Final Report

Project Title: Innovative Ballasted Flat Roof Solar PV Racking System

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Executive Summary

The objective of this project was to reduce the cost of racking for PV solar on flat commercial rooftops. Cost reductions would come from both labor savings and material savings related to the installation process. The rack would need to accommodate the majority of modules available on the market. Cascade Engineering has a long history of converting traditional metal type applications over to plastic. Injection molding of plastics have numerous advantages including selection of resin for the application, placing the material exactly where it is needed, designing in features that will speed up the installation process, and weight reduction of the array. A plastic rack would need to meet the requirements of UL2703, Mounting systems, mounting devices, clamping/retention devices, and ground lugs for use with flat-plate photovoltaic modules and panels.

Comparing original FOA data to the end of project racking design, racking material costs were reduced 50% and labor costs reduced 64%. The racking product accommodates all 60 and 72 cell panels on the market, meets UL2703 requirements, contributes only 1.3 pounds per square foot of weight to the array, requires little ballast to secure the array, automatically grounds the module when the module is secured, stacks/nests well for shipping/fewer lifts to the roof, provides integrated wire routing, allows water to drain on the roof, and accommodates various seismic roof connections. Project goals were achieved as noted in the original FOA application.

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Background

This project was initiated in response to Funding Opportunity Announcement (FOA) Number: DE-FOA-0000493, "Extreme Balance of System Hardware Cost Reductions (BOS-X)" that was issued on April 8th, 2011. There were four topics within the FOA. Specifically this project addressed topic 2, "Roof and Ground Mount Innovations". The goal of topic 2 was to develop extremely low installed cost (materials and labor) for ground and roof mount applications. Data, provided within the FOA listed rooftop labor at $0.49/watt and the mounting (racking) hardware at $0.30/watt.

Suggested research within topic 2 included: reductions in weight, reductions in equipment/tool needs to complete an installation, utilization of existing supply chains, innovations that support the use of high-voltage systems, wiring innovations that reduce install time (e.g., plug-and-play), racking systems that enhance energy production, racking systems that require less robust engineering, materials innovations, uniform packaged system designs that reduce hard PV BOS costs, and hardware innovations that have the potential to reduce soft costs. This project was written with an attempt to address all the suggested research items.

Many of the solar racking systems available on the market in 2011 were metal. There were a couple of polymer type systems available. The solar racking subject, UL2703, was relatively new to the industry, and very few metal racking systems were listed to this standard. No polymer racking products were listed to UL2703. The main goal of this project was to develop a polymer based racking system that would be listed to UL2703 and address all of the suggested research ideas in topic 2 of the FOA.

Introduction

In many applications, plastics or polymers materials have been chosen to replace traditional metal components. The advantage that plastics have is that they can be shaped easily to accommodate various fit and function instances where more traditional attachments of nuts and bolts are used to hold various metal components together. The key to changing a traditional metal product over to plastics is understanding the needs of the particular product. The needs include, but are not limited to: environmental conditions, attachment requirements, load carrying capabilities, intended life of the product, packaging, shipping, handling, use of the product in the field, cost, quality, standards, durability, recyclability, and design. There were 6 main phases within the Statement of Project Objectives that included: Program Authorization, Program Definition, Engineering/Design, Tool/Process Development, Product/Process Validation, and Production. The bulk of the work for this project took place in Engineering/Design, Tool/Process Development, and Product/Process Validation where a solution was sought, trialed and confirmed.

Project Results and Discussion

The first two phases of the SOPO included Program Authorization and Program Definition. The main purpose of these phases is to introduce the project into Cascade Engineering and set up various accounting, budget and resources. Award of the contract is recognized through receipt of funding notification from the DOE. Budgets are reviewed, internal and external resource needs are identified, and the statement of work is confirmed. Information is shared about the project with key company personnel including: basic timelines, key milestones, customer requirements, risk analysis, and key contacts. These phases were completed without delay in one month.

Engineering/Design

The third phase of Engineering/Design took nearly a year to complete and included the subtasks of competitive benchmarking, application research, brainstorming & conceptualization, CAD, wind tunnel consulting, design revision, wind tunnel testing, prototyping, and design modification.

Competitive Benchmarking: The design team put together a list of competing racking solutions that were available on the market. This was accomplished through tradeshows, online research, and interviews with installers. Data for 33 different racking systems was compiled into a master spreadsheet where a database was built to compare various attributes including cost, market share, panel orientation, tilt angle, material type, warranty, advertised assembly rate, UL2703 listing, and other market data. Each system was evaluated by two different persons regarding: perceived value, assembly, appearance, interface to the roof, wire management, tilt angle options, acceptance of different module sizes, row spacing adjustability, integrated grounding, and overall assessment.

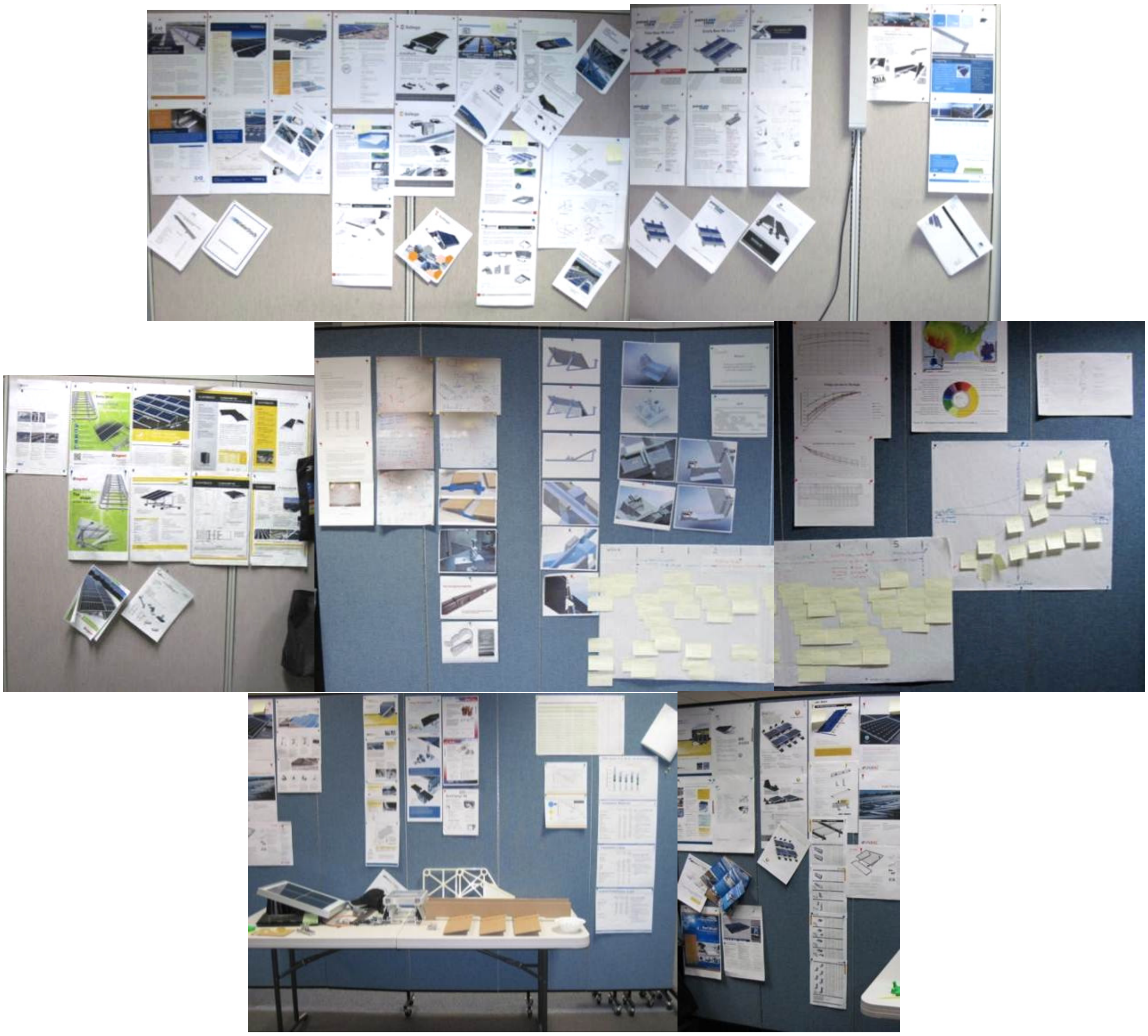


Figure 1 – Competitive Benchmarking

Based on the results of benchmarking, the top 5 systems were chosen for evaluation using a “House of Quality”. The house of quality evaluates customer requirements along with functional requirements. It looks at interactions between the two, weights customer requirements, and compares products against each other. The house of quality is shown below in figure 2.

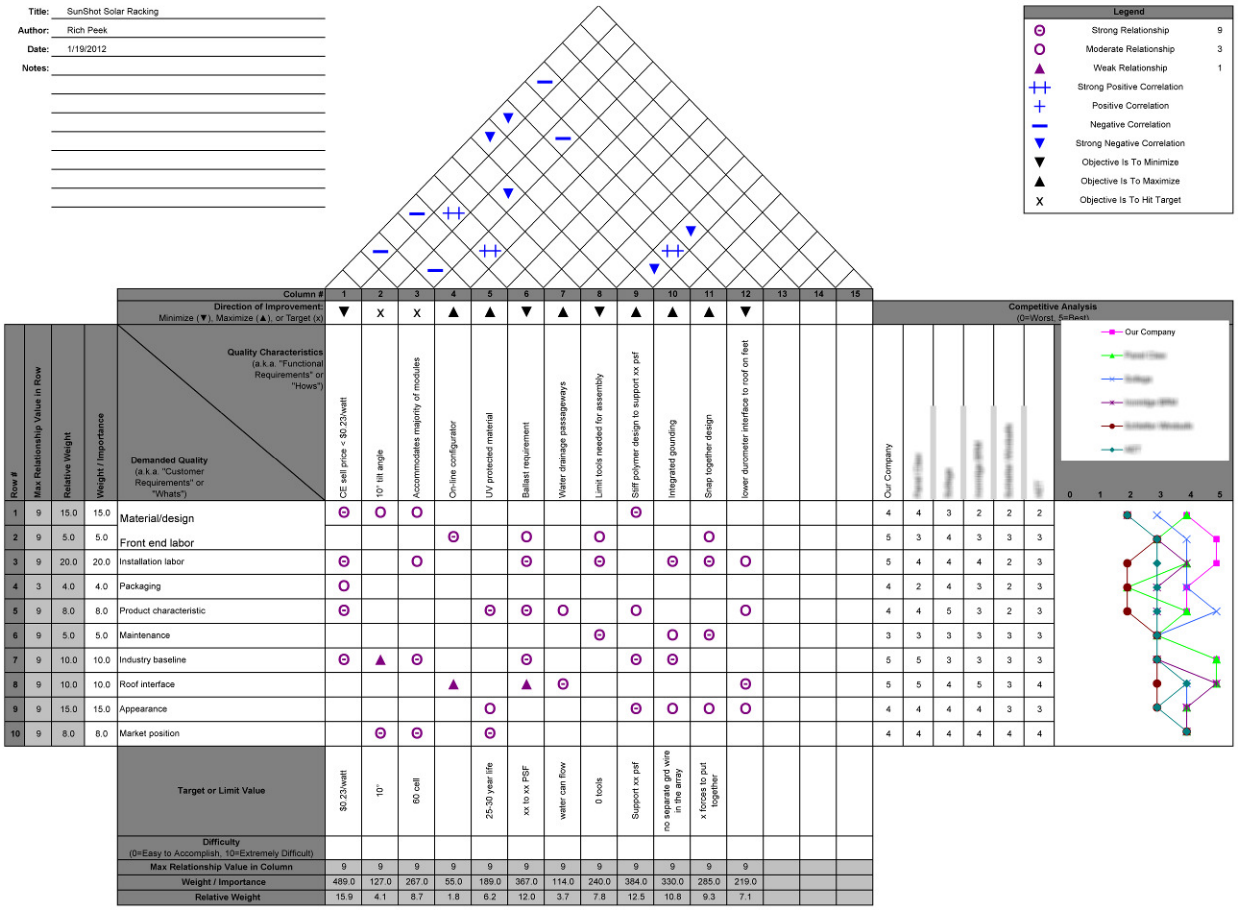


Figure 2

House of Quality

Based on the results of the house of quality, product attributes were established. Product attributes guide the product design to insure features are not lost through the design/engineering phase. Product attributes established are shown in figure 3. The goal was to design a solar rack that includes nearly all of the attributes listed.

Cost	Material/design	adequate margin for integrator
		low cost
		low cost to ship
	Front end labor	ease of configuration
		simple ordering
		technical support for installation
	Install labor	adequate room for walking between rows for install
		common tool for assembly
		easy to convey/carry
		easy to installation
		fast installation
		simple/quick grounding
		layout on roof is easy
		location for combiner box/micro inverter
		location for conduit
		manageable to handle
		no loose hardware
		no tools needed
		palletized racking
		places to manage wires
	Packaging	arrives at location undamaged
		minimal packaging to reduce waste/site cleanup
Features	Characteristic	30 year product life
		limited snow capture
		low part count
		modules in landscape
		no sharp edges
		recyclable
		variable inter row spacing
	Maintenance	adequate room for walking between rows for maintenance
		easy to remove and replace modules
		easy to service
	Industry baseline	grounding per UL2703
		low ballast requirement
		meets ASCE 7-05 Wind Loading for 90 MPH Category B & C - 60' building height
		mounting per UL2703
	Roof Interface	accommodates flat roof slope
		allows water to flow to drains on roof
		does not violate roof warranty
		optional roof anchor
		works with all roof types
Perceived Value	Appearance	easy to understand how it works
		high quality appearance
		looks attractive
		robust appearance
	Market Position	10 year warranty
		accommodates module of choice
		optimizes energy production
		optimizes roof area

Figure 3

Product Attributes

Research the Application: This was done concurrently with the previous section. Various aspects of the installation were researched including: understanding the commercial roofing materials the solar array would be installed on, available roof attachments, understanding the process of installing solar on a roof, and interfacing with available solar PV panels that were offered from manufacturers.

Roofing Materials: Work was focused on understanding materials that are used on a flat commercial roof, manufacturers of the materials, and concerns of solar racking from a manufacturer perspective.

From a building maintenance perspective, solar is generally installed on a brand new or recently refurbished roof. Replacement of a roof is more costly if solar panels would need to be removed and replaced. Research found the majority of flat commercial roofs were covered with PVC, TPU, EPDM, or modified bitumen. Single ply roofing membrane (PVC, TPO, and EPDM) dominated the market. Each of these products is available in different thicknesses. Thickness directly correlates to the roof warranty period. Thicker ply roofing results in longer roof warrantees. Roofing manufacturers only honor roof warrantees when the roofs are installed and maintained properly. Maintenance includes placing items on top of the roof such as air handling units, solar PV, and other equipment. Development of a solar racking system would need to be compatible with PVC, TPO, and EPDM single ply roofing.

Roofing Attachment: The goal of this project was to develop a ballasted racking system. A ballasted system would not need to be attached to the roof for wind loading purposes. However, some areas of California have requirements of attachment to meet seismic needs. Therefore, some investigation was done to determine existing products that could be used to attach to a roof. Several products were identified that could be used to attach a system to the roof. All of these would work with every roof type. A few of the potential products are listed in table 1.

Manufacturer	**Product**	**Roof Type**
Anchor	U-Anchor	PVC, TPO, EPDM, Asphalt
OMG	Power Grip	TPO, PVC
EcoFasten	Eco44R	PVC, TPO, EPDM, Asphalt
QuickMount	Qbase	PVC, TPO, EPDM, Asphalt

Table 1

Roof Anchor Products

Installation Site Evaluations: Solar installation sites were visited to understand the assembly process and hear the likes and dislikes of existing systems. Three different rooftop installation and two ground mount sites were visited. Interviews were conducted with laborers, foremen, electricians, and owners. These interviews helped to understand product delivery, material conveyance, packaging, roof layout, assembly steps, wiring, ballast, code requirements, product positioning, interface with roofing, and part staging. The design team compared information between sites to determine where opportunities could exist to reduce installation labor. Reductions in labor could be realized in the following steps:

- Removal of product from delivery vehicle - make it easier/faster to remove product from the delivery truck
- Placement of product on roof – fewer lifts to the roof results in time savings.
- Unpacking of product – easy to remove product from packaging
- Placement of product – Once product is removed from packaging, limit the number of times it needs to be handled. Get the product in its final position as soon as possible
- Intuitive assembly – Keep the product simple and easy to understand how it works and assembles.
- Limit the number of pieces/parts – If there are fewer pieces, this means there are fewer parts to install. Less installation means less labor.
- Keep the need for tape measures to a minimum for the array layout.
- Integrate the ground wire within the rack to reduce the need for a separate ground wire installation.
- Keep packaging to a minimum to reduce cleanup time.
- Reduce the amount of ballast needed to hold down the system.
- Incorporate a “slip sheet” within the product, or make the product so that it does not need a slip sheet.
- Many installers use “zip ties” to hold wiring in place. Incorporate wiring guides within the product so separate “zip ties” are not needed. (material and labor savings)
- A UL2703 approved system can make the inspection process go faster.
- Minimize the number of tools needed for assembly
- Make the parts lightweight and easy to carry.
- Minimize the number of fasteners required
- Allow maneuvering between rows during installation so installers can access wire runs.

Solar PV Panel: Ideally the solar rack developed would work with all the solar panels available on the market. A study was done to understand the sizes of panels that were being installed in commercial applications. Since California led the nation in solar installations, and provided data that was updated weekly, this information was used to determine which panels were being installed. The data was filtered to remove large utility ground mount and small residential installations. The majority of the panels sold were 60 cell that used the standard 156 mm x 156 mm solar cell. There were some 54 cell panels, and 72 cell panels were becoming more popular. This data was confirmed through a sampling of products being offered at the 2012 Solar Power International Industry show in Dallas Texas. Panel manufacturers were showing mostly 60 cell panels with some 72 cell offerings.

While all panel manufacturers used the standard 156mm x 156 mm cell, overall panel dimensions varied in width, length, and thickness. The solar rack would need to accommodate the slightly varying dimensions. A study was completed to evaluate the panel dimensional variation.

For 60 cell panels, the following ranges of dimensions were found:

- Height: 31 to 50 mm (19 mm range)
- Width: 982 to 1001 mm (19 mm range)
- Length: 1638 to 1675 mm (37 mm range)

72 cell panels had similar ranges in dimensions. The length was longer due to the two additional rows of solar cells. Different panel manufacturer lengths varied from 1952 to 1990 mm, a 38 mm range.

Row Spacing: Shading can have a dramatic effect on energy production. To understand the effect of inter row spacing on shading, a virtual model was built and run using PVsyst, a software program that predicts energy generation. The graph in figure 4 was developed by running scenarios of location and inter-row spacing for a tilt angle of 10 degrees. This graph helped to understand the spacing needed between rows to prevent shading on the winter solstice.

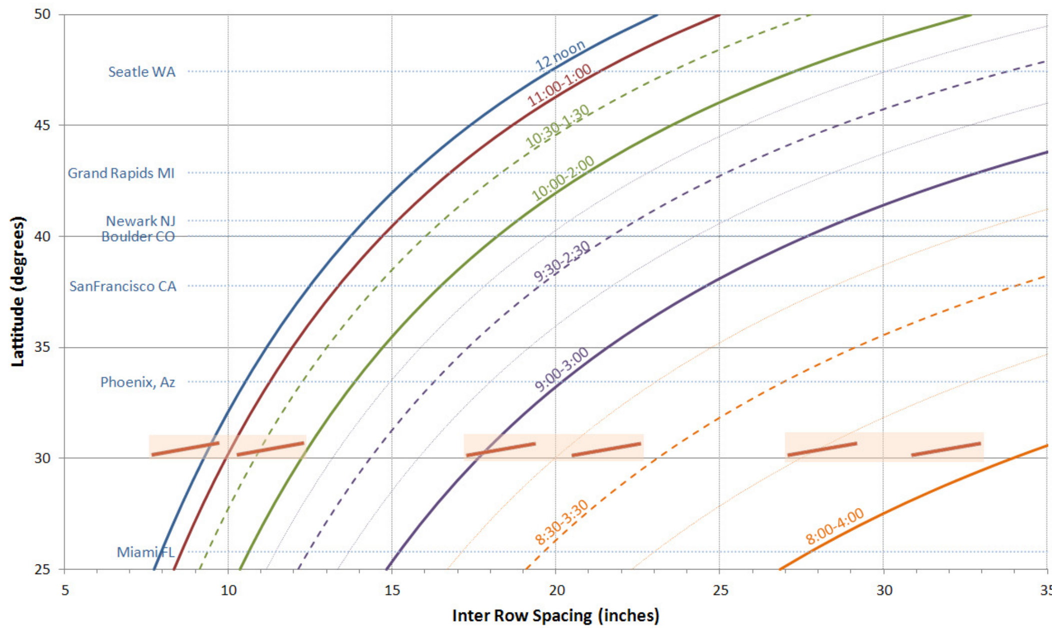


Figure 4 – Inter Row Spacing on the Winter Solstice

The previous graph only considered the winter solstice. The next graph in figure 5 took into consideration the energy produced throughout the year. It compares inter row spacing with energy production at two different tilt angles. Two tilt angles of 7 and 15 degrees highlight the tradeoff between inter row spacing and total energy production. A 7 degree tilt can be placed much closer together than a 15 degree tilt. If spaced far enough apart, a 15 degree tilt will produce more energy, but the density of solar panels on the roof will be lower with the 15 degree tilt.

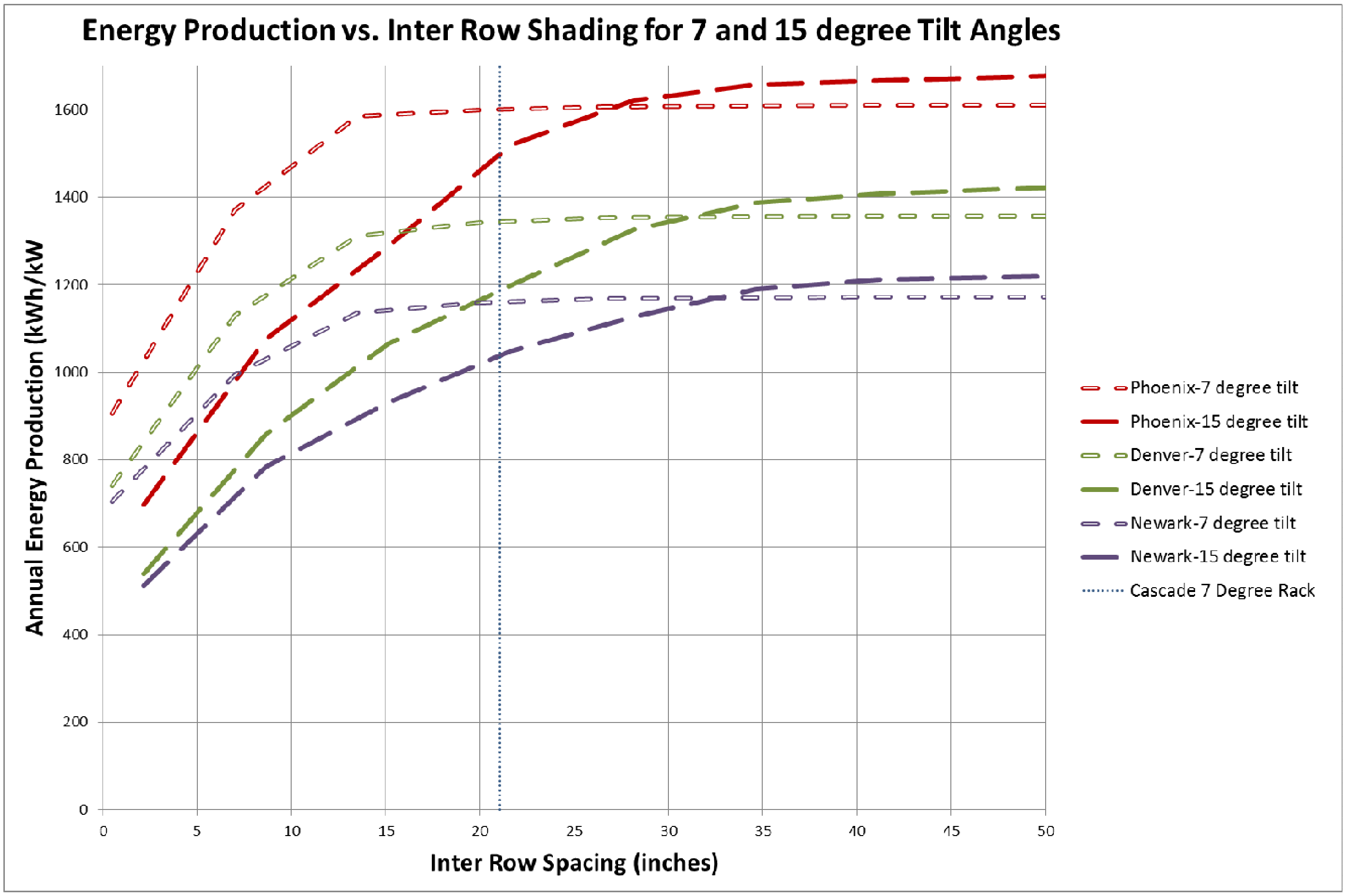


Figure 5 – Annual Energy Production

Brainstorming and Conceptualization: Reduction of solar racking costs can be accomplished through roof labor savings and/or product material/cost savings. Any product material enhancement would need to be justified by labor savings. Successful completion of this project to cost targets would take into consideration all aspects of the installation process and materials.

The brainstorming and conceptualization phase took into consideration data gathered during the competitive benchmarking and research of the application phases. The design team had a better understanding of the problem, needs of the customer, code requirements, and expectations of the assembled array on the roof. First, racking design was viewed on a "macro" view. Support of the solar panel, room for ballast, connection of panels east-west/north-south were considered. An example of the ideas that were sketched is shown in figure 6.

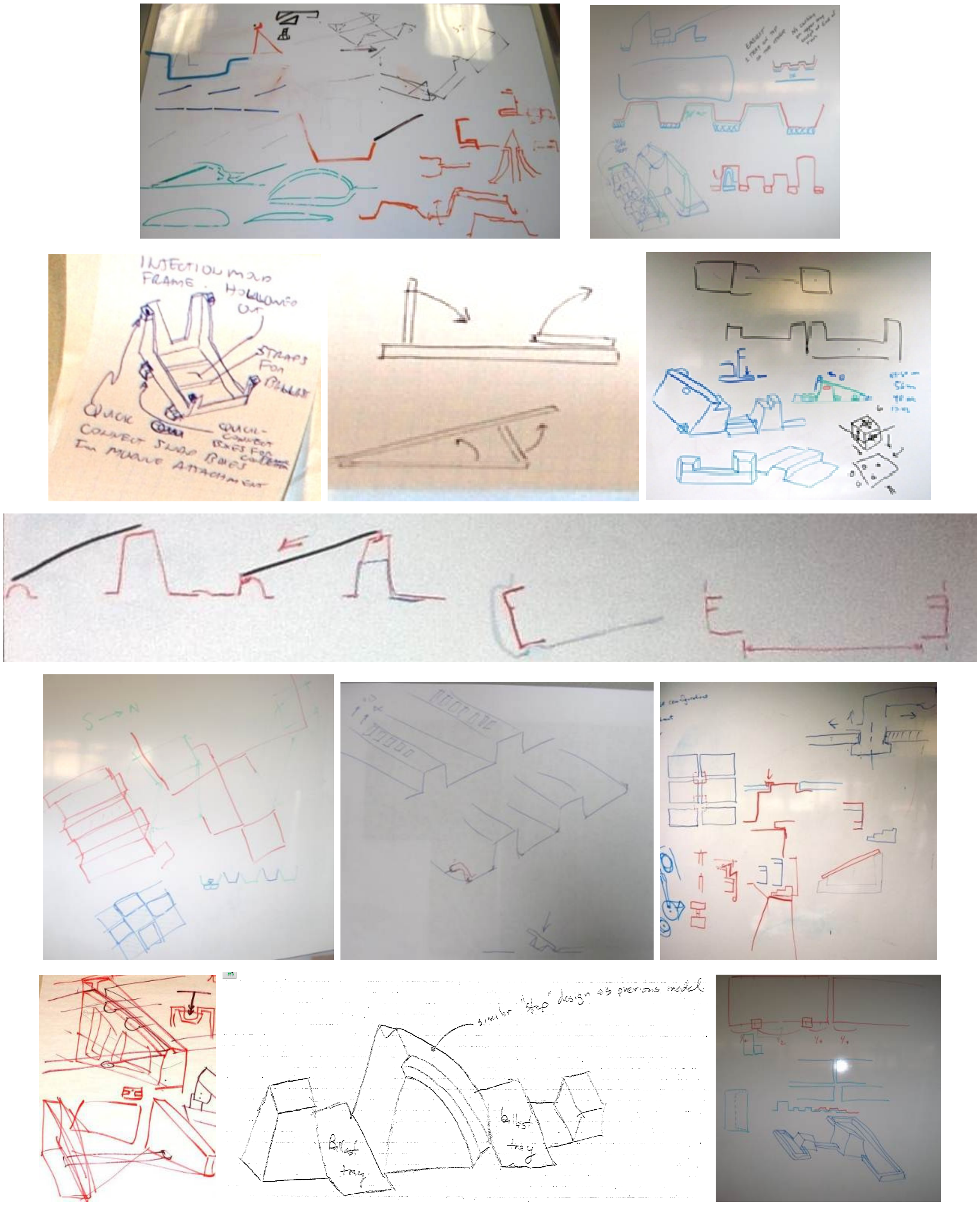


Figure 6

Brainstorming Sketches

To further develop the concept sketching, various modeling tools were utilized to make rough scaled prototype of different concepts. An example of the scaled prototypes is shown in figure 7.

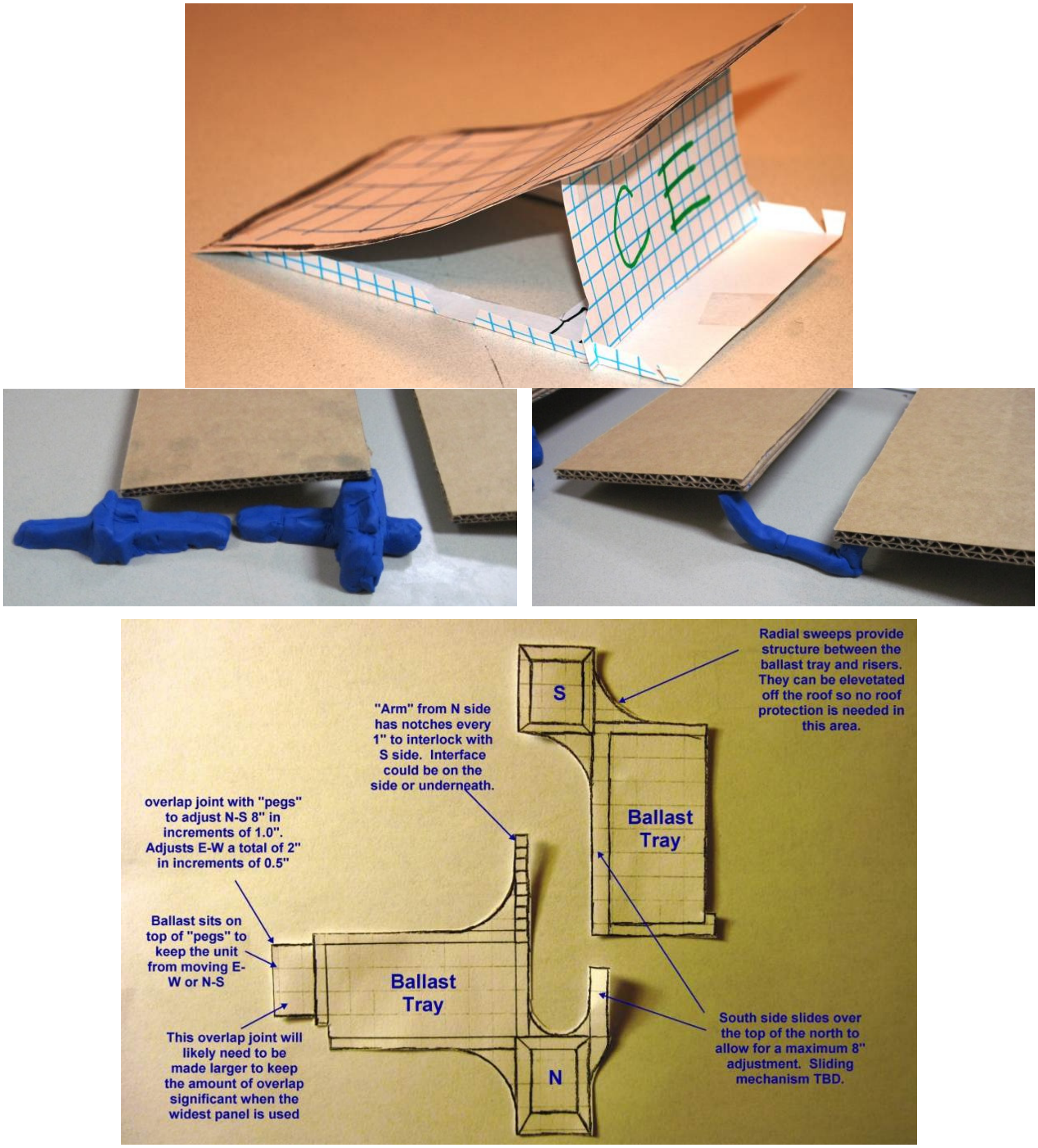


Figure 7

Examples of Scaled Models

Attachment of the PV panels to the racking was explored concurrently along with the "macro design". Nearly all of the PV racking products on the market utilized a bolt to secure the panels to the rack. The team researched other clamping means that would be adjustable to various PV panel dimensions. Various products in other industries were researched to determine how they accommodated the length adjustment in their respective environments. The goal was to determine if similar methodology could be applied to securing solar panels. Some examples of existing attachment/clamping means are shown in figure 8.

Figure 8

Attachment/clamping Surrogate Products

The design team brainstormed different ways to attach the PV panel. Previous research found PV panel thickness to vary between 31 and 50 mm. The attachment feature would need to be able to accommodate this range. Other attachment methods were explored including attaching the PV panel from behind the frame. Some of the attachment ideas are shown in figure 9.

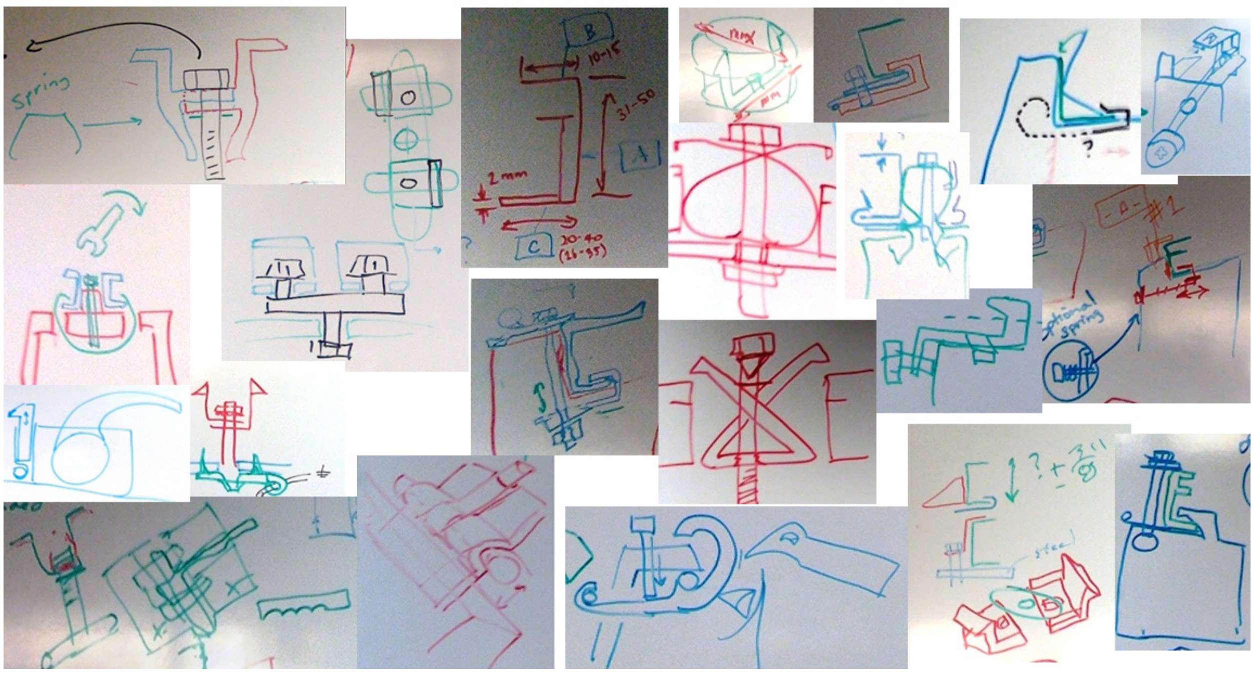


Figure 9

Attachment Ideas

Computer Aided Design (CAD): Ideas and concepts generated in the brainstorming and conceptualization phase were translated into CAD models so the design ideas could be looked at more closely. In the beginning of this phase, models were basic and rough. The goal was to develop a couple of leading candidates which could then be refined further in their design. Examples of the starting CAD models are shown below in Figures 10 and 11.

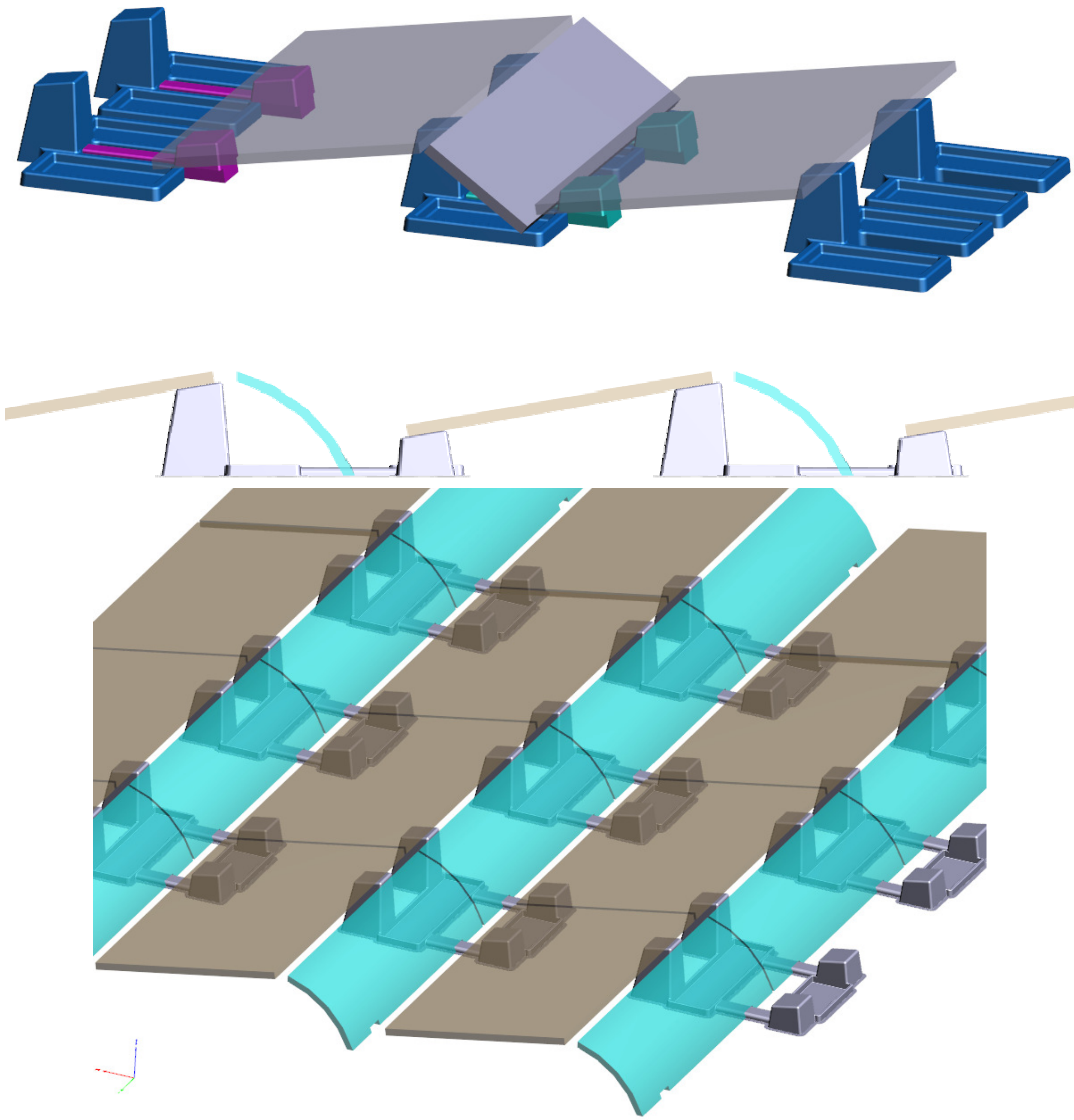


Figure 10

CAD Examples

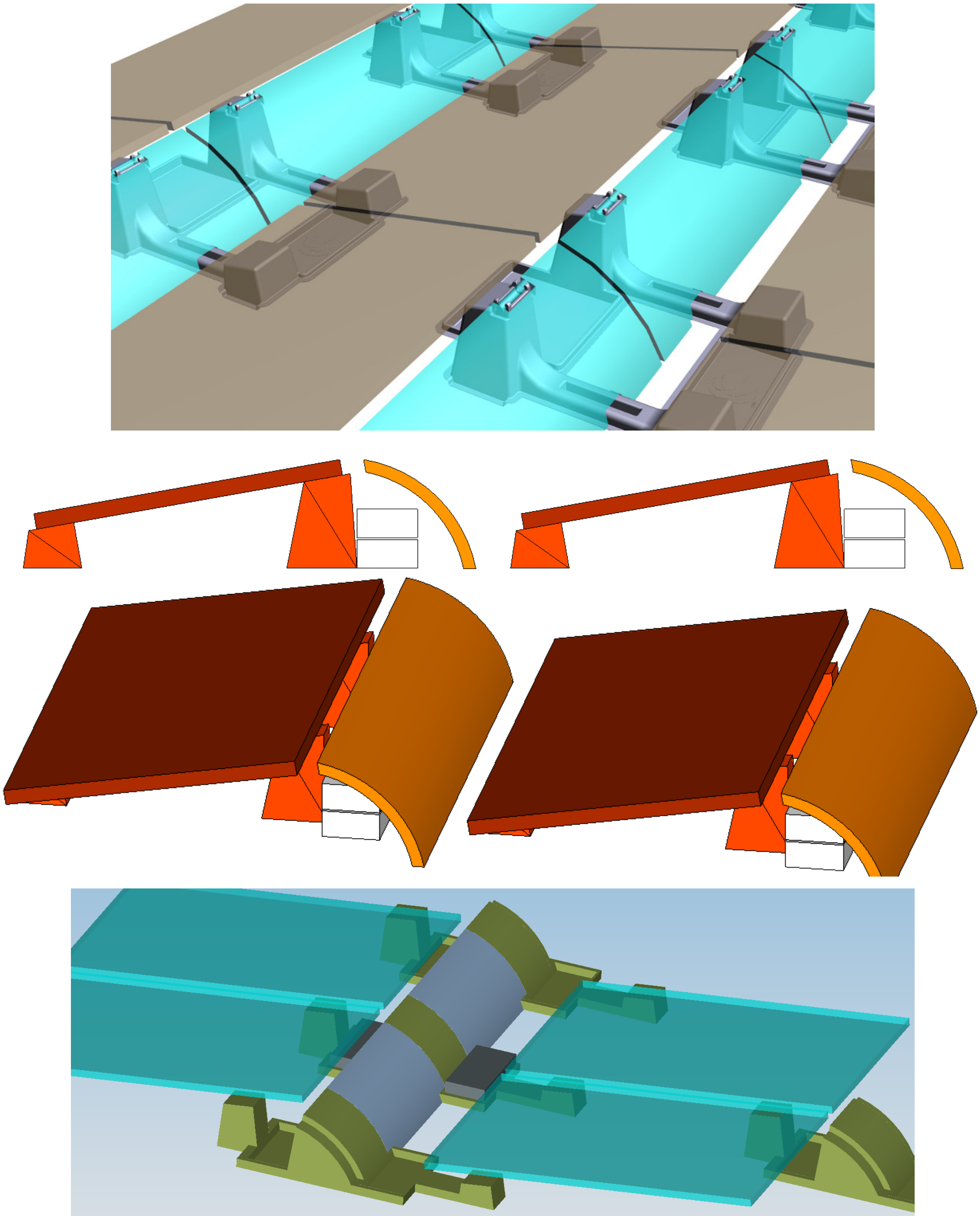


Figure 11

CAD Examples

Models were critiqued, changed, and evaluated. Each one was compared to the original product attributes to determine if the design satisfied all the requirements. Eventually two models became the leading design candidates. These two models were prototyped in ¼ scale size through a vacuum forming process. Both are shown in figures 12 and 13.

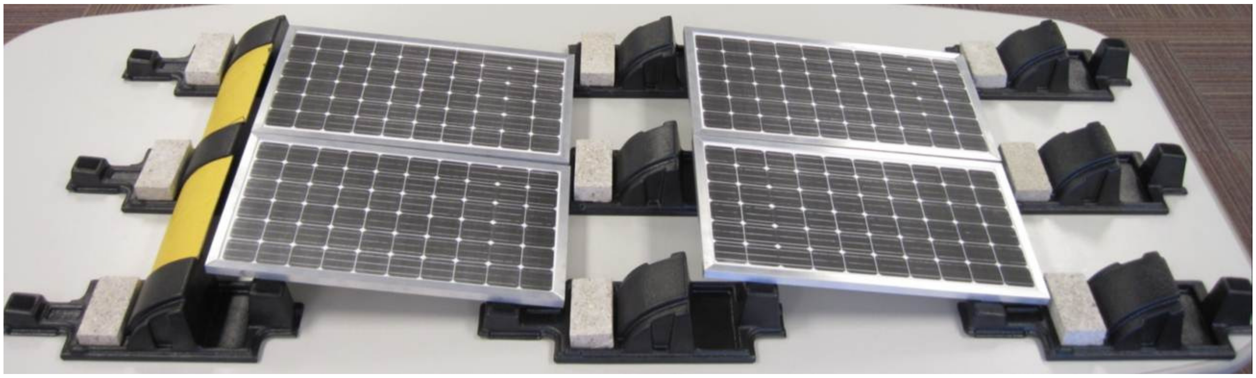


Figure 12

¼ scale Model - Portrait Orientation

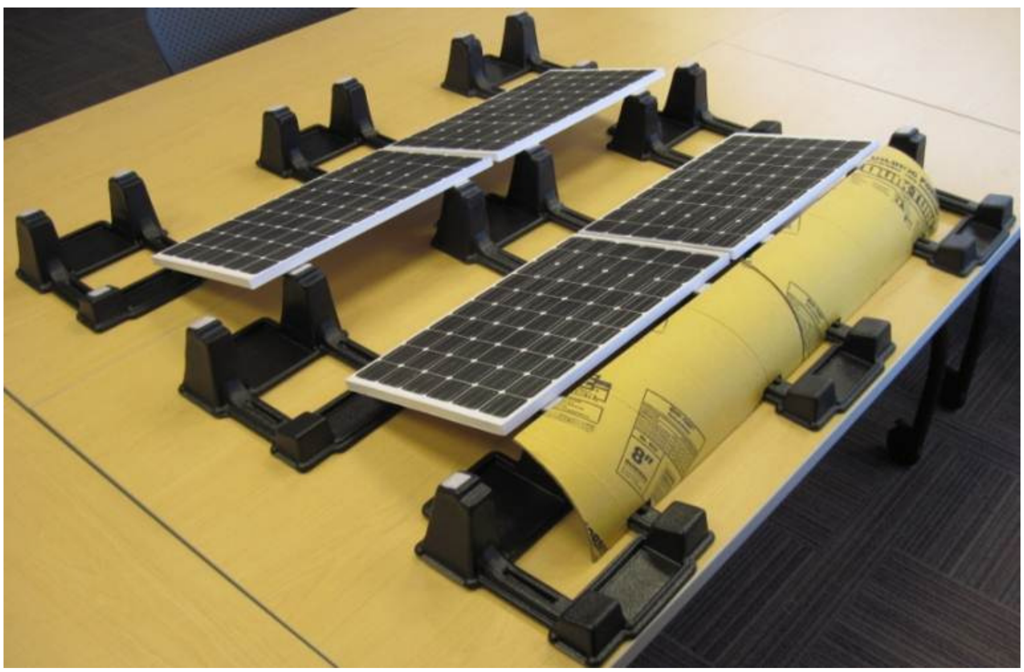


Figure 13

¼ scale Model - Landscape Orientation

Finite Element Analysis: Support of the panel under snow loading is a requirement of the racking. As a preliminary step in the design process, each landscape and portait design was analyzed for a snow load of 45 lbs/ft^2. Deflection and stress are shown in figures 14 and 15 for the two racking designs. Both results were considered acceptable for the level of design detail.

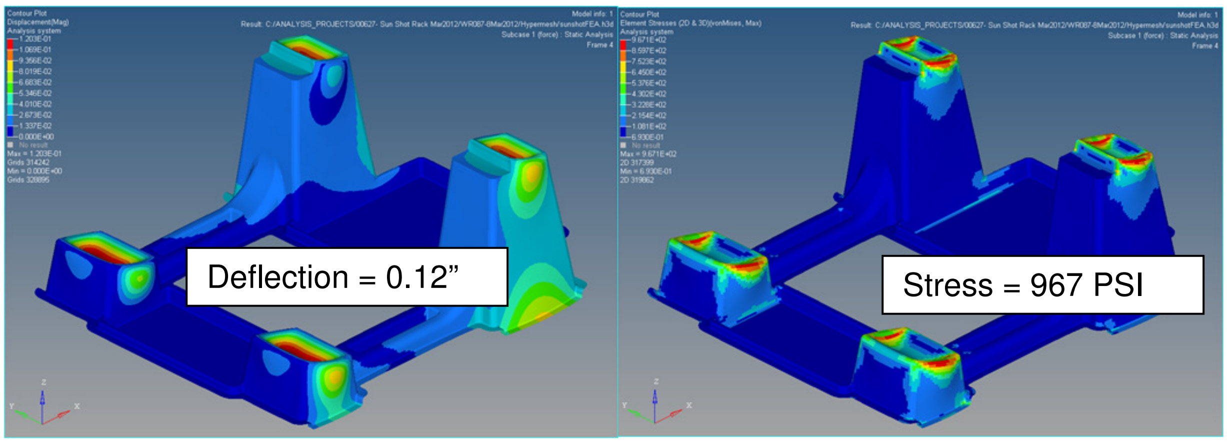


Figure 14

45 lbs./ft^2 Snow Load – Landscape Design

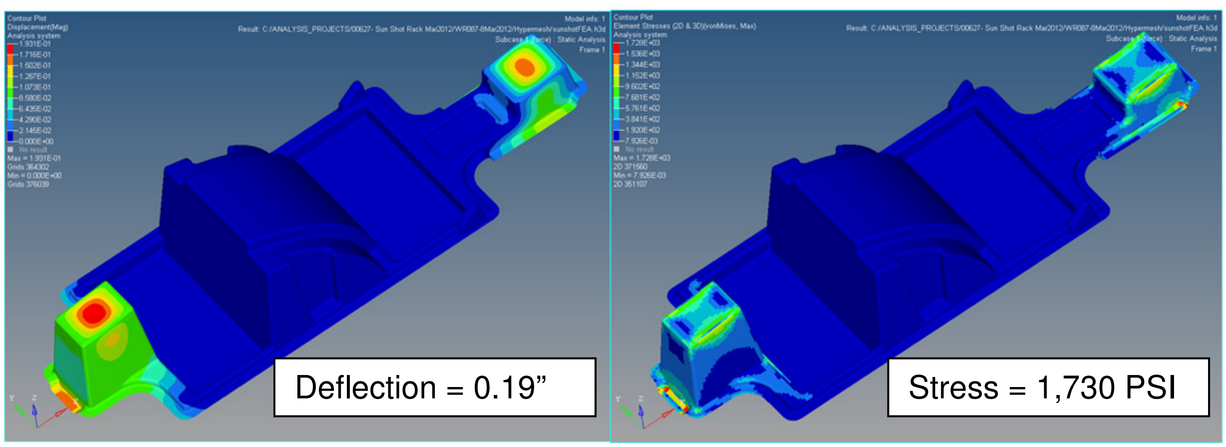


Figure 15

45 lbs./ft^2 Snow Load – Portrait Design

Moldflow Analysis: To evaluate the two racking designs from a plastics manufacturing perspective, Moldflow simulation software was used to determine the number of gates required to fill the part. A “gate” is an entry point where the plastic is introduced into the tool. Material flow, part thickness, tool temperature, and part geometry are some things that can effect flow of material into the part. After several itterations of trying various gate locations and scenarios, it was determined there would need to be 5 gates for the landscape version, and 3 gates for the portrait version.

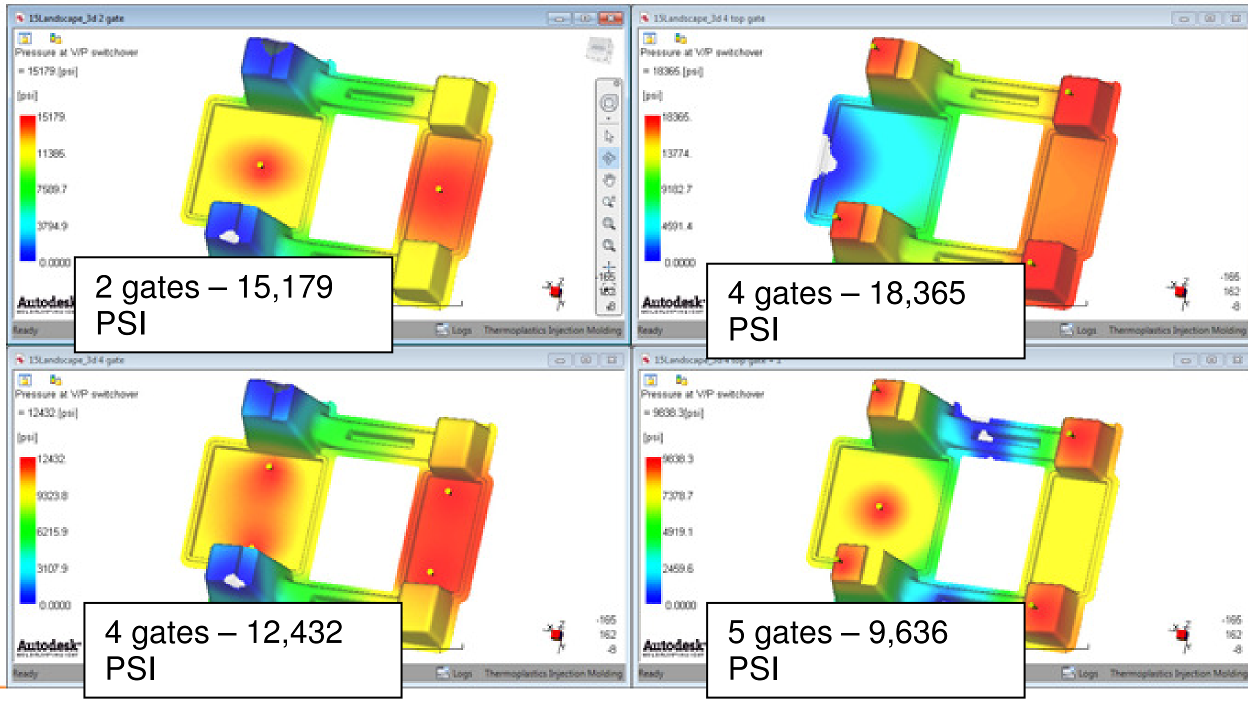


Figure 16

Moldflow - Landscape Design

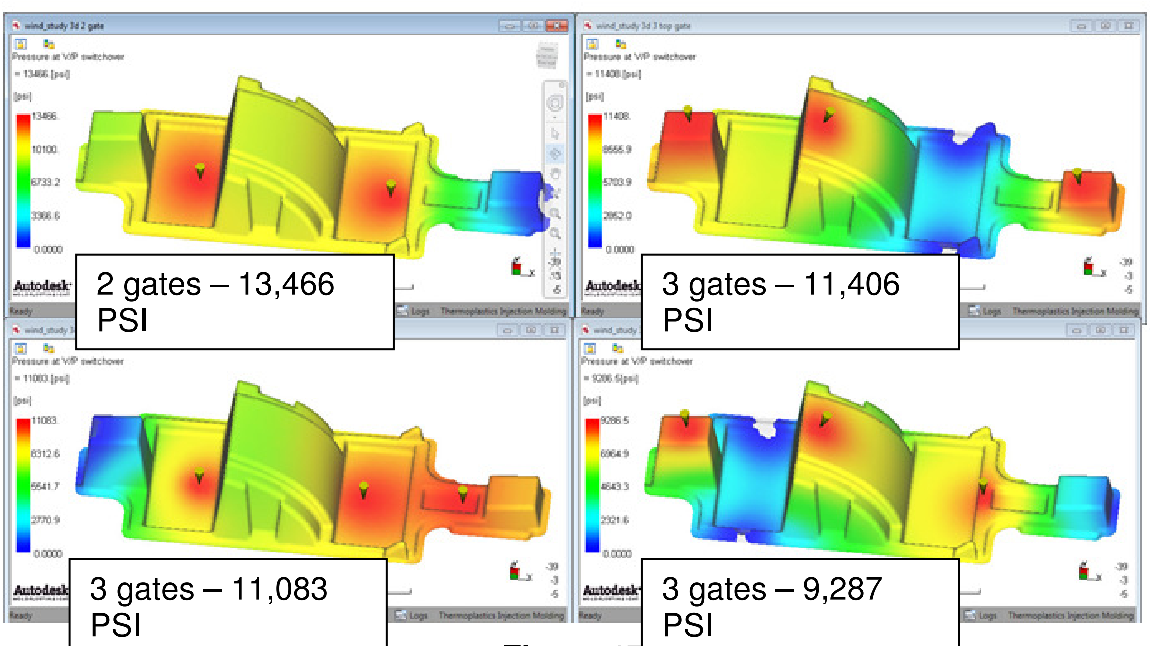


Figure 17

Moldflow – Portrait Design

Triple Constraint: An “optimal” solar rooftop design is dependent upon which characteristic is being measured. Optimal energy generation implies a higher tilt angle, or one that is oriented directly to the sun. Optimal reduction of weight on the roof (low PSF) implies a flat or no-tilt installation. Optimal cost can be evaluated different ways. In general, optimal cost implies a lower $/watt cost of installation (labor and materials). On a macro level, the lowest cost of racking could be gluing the panels to the roof of the building. This however reduces energy output, makes installation difficult, and maintenance difficult.

The team approached the “optimal” design from the three different variables of: energy production (kwh/year per kw installed), weight of the array on the roof, and cost of installation (labor and materials). Making any one of the variables drastically high or low affects the other two variables. For example, increasing the tilt angle increases the amount of ballast required. Additionally, it increases the row to row spacing due to shading. It could also increase racking cost since more material is needed to be placed underneath the PV panel to support it. Reducing the tilt angle to 0 degrees helps reduce the ballast needed, but also reduces the energy generation.

Design of this rack sought to optimize the triple constraints of energy production, ballast weight, and cost. Energy production could be simulated using PVsyst or System Advisory Model (SAM). Graphs were generated for various arrays with different tilt angles and inter row spacing. Installation cost of the materials could be estimated based on the design. Installation labor cost could be estimated based on the parts, and comparison to existing racking systems. Energy generation and installation cost could be estimated accurately analytically based on the CAD. The third constraint of accurately determining ballast requirements would require wind tunnel testing.

Wind Tunnel Consulting: ASCE 7-05, “Minimum Design Loads for Buildings and Other Structures” is the accepted standard for determining wind loads. Section 6.6 Method 3, Wind Tunnel Procedure, specifies the wind tunnel test conditions. The wind tunnel testing produces pressure coefficients for a specific design. These pressure coefficients are input factors to determine ballast needed for the solar array.

The design team elected to take two designs to the wind tunnel to determine ballast requirements. In addition to testing the two designs, certain variables were changed to optimize the design and understand how design decision could affect wind loading. Upon discussing the designs with wind tunnel consultants, four different design attributes were varied between “hi” and “lo”. A design of experiments was set up determine which variables influenced the ballast the greatest. The four variables and reasons for each are provided below:

- Flat or curved wind deflector – Either shape could be incorporated into the design, as plastic can be molded in different shapes.
- 3” or 6” gap on the north side of the panel – Since panel lengths vary between panel manufacturers, the team wanted to understand how panel length could affect ballast requirements.

- ½" or 2.5" gap between panels east-west – Panel widths vary between panel manufacturers. The team wanted to understand how a gap between panels could affect ballast requirements.
- 2 position tilt (10˚ or 15˚) – This could be a product offering of changing the tilt for different seasons. (summer and winter)

All scenarios are shown in figures 18 to 21.

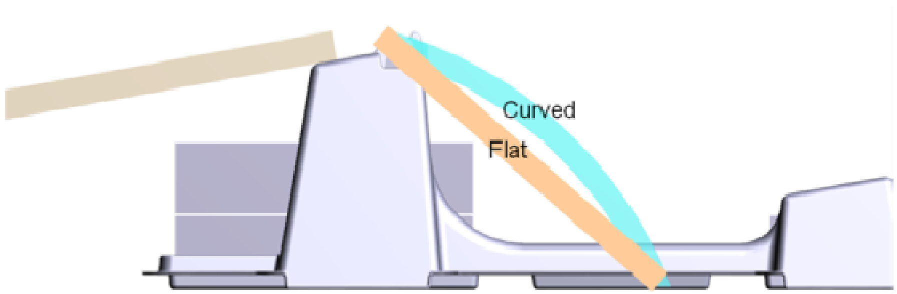


Figure 18

Wind Deflector Shape

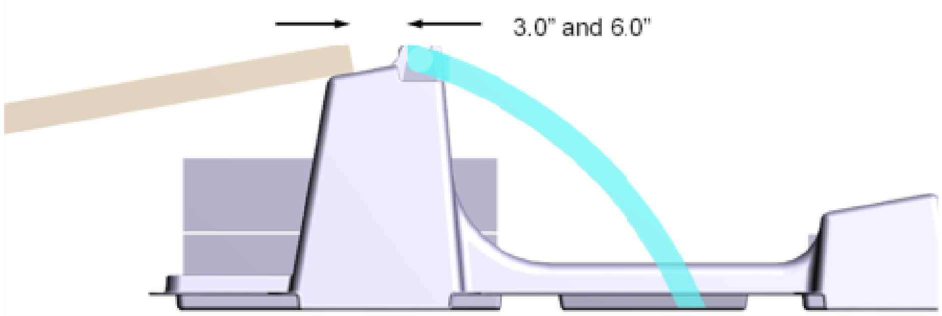


Figure 19

North Edge Gap

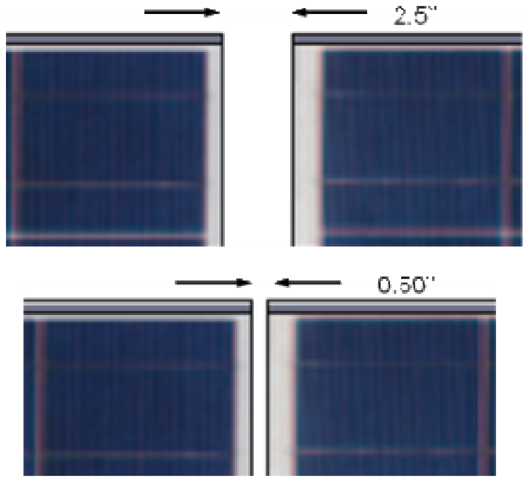


Figure 20

East/West Gap

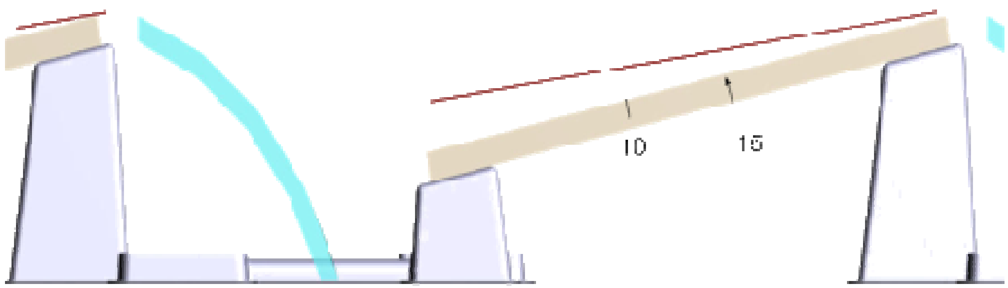


Figure 21

2 Position Tilt

Wind Tunnel models of both the portrait 7˚ and landscape 15˚ solar racks are shown in figures 22 and 23.

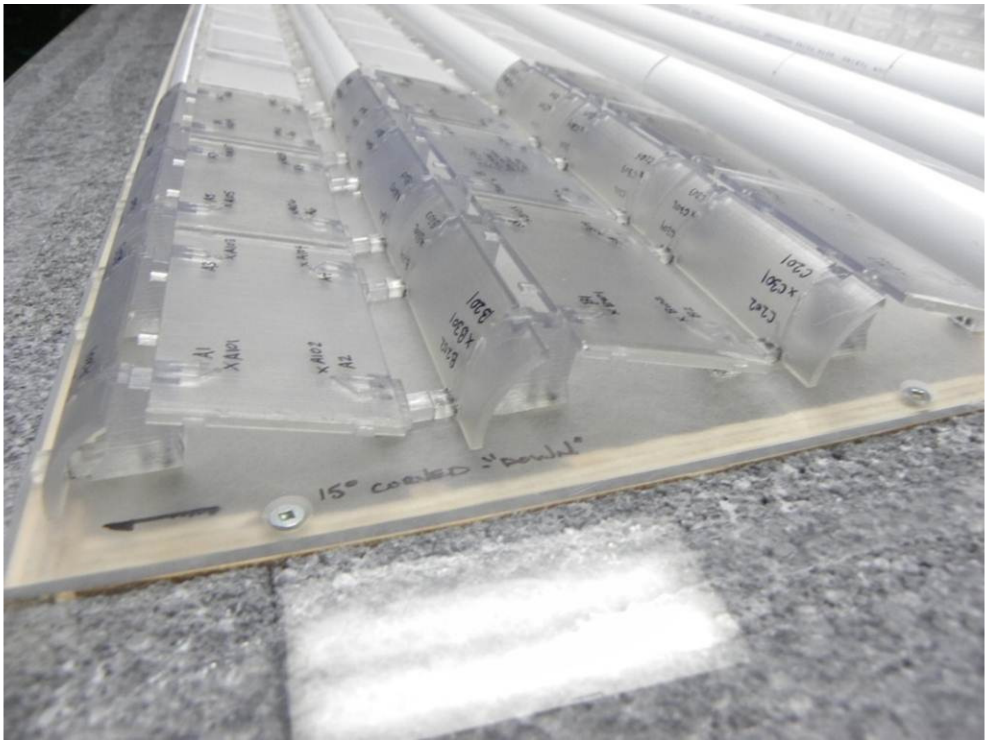


Figure 22

Wind Tunnel Landscape Orientation at 15˚

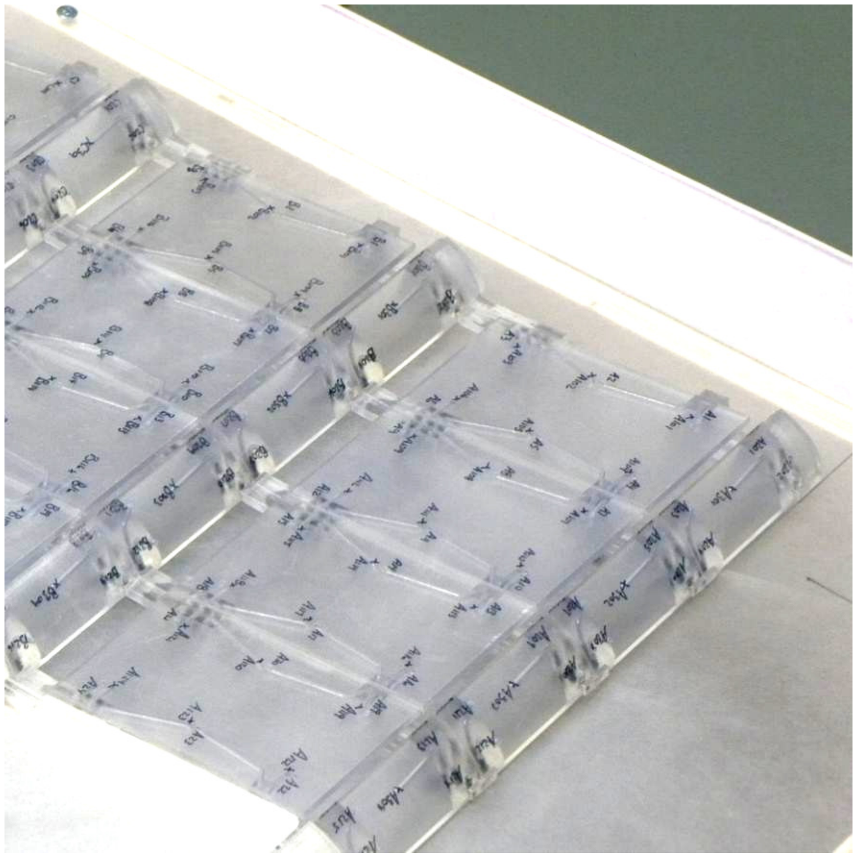


Figure 23

Wind Tunnel Portrait Orientation at 7˚

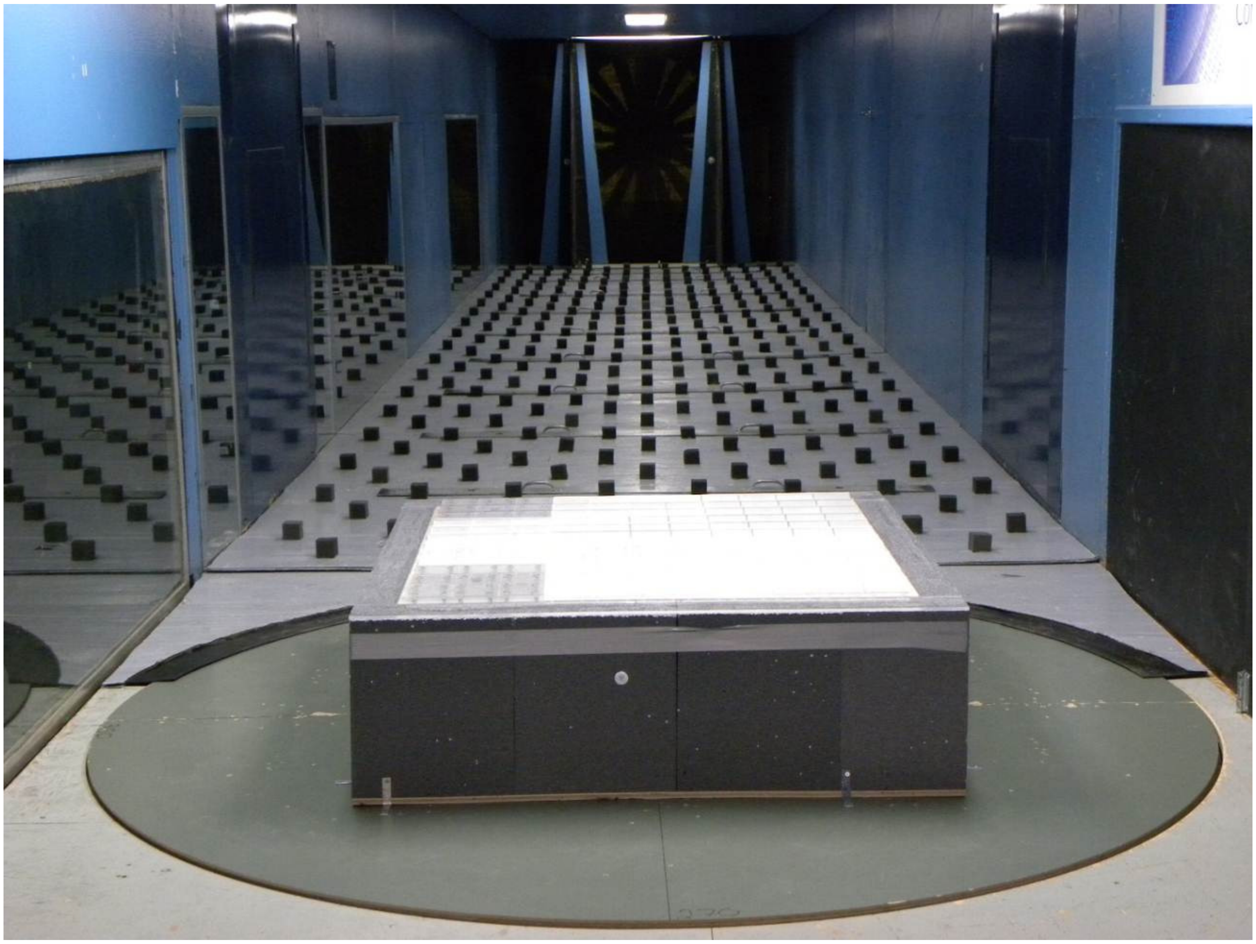


Figure 24

Wind Tunnel

Wind Tunnel Design of Experiments Results: A ballasted rooftop solar array has potential to move on the roof due to two separate load conditions. A drag force would cause the solar array to slide. A lift force would cause the array to be lifted. Both conditions were considered and evaluated in the wind tunnel.

The most significant finding from the wind tunnel testing is that a curved wind deflector results in less lift and drag as compared to a flat wind deflector. Secondly, a larger gap at the north end of the panel reduces lift and drag. The other two variables east/west gap and 2 position tilt either had negligible effect or conflicting effect between lift and drag. Overall lift and drag coefficients were similar between the 7 degree portrait and 15 degree landscape designs.

Figure 25

Design of Experiments Results

Design Revisions: Outputs regarding the triple constraint of energy output, ballast, and installation cost were reviewed to determine a design direction for the project. In all installations throughout the contiguous United States, a properly spaced 15 degree tilt array will produce more energy than a 7 degree tilt array. Maintaining the same panel orientation, a 15 degree tilt array will be higher off the roof and require more ballast. Additionally, more support material will be needed underneath the panel to achieve the higher 15 degree tilt. A 15 degree tilt will also need to be spaced further apart than a 7 degree tilt due to shading concerns. Further apart row spacing would result in fewer panels on the roof. Figure 26 compares a 7 degree portrait with the 15 degree landscape design. Due to shading, a 7 degree will produce more kWh/kW for lower inter row spacing. It is not until the rows are spaced further apart until the 15 degree array out-produces the 7 degree array. A 7 degree array designed for a 21” inter row spacing, as indicated by the blue vertical line will produce more energy than a 15 degree at the same inter row spacing. The 15 degree would need to be spaced approximately 9 inches further apart (on average for all three cities shown) in order to produce the same kWh/kW than the 7 degree portrait design at 21 inch row spacing. Another way to compare the two designs is to for a same size rooftop and same kWh/kw, the 7 degree tilt would allow 8.5% more panels on the roof. This would result in more kwh per rooftop or area.

Cost of the 15 degree landscape rack is approximately 25% higher than that of the 7 degree portrait rack. This is due to more material being needed to raise the panel higher and more material per wind deflector. In the case of the landscape 15 degree, the wind deflector is both higher and longer than the 7 degree portrait design.

A decision was made to pursue the 7 degree portrait rack based on the discussion above. Design focus turned to assembling the parts together, attachment of the panel to the rack, wire management, material, part count, and cost.

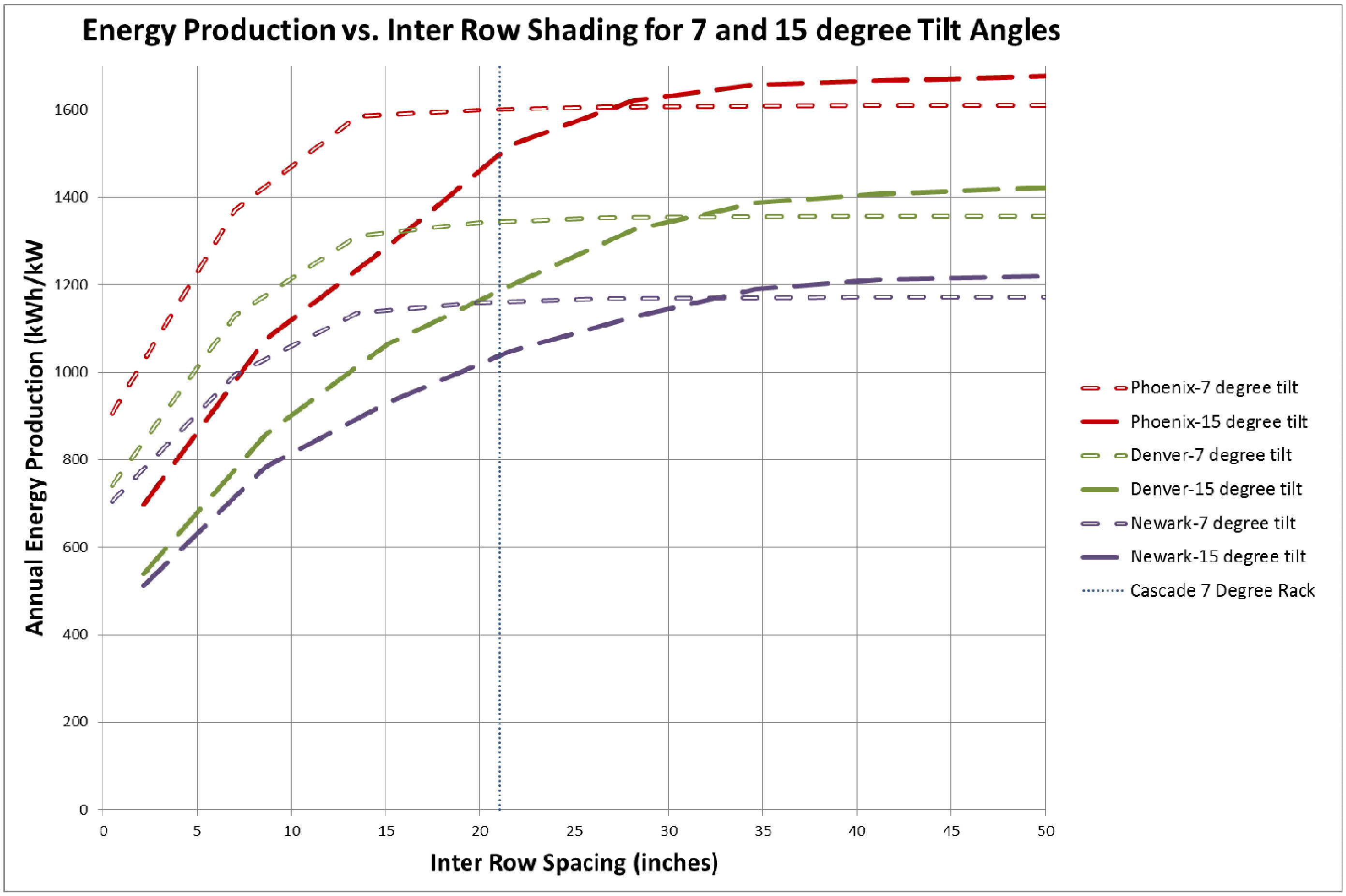


Figure 26

kWh/kw for US Cities compared with Row Spacing

Figure 27 shows the design before the design of experiments wind tunnel testing took place. Material was reduced where possible and assembly/connection points were considered. Plastic material was kept only where required to satisfy wind testing, support the PV panel, maintain part rigidity, and maintain plastic flow in manufacturing. Figure 28 shows the design after optimizing material placement.

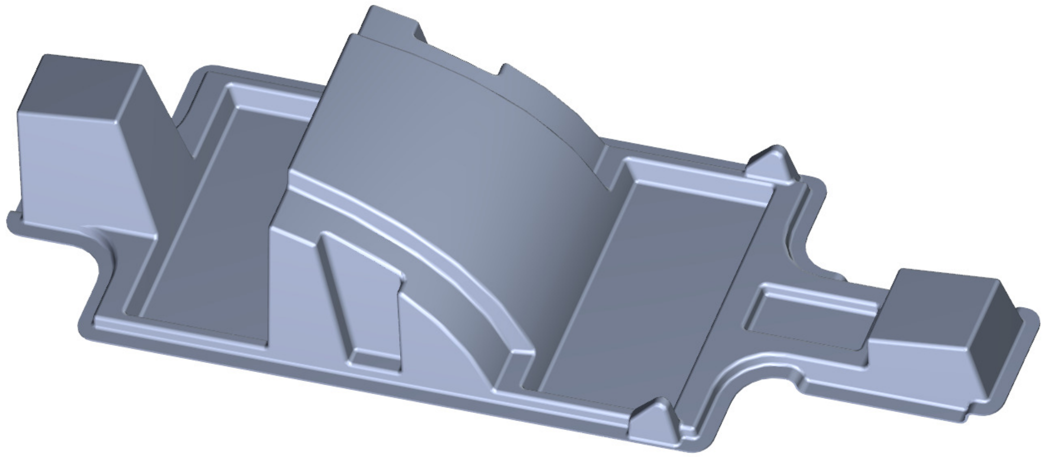


Figure 27

Base Part before Material Optimization

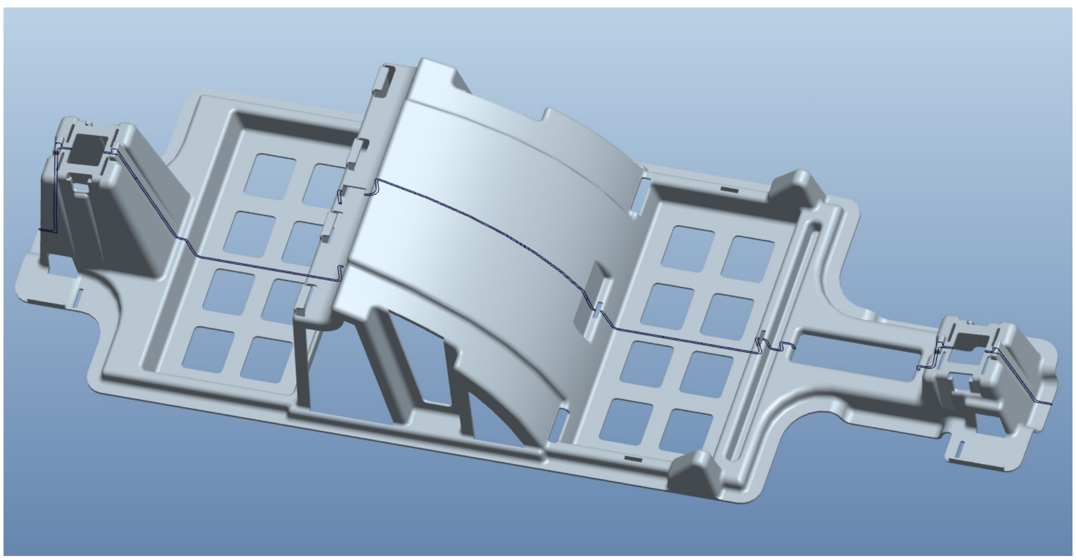


Figure 28

Base Part after Material Optimization

Integrated grounding was a desired product attribute identified at the beginning of the project. The team wanted to make electrical grounding of the array as simple as possible. When interviewing installers, electrical grounding was time consuming and required additional materials at the installation site. The development team focused on making the electrical grounding a part of the panel securement step. During solar array installation on the roof, securement of the panel was viewed as a required step since nearly all panel manufacturers dictate how and where the panel should be secured. The team sought to electrically ground the panel at the same time the panel would be physically secured. Several ideas were considered, designed in CAD, and proved out through prototyping. Some of the steps are shown below in figures 29 and 30.

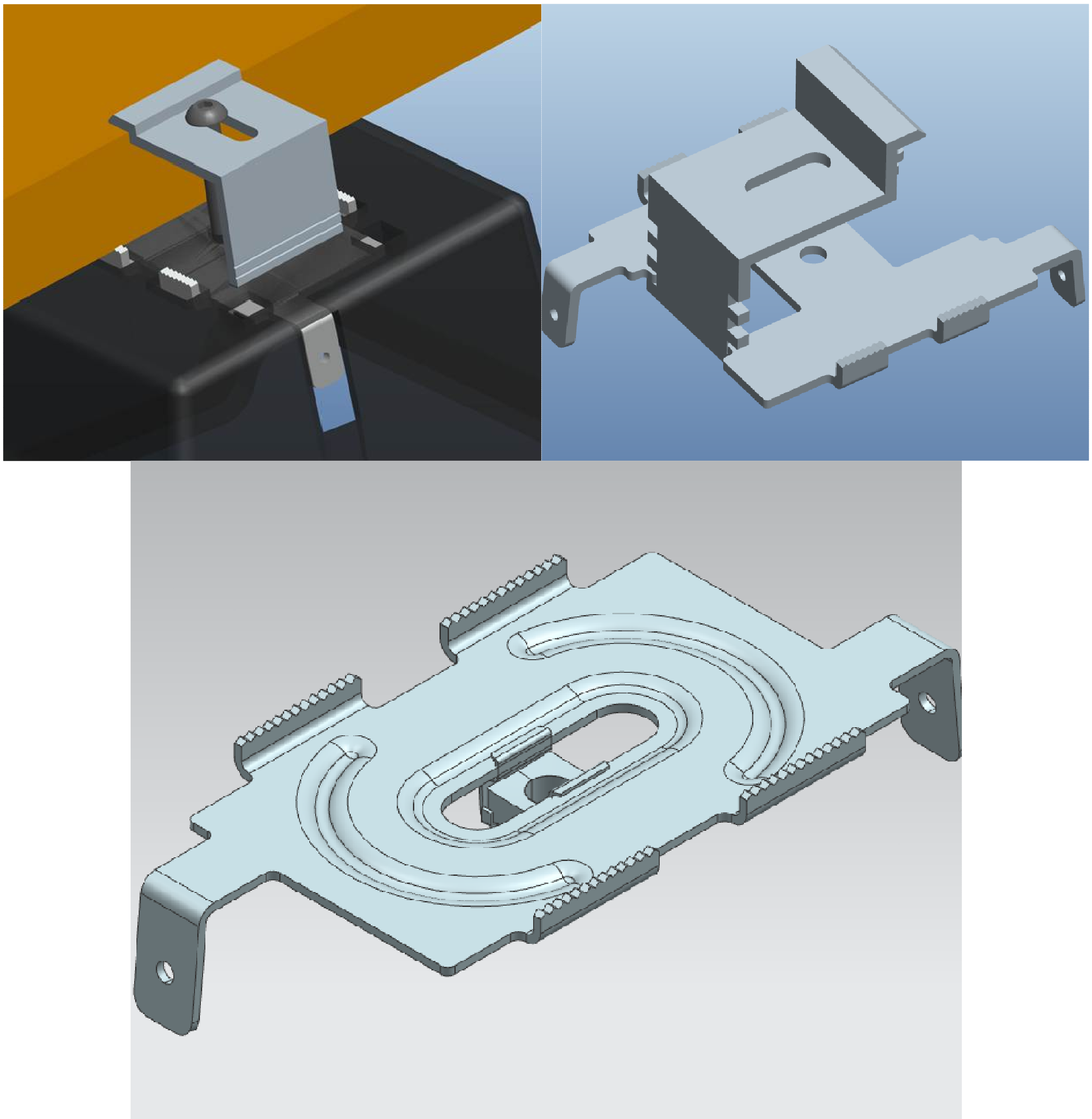


Figure 29 – Bracket Grounding Development

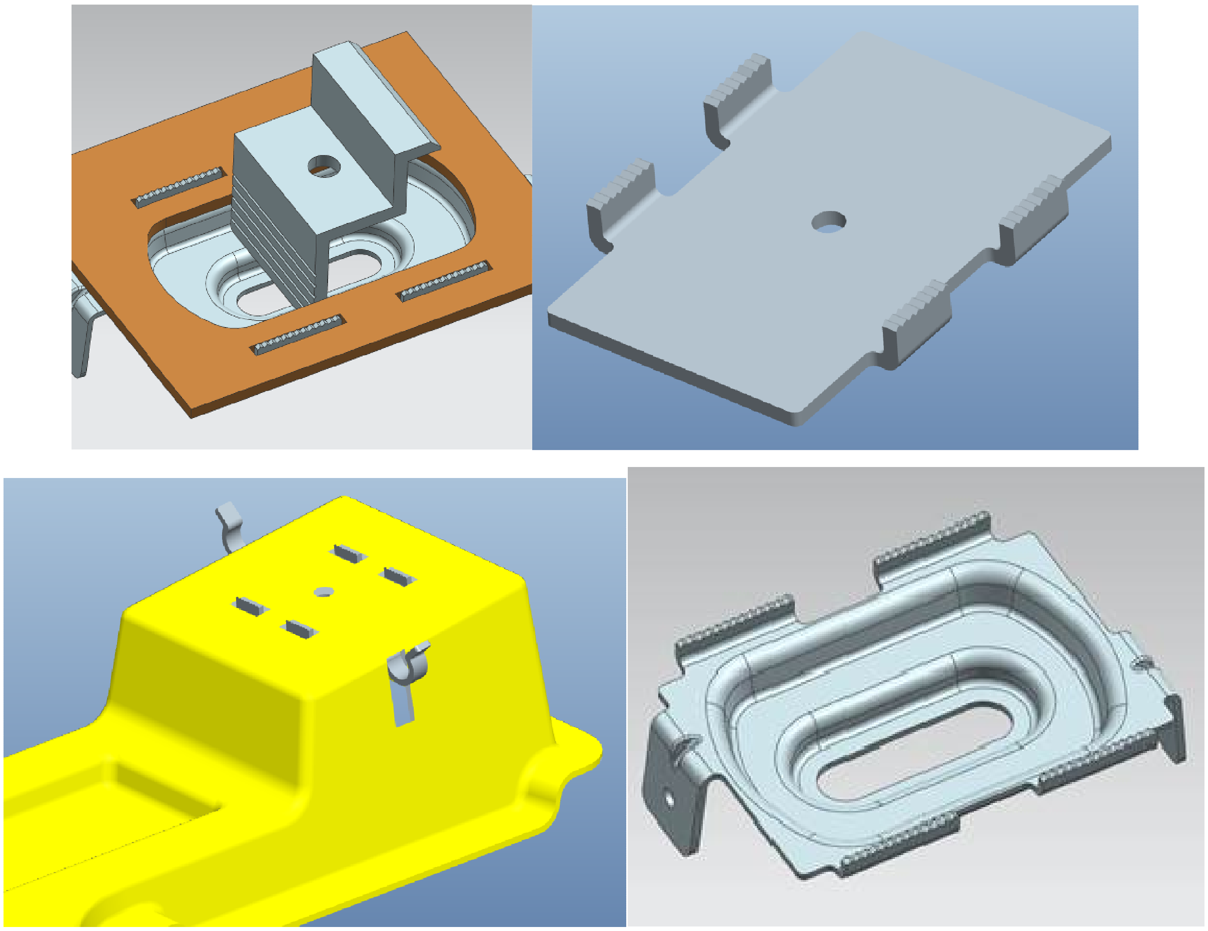
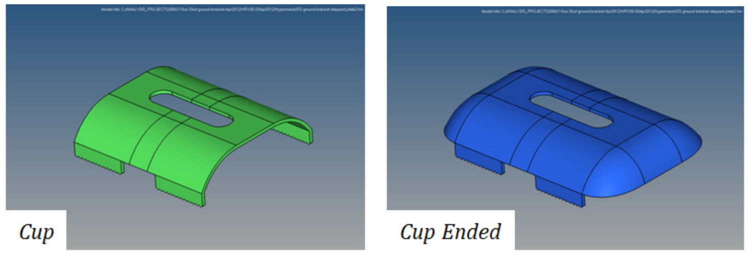


Figure 30 Bracket Grounding Development

Concurrently with CAD development of the grounding bracket, FEA was performed on various geometry shapes to determine the design direction. Some of the shapes that were explored along with their deflections are shown in figure 31. Progressively adding geometry from the flat design reduced deflection.

Model	Displacement (in)
Flat Plate	0.557
Cup	0.353
Cup Ended	0.186
Stepped 1	0.140
Stepped 2	0.083



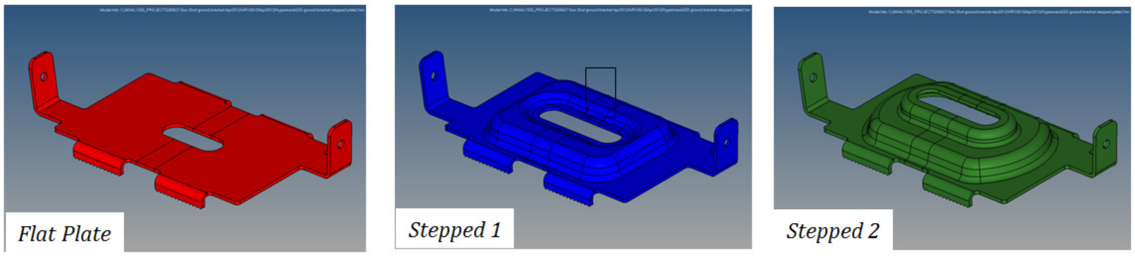


Figure 31 – Grounding Bracket FEA

Physical prototypes were created along with the CAD and FEA exercises to check for actual force and deflections. Examples of the prototypes created are shown in figure 32. As confirmed with the FEA, progressively adding shape and depth to the bracket resulted in a part that could withstand the force induced by the torque required to hold a PV panel in place.

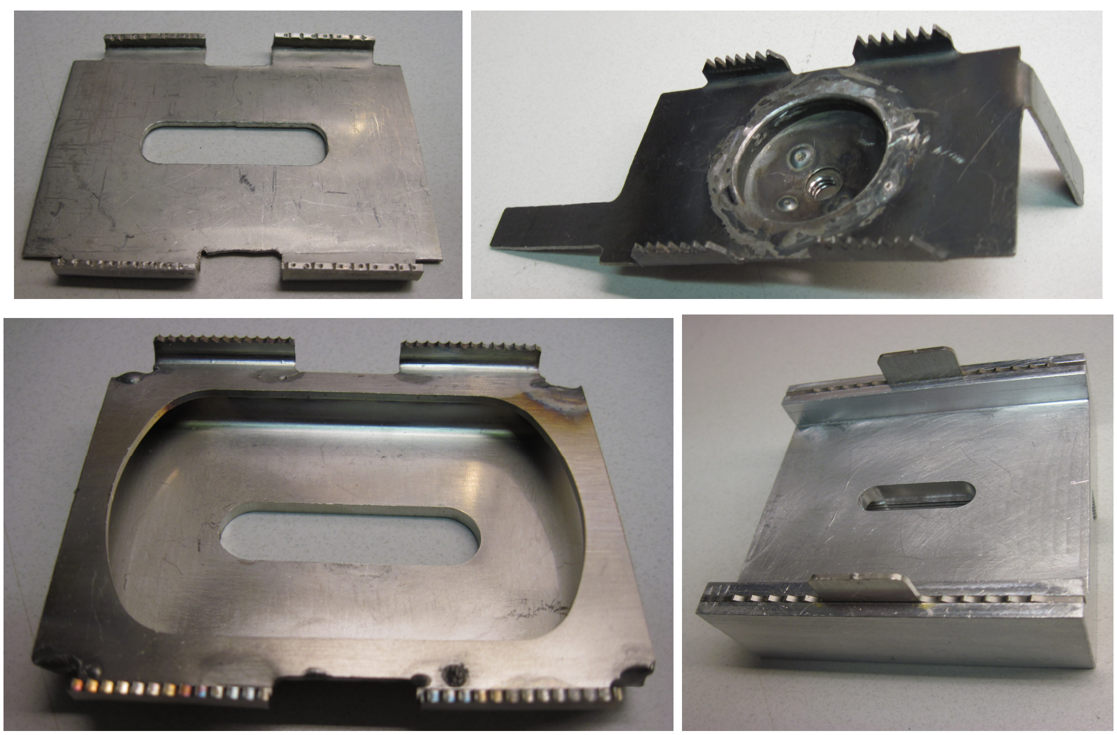


Figure 32 – Grounding Bracket Prototypes

Figure 33 demonstrates the east-west grounding scheme. The grounding bracket is pre-installed during the manufacturing process with the cage nut (shown in magenta) in place. PV modules are placed on the rack on the roof. A mid clamp is installed with a bolt to secure the modules. As the bolt is tightened, the teeth on the bracket penetrate the anodized coating on the PV module frame and create a path for the electrical ground.

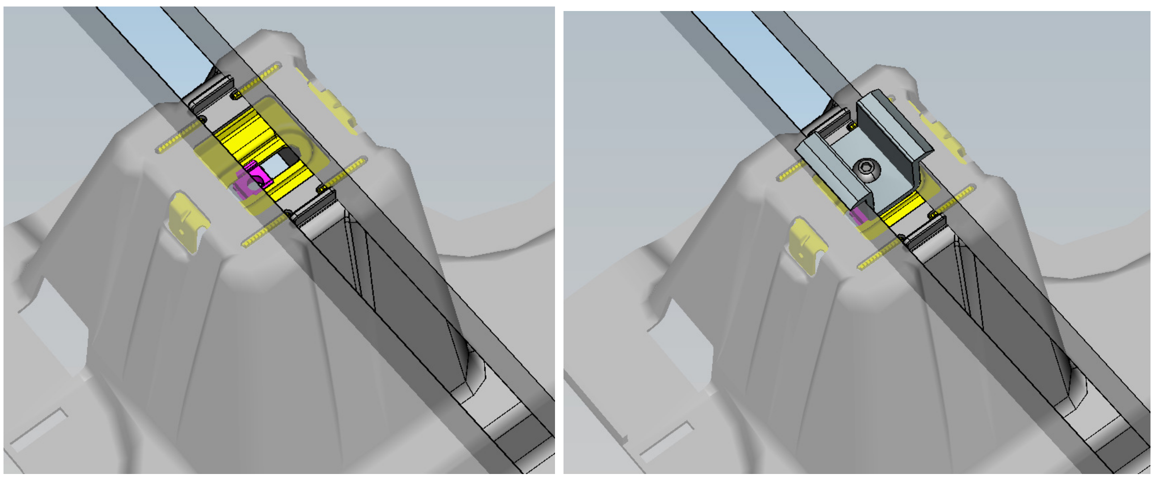


Figure 33 – Grounding Bracket

Connection of the electrical ground between rows could be handled on the roof through the use of ground lugs and ground wiring. This would add time and labor to the installation process and cost. The team sought to find a way to integrate the north-south ground within the rack product. Both copper wire and aluminum wire were considered. Upon investigation of cost, manufacturing, and connections, aluminum was selected. The integrated ground wire is shown (in green) in the base part in Figure 34.

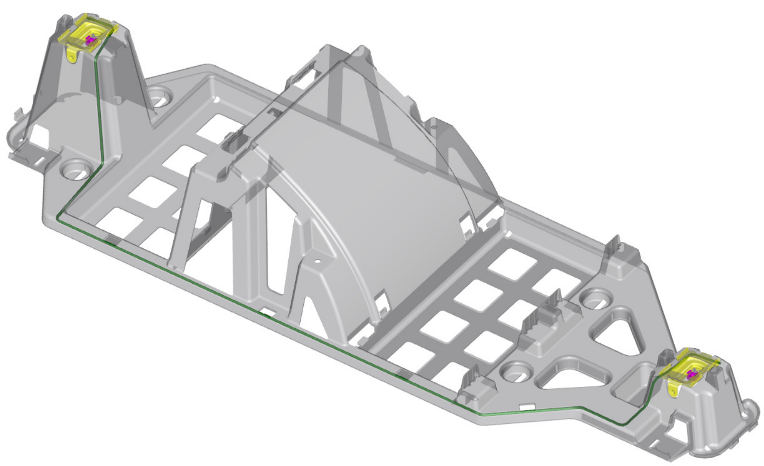


Figure 34 – Integrated Ground Wire Connecting Ground Brackets

A sample 6 x 6 array is shown in figure 35 in a top-down view. The orange squares represent the ground brackets and the grey lines represent the integrated ground wire.

The green dashed lines show the ground being carried east-west through the array, and the purple dashed lines show the ground north-south within the PV module frame. With this "web" type connection, the entire array can then be grounded on the roof with one ground lug connection. This method also allows service of one module without compromising the array electrical ground.

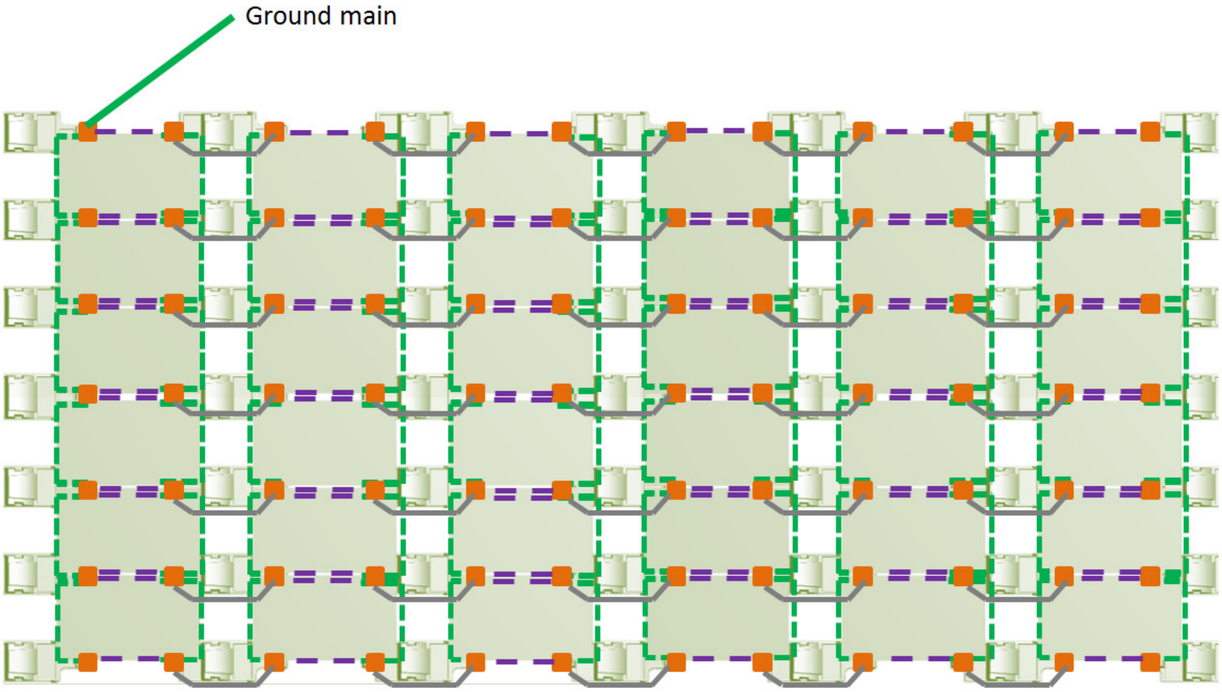


Figure 35 – Array Grounding

As noted previously, solar module sizes vary between manufacturers. The solar rack needs to accommodate the slight differences. A couple of the desired key product attributes included "easy to install" and "accommodates module of choice", "fast installation", and "easy to understand how it works". In all the installations that were benchmarked, tape measures were used by the installers to locate the racking in the proper position. A goal of this rack was to minimize/eliminate the measuring that increased installation time. The team's approach was to have the racking parts positioned the same way on the roof no matter which solar panel manufacturer was chosen. "Spacers" are used to space the support bases apart. Figure 36 shows layout of the racking with the long spacers separating the support bases. The spacer also works as a place to route wires east to west.

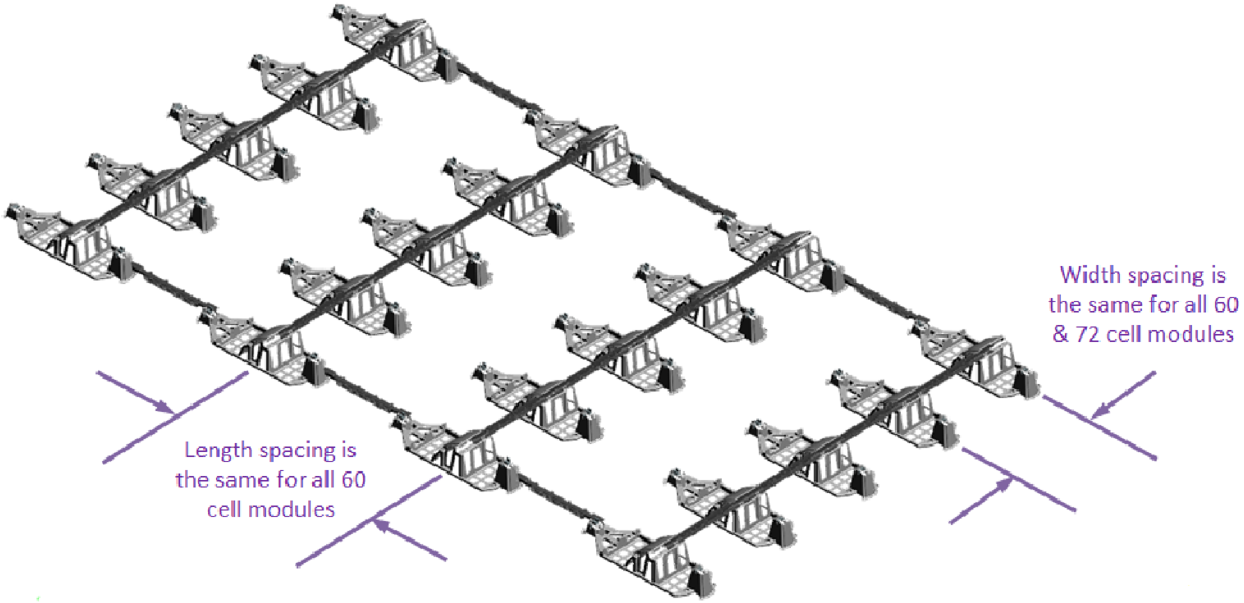


Figure 36 – Racking layout

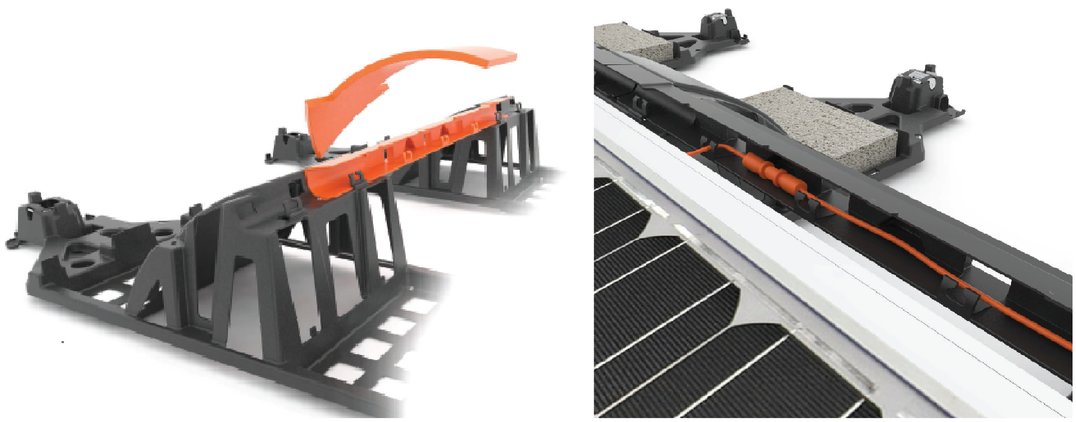


Figure 37 – Spacer shown for installation and wire routing

Module length variation of 37 mm would be taken up by the gap in the north edge of the rack as demonstrated in figure 38.

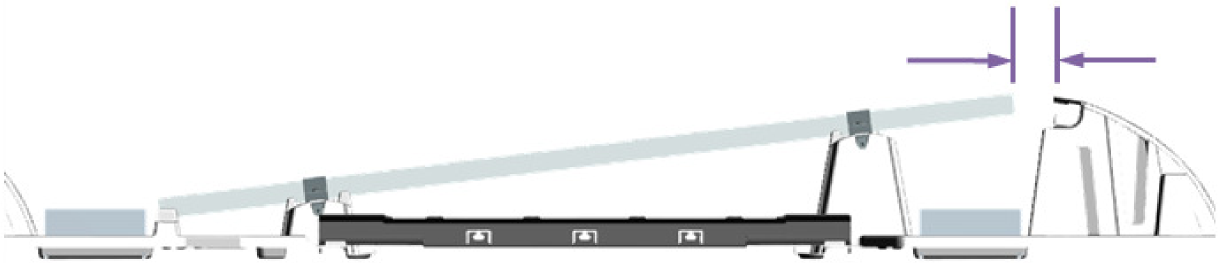


Figure 38 – View from the "East" showing gap for module length variation

Module thickness and width are dealt with by a combination of using the correct clamps and the bolt that holds the module in place. Each installation uses 1 of 4 mid clamps for width variation and 1 of 4 end clamps for height variation. Module width variation is taken up by using the proper mid clamp width for the module. Figure 39 shows the correct mid clamp for each module width. For example, the widest mid clamp is used with the 982 mm module. By using different size mid clamps, the base rack spacing is the same on the roof.

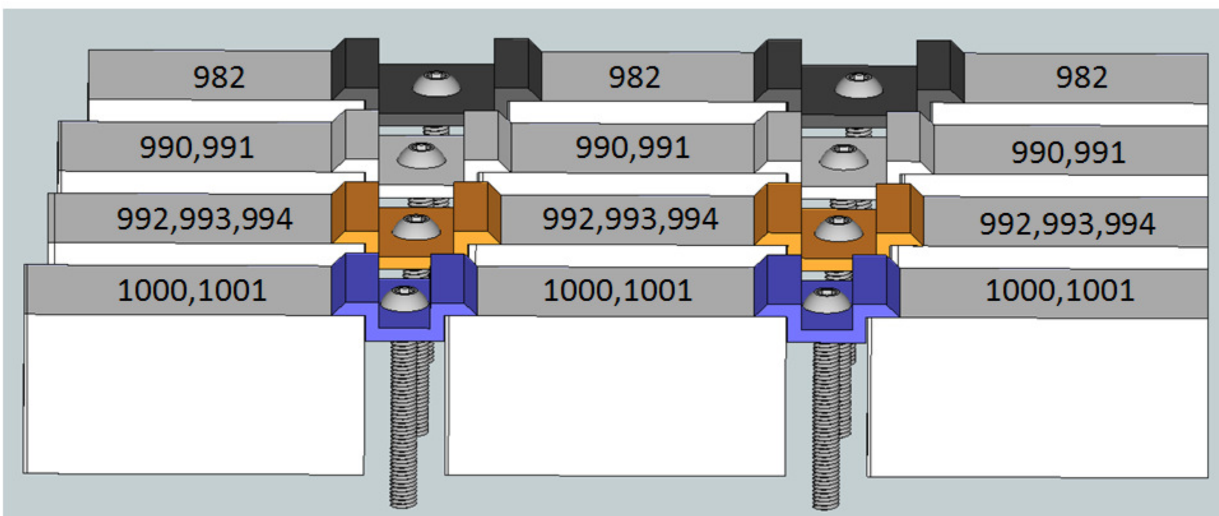


Figure 39 – Mid Clamps for Module widths (mm)

The bolt and cage nut work together for the various module thicknesses and widths. The cage nut slides within the bracket to match up with the width, and the bolt can be tightened down for thinner module frames. Similar to how the mid clamp works with width, there are 4 different end clamps to meet the thickness range as shown in figure 40.

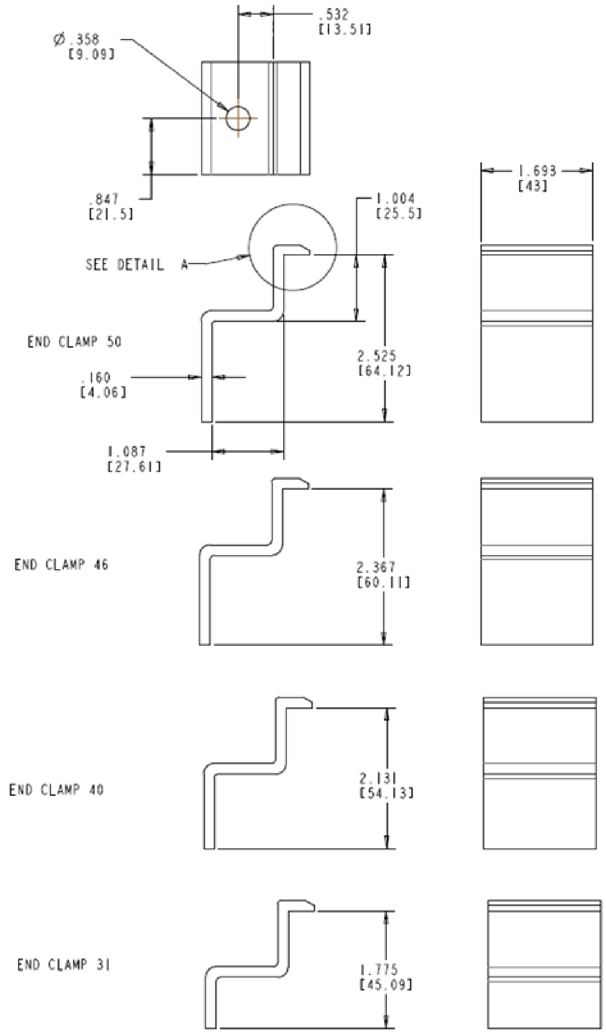


Figure 40 – End Clamps

Sections through the brackets are shown in figure 41 for both the end and mid clamps. This demonstrates how the clamp sizes, bolt length, and cage nut all work together to fit various module sizes.

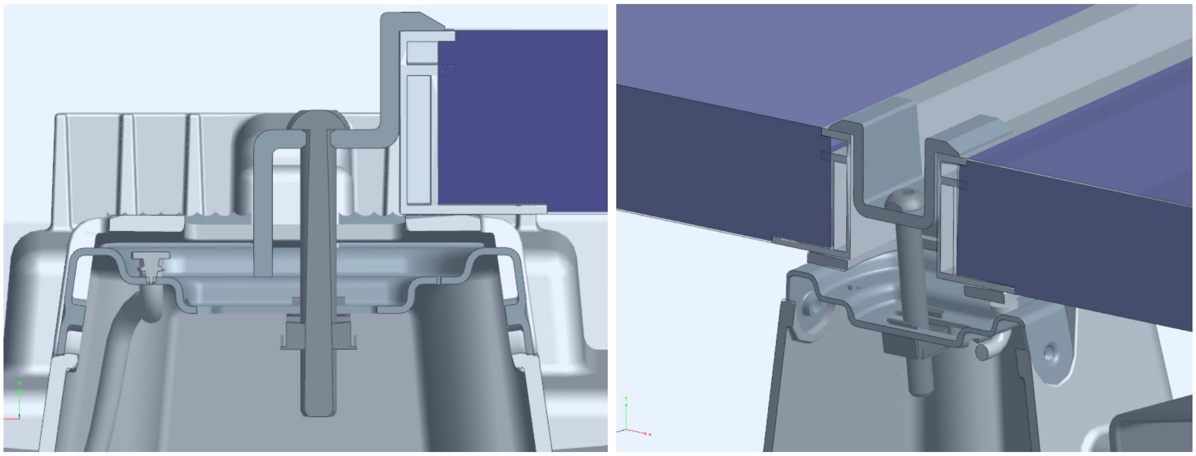


Figure 41 – Bolt, cage nut, and clamp interface

Wind Tunnel Testing: The previous wind tunnel testing was done to determine effects of ballast requirements based on design changes. Purpose of the next wind tunnel testing was to determine final GCp values for the completed design that would dictate the ballast needed for an actual array on a roof. Testing was done in a certified Boundary Layer Wind Tunnel according to American Society of Civil Engineer (ASCE) 7-05 Standard. Results of the testing indicate a typical array to require about 1.1 lbs. per square foot (PSF) of ballast. Adding in the weight of modules and racking brings the total PSF to 3.3 lbs. This racking design would allow solar to be placed on rooftops with minimal mass impact.

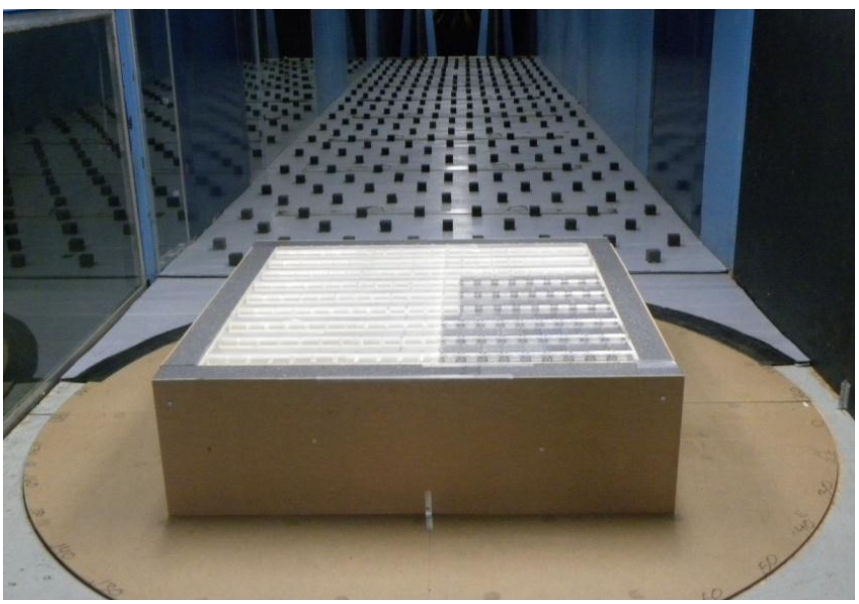


Figure 42 – Wind Tunnel Testing

Prototype tool build: The purpose of building prototype parts is to prove out the design concepts that were developed in CAD. Composite wood renboard vacuum forming tools were cut to form full size prototype parts. The tools made from CAD data. Pictures of tools for the wind deflector and base are shown in Figure 43.

Figure 43 – Prototype Tooling

Prototype part manufacturing: Vacuum forming or thermoforming was the process used to create the wind deflector and base parts. Approximately 50 parts of each were made with the prototype tools. The spacer part was made by casting 2 part urethane material into a mold that was created from SLA parts. Materials were selected to match the intended production material as close as possible.

Product Validation: Parts were assembled together and a design review was held to identify potential issues for the next phase of design modification. A small 2x2 array was place on the roof for environmental testing.

Figure 44 – Prototype Part Assembly

Design Modification: Notes from the product validation assembly build were reviewed to identify the design changes for the product. Material was added to strengthen areas, clearances noted for handling, assembly interfaces modified, and other design features as noted. These were the final design changes before tooling the next phase.

Tooling and Process Development

Tool, Fixture and Equipment Build: Tools needed to produce the racking parts in the intended manufacturing process were built during this phase. Prior prototype parts were made using alternative, lower volume, processes that did not necessarily allow the use of the correct intended materials. Tools made in this phase can manufacture parts that will mimic the intended production pieces for both material and method.

Process Development: Manufacturing of the parts involves stamping, injection molding, and wire bending. Once tools were completed, the process to manufacture each part was developed. Parts were produced and measured to verify they process was capable of producing the parts within the tolerances needed for assembly and final use in the end product.

Process Flow: Concurrently with process development, process flow was established. Process flow defines a step by step process of what it takes in materials, equipment, and labor to produce a finished good. Process flow is used to set up a Process Failure Mode and Effects Analysis (PFMEA). The PFMEA ranks the manufacturing steps and identifies high risk failures that could occur. The team then works on these areas to reduce risk and results in a more robust manufacturing process.

Product and Process Validation

Product Testing: Parts from production intended processes are testing according to the Design Validation Plan and Report (DVPR) that was identified at the beginning of this project. The DVPR calls out specific tests the product must meet. These tests are all contained within UL2703, Mounting Systems for use with PV modules, and include temperature cycling, grounding, mechanical load testing, over current testing, and other material specific tests. Intertek, an A2LA accredited laboratory, performed all the UL2703 testing. The solar rack passed all the tests.

Process Validation: All the process development items identified in the previous phase were addressed and completed. This step of process validation includes a “production” type manufacturing setup to prove out the entire production process.

Layout: Parts from the process validation run were selected for measurement. These parts were checked with a coordinate measuring machine (CMM) against their respective part prints for dimensional accuracy. Any dimensions that were out of print had modifications made to the tool or the prints were changed.

Project Closeout: Tasks in the project closeout phase are mostly clerical in nature to complete the project. Lessons learned are added to the company database, open issues are closed out, and part costs are updated.

Conclusions

The main purpose of this project was to reduce cost of materials and installation labor for a flat commercial roof solar rack. At the beginning of this FOA, hardware racking costs were $0.30/watt with labor installation costs at $0.49/watt. Cascade Engineering's FOA application identified the 2017 cost goals to be $0.19/watt for racking materials, and $0.29/watt for racking labor. The product described in this report that includes integrated grounding and is tested to UL2703 can be sold for $0.15/watt. Installation labor is expected to be $0.16 – 0.19/watt. That is a 50% reduction in material cost, and 64% reduction in labor cost. The project has exceeded the cost target goals as set up in the FOA application.

Budget and Schedule

This project was planned for a two year duration. Year 1 had a budget of $429,684 with the DOE contributing 80% ($343,747) and Cascade Engineering 20% ($85,937). All tasks were completed in the first year. Total actual spending was $347,649, with the DOE portion at $278,119, and CE cost share at $69,530. Cascade submitted a request for continuation, and was granted the 2nd year award of $517,752. This was split equally between the DOE and CE for $258,876 each. CE elected to seek out a channel partner who could eventually commercialize the product. This activity put the project on hold for approximately 1 year. Year 2 work started up again on August 1, 2013. Tasks 4, 5, 6, & 7 were scheduled to be completed by 7/30/2014. Timing slipped during the testing phase of the project. Not all parts were available for testing as planned. The project was given an extension out to 10/30/14. The project finished on 10/30/14, and was under budget. Planned project budget was $956,909. Actual spending for the project was $951,080.

Path Forward

No patents resulted in this work. The product is being marketed and is expected to be fully commercialized in the first quarter of 2015.