Summer Internship

05/12/2015 – 07/21/2015

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SPARTAN SUPERWAY

SAN JOSÉ STATE UNIVERSITY

Summary

1. Internship Overview

The Spartan Superway is a San Jose State University project that started in 2013 which consists of a suspended ATN that moves under a guideway powered by solar panels. The project team is composed by students that split in several teams, which are: bogie team, solar team, controls team, cabin team and guideway team.

During the summer of 2015, the author of this document worked in the solar team with the goal of improving the solar configuration for this system. The idea was to use the guideway as a base to the solar configuration to be designed and installed.

In the beginning, studies were made to learn what have already been done in the project during the years of 2013, 2014 and 2015, and what could be improved in the solar design.

The students working in the project have built two models of the transportations system: a full scale model and a twelth scale model. The particular goal of the author was to design different configurations for the solar in the full scale model, simulate them in NREL - SAM (System Advisor Model) and then choose the one with the best performance, economic and estetic characteristics. The chosen design would be built above the full scale model and then connected to a battery using the appropriate circuit equipment, like inverters, charge controllers and batteries.

In the beginning, the full scale model had two solar panels on the top, one of them attached to a frame with an actuator that could make the structure rotate following an ARDUINO program routine, and the other one fixed, like shown below.

Figure1: Stion rigid solar panel that can be rotated by an actuator

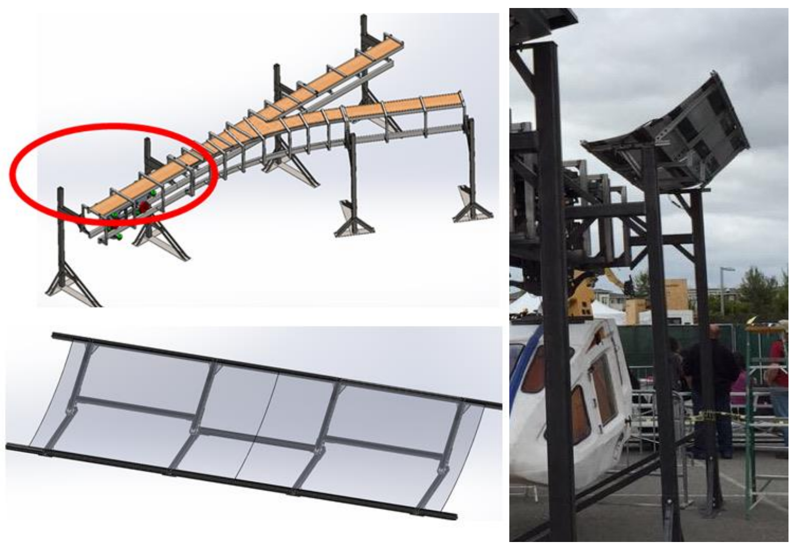

Figure 2: Miasole Thin Film Module fixed by a metal frame

The following sessions will show the drawings of the designs, that were made in Solidworks, the simulations on SAM and the conclusions that could be extracted from this analysis.

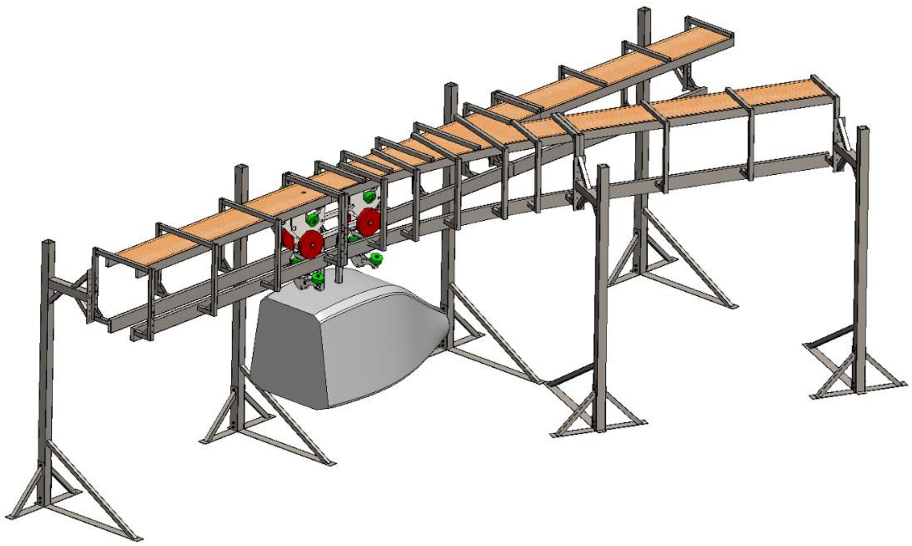

Figure 3: Full Scale Model Drawing in SolidWorks

2. Drawings

The author could get the Full Scale drawings from other students of the project and work on the solar configuration for it. One of the project sponsors is the Thin Film Module Manufacturer Miasole, which had 4 available types of solar module:

- FLEX-02 N – Dimensions: 102.3 in x 14.6 in
- FLEX-02 NS – Dimensions: 67.8 in x 14.6 in
- FLEX-02 W – Dimensions: 102.3 in x 39.4 in
- FLEX-02 WS – Dimensions: 67.8 in x 14.6 in

All of these modules were flexible, so it was necessary to design a frame to be used as a backing for the panels. The team agreed that it would be better to keep the modules plane and tilted in a specific angle, to minimize cosine losses and to avoid water and dust accumulation on the panel. The model designed would use fixed panels to simplify the following manufacturing working and to minimize costs. For fixed panels there is an expression that optimizes the power output:

- For latitude below 25°, use the latitude times 0.87.
- For latitude between 25° and 50°, use the latitude, times 0.76, plus 3.1 degrees.
- For latitude above 50°, there are other factors to consider.

The latitude of San Jose is 37°20’21’’, so the optimal tilt angle would be 31.22°.

The drawings made used the types of modules mentioned above, using its dimensions to see the best geometric disposition for each panel. The designs made were the following.

The goal of the solar design was to cover the trail as much as possible in such a way that optimizes power, energy and cost.

1)

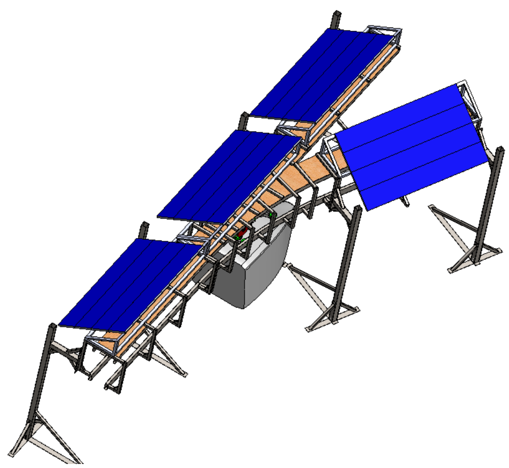

Figure 4: Design 1

This design consists of 16 solar panels of the FLEX-02N type being supported by a metal frame with a tilt angle of 31.22°. It does a good job on covering the trail on the left part of the trail, but it shows the guideway on the right. It would not be convenient to put panels on the right side cause they would be shaded by the other left ones.

2)

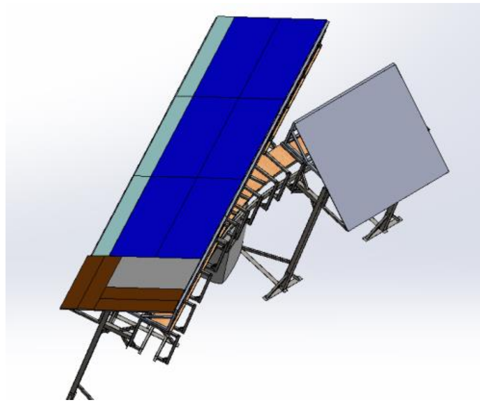

Figure 5: Design 2

The configuration uses all the types of the available solar panels. The blue ones are of the FLEX-02NS type, the green ones of the FLEX-02N type, the brown ones of the FLEX-02W type, and the gold ones of the FLEX-02WS. This design is very good for covering the sides of the trail even though there is a higher setup costs because more supports have to be built. The gray plate is a metal sheet that goes behind the panels to be used as a backing. The panels would be attached to the sheet by using clamps.

3)

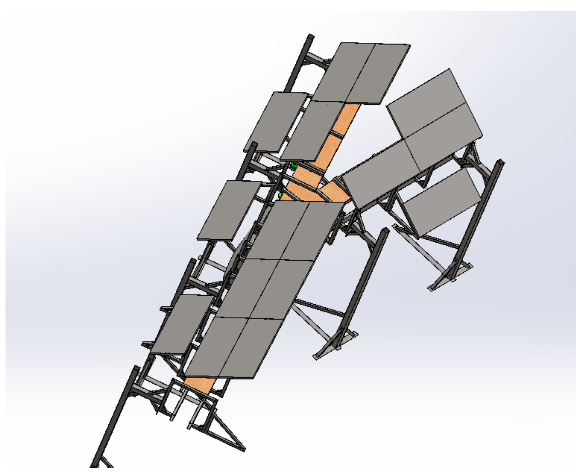

Figure 6: Design 3

This is a more complex design with supports on the side of the rail. The panels are of the FLEX-02N type. It is similar to the first one in terms of power output, because it has the same number of modules disposed in the same geometric position, but it would be more difficult to install this one, because more supports would be needed.

4)

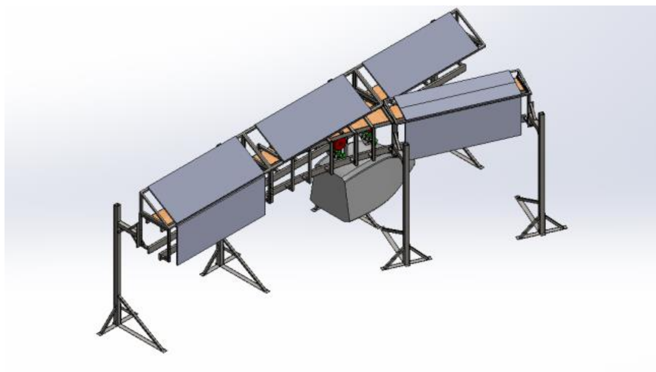

Figure 7: Design 4

This design does not have a good efficiency compared to the previous ones, because of the vertical panels, that can collaborate to the power supply, but have the main function of covering the trails. Also, one of the panels on the top is almost horizontal, so it won`t shade the panels behind it.

3. Simulations

The simulations were made using the software NREL – SAM and they evaluated performance and cost characteristics of the solar configurations made. The initial interface of the program is the one shown below:

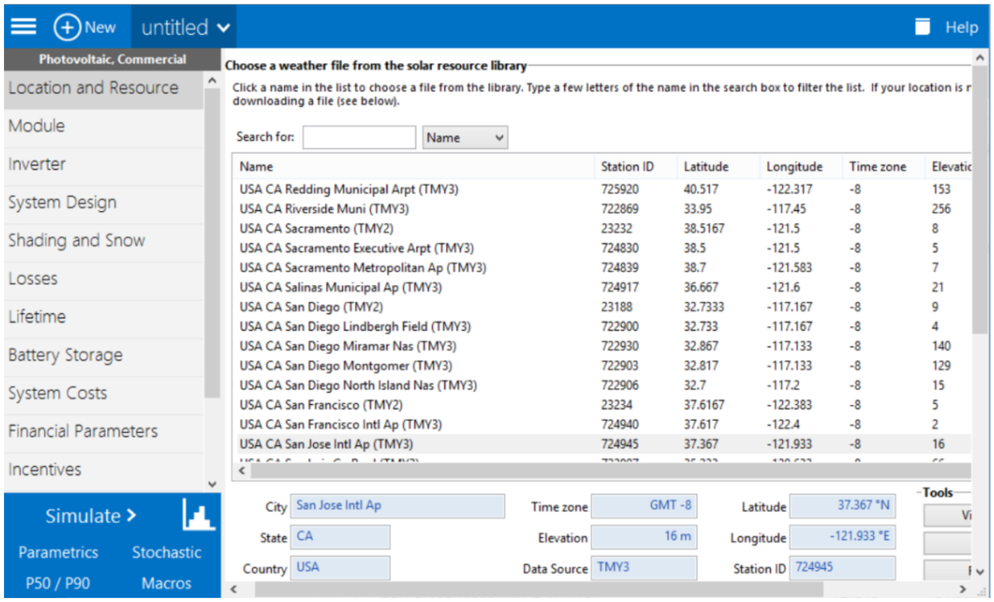

Figure 8: Initial interface of SAM

The parameters shown in the left side of the screen can be configured for any solar configuration to be simulated. In our case, the parameters that change between solar configurations are the System Design and the Module. The remaining system characteristics were configured as the following:

Financial Model: Commercial System

Location: USA CA San Jose International Airport

Inverter: ABB MICRO-0.3-I-OUTD-US-208 208V

The inverter of a solar system converts the DC current that comes from the solar modules into AC current to be used grid-connected or in off-grid systems.

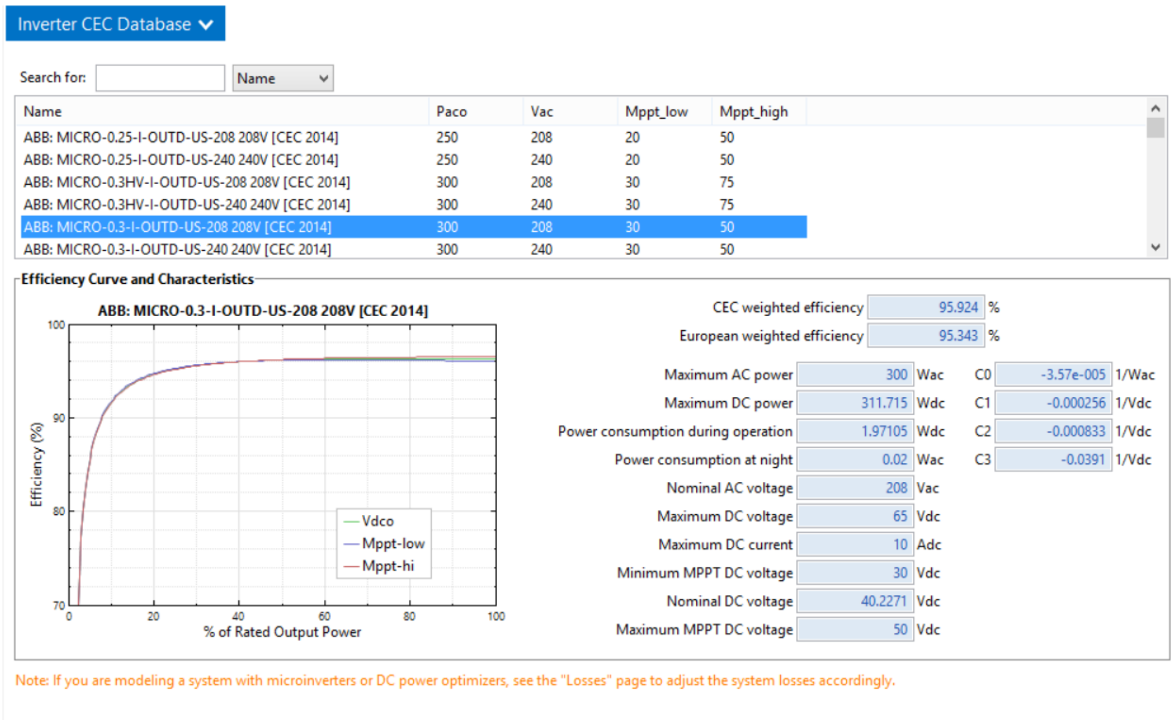

Figure 9: Datasheet of the chosen inverter

This inverter has the efficiency of 95.924%, with minimum MPPT DC voltage of 30V and maximum MPPT DC voltage of 50 V, which is an interval the contains most of the available modules output DC voltage. The remaining data about the chosen inverter is shown below.

A MPPT (maximum power point tracking) is an electronic device that converts DC to DC to optimize the match between solar systems and the battery or utility grid. The charge controller compares the output of the panels and the battery voltage to estimate the best power and voltage conditions to maximize the current into the battery. The inverter in use has the interval of 30V to 50V to the MPPT DC voltage.

To simplify the models of the solar systems, it was not considered shading or snow losses in any of the analysis.

The overall losses assumed of the models were the following:

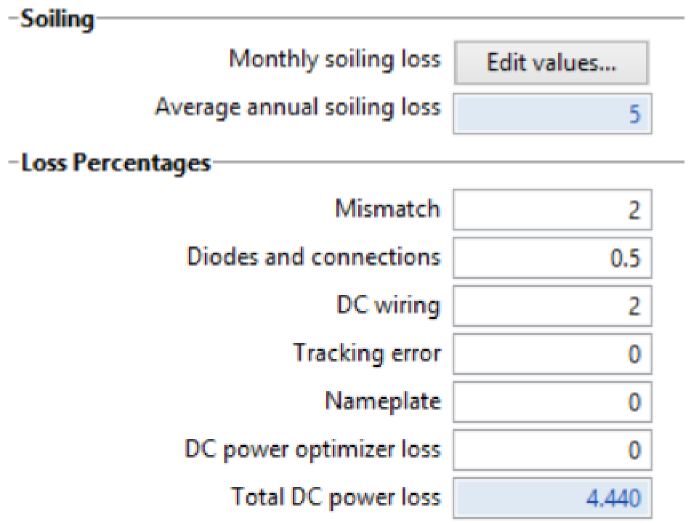

Figure 10: Losses Assumptions

Soiling losses reduce solar radiation incident in subarray. SAM calculates the incident radiation from its weather files and sun and array angle and subtract the soling loss from it.

The losses in the circuit caused by mismatch (difference of performance between modules in array), diodes and connections (voltage drops across blocking diodes and electrical connections), wiring (resistive losses on the wiring on the DC side of the system) can be seen above.

The total power loss was calculated by this formula:

$$\text{Total DC power loss} = 100\%\times\{1-[(1-\text{Mismatch}\div 100\%)\times(1-\text{Diodes and connections}\div 100\%)\times(1-\text{DC wiring}\div 100\%)\times(1-\text{Tracking error}\div 100\%)\times(1-\text{Nameplate}\div 100\%)\times(1-\text{DC power optimizer loss}\div 100\%)]\} \quad (1)$$

The performance of a solar array decreases over the years, and in SAM model there is an estimate rate to the degradation, which was assumed to be of 0.5% per year. No battery storage was enabled for this particular case.

For the system costs, only the direct capital costs were considered. From the modules datasheet, there is a costs of 1.03 $/Wdc for each solar panel, and a good average value for the inverter cost is 1.00 $/Wdc.

The remaining system costs are shown below:

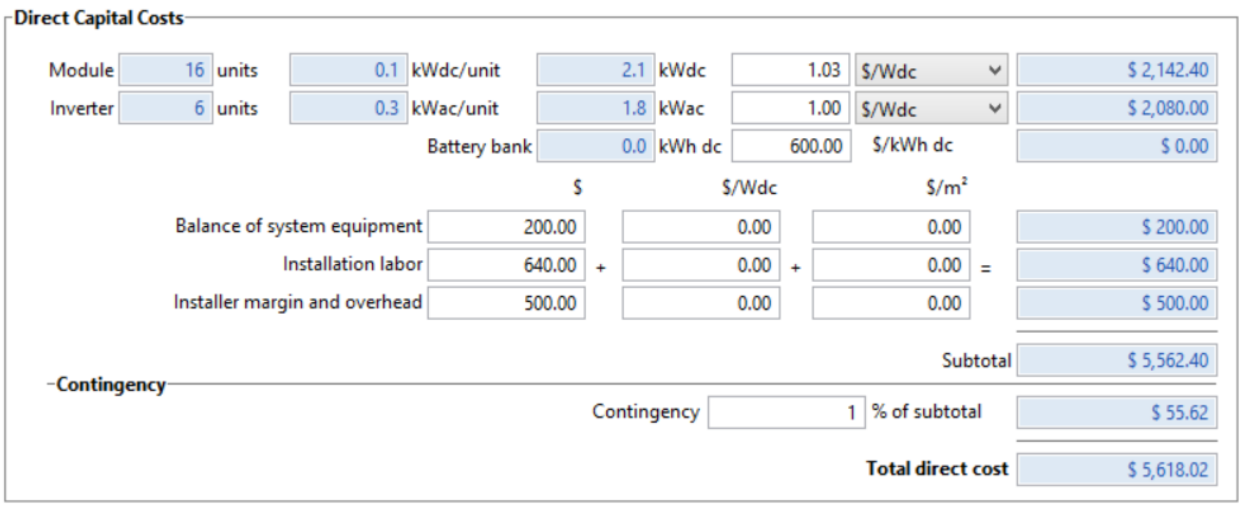

Figure 11: System Costs

Contingency is a percentage of the total direct cost that can be accounted for expected uncertainties in direct cost estimates.

The equipment necessary to install the equipment would be the materials to do the racking and the backing, clamps to attach the modules to the support and bolts to keep the parts together with the structure. The shop were the project was being develop already had some materials that would be used in the racking, which decreased the equipment costs.

The costs with the installer (installation labor and Installer margin and overhead) are not very high, considering that this is a small solar system, only to generate power for the bogie in the full scale model.

The following picture shows the financial parameters assumed for the model:

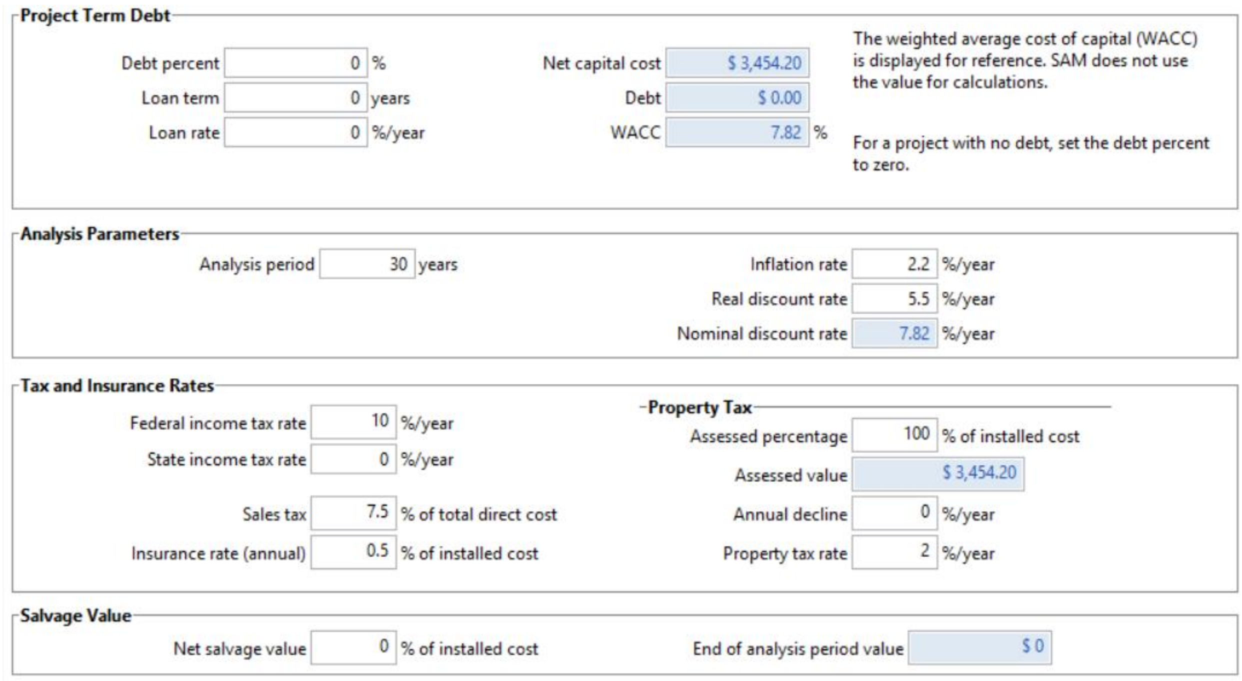

Figure 12: Financial parameters

The values for the inflation rate (annual rate of change of costs), real discount rate (time value of money expressed as an annual rate), federal income tax rate, state income tax rate, sales tax, insurance rate and property tax rate were assumed following the economical characteristics of California in the first semester of 2015. The analysis period of 20 years was chosen to allow an analysis for a time greater than the payback period.

Sam calculates the nominal discount rate by the following equation:

$$\textit{Nominal Discount Rate} = (1 + \textit{Real Discount Rate}) \times (1 + \textit{Inflation Rate}) - 1 \quad (2)$$

To develop a solar system in USA, it is important to look for federal and state incentives that could financially help in the project development. SAM suggests the DSIRE (Database of State Incentives for Renewables & Efficiency) website to look for policies and Incentives: http://www.dsireusa.org/.

In the state of California, this policies and incentives were assumed to be applied for the project:

Property Tax Exclusion for Solar Energy Systems: It is a state implemented property tax incentive that offers 75% of system value exemption for this case of power generation system. Other eligible technologies are Solar Water Heat, Solar Thermal Electric and Solar Thermal Process Heat.

More details about this incentive can be found at the following link:

http://programs.dsireusa.org/system/program/detail/558

Business Energy Investment Tax Credit (ITC): It is a federal implemented corporate tax credit program that claims a credit of 30% of expenditures for solar systems. It also offers incentives for fuel cells, microturbines, small wind turbines and other technologies.

More details about this incentive can be found at the following link:

http://programs.dsireusa.org/system/program/detail/658

The electricity rate determines how the system owner will be financially compensated by the energy generated. For commercial financial models, the electricity generate offsets purchases of electricity to meet the ATN load.

The image shown below shows the assumptions made for the electricity rate:

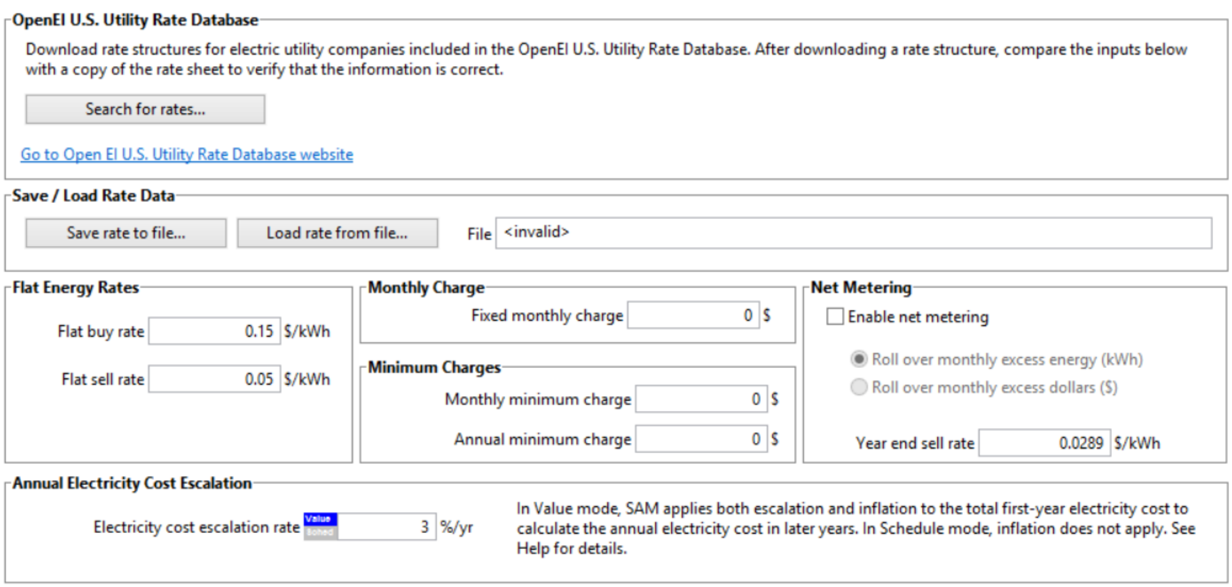

Figure 13: Electricity Rate

For disabled net metering, every month that the produced energy is less than the load, electricity will be bought at the flat buy rate, which for this case is 0.15$/kWh and if the opposite happens, electricity will be sold at the flat sell rate, which for this case is 0.05$/kWh.

For enabled net metering, there is no sell rate, because for month that the systems produces more electricity than the monthly load, there is a credit in kWh or dollar to the next month electricity bill, and credit at the end of the year are established at the year end sell rate.

Like shown above, the analysis did not enable net metering, so there is a sell rate. The electricity cost escalation rate shows how the electricity price increases from year to year.

The load of the system is the power necessary to move the bogie in full scale model. From the annual report of 2015, this value is 34.911 W. The monthly load is 20.95 kWh then, considering that the podcar is always moving.

The analysis of the solar systems had the same configuration for the parameters described previously. The solar arrays that were simulated were the ones shown below:

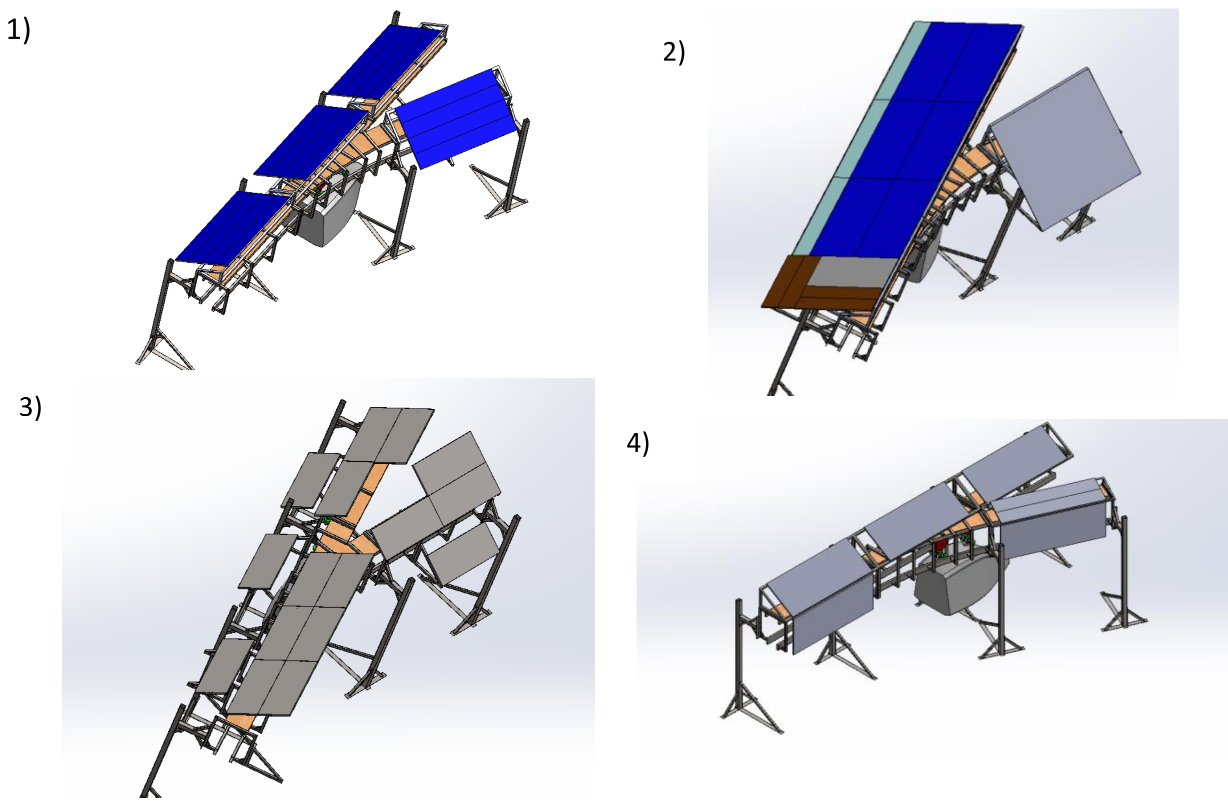

Figure 14: Solar designs

For maximum power output, solar modules in the north hemisphere should face true south, which is different from magnetic south, the south pole of the Earth`s magnetic field. So, it was assumed that the side of the guideway with more panels was facing south. These assumptions were made for all four configurations.

The system design consists of choosing specific characteristics for the arrays, like: how many modules in series per string and how many strings in parallel, number of inverters to be used and for each subarray, define azimuth and tilt angles. It is important to mention that the power outage of the circuit of solar panels is as greater as the current generated by the system, so to get the maximum power to the grid it is necessary to maximize this current, which can be done putting the modules in parallel (the total current is the sum of the currents generated by each module, and the total voltage is the same as of panels). In bigger systems, it is necessary to mount some strings of modules in series (which increases the total voltage), because usually there is a limit for the maximum current output into the grid or in a battery.

3.1 Solar array 1

The first solar configuration consists of sixteen modules of the FLEX-02N type in a tilt angle of 31.22°. One side of the guideway contains 12 panels and the opposite site has the remaining 4. The angle between the tracks in the switching section of the guideway is 23.62°, like shown below:

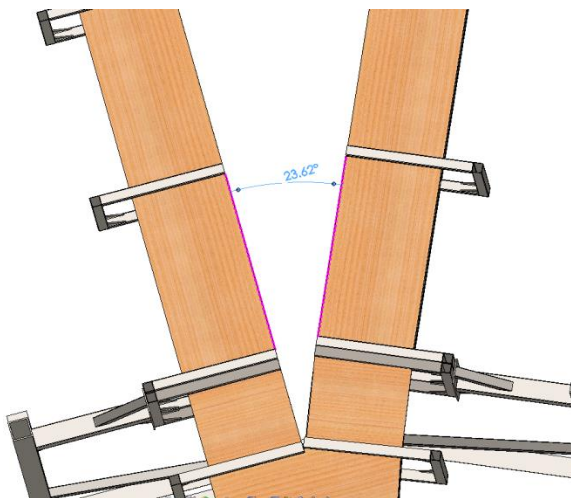

Figure 15: Angle between tracks

The system design consists of 2 subarrays, one of them with 12 modules at azimuth 180°, and the other one with 4 modules at azimuth 23.63°. Information about the module used is shown below:

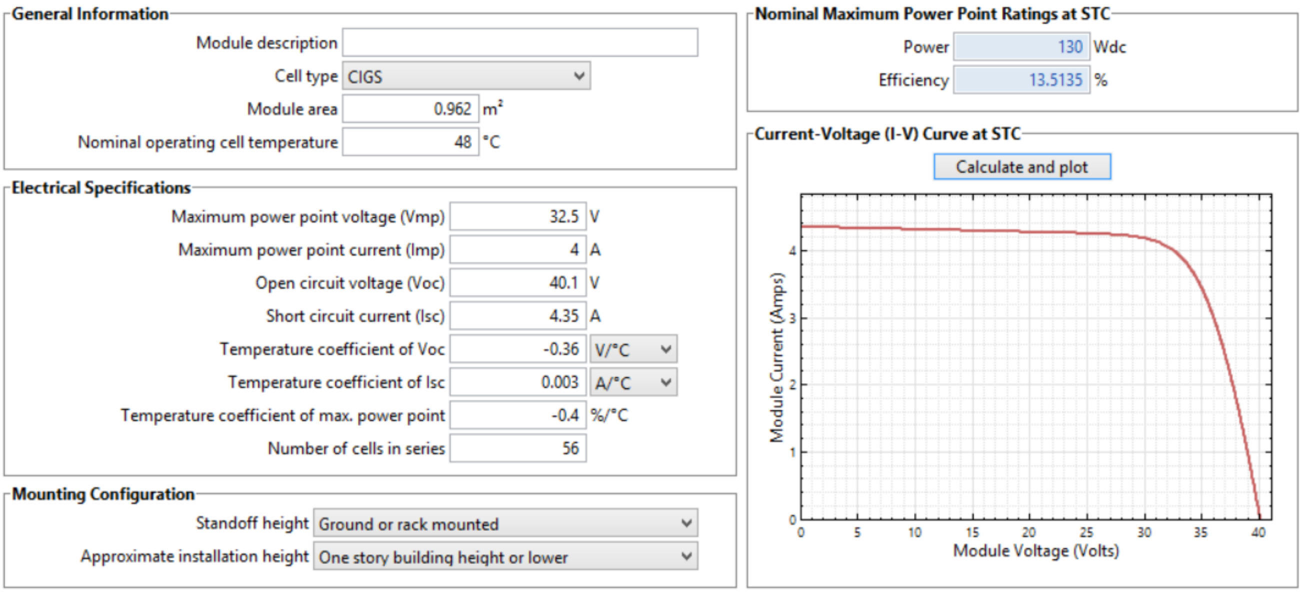

Figure 16: Module characteristics

The module performance data was extracted from the manufacturer datasheet. The module is of the CIGS (Copper, Indium, Galium and Selenium), one of the thin film module categories. These modules usually have efficiency between 7 and 14%, but are cheaper then panels of other types with greater efficiencies, because its manufacturing doesn't use expensive raw materials or high purity silicon wafers, unlike other kinds of modules, like polycristaline silicon, for instance.

The maximum power point voltage, 32.5 V, is a reasonable value, cause it is within the MPPT voltage range of operation for the chosen inverter, 30V to 50V. At the STC (Standard Test Conditions), the power is the product current (4 A) and voltage (32.5 V), which gives the value of 130 Wdc. The efficiency of 13.5135% is a typical value for a CIGS cell type module.

The next datasheet gives information about the system design parameters:

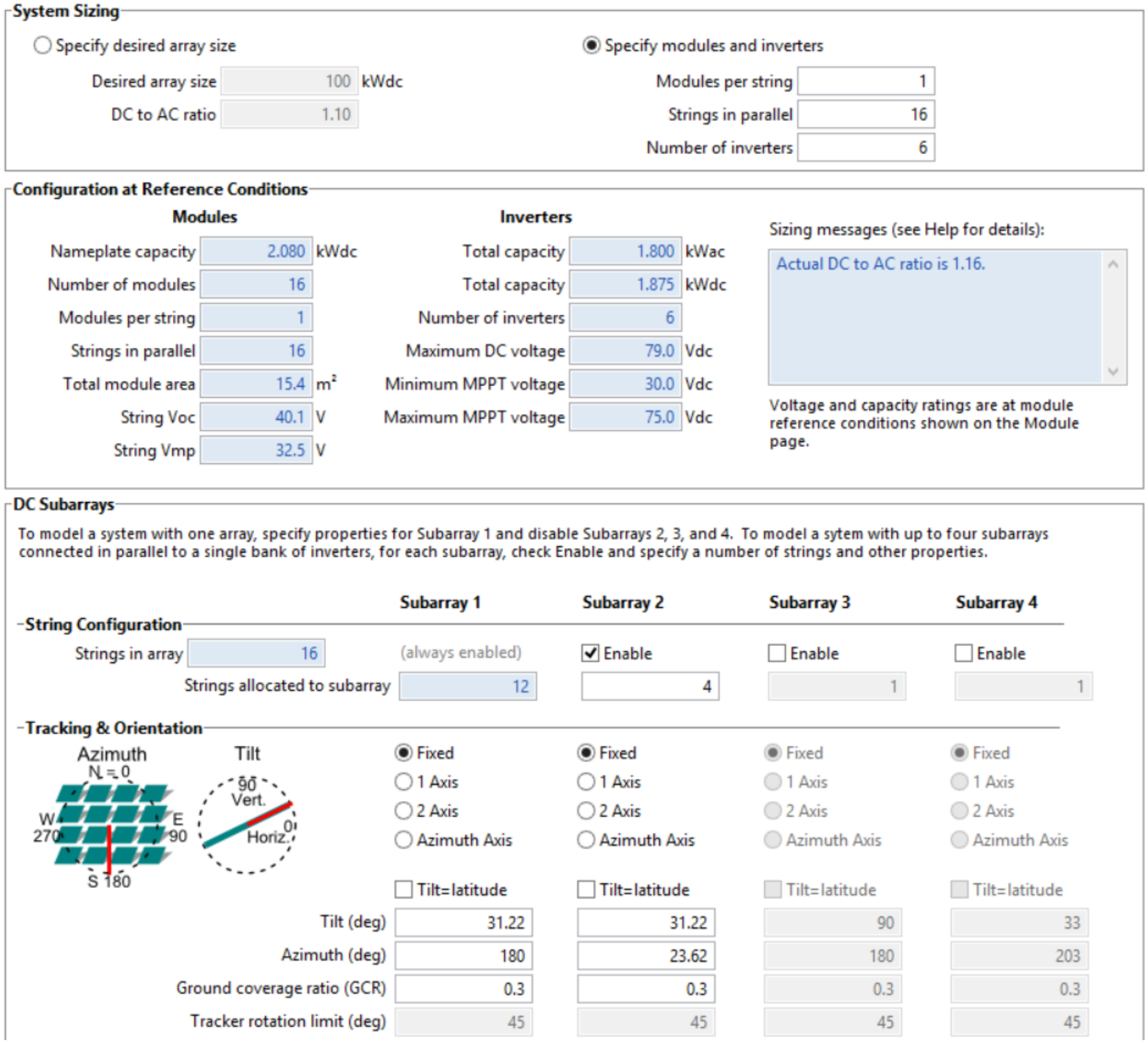

Figure 17: System Design

The system is composed by 2 subarrays: one of them with 12 panels at azimuth 180° with tilt angle of 31.22°, and the other one with 4 panels at azimuth 23.62° with tilt angle of 31.22°. All the panels are fixed to avoid costs in the development of a tracking system. The Ground Coverage ratio (GCR) is the ratio between the photovoltaic area and the ground area. It represents the spacing between rows of solar modules.

It was assumed that all the strings are in parallel so the string voltage would be 32.5 V and the current output would be maximum: 4 A per module, which results in the total of 64 A.

The number of inverters was 6 so it would result in a good DC to AC ratio, because the nameplate capacity (maximum power developed by the modules in the reference conditions) was 2080 kWdc and the maximum AC power for each inverter is 300 kW, so with 6 inverter the maximum AC power is 1800 kWac, which gives an DC to AC ratio of 1.16.

The equations behind the calculated parameters are:

<u>Module</u>

- AC to DC ratio: ration between total DC power generation and AC power output obtained from the inverter.

$$Actual\ DC\ to\ AC\ ratio\ = Total\ Nameplate\ Capacity\ in\ DC\ kW$$

$$\div\ Total\ Inverter\ Nameplate\ Capacity\ in\ AC\ kW \times 100\% \quad (3)$$

- Nameplate capacity: The maximum DC power output of the array at the reference conditions.

Nameplate Capacity (kWdc) = Module Maximum Power (Wdc) × 0.001 (kW/W) × Total Modules (4)

- Total module area: The total area in square meters of modules in the array, not including space between modules.

$$Total\ Area\ (m^2) =\ Module\ Area\ (m^2) \times\ Number\ of\ Modules\ (5)$$

- String Voc: The open circuit DC voltage of each string of modules at 1000 W/m^2 incident radiation and 25°C cell temperature.

$$String\ Voc\ (Vdc) =\ Module\ Open\ Circuit\ Voltage\ (Vdc) \times\ Modules\ per\ String\ (6)$$

- String Vmp**:** The maximum power point DC voltage of each string of modules at the module reference conditions shown on the module section:

String Vmp (Vdc) = Module Max Power Voltage (Vdc) × Modules per String (5)

<u>Inverter</u>

- Total capacity, kWac: The total inverter capacity in AC kilowatts:

Inverter Total Capacity (kWac) = Inverter Maximum AC Power (Wac) × 0.001 (kW/W) × Number of Inverters (6)

The inverter's nominal AC power rating is from the inverter section.

- Total capacity, kWac: The total inverter capacity in DC kilowatts:

Inverter Total Capacity (kWdc) = Inverter Maximum DC Input Power (Wdc) × 0.001 (kW/W) × Number of Inverters (7)

3.3 Solar arrays 2 and 3

SAM does not support systems with different types of modules, so it was not possible to simulate the second solar design. The solar array 3 has the same performance characteristics as the solar array 1, because it has the same kinds of subarrays: one of then with 12 modules FLEX 02N at azimuth 180° with tilt angle 31.22° and other one with 4 modules FLEX 02N at azimuth 23.62° with tilt angle 31.22°. As the calculations are not considering shading losses, the results for the analysis would be the same for both designs.

3.3 Solar array 4

The fourth solar configuration consists of four subarrays of FLEX-02W modules. One of them is consisted of three modules at azimuth 180° with tilt angle of 31.22°, other one consists of 1 module at azimuth 180° with tilt angle 90°, other one consists on one module at azimuth 203° with tilt angle 90° and the last one consists of one module at azimuth 203° with tilt angle 203°. Information about the module used is shown below:

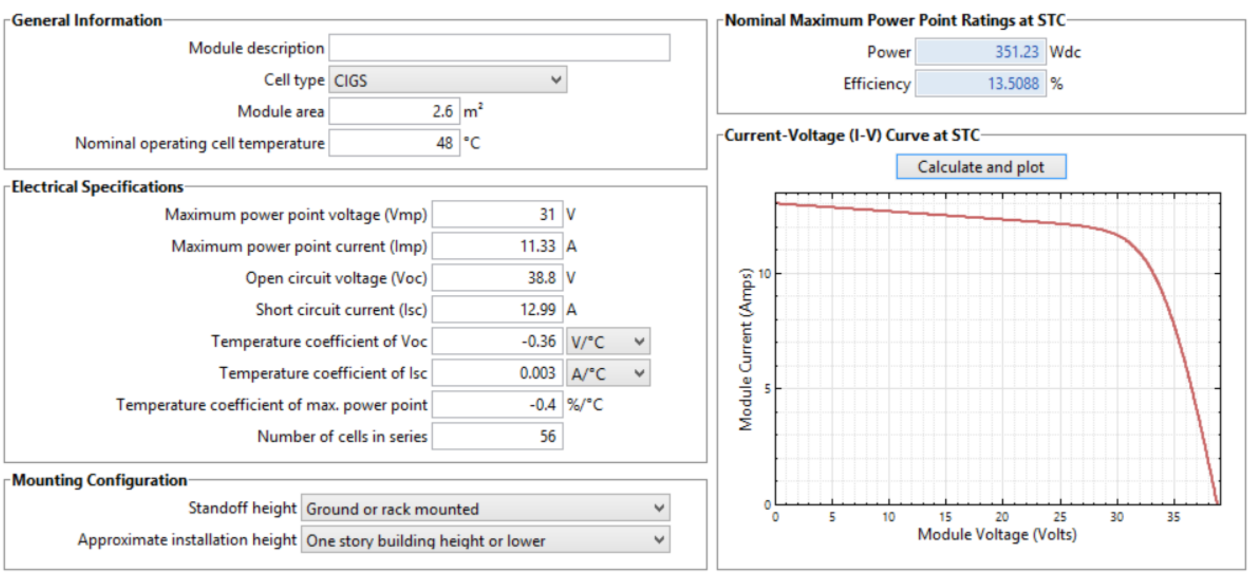

Figure 18: Module characteristics

The maximum power point voltage, 31 V, shows that the module can be used with the chosen inverter, because it is within its MPPT voltage range of operation, 30V to 50V. At the STC (Standard Test Conditions), the power is the product current (11.33 A) and voltage (32.5 V), which gives the value of 351.23 Wdc. The efficiency of 13.5088% is a typical value for a CIGS cell type module.

The next datasheet gives information about the system design parameters:

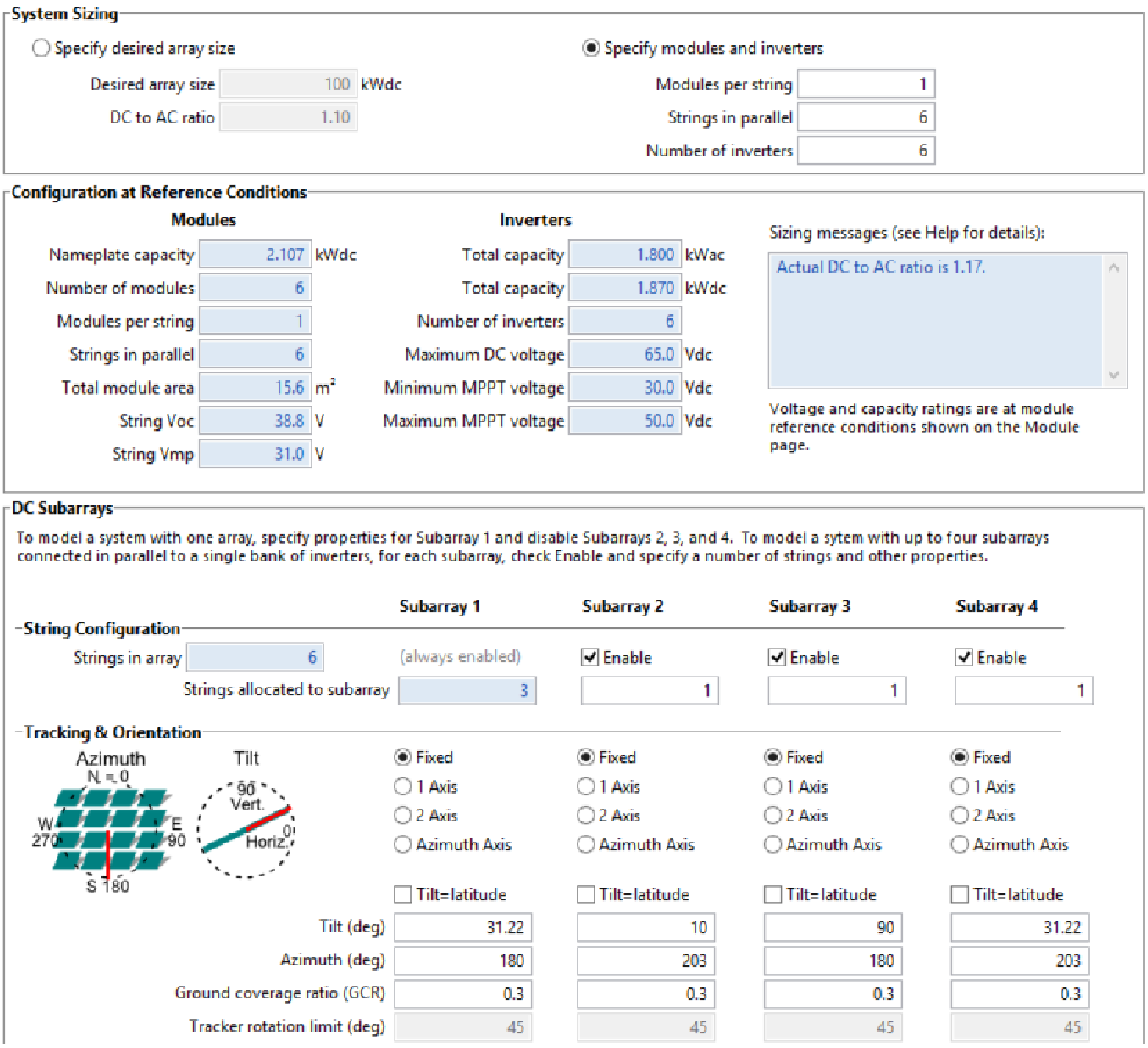

Figure 19: System design parameters

The Tracking & Orientation section shows the four subarrays described previously. The panel in Subarray 2 is almost flat so it won`t shade the modules located behind it, the ones on top of the structure that are tilted 31.22°.

It was assumed that all the strings are in parallel so the string voltage would be 31 V and the current output would be maximum: 11.33 A per module, which results in the total of 67.98 A.

The number of inverters was 6 so it would result in a good DC to AC ratio, because the nameplate capacity (maximum power developed by the modules in the reference conditions) was 2107 kWdc and the maximum AC power for each inverter is 300 kW, so with 6 inverter the maximum AC power is 1800 kWac, which gives an DC to AC ratio of 1.17.

4. Results

The summary of the results obtained for the simulations are shown below:

4.1 Solar array 1

Table 1: Perfomance and financial parameters for Solar array 1

Metric	Value
Annual energy	3,076 kWh
Capacity factor	16.9%
First year kWhAC/kWDC	1,479 kWh/kW
Performance ratio	0.79
Battery efficiency	0.00%
Levelized COE (nominal)	6.11 ¢/kWh
Levelized COE (real)	4.85 ¢/kWh
Electricity cost without system	$69
Electricity cost with system	$-85
Net savings with system	$154
Net present value	$535
Payback period	5.4 years
Net capital cost	$5,618
Equity	$5,618
Debt	$0

The annual energy shows that this is a small solar system, which is coherent with the goal of supplying the full scale model of the Spartan Superway. The capacity factor is the ratio between the annual energy produced and the amount of energy that would be produced if the system worked in its full nameplate capacity. For photovoltaic systems, it is usually below 25%. The result obtained for this parameter is not so good, but it satisfies the necessities for this project. It shows the system design could be made in other ways to improve the solar irradiation catching efficiency.

The performance ratio represents the relationship between the actual and theoretical energy output of the PV plant, showing the proportion that is available for export to the grid. It is calculated be deducing the losses that were showed in the losses section. High-performance PV plants can reach a performance ratio up to 80%.

$$PR = \frac{Actual\ plant\ output\ in\ kWh}{Nominal\ plant\ output\ in\ kWh} \qquad (8)$$

Levelized Cost of Energy (LCOE) is the overall cost of installing and operating a project in dollars per kilowatt hour of electricity. The calculation of this parameter includes all the costs over its lifetime: initial investment, operations and maintenance, and others. Another definition for it is the price per unit of energy that causes the investment to just break even. There are several ways to estimate it. SAM evaluates the data showing the nominal LCOE and the real LCOE. The first one is a constant dollar, inflation-adjusted value, and the second one is a current dollar value. The value of Real LCOE is less than the nominal LCOE whenever the inflation rate is greater the zero. Because the nominal discount rate used to compute the nominal LCOE includes inflation, it is factored out of nominal LCOE evaluation. The inflation rate in the analysis conducted is 2.2% per year, which explains why the nominal LCOE is greater than real LCOE. The values obtained for both types of LCOE are low, because of the low cost for the small solar system and the two incentives that were assumed in this analysis. The net savings with system were not too high, but the payback period of 5.4 years is less than the average value for solar systems (usually it is around 15 years), because of the incentives assumed.

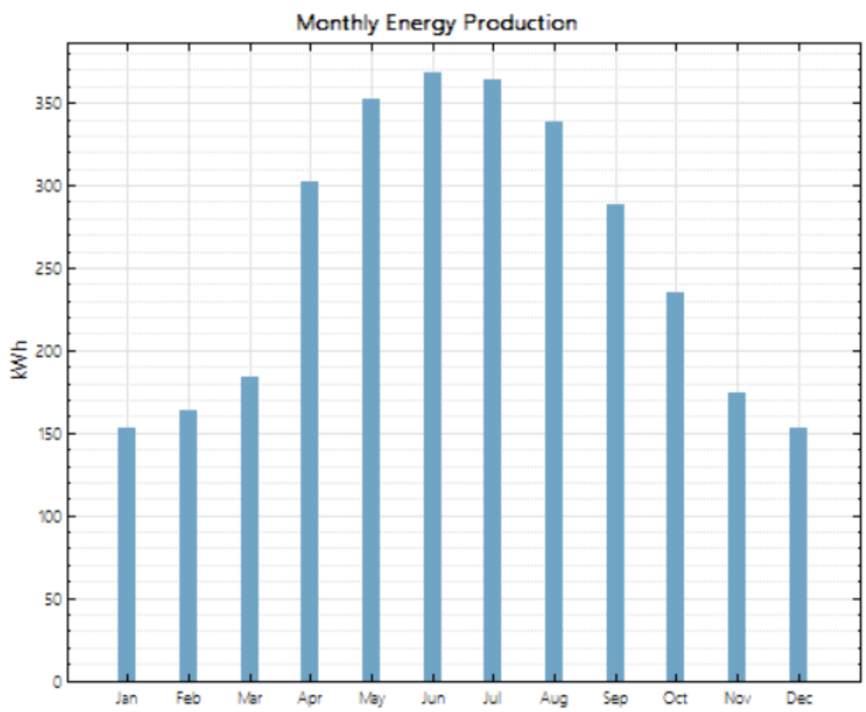

Figure 20: Monthly Energy Production for Solar Array 1

The profile above shows how energy production varies during the year. In the summer, the amount of energy produced increases by 100% because of the higher solar radiation. The following figure shows the degradation of the system during the years, according to the chosen degradation rate of 0.5%.

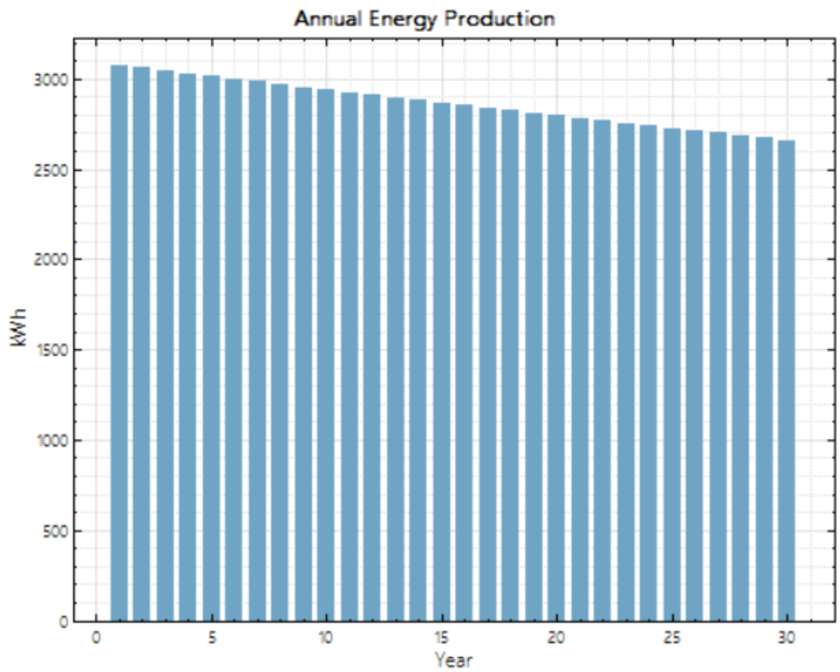

Figure 21: Annual Energy Production for Solar Array 1

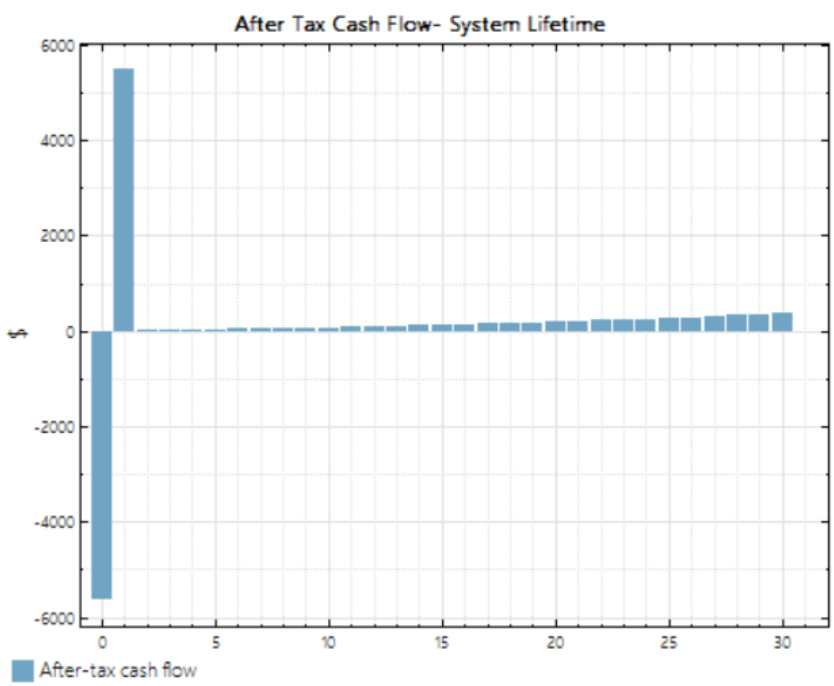

Figure 22: After Tax Cash Flow for Solar Array 1

The incentives are almost equal to the system costs in month zero, and the positive cash flow along the years contributes to a low payback period. The net present value is the difference between the cash inflow and the cash outflow by the end of the analysis period, and the positive value of $535 shows that the system is generating profit by the end of year.

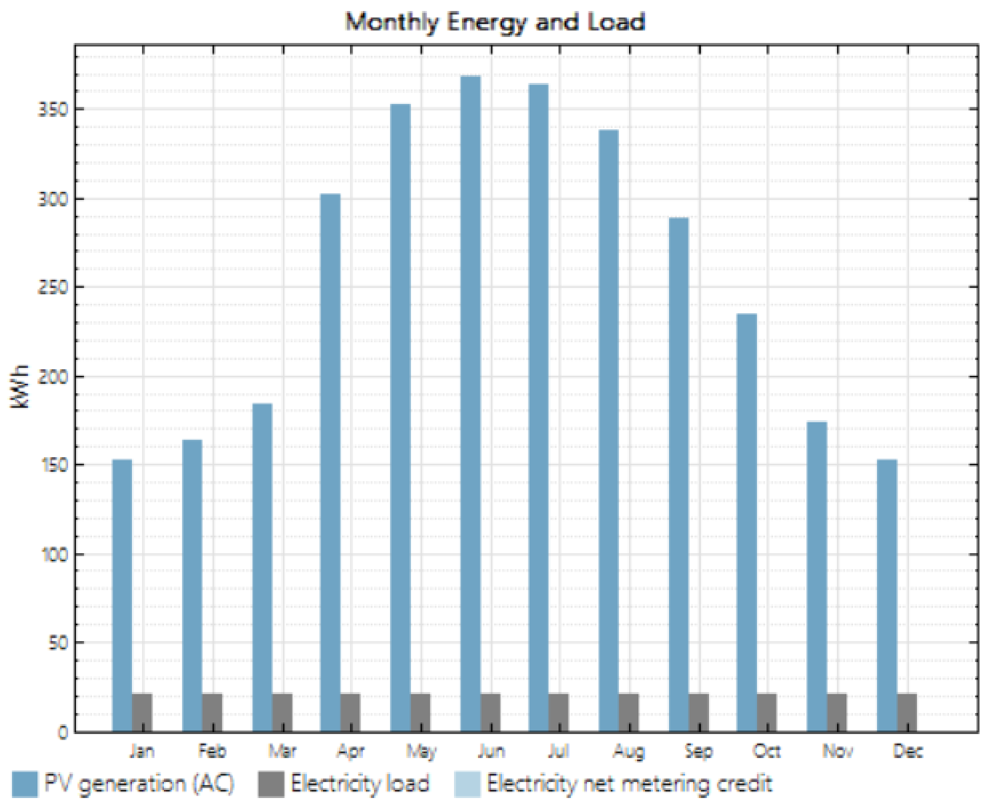

Figure 23: Monthly Energy and Load for Solar Array 1

This graph shows that the system was over design for the required load, which means that the majority of the monthly energy was sold for the Flat Sell rate.

4.2 Solar array 4

Table 1: Performance and financial parameters for Solar array 1

Metric	Value
Annual energy	3,215 kWh
Capacity factor	17.4%
First year kWhAC/kWDC	1,526 kWh/kW
Performance ratio	0.80
Battery efficiency	0.00%
Levelized COE (nominal)	5.90 ¢/kWh

Levelized COE (real)	4.68 ¢/kWh
Electricity cost without system	$69
Electricity cost with system	$-92
Net savings with system	$161
Net present value	$631
Payback period	4.8 years
Net capital cost	$5,674
Equity	$5,674
Debt	$0

The performance and financial parameters are both better in this design, comparing to the solar array 1. The basic parameters of solar systems are the annual energy, the capacity factor, LCOE, net present value and payback period. All these parameters are better for this design. The profiles shown below for Solar Array 4 are very similar to the ones showed previously. It is possible to see a small increase in the system performance, which results in better cash flow parameters.

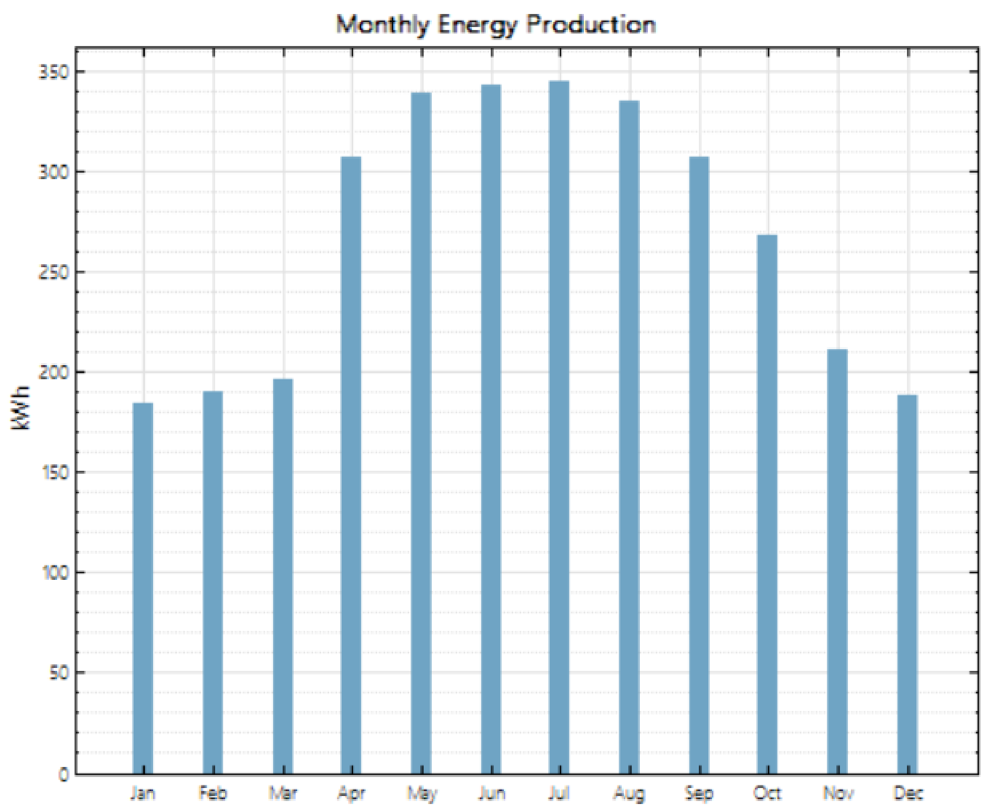

Figure 24: Monthly Energy Production for Solar Array 4

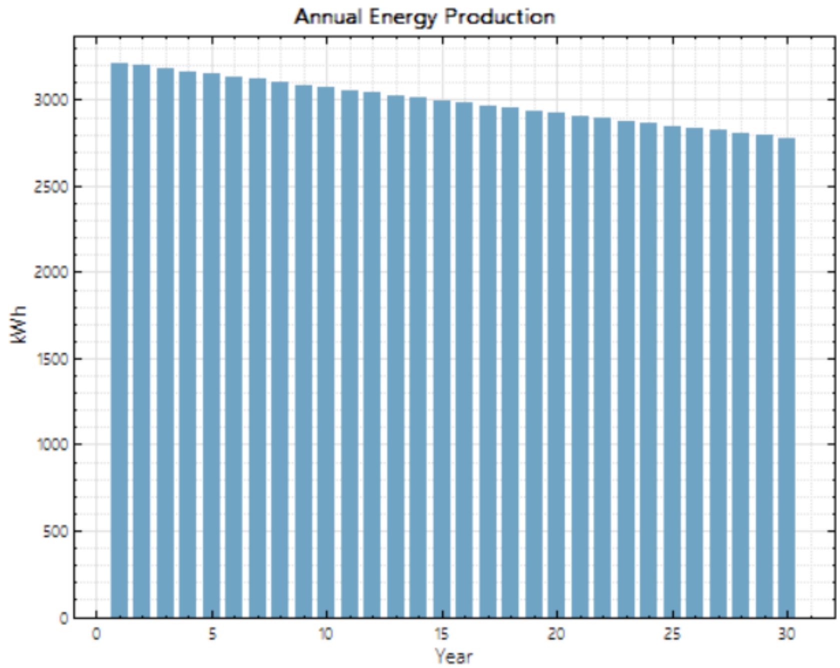

Figure 25: Annual Energy Production for Solar Array 4

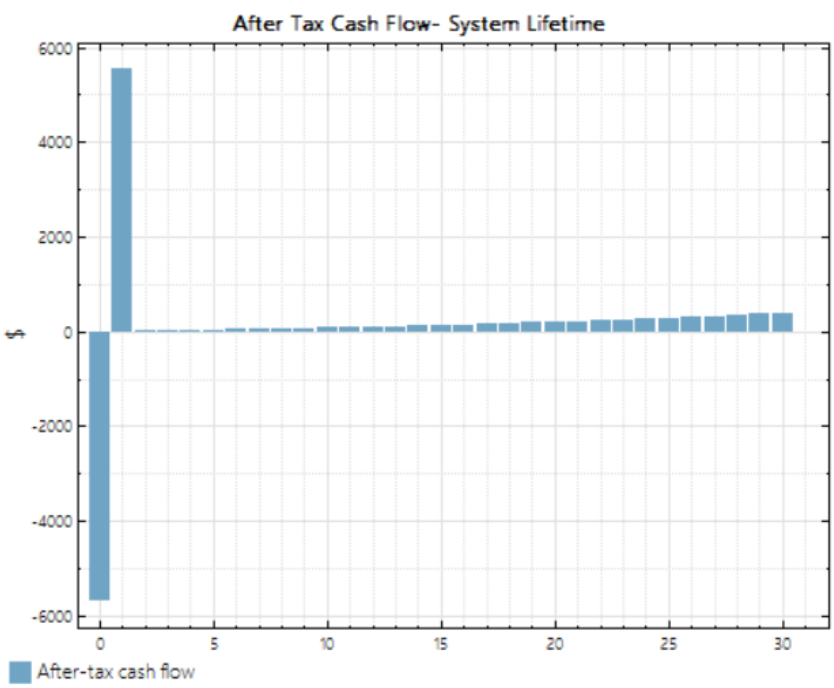

Figure 26: After Tax Cash Flow for Solar Array 4

5. Conclusion

The comparison between the two analysis shows that the solar array 4 is the best choice for the solar system to be installed on the full scale model, because of the better financial and performance parameters.

The analysis that was made possible by SAM shows how useful this software can be to design energy systems, and there are lots of engineering applications for projects made by this software. Making this project added knowledge about how PV panels are designed, what are the important parameters for it, and which variables have to be considered when it is necessary to decide to install a PV energy system or not.

6. Elements Building

It was only possible to start the building of the frame for the first panel by the end of the summer internship period. The materials available in the shop were some metal bars with an L-shaped cross section, which were cut in the properly size. Holes were made in some locations by machining, so it would be possible to attach the bars using bolts. The cutting and machining machines were available in the shop as well.

The drawing of the final piece after the process of machining is shown below:

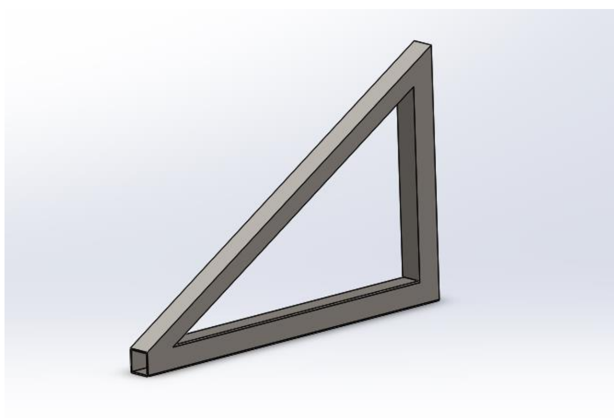

Figure 27: Support with an angle of 31.22°

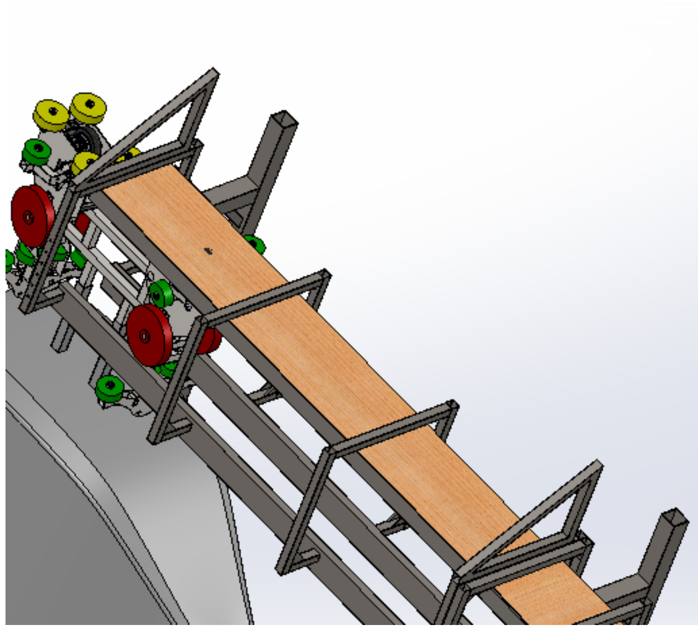

Figure 28: Position of the supports in structure

7. References

[1] Yang, S., "OGZEB PV system analysis with System Advisory Model (SAM)", *Template Collection,* FSU Energy and Sustainability Center, 2015.

[2] Ordones,J.,Yang,S, Vargas, J.V.C, Solano, T, Bublitz M., Collins E. "Thermal Simulation of an Off-Grid Zero Emission Building",*Proceedings of the ASME 2014 8th International Conference on Energy Sustainability"*, FSU Energy and Sustainability Center, 2015.

[3] *Technical Information*, SMA Solar Technology AG