Final Technical Progress Report: Development of Low-Cost Suspension Heliostat

December 7, 2011 — December 6, 2012

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Subcontract Report
NREL/SR-5200-57611
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NATIONAL RENEWABLE ENERGY LABORATORY

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Background

SunShot Incubator Program

The SunShot Incubator project is a significant effort of the U.S. Department of Energy (DOE) to partner with U.S. industry to accelerate the commercialization of solar energy systems that can meet aggressive cost and capacity goals by the end of the decade. Specifically, the SunShot Incubator projects fund technologies with a disruptive potential to reach the DOE SunShot Initiative goal of an unsubsidized cost-competitive levelized cost of energy by the end of the decade. This is estimated to be approximately 6 cents/kW-hr at utility scale.

Concentrated Solar Power

Concentrated solar power (CSP) uses a large field of mirrors (heliostats) that continuously adjust their position so that they reflect the sun to a receiver mounted on a central tower. This concentrated energy can be used to make steam or heat molten salt, which can then be stored or used to generate electricity. Heliostats constitute between one-fourth and one-half of the total cost of a CSP system. Many of the remaining components of a CSP system comprise mature components, such as steam turbines and electric generators. These are unlikely to be reduced in cost, so reducing the cost of the heliostat field is one of the most viable paths to reducing the overall cost of a CSP plant.

Figure 1

Two Solaflect Energy Baseline Heliostats in Stow Mode

60% to 65% Less Steel per Square Meter at Baseline

The SunShot goals for CSP solar field costs are on the order of $100 per square meter or less[1], and ideally would cost as little as $70 per square meter[2]. However, the base case reference heliostat used by Sandia National Laboratories uses 59 pounds of fabricated steel per square meter, estimated to cost $1.00 per pound or more in large volumes[3]. It seems unlikely that the SunShot goals can be met using the base case style of heliostat, as it is optimistic to think that all other components of the heliostat, including mirrors, motors, electronics, and foundation, would cost only $11 to $41 per square meter ($70 - $59 = $11; $100 - $59 = $41).

[1] National Renewable Energy Laboratory (2011). *Solicitation for Letters of Interest (LOI)* No. REU-1-11979, pg. 35.
[2] Tex Wilkins (2011), at DOE/CSP Industry Meeting. Washington, DC: March 8-9, 2011. Personal communication.
[3] Kolb, Gregory J., Scott A. Jones, Matthew W. Donnelly, David Gorman, Robert Thomas, Roger Davenport, and Ron Lumia, (2007). Albuquerque, N.M.: Sandia National Laboratories, SAND2007-3293. Pages 47-49. Marmon-Keystone (2011): personal communication. (www.marmonkeystone.com).

Solaflect Energy's Suspension Heliostat

Solaflect Energy has developed a fundamentally new and innovative approach to heliostat design. It provides a quantum leap in material efficiency with comparable performance. The traditional heliostat is built like a truss bridge, with a large steel truss structure built behind the mirrors to hold them in place (Figure 2). In contrast, the Solaflect heliostat is built like a suspension bridge, stabilizing the mirror structure with steel cables from the front and rear (Figure 1). As with a suspension bridge, this design is very material efficient yet structurally very effective. This design, which is called a Suspension Heliostat, is differentiated from the traditional design by utilizing steel primarily in tension and compression, where it is strongest, in comparison to a traditional design, which uses a steel support structure that must resist bending. This disruptive technology has been demonstrated in a 16 m^2 heliostat to use 60% to over 80% less steel per square meter than the traditional design, allowing the SunShot cost goals to be within reach for heliostats.

Figure 2

Traditional "Truss" Heliostats

Too Much Steel to be Grid Competitive

Project Goals

There were several principal goals for this project, including:

1. Reduce heliostat costs by a total of at least $25 per square meter, when manufactured in volume;
2. Rigorously test and validate the performance of the heliostat; and
3. Create additional high-quality information that can be used to further reduce the cost and improve the performance of the heliostat in the future.

These overarching goals were achieved through five principal research and development (R&D) objectives in the project. These five objectives included:

1. Redesign the heliostat elevation assembly to reduce component cost and improve manufacturability;
2. Optically test the heliostat in different wind environments to determine the contribution of different heliostat components to overall optical errors;
3. Redesign the heliostat controller to significantly reduce costs and improve manufacturability;
4. Use a variety of accelerated testing methodologies to evaluate reliability and identify components to be redesigned; and
5. Test the cable drive system and create new design options.

Baseline Heliostat

Solaflect Energy is a small R&D-based start-up developing the Suspension Heliostat design. Two patents have been issued on this technology, and more are pending. Numerous hurdles in making this design operational have been overcome, and the concept is successfully proven. The first generation design used 28.5% less steel per square meter than the base case heliostat, and the second generation saves more than 65% of the steel per square meter.

The initial size of the Solaflect Energy heliostat is a 16 m^2 heliostat. This is composed of a four-by-four matrix of facets, each of which is 1 meter by 1 meter in size. The innovation of this heliostat is that there is a compression rod that is perpendicular to the mirrors and runs through the center of the mirror array. A side view of the heliostat in stow in Figure 1 shows that this compression element is very slender in front of the mirrors, and is structural behind the mirrors. Sets of steel cables run from the front and rear of this compression rod to the corners of each facet.

The bi-directional shading from the components in front of the mirror is very small, on the order of 1%–2%. In addition, the slight curvature of the heliostat can be seen in Figure 1. By adjusting the position of each set of cables, the individual facets are symmetrically canted to the exact slant range for each heliostat. This process is much faster than the manual canting method on each facet traditionally done upon installation. It can be seen that there is no steel superstructure behind the mirrors, in comparison to the traditional heliostat designs shown in Figure 2.

Redesign Heliostat Elevation Assembly

The elevation assembly (Figure 3) is a structural component perpendicular to and behind the mirrors. It has several functions, including forming one of the points to which the mirror connectors are attached, resisting rotational forces on the mirror structure, and controlling the elevation position of the heliostat mirrors. Table 1 indicates the success that Solaflect Energy had in reducing the material content of the elevation assembly on the heliostat. There was a nearly 50% reduction in material usage, along with a significant reduction in part count. The final prototype was manufactured using high-volume processes wherever possible. For example, cuts were made on a CNC bandsaw (see Figure 4); holes were drilled using a CNC mill; and welding was accomplished using a robotic welder (see Figure 5).

Figure 3

Robotically Welded Elevation Assembly

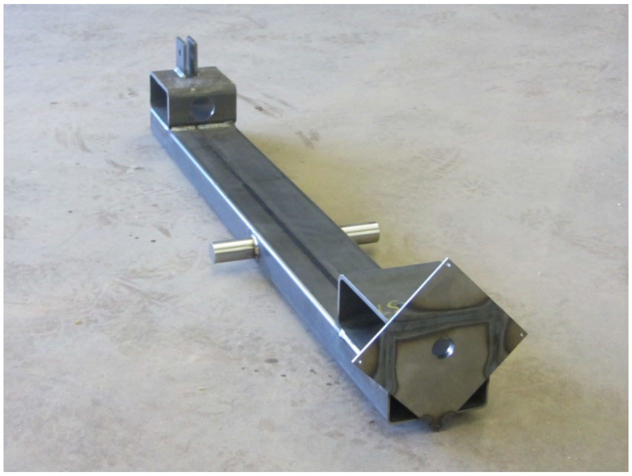


Table 1

Summary of Steel Used in Elevation Assembly

(In Comparison to Baseline Heliostat at Start of Project)

	Initial Prototype	Final Prototype
Carbon Steel in Elevation Assembly (pounds)	-39.0%	-37.1%
Stainless Steel (pounds)	-46.9%	-46.9%
"Rabbit Ears" (pounds)	0.0%	-54.1%
Part Count	-5	-8

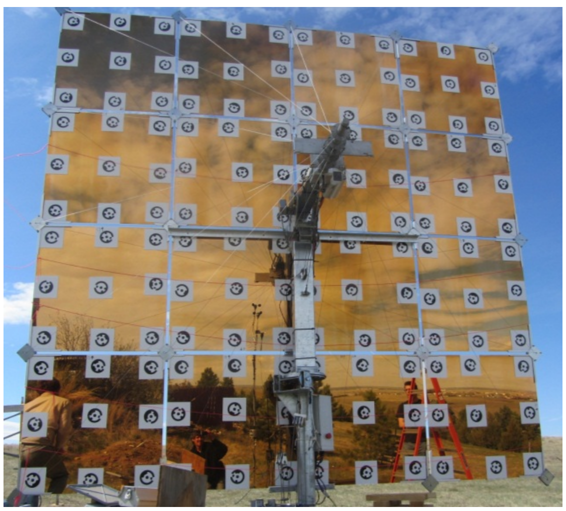


Figure 4

CNC Bandsaw

Figure 5

Robotic Welder on Elevation Assembly

Optically Test the Heliostat

The goal at the beginning of this project was for the Solaflect Suspension Heliostat to have a canting accuracy of better than 3 mrad RMS, and to have vibration of less than 5 mrad RMS in a 20 mph average wind speed. Solaflect surpassed both of these goals.

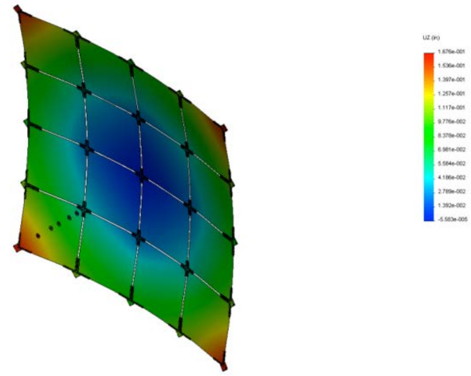
Canting accuracy was examined with three methodologies, but the primary method utilized was photogrammetry (see Figure 6). Nine photogrammetry targets were placed on each of the 16 facets on the heliostat. Photogrammetry software was used to accurately determine the location of each target. The nine targets on each facet determined the plane of the facet, and this tilt was compared to the desired canting. On multiple heliostats, the desired canting accuracy could be replicated upon installation of the mirrors. The photogrammetry calculations were in agreement with optical observations of the heliostats reflection of the sun onto a target at the focal distance of the heliostat.

Figure 6

Photogrammetry Targets Used for Measuring Canting Accuracy

Figure 7

Finite Element Analysis of Mirror Structure (Displacement)



Finite element analysis (FEA) was used to improve the canting accuracy. The basic assumption here was that the stiffness of the cables was very high relative to the transverse stiffness of the mirrors. The validity of this assumption was later investigated using FEA (Figure 7) and was found to be incorrect. Canting procedures were significantly improved by accounting for the interaction of the mirrors and the suspension structure.

Another factor found to substantially affect canting accuracy is the stiffness of the gaskets used to hold the mirrors in place. An Instron materials testing machine was used to determine the elastic modulus of the gasket material in compression for a range of strain states. A sample of these results is shown in Figure 8. It is clear that the material is highly nonlinear, but over small ranges of strain it was assumed to be nearly linear to allow for linear FEA.

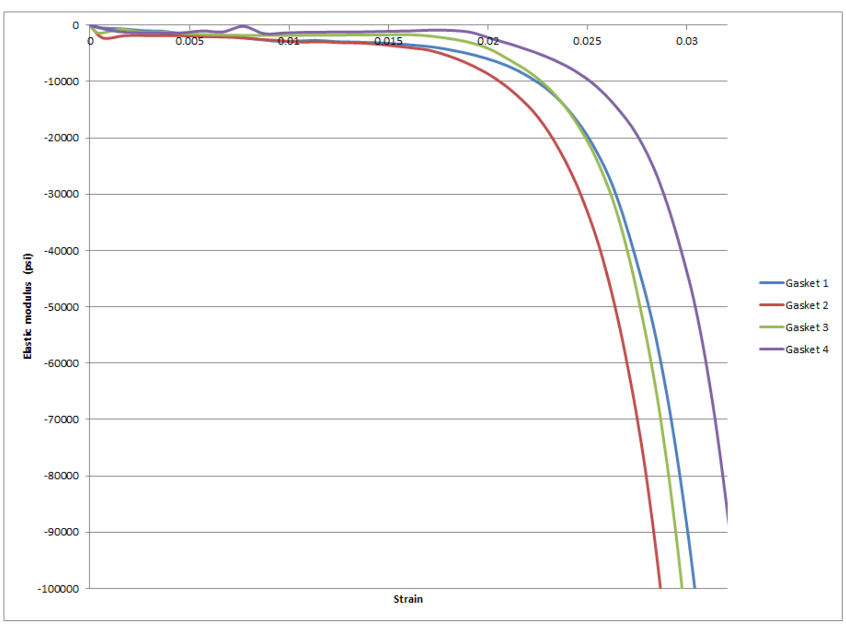
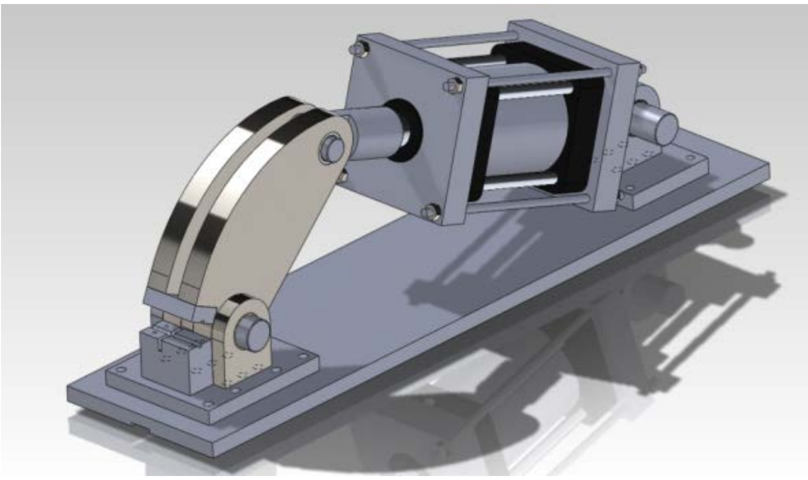


Figure 8

Elastic Modulus of Gasket Material in Compression

Figure 9

Custom Swaging Machine



Finally, an important aspect of canting accuracy is consistency in the length of the suspension cables. A custom swaging machine (Figure 9) was initially designed by a student team at the Thayer School of Engineering, and this is capable of producing wire lengths 10 times more consistent in length than the industry standard.

The vibration characteristics were measured at the high-wind test site in Cheyenne, Wyoming. At this location, winds consistently exceed 10–20 mph in the summer, and regularly exceed 50 mph in the winter. This also frequently happens in conjunction with sunny days, so it is ideal for optically measuring the movement of the reflected image of the heliostat on a receiver. The target, at a focal distance of 25 meters, is viewed by a machine vision camera at approximately 16 frames per second. Each of these images is then processed to calculate the centroid of the fully saturated white focal spot in the image. The vibration characteristics of the heliostat at differing wind speeds and relative azimuth orientations of the wind angle of attack on the heliostat were calculated from this centroid data.

Redesign the Heliostat Controller

Solaflect Energy examined a number of commercial controller options from three continents, but did not find a controller that met the cost and performance criteria for this project. As a result, Solaflect designed a new controller circuit board integrating the desired features. This is now successfully controlling Solaflect heliostats with the desired tracking accuracy. The new Heliostat Controller includes a number of desirable features relating to operation, communication, and power.

Motor control on the new controller utilizes pulse width modulation (PWM) to ensure optimal performance. Normal operation involves moves of 0.5 to 1.0 milliradians every 10 seconds or as needed. A separate circuit is utilized for a high-wind emergency stow, which requires significantly more current than normal heliostat operation. This ensures that the heliostat can successfully stow at wind speeds of up to 70 mph. The controller can receive feedback from encoders on the heliostat and/or from the heliostat area controller (HAC, or field controller) to ensure it is at the desired position. Heliostat positioning can be measured to considerably less than one-tenth of a milliradian.

The controller has been designed so that either wired or wireless communication can be used, and either wired or wireless power can be used. The preferred alternative is to use both wireless communication and wireless power to eliminate the need for heliostat field wiring. Continued development and testing is ongoing to prove reliability and longevity of the current wireless solutions in larger fields.

The controller is housed in an IP65 (weatherproof) box on the heliostat. It is designed as a field replaceable unit (FRU) to enable easy field maintenance or upgrades in minutes.

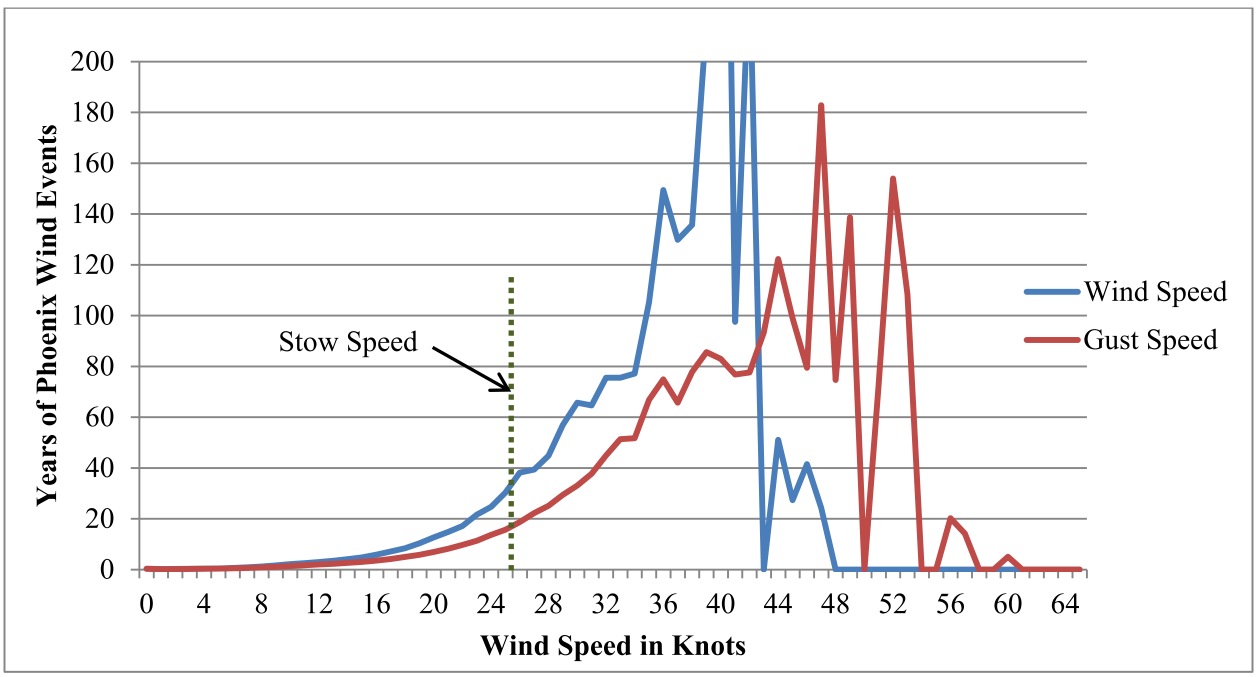
Conduct Accelerated Testing

There were two strategies for testing the performance of the heliostat in high winds. First, Solaflect Energy has a high-wind test facility in Cheyenne, Wyoming. Solaflect defines a “wind event” as a wind speed that would cause a heliostat to stow, typically around 30 mph. With this definition, it can be seen in Figure 10 that Cheyenne sees about 40 times as many wind events as Phoenix, or a full heliostat lifetime of high wind events per year of testing. This ratio is even higher for more extreme winds: Cheyenne has about 100 times as many recorded wind speeds averaging 40–45 mph when compared to Phoenix, and about 100 times as many gusts of wind in the 50–60 mph range. It is a great location to study a heliostat’s performance in high winds. Several components and design features have been modified as a result of this testing to improve performance, reliability, and longevity.

Figure 10

Cheyenne Winds as Number of Years of Phoenix Winds

(Ratio calculated from number of minutes of each wind speed in the two locations)



Second, Solaflect used a portable ground-mounted jet engine to create extreme wind events on demand (see Figures 11 and 12). Using a heliostat of the most recent design, Solaflect conducted a series of tests at varying wind speeds and heliostat orientations relative to the wind, including heliostat motions between orientations while under wind load.

Figure 11

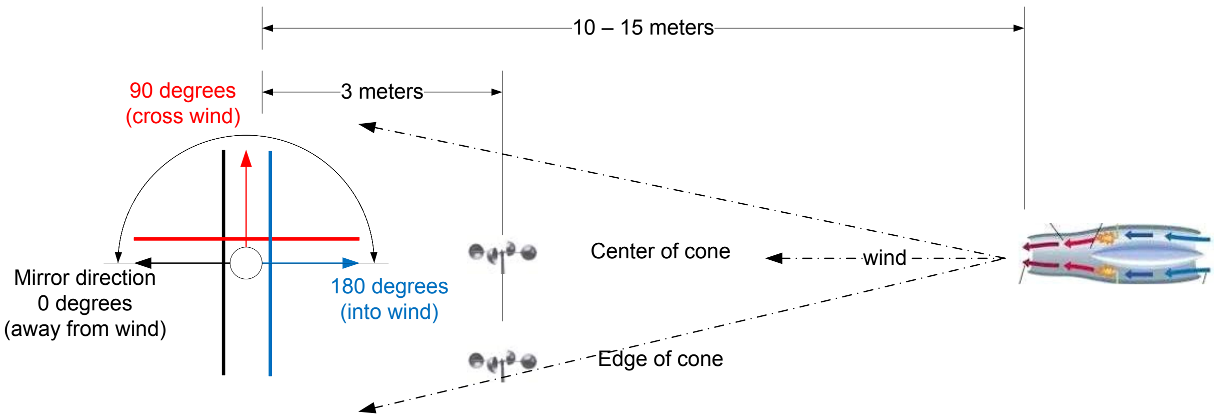
Testing Heliostat with Jet Engine

The testing indicated that the Solaflect heliostat can survive the following conditions:

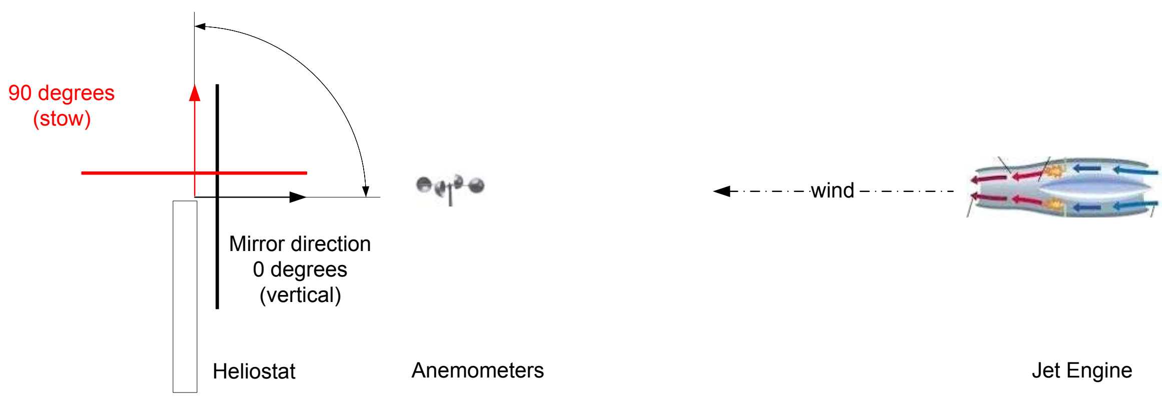
- Can survive 50 mph winds in any orientation;
- Can stow above 50 mph in multiple orientations;
- Can survive 70 mph winds with vertical mirrors in multiple orientations; and
- Can survive 90 mph winds in stow (see Figure 13).

Figure 12

Suspension Heliostat Test Using Jet Engine



Top View

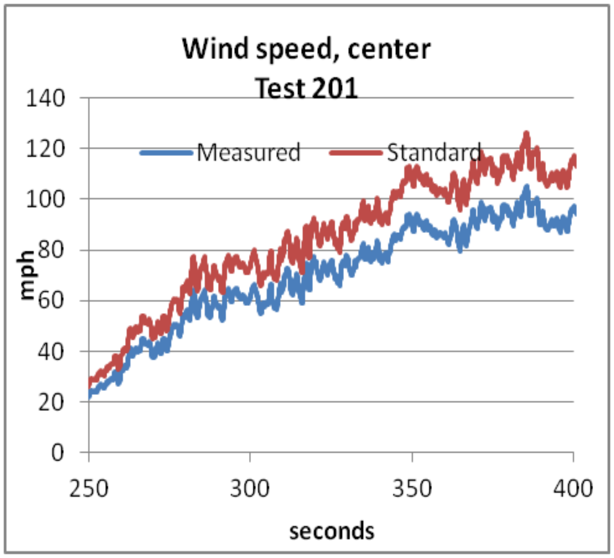


Side View

Figure 13

Sample Wind Speeds during Jet Testing

(Red Line is Standardized to Meteorological Anemometer Height of 10 Meters)



In addition to the accelerated wind testing, Solaflect also created a bank of heliostat motors that are tested under heavily loaded conditions at an acceleration rate of 48 times actual heliostat operation (see Figure 14). The accelerated testing identified a failure point in the control circuitry that has been eliminated through a redesign of the controller. These tests have continued, and most of the motors have exceeded 15 years of equivalent life by mid-December. There have been no motor failures or excessive wear other than the redesigned control circuitry. Finally, full-scale heliostats are being tested at an acceleration rate of 20 times actual operation.

Figure 14

Accelerated Winch Testing (as of October 3, 2012)

Equivalent operation time (years)									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
6.14	5.13	5.25	5.16	4.71	5.01	4.06	3.49	5.23	3.28

Test the Cable Drive System and Consider Redesign Options

As a result of the wind testing in Cheyenne and the accelerated motor and heliostat testing, it was decided to redesign the cable drive system. The revision solves a potential problem of the cable drive system becoming detensioned when the highest operational wind was coming from a particular azimuth orientation.

The major design change in the updated heliostat inverted the azimuth cable drive system and incorporated a new plastic bushing. The Pedestal Tube Welded Assembly is now much shorter and constructed of thinner-wall, less-expensive steel tubing. An additional section, the Base Welded Assembly, was added, but this configuration offers more flexibility in foundation options, including the possibility of having steel piles that extend above grade. The inversion of the azimuth cable drive also created a more straight forward manufacturing process. The previous version had rectilinear drive components attached to round structural steel tubing, and curvilinear drive components attached to square structural steel tubing. The inversion of the azimuth cable drive swapped these components so that the attachment mechanism is much simpler and less expensive to manufacture. With the cable drive more compactly secured to the stiffer vertical tube, the detensioning issue in the old design in certain wind orientations is eliminated.

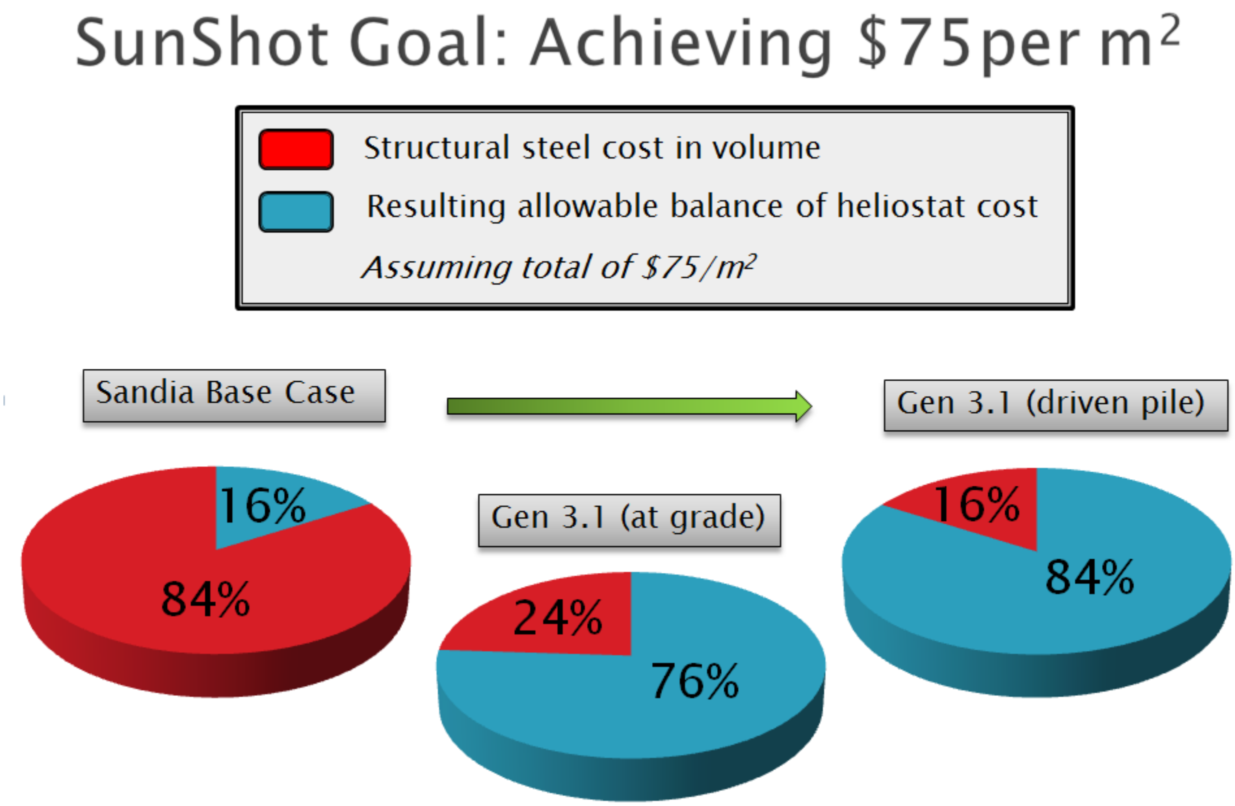
The drive system inversion also results in improved performance and easier manufacturing. The drive cable tensions have been tested and optimized to reduce drive system backlash. A significant side benefit of this redesign is that the primary heliostat shipping unit is reduced in size by 32%. This increases the heliostat packing density that can be achieved for shipping by truck, container or rail. This configuration also offers more flexibility in foundation options, enabling different foundation designs in different soil conditions.

Cost Reduction

An important goal of this project is to redesign the heliostat to enable high-volume manufacturing and to reduce the overall cost of the heliostat in volume. Costs were reduced by more than $25 per square meter through a reduction in material and improvements in the design for manufacture. The redesigned elevation assembly, discussed above, contributed more than $10 per square meter to the reduction in cost of the heliostat in large volumes. Nearly two-thirds of this cost reduction was from a reduction in steel, with the remainder composed of a reduction in fabrication costs from fewer holes and savings in labor costs. The lessons learned redesigning for robotic manufacture can be applied to additional components moving forward, resulting in further cost reductions.

An additional reduction of about $17 per square meter was obtained from the redesigned heliostat controller. This cost savings resulted from replacing individual components and wiring with a printed circuit board, with obvious savings in materials and assembly labor costs. In addition, expensive relays were replaced with solid state motor controllers, and wiring and enclosure costs were reduced.

Figure 15



In comparison to the Sandia base case heliostat, the Suspension Heliostat saves $50 per square meter in steel alone when produced in high volumes. In Figure 15, the red segments of the pie charts represent the steel cost as a proportion of the $75 per square meter SunShot goal, when heliostats are produced in high volume. The blue segments of the pie charts represent the portion of the total cost of the heliostat that can be allocated to non-steel components such as mirrors, heliostat controller, power and communication, foundation, and installation. The Suspension Heliostat design makes the SunShot goal feasible due to the extreme steel efficiency of the design.

Conclusion

The project succeeded in demonstrating that the Suspension Heliostat design is viable for large-scale CSP installations. Canting accuracy is acceptable and is continually improving as Solaflect improves its understanding of this design. Cost reduction initiatives were successful, and there are still many opportunities for further development and further cost reduction. The suspension design is inherently very material efficient, and further experience with this heliostat will continue to lead to further design and performance improvements.