RE<C: Heliostat Project Overview

Introduction

RE<C was a Google initiative to drive innovation in renewable energy, with the goal of making renewable energy cheap enough to compete head-to-head with coal-fired power plants. As part of this initiative, Google formed an engineering team to develop promising technologies in the field of solar energy power generation. After evaluating many technologies, we focused our engineering efforts on concentrating solar power (CSP), where we felt we had the biggest opportunity to innovate.

Concentrating solar power plants use mirrors or lenses to focus a large amount of sunlight onto a heat absorbing target, called a receiver[1]. On typical plants, the receiver heat exchanger creates high pressure steam, which then drives a turbine to power an electric generator. Spray water cooling is typically used to condense the steam. These CSP power plants require economies of scale to be cost effective, and are often rated at 50MW of power or more. Water use can be a factor limiting the adoption of steam CSP plants, since area with the most sunlight that would be ideal for CSP often have limited water resources.

We focused on designing and developing a modular "power tower" CSP that uses a smaller gas turbine (Brayton) engine to perform power conversion. This turbomachinery is similar in size to turbochargers for large truck or marine diesel engines, and can benefit from economies of scale pricing. Brayton engines do not need spray water cooling and are in that way better suited to dry desert environments. We discuss this in a companion document RE<C: Brayton Summary.

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[1] Information on other forms of CSP and companies working on developing them is available from Wikipedia, NREL, Sandia, and SolarPACES.

Power Tower Example: the PS10 system located in Spain
(Image courtesy of afloresm, Wikimedia Commons, 2007)

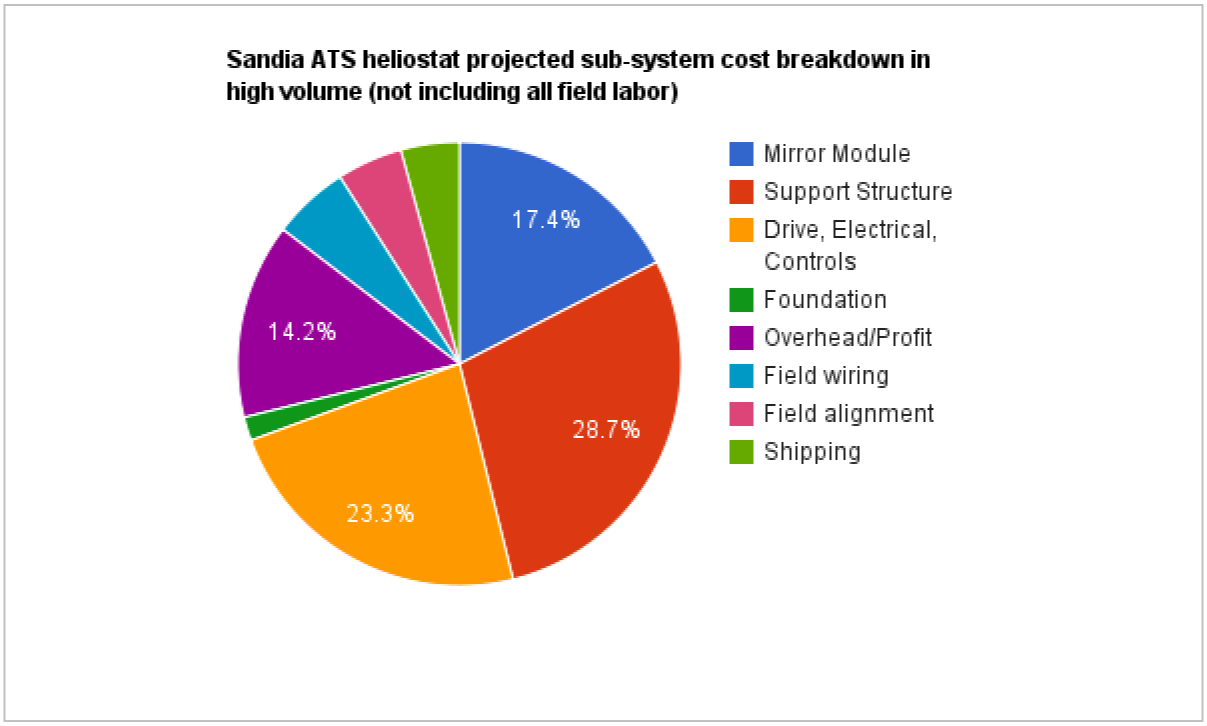
The other major component of a CSP power plant is a field of controlled mirrors, called heliostats. This field has thousands of square meters of heliostats that concentrate solar energy on the receiver of the power plant. The heliostat field forms a significant part of the cost of a CSP plant, and thus drew our attention for cost reduction opportunities.

This document provides an overview of our heliostat-related research and development, including information for cost-saving designs of reflector modules, frames, actuators, ground attachments and ways to mitigate shipping and site preparation costs. Experimental results from our control system demonstrate good results in spite of a host of challenges introduced by our heliostat design, and the more stringent pointing requirements of the Brayton power plant. Finally, studying desert wind characteristics led us to a cost-aware choice of operating conditions and wind-mitigation strategies.

Heliostat Cost Reduction Opportunities

Our primary goal was to reduce the levelized cost of energy (LCOE) for CSP plants. We applied a systems cost-benefit trade off approach and a general principle to use software intelligence and cheap electronics to enable other cost reductions.

Other approaches to heliostats have focused on large-area (>100m^2) heliostats and have large costs associated with the support structures and actuation/control schemes (see chart below). Missing from this cost breakdown is complete installation costs, which can be significant, especially with the large structures that require advanced custom equipment and large crews to install. With modern control capabilities and low cost electronics, a field of smaller ($1m^2$ to $10m^2$ per heliostat) is likely to have a lower overall system cost.[2]



Cost breakdown for the ATS heliostat production and deployment[3]

We also assumed that on a long-term scale, government incentives will disappear or shrink significantly. This is already the case in the photovoltaic industry in Europe, where individual countries provide feed-in tariffs that promote construction of large-scale solar plants, and then gradually reduce the tariffs over time.

There are many trade offs, including how large to make the reflector area versus structure and shipping cost, how light and flexible to make the structure versus how wobbly it is in the wind, how large to make the drive motors versus stowage requirements, what kind of sensors to use versus the pointing requirements, choosing the range of wind speeds over which to generate electricity, how to survive extreme wind, etc. All of these factors impact LCOE, and all influenced our focus of study and analysis, thought process and designs.

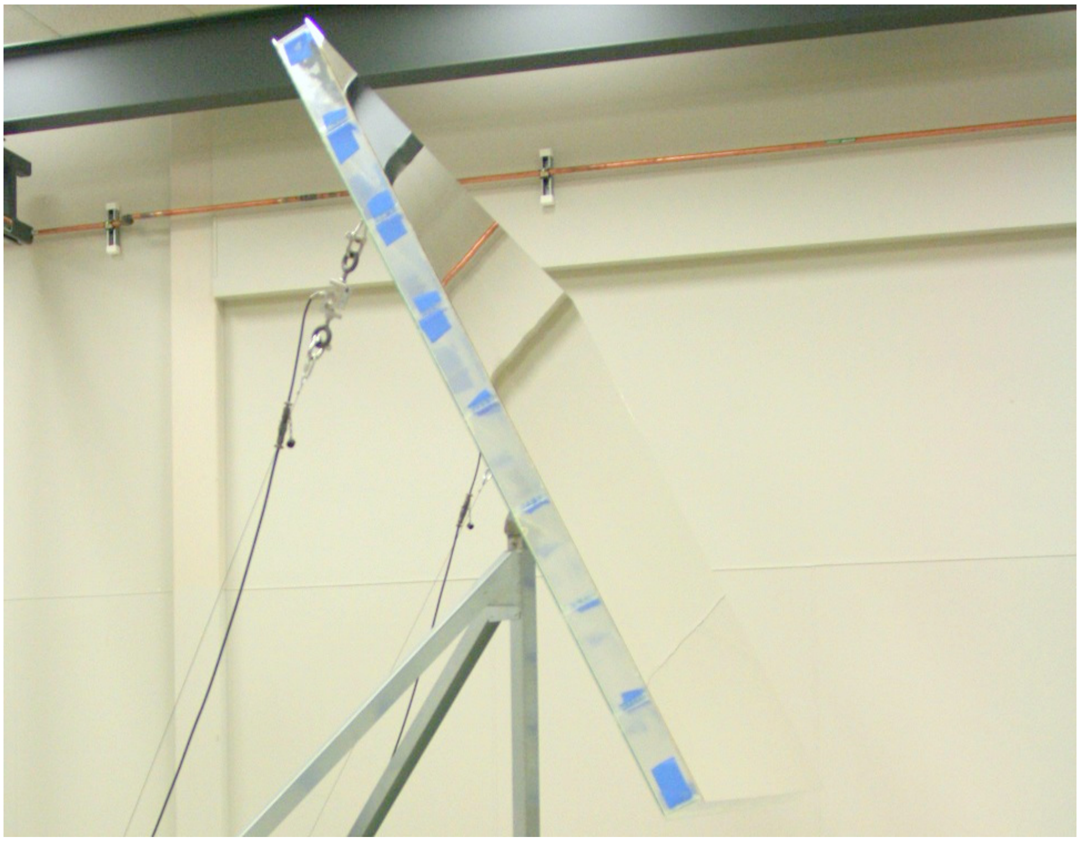
Our Heliostat Design

The Reflector Module

[2] As just one example of work in this field, see this eSolar heliostat paper from the SolarPACES 2010 conference, or look at work by Brightsource, other companies' heliostat concepts, or discussions over the past few years at the SolarPACES conferences.

[3] Cost information based on Sandia heliostat cost reduction study (2007); Shipping costs added as 6% of total heliostat component cost, not all installation costs included

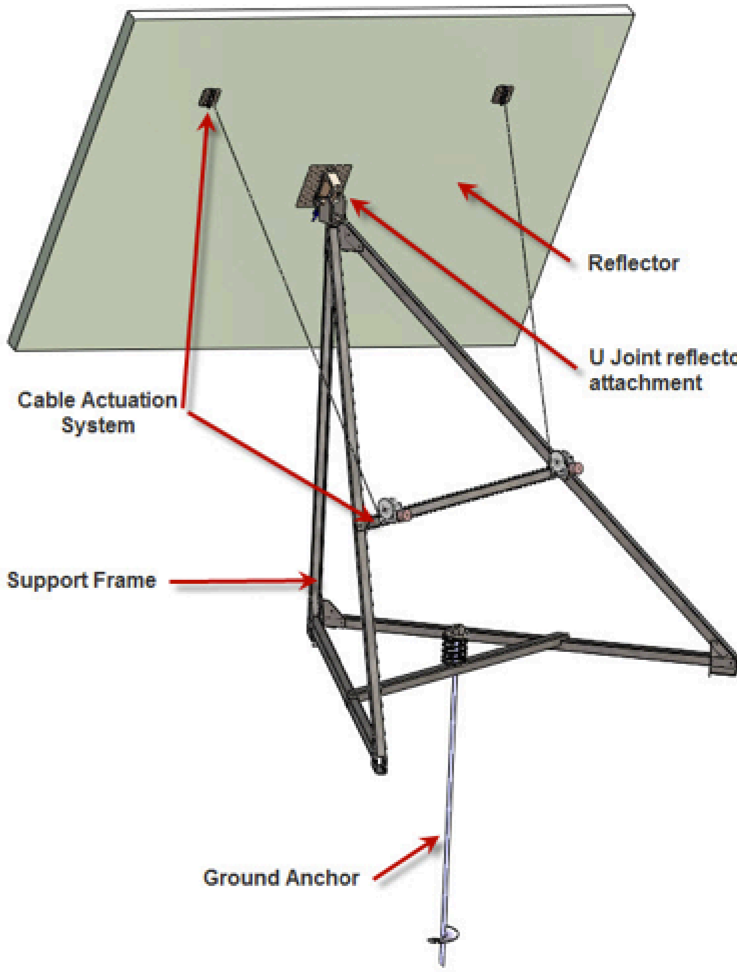
Each heliostat had a 2m x 3m focusing mirror articulated at the top of its frame. The weight of this module impacted cost, so a lightweight design was used. To avoid thermal expansion challenges, such as warpage and loss of focus, the mirror reflector module was made entirely of glass. Hail testing was done to verify compliance with industry standards. This design, including a hail testing video are provided in RE<C: Heliostat Reflector Design.



Our glass mirror module on top of a frame

The Heliostat Frame and Base

Many existing heliostat frames and bases are sturdy structures mounted on a poured concrete foundation in a site that has been graded flat. They use precision drives and large actuators to perform rigid pointing. To reduce cost, our design had a lightweight, easy to transport frame that was easily assembled and installed, and required minimal site preparation. It was held down by a ground anchor, so no concrete foundation was required. Mounted on the frame were two cable drive actuators that used cheap small motors. The heliostat had a U-joint, which articulated in pitch/roll, not azimuth/elevation, because this provided advantages for sensing and controls. Design details including a motor operation video are available in the RE<C: Heliostat Frame Design document.



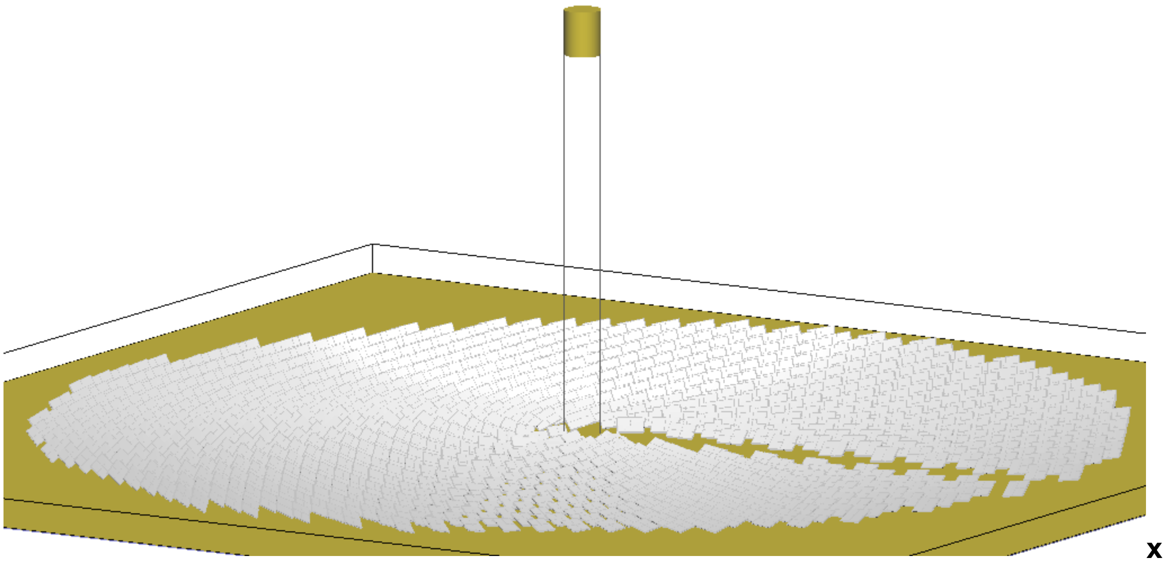
Prototype heliostat frame design

The Field Layout

Each of our Brayton engine modular power conversion systems was designed to produce a planned electrical output of 890kW per tower, which would require 2600kW of solar thermal power coming in the aperture at the receiver.

We used our heliostat optics simulation (HOpS) software to experiment with different field configurations for heliostat placement and tower height, together with heliostat kinematics and expected aiming error. This HOpS software is available as open source.

We settled on a field size of 862 heliostats surrounding a 44m tower, each heliostat being approximately 6m^2. The heliostats are laid out in a hexagonal pattern, at a maximum horizontal distance of 60m from the tower. A typical utility-scale installation would have hundreds of towers.

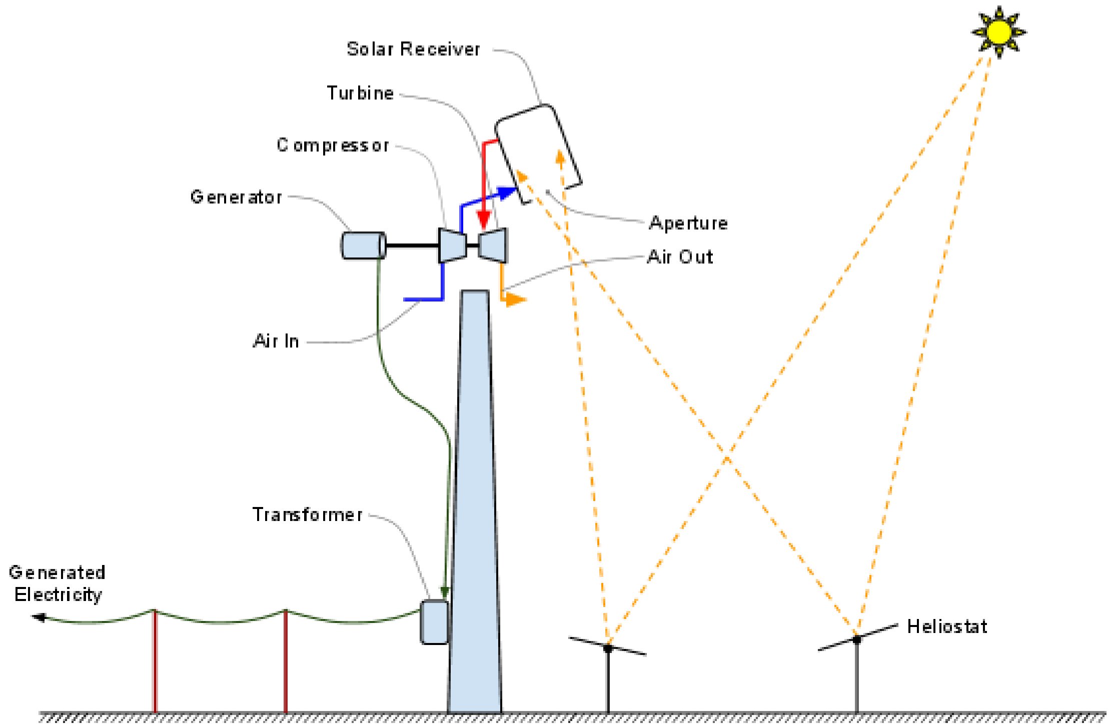


A representation of a heliostat field layout we considered with the location of the receiver shown to scale.

We considered making the heliostats have the functionality of targeting multiple towers - switching their light from one tower to another during the day to reduce cosine losses. Through simulation, we determined the gain to be only about 8% and kept with the simpler approach of having heliostats assigned to specific towers.

Control System Targeting Requirements

To convert power efficiently, the Brayton engine requires a higher temperature cavity receiver than a typical steam plant's receiver. Operating it cooler causes inefficient power conversion, while running it too hot causes catastrophic failure (i.e. melting). Ideally there should be small and infrequent changes in the heat flow through its heat exchanger. Rapid changes dramatically affect creep and fatigue, reducing the heat exchanger's life, so these are to be avoided if possible. Further details on the Brayton engine are available in RE<C: Brayton Project .



Power conversion plant and field with heliostats

A higher temperature receiver requires a smaller aperture to reduce radiant heat loss. As can be seen from the diagram above, individual heliostats need to be precisely controlled to put their light into the small aperture. Even more significantly, to extend the life of the high temperature receiver, the flux must be carefully distributed within the receiver cavity. For a controller to create such “designer flux” requires 10cm targeting precision. To achieve this, the furthest heliostats need to be individually aimed with a 1 milliradian precision.

The already tight heliostat aiming requirements are made even more challenging because of our deliberately lighter and flexible heliostat frame and reflector structure, which can bend in the wind, as well as by the simple field installation which results in small position offsets and base tilt angle offsets from ideal.

Sensing and Control System

We developed and demonstrated a control system that could simultaneously control the light spots from multiple heliostats to a high degree of precision to a desired place on a target. It tracked to compensate for the sun’s movement across the sky while also correcting for steady wind effects. By holding and tilting the frame during operation, we satisfied ourselves that it was not sensitive to the effects of foundation shifting or frame thermal expansion.

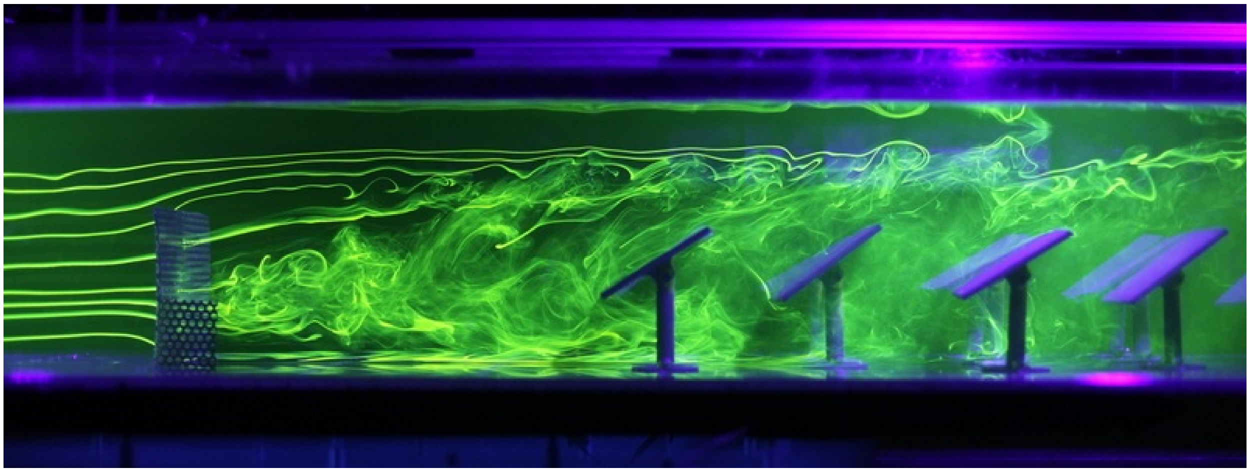
A prototype heliostat keeping light on target

We used a low-cost heliostat-mounted 3-axis accelerometers combined with a central multi-scopic photometry system to resolve individual light spot positions on target. High-level design, experimental results and videos are in this RE<C: Heliostat Control and Targeting document. The low-cost actuators are described in the RE<C: Heliostat Cable Actuation System Design document.

For more detailed information, see technical deep dives on RE<C: Heliostat Orientation Estimation using a 3-axis accelerometer, RE<C: Multiscopic Photometry for Heliostat Spot Tracking, and RE<C: Pitch/Roll Heliostat Control .

Wind Mitigation

Wind presents a particularly difficult design challenge, especially when trying to design lighter, low cost heliostats. Large, flat areas of land where heliostats are mostly likely to be built are also the areas most prone to unrestricted wind. Understanding how wind affects heliostat structure design and targeting was a large focus of our prototype development, including understanding the cost-benefit tradeoff with different wind mitigation strategies.



Scaled heliostats and a porous fence in a flow chamber

We explored several different wind mitigation strategies through analysis and experimentation (including collecting 3-dimensional high-frequency wind data in a field, and using a flow visualization chamber to understand how wind might affect structures in the field).

It appeared that heliostats along the outer edge of a field shield the heliostats in the middle from much of the impact of the wind. In addition, simple wind fences can reduce the impact of wind on heliostats dramatically. Our analysis and experiments showed porous wind fences to be the most effective. See RE<C: Heliostat Wind Mitigation, RE<C: Heliostat Flow Visualization Experiments, RE<C: Wind Tunnel Experiments, and RE<C: Surface Level Wind Data Collection documents for more information.

Conclusions

Using software and inexpensive electronics allowed us greater freedom in designing the mechanical components of our heliostats. We were able to design cheaper heliostats by relying on real-time control to keep heliostats on target, and by using a stowage position to ensure survival in high winds. Our simple hardware design also made it easy to prototype and test our systems in-house.

While our designs and test plans were geared towards building a full scale field, we ended our research project after constructing three heliostats. In experiments and demonstrations, the system largely performed as expected, keeping the heliostats' reflected light spots on target for days on end. We learned that handling glass is tricky, and also experienced a stationary mirror module structural failure.

At our project's close, we performed a detailed cost evaluation in terms of manufacturing, components, and implementation, getting high-volume quotes from manufacturers and specialized contractors. Our cost analysis projected that our heliostat field would be modestly less expensive than previous approaches. A fundamental cost challenge remains the cost of glass mirrors - a reliable and effective reflector for CSP plants.

While we have ended our internal CSP research, we've learned a lot, and we're publishing our results to help others in the field advance the state of this technology.

Acknowledgements

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We dedicate this work to the memory of Tim Allen.