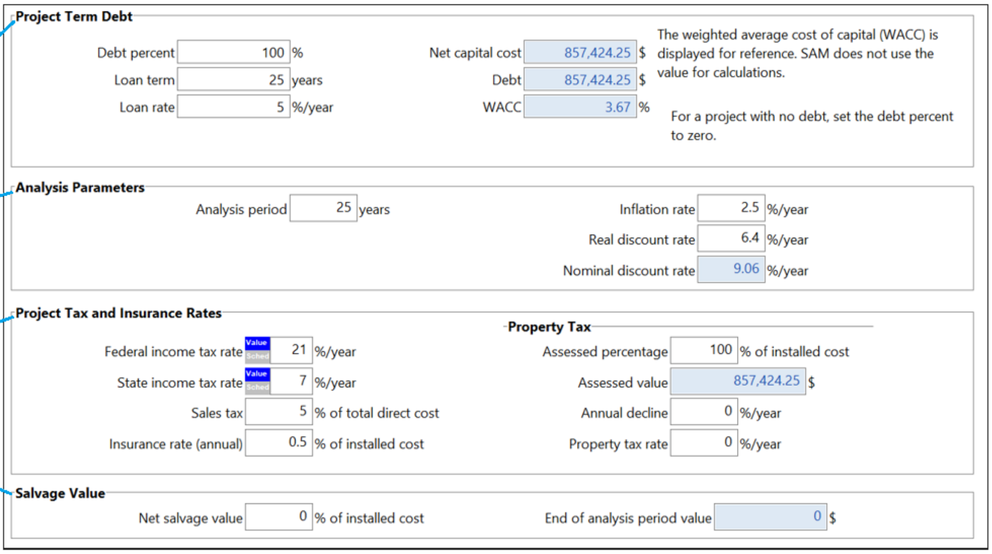
Table 23: Financial Parameters

To pay for inital capital costs a loan must be taken into account.

Time period and inflation is accounted here

Taxes are accounted here.

Accounting for salvage value if system were ever to be sold.



Project Term Debt

Debt percent	100	%	Net capital cost	857,424.25	$
Loan term	25	years	Debt	857,424.25	$
Loan rate	5	%/year	WACC	3.67	%

The weighted average cost of capital (WACC) is displayed for reference. SAM does not use the value for calculations.

For a project with no debt, set the debt percent to zero.

Analysis Parameters

Analysis period	25	years	Inflation rate	2.5	%/year
			Real discount rate	6.4	%/year
			Nominal discount rate	9.06	%/year

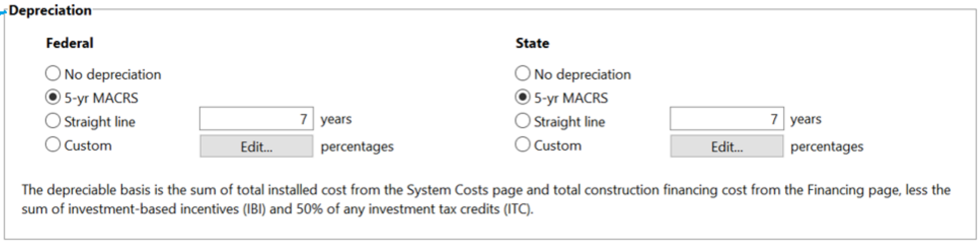
Project Tax and Insurance Rates

			Property Tax		
Federal income tax rate	21	%/year	Assessed percentage	100	% of installed cost
State income tax rate	7	%/year	Assessed value	857,424.25	$
Sales tax	5	% of total direct cost	Annual decline	0	%/year
Insurance rate (annual)	0.5	% of installed cost	Property tax rate	0	%/year

Salvage Value

Net salvage value	0	% of installed cost	End of analysis period value	0	$

Accounts depreciation for tax and cash flow purposes. For each engineering projects a 5 year MARCS system is used.



Depreciation

Federal

○ No depreciation
● 5-yr MACRS
○ Straight line — 7 years
○ Custom — Edit... percentages

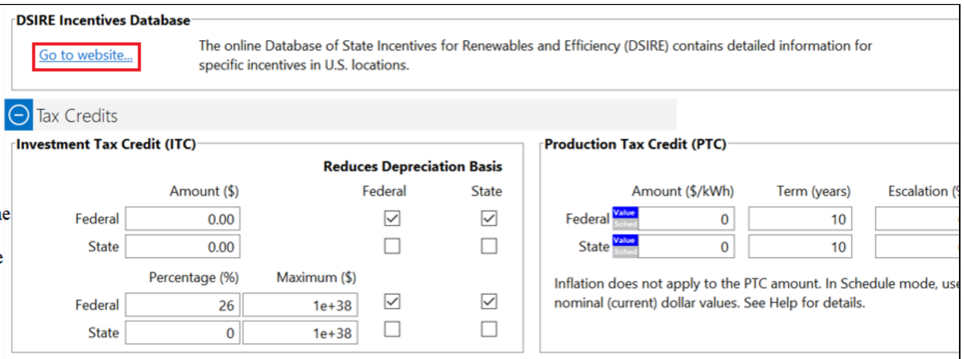
State

○ No depreciation
● 5-yr MACRS
○ Straight line — 7 years
○ Custom — Edit... percentages

The depreciable basis is the sum of total installed cost from the System Costs page and total construction financing cost from the Financing page, less the sum of investment-based incentives (IBI) and 50% of any investment tax credits (ITC).

Table 24: Incentives

Tax reductions are accounted for here. Use the website above to find the rates for your state and the current federal rates.



DSIRE Incentives Database

Go to website...

The online Database of State Incentives for Renewables and Efficiency (DSIRE) contains detailed information for specific incentives in U.S. locations.

Tax Credits

Investment Tax Credit (ITC)

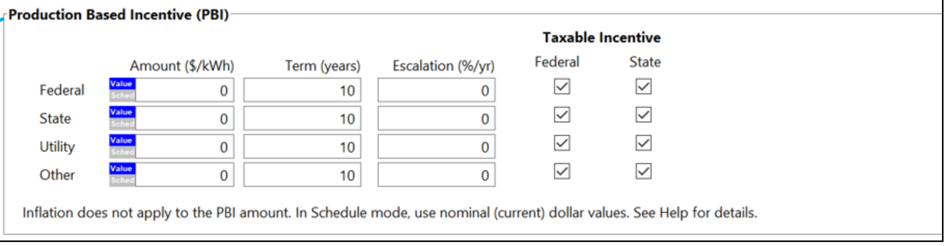
			Reduces Depreciation Basis	
	Amount ($)		Federal	State
Federal	0.00		☑	☑
State	0.00		☐	☐
	Percentage (%)	Maximum ($)		
Federal	26	1e+38	☑	☑
State	0	1e+38	☐	☐

Production Tax Credit (PTC)

	Amount ($/kWh)	Term (years)	Escalation (
Federal	0	10	
State	0	10	

Inflation does not apply to the PTC amount. In Schedule mode, use nominal (current) dollar values. See Help for details.

Incentives and further rebates are given through how much energy one can produce. Fill out this area to account for the change.

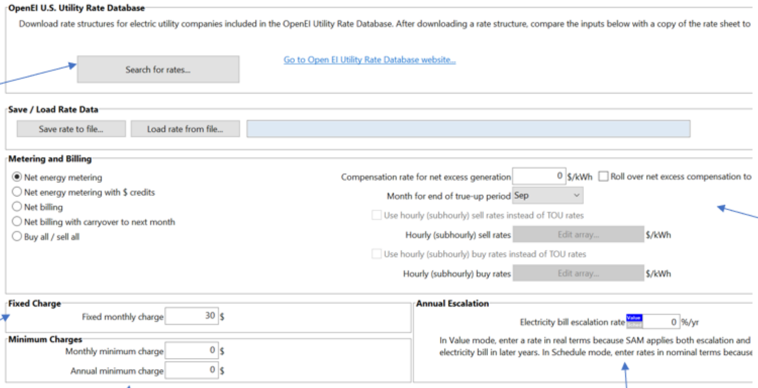


Production Based Incentive (PBI)

				Taxable Incentive	
	Amount ($/kWh)	Term (years)	Escalation (%/yr)	Federal	State
Federal	0	10	0	☑	☑
State	0	10	0	☑	☑
Utility	0	10	0	☑	☑
Other	0	10	0	☑	☑

Inflation does not apply to the PBI amount. In Schedule mode, use nominal (current) dollar values. See Help for details.

Table 25: Electricity Rates



OpenEI U.S. Utility Rate Database

Download rate structures for electric utility companies included in the OpenEI Utility Rate Database. After downloading a rate structure, compare the inputs below with a copy of the rate sheet to

Save / Load Rate Data

Metering and Billing

● Net energy metering
○ Net energy metering with $ credits
○ Net billing
○ Net billing with carryover to next month
○ Buy all / sell all

Compensation rate for net excess generation 0 $/kWh ☐ Roll over net excess compensation to
Month for end of true-up period Sep
☐ Use hourly (subhourly) sell rates instead of TOU rates
Hourly (subhourly) sell rates Edit array... $/kWh
☐ Use hourly (subhourly) buy rates instead of TOU rates
Hourly (subhourly) buy rates Edit array... $/kWh

Fixed Charge

Fixed monthly charge 30 $

Minimum Charges

Monthly minimum charge 0 $
Annual minimum charge 0 $

Annual Escalation

Electricity bill escalation rate 0 %/yr

In Value mode, enter a rate in real terms because SAM applies both escalation and electricity bill in later years. In Schedule mode, enter rates in nominal terms because

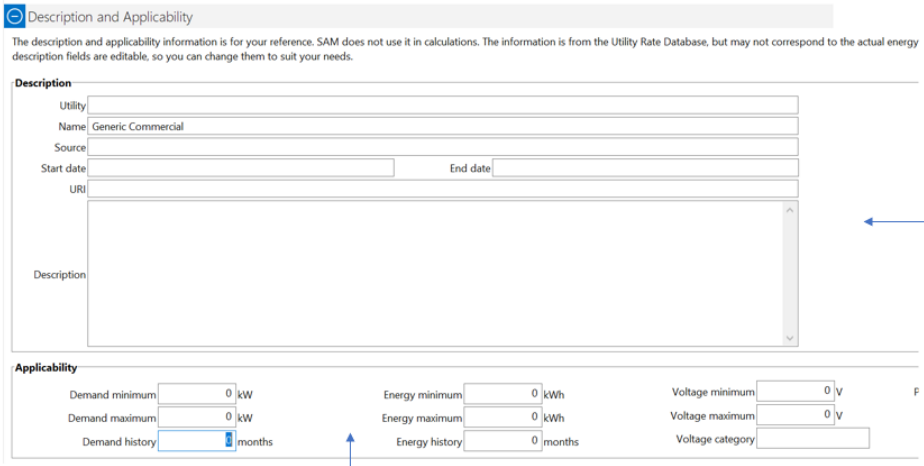
In this section, you can search for the utility rate that is near the site you are looking at. This will automatically fill in all the information

In this section, y
the type of utilit
your site has.

In this section, if the utility that your site has is fixed, then you can input that here

In this section, if the utility rate that your site has a minimum monthly and annual rate, then you can input that here

In this section, you can enter the utility bill's annual escalation rate which is the current cost minus the initial price divided by the initial price of one year.



Description and Applicability

The description and applicability information is for your reference. SAM does not use it in calculations. The information is from the Utility Rate Database, but may not correspond to the actual energy description fields are editable, so you can change them to suit your needs.

Description

Utility
Name Generic Commercial
Source
Start date
End date
URI
Description

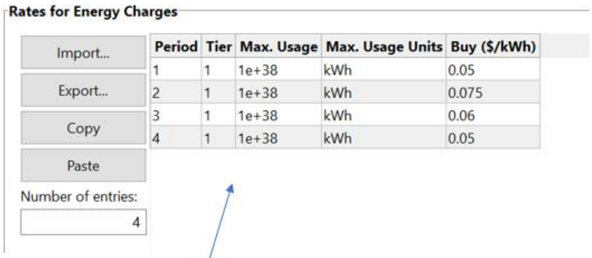
Applicability

Demand minimum 0 kW
Demand maximum 0 kW
Demand history 0 months
Energy minimum 0 kWh
Energy maximum 0 kWh
Energy history 0 months
Voltage minimum 0 V
Voltage maximum 0 V
Voltage category

In this section, you can manually enter the utility details

In this section, you can manually enter the demand power, the energy, and the voltage of the utility.

Table 25: Electricity Rates Cont.

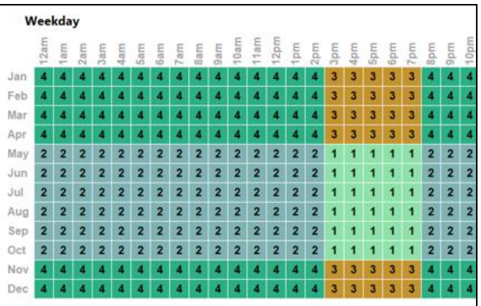


Period	Tier	Max. Usage	Max. Usage Units	Buy ($/kWh)
1	1	1e+38	kWh	0.05
2	1	1e+38	kWh	0.075
3	1	1e+38	kWh	0.06
4	1	1e+38	kWh	0.05

Number of entries: 4

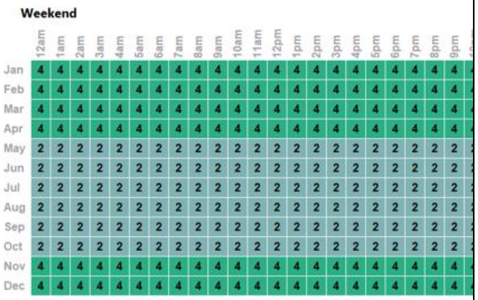
In this section, you can manually enter the utilities' energy charges with the different periods. These periods have different tiers, different max usage, and can have different $/kWh.

After inputting the energy rates, you can change how the rates are on the weekday and weekend on these calendars



Weekday

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm
Jan	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Feb	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Mar	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Apr	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
May	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Jun	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Jul	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Aug	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Sep	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Oct	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2
Nov	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4
Dec	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4	4	4



Weekend

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm
Jan	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Feb	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Mar	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
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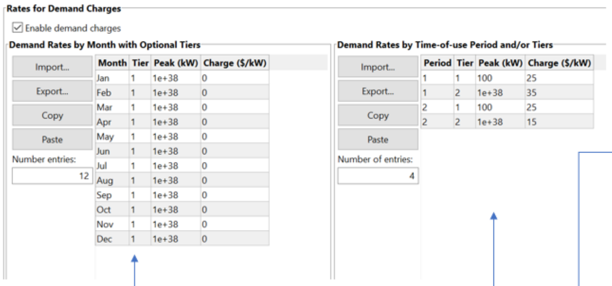
May	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Jun	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Jul	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Aug	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Sep	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Oct	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Nov	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Dec	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4



☑ Enable demand charges

Demand Rates by Month with Optional Tiers

Month	Tier	Peak (kW)	Charge ($/kW)
Jan	1	1e+38	0
Feb	1	1e+38	0
Mar	1	1e+38	0
Apr	1	1e+38	0
May	1	1e+38	0
Jun	1	1e+38	0
Jul	1	1e+38	0
Aug	1	1e+38	0
Sep	1	1e+38	0
Oct	1	1e+38	0
Nov	1	1e+38	0
Dec	1	1e+38	0

Number entries: 12

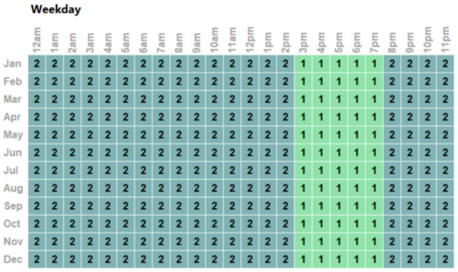
Demand Rates by Time-of-use Period and/or Tiers

Period	Tier	Peak (kW)	Charge ($/kW)
1	1	100	25
1	2	1e+38	35
2	1	100	25
2	2	1e+38	15

Number of entries: 4

In this section, you can manually enter the demand charges from your utility with the different months and TOU periods

After entering the demand charges rates, you can manually enter the periods and tiers on the weekday and weekend calendars



Weekday

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2	2
Feb	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2	2
Mar	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2	2
Apr	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2	2
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Jul	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2	2
Aug	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2	2
Sep	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2	2
Oct	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2	2
Nov	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	2	2
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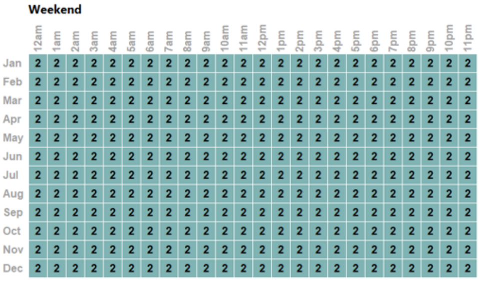

Weekend

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Feb	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
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Dec	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

I. Battery Energy Storage System Design 5 (3 String) Single Axis Tracking [19]

This section presents a battery energy storage system for design 5 (3 string) single axis tracking. It is not shown in chapter 19 since design 6 was better suited in the design requirements. Table 26 and 27 show the hour power production on June 21st and December 21st respectively.

Table 26: Hourly kW on June 21st SAM Simulation Design 5

Time of Day	Predicted Power Production [kW]
6am	31.56
7am	121.74
8am	148.50
9am	148.50
10am	148.50
11am	148.50
12pm	147.95
1pm	147.75
2pm	147.81
3pm	148.20
4pm	148.43
5pm	148.50
6pm	103.48
7pm	19.60

Table 27: Hourly kW on December 21st SAM Simulation Design 5

Time of Day	Predicted Power Production [kW]
8am	17.62
9am	97.10
10am	148.5
11am	148.45
12pm	109.75
1pm	141.55
2pm	148.50
3pm	148.50
4pm	71.76
5pm	3.76

Maximum Capacity: 900kWh

Peak Load Shaving on Year 1 June 21st (6am-12pm): 895.25kWh

Peak Load Shaving on Year 1 December 21st (8am-12pm): 521.42kWh

From looking at the data above, on June 21st charging the batteries between the hours of 6am to 12pm would need a battery energy storage system capable of storing 895.25kWh, which would be just under the maximum capacity of the battery energy storage system. Therefore, the maximum 900kWh should be installed for this design.