

# RE<C: Heliostat Wind Mitigation

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## Overview

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. Our prototype development process focused on understanding key areas of wind mitigation, including how wind affects heliostat structure design, light spot targeting, and electric power generation. We also examined cost-benefit tradeoffs with different mitigation strategies.

A strong enough wind gust can damage the reflector or topple the entire heliostat. Heliostat reflectors are also prone to wind changes that can turn or deflect the light spot away from its intended target - either as a steady force or as irregular vibrations. The first step to addressing possible wind issues is understanding the magnitude and nuances of wind-induced deflection and the potential for wind-induced destruction.

Our design had to balance two design requirements: operating efficiently in all but the most significant wind conditions and surviving relatively extreme weather without damage. Meeting these design requirements affected our heliostat system in different ways, and the design solutions we came up with included modifications to the actual heliostat design, the landscape of the heliostat field, and the heliostat control system.

## Design for Survival

Most structures have “design for survival” requirements that specify what wind speeds a structure must be able to withstand. The civil engineering standard created by the ASCE (American Society of Civil Engineers) suggests that our heliostats remain structurally functional in 90 mph (40 m/s), 3-second wind gusts.

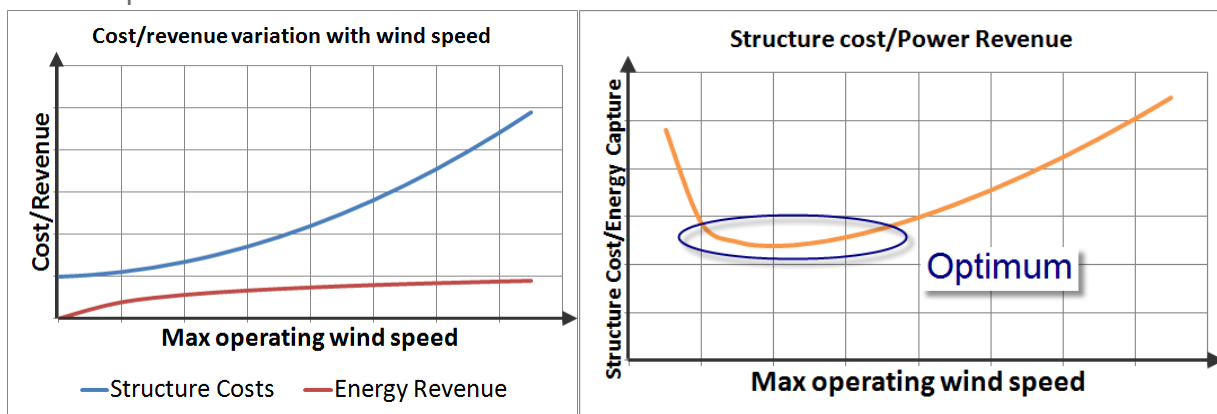
We interpreted the survival requirement as “heliostats will remain anchored and no structures will break free and cause damage to other structures during severe wind gusts”. This interpretation allowed us to decouple heliostat survival and heliostat operation for each

subsystem. For example, in severe weather, heliostats could be put into a “stow” position that will reduce the wind loads on the reflector to improve survival, at the expense of being non-operational (i.e. not reflecting any solar energy).

## Determining Maximum Operating Wind Speed

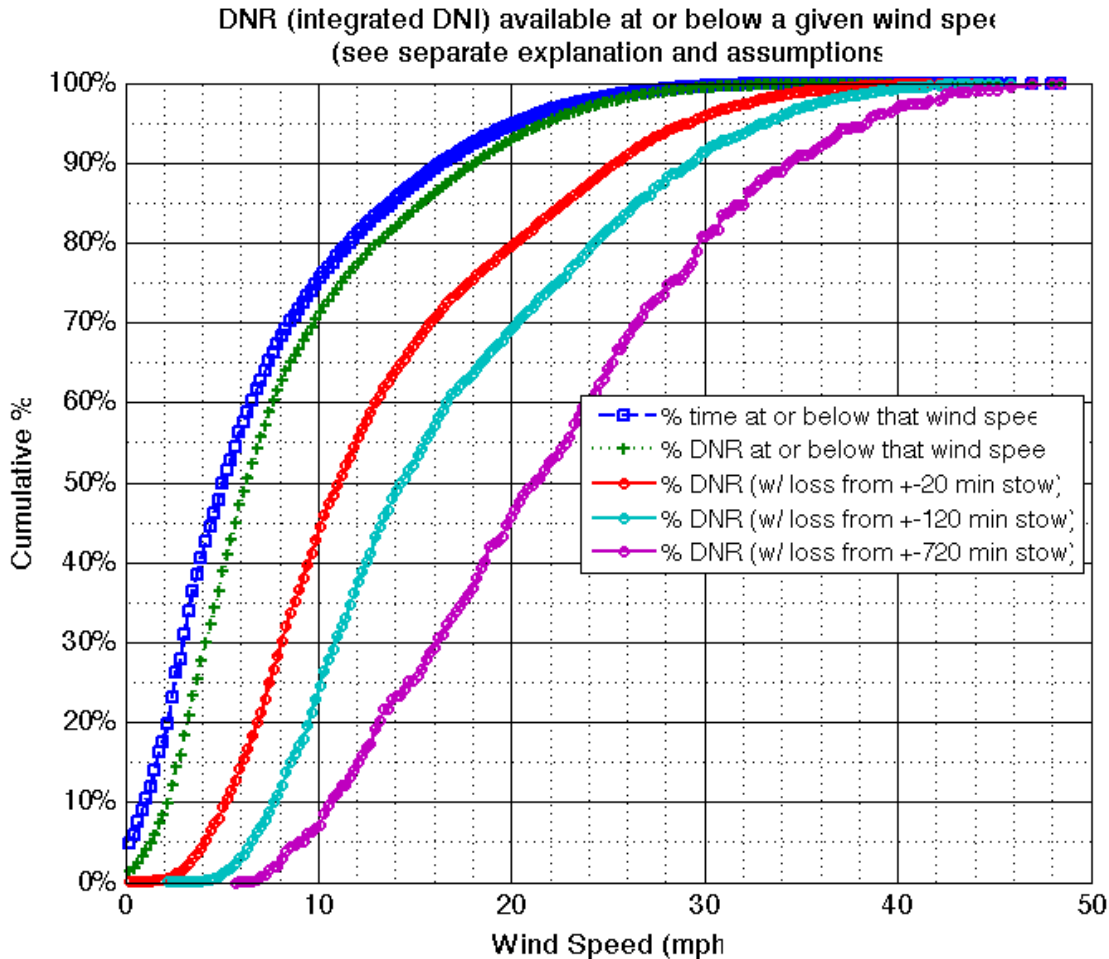
Unlike our requirements for heliostat survival, designing for optimum operation is a trade-off: the costs of achieving the largest range of operational conditions must be balanced against the benefits of doing so. It would not make sense to make the heliostat reflector and structure really stiff to operate in 40 m/s winds at a cost premium of 10%, if the resulting increase in electricity revenue is only 3%. The question that this design challenge immediately raises is “What is a reasonable range of operational conditions?”

We know that an optimum trade-off exists between heliostat cost (which is directly related to how much wind load the heliostat can withstand) and the amount of available direct normal solar radiation the heliostat could reflect (which is directly related to amount of revenue from power sales). The optimum trade-off can be found by examining the ratio between heliostat structure cost and power revenue.



**Trends comparing structure costs and power revenue with max operating wind speed**

To find the optimum trade-off for a target site, we analyzed data on annual wind speed vs. direct normal solar radiation (DNR) for a location in Nevada. We examined annual wind speeds and how changing the stowing time of the reflector impacts the percentage of annual DNR that we can collect.



**Available DNR (as a percent of total DNR available) vs. wind speed<sup>1</sup>**

From the data, if our heliostat can accurately reflect sunlight to the receiver at wind speeds up to 35 mph (15 m/s), we will capture 99% of the available annual DNR. If we limit our operational wind speed to 25 mph (11 m/s), we can capture about 90% of the available annual DNR, but we can reduce our structural costs significantly. Both of these assume that the heliostat reflector can be moved to a “stow” position within 20 minutes prior to the wind event and can return to its operational position within 20 minutes. Therefore detecting severe wind events in advance (e.g. by using locally installed anemometers) is an important operational strategy allowing heliostat stowage when necessary.

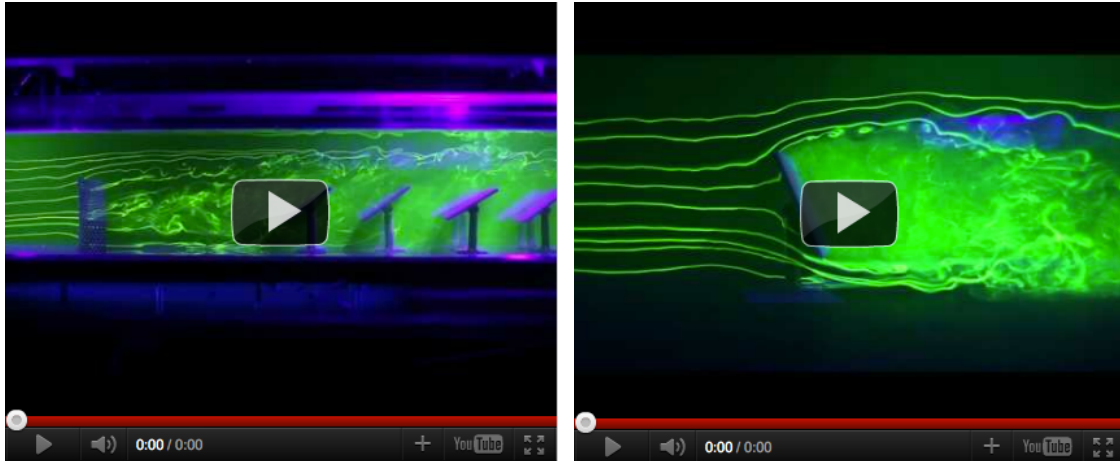
## Flow Visualization

Quick, qualitative experiments can be extremely valuable to model complex physical interactions during the development phase. We used a flow visualization chamber to understand how flow moves through a heliostat field and explore potential ways to reduce aerodynamic loading. We validated some of our expected flow behaviours and found new interesting behaviours that helped to shape other experiments in a wind tunnel. For example,

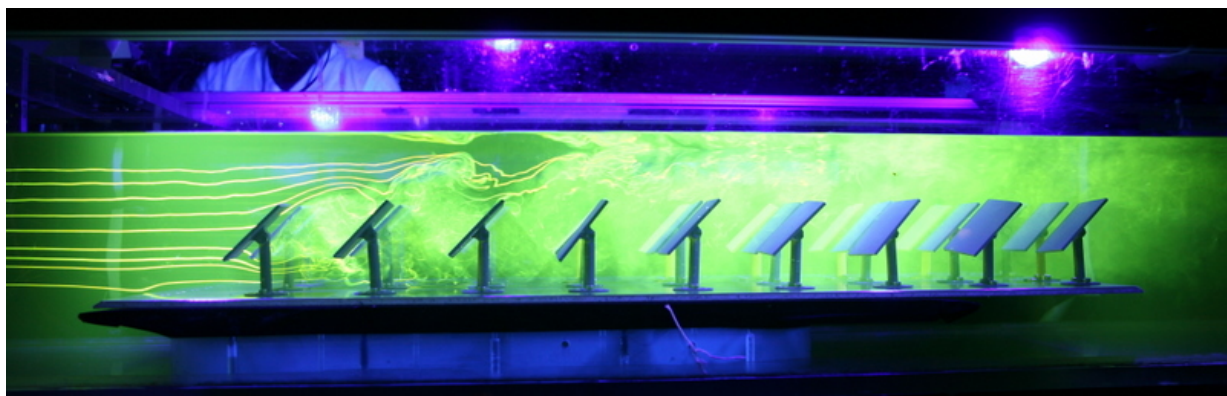
<sup>1</sup> The raw data for this study was provided from [University of Nevada - Las Vegas](http://www.unlv.edu).

we found that semi-porous fences have a significant qualitative effect in reducing air flow velocity through the field but that using solid walls, berms or mounds of earth may actually increase wind loading.

For more details and our other findings, see the [REC: Flow Visualization Experiments](#).



Videos ([left](#) and [right](#)) of flow visualization experiments



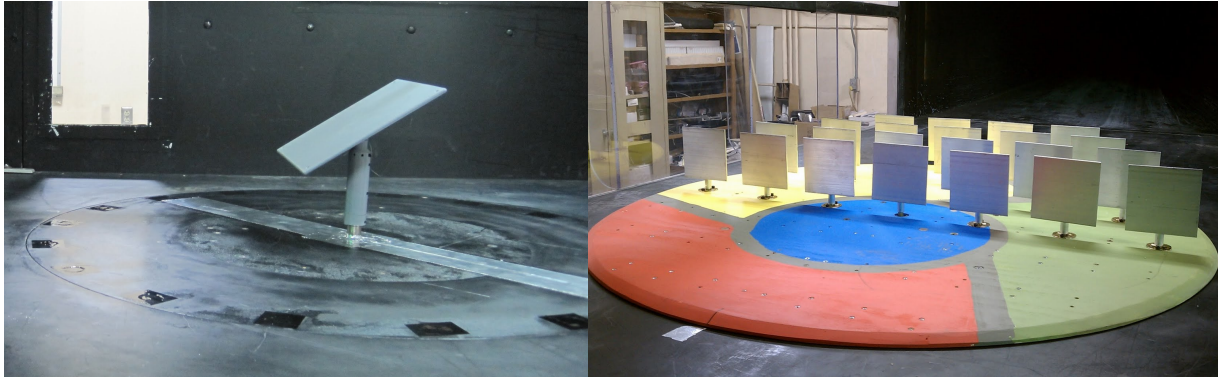
Heliostat field in flow visualization chamber

## Wind Tunnel Studies on Heliostat Loading

Static wind loading of heliostats (e.g. the forces and moments applied by steady wind) has a strong influence on the design of heliostat components. It determines how robust structural components need to be to prevent wind deflection or structural failure. To discover how wind load would affect our design, we performed a series of experiments in a wind tunnel. We gathered information on the steady state aerodynamic loads experienced by isolated heliostats and heliostats in various locations within a larger field of heliostats.

This work provided us with a set of load coefficients that we used to size heliostat subsystems. From our model, we discovered that if we stow a mirror parallel to the ground, a 90 mph (40 m/s) wind only produces 500N of lift on an isolated heliostat. There's not much of a difference between that force and the 400N force expected while the mirror is operational in 25 mph (11 m/s) winds.

For more details and our other findings, see the [RE<C Wind Tunnel Experiments](#) document.



**Left to right: Single heliostat and heliostat field models in wind tunnel**

## Surface Level Wind Data Collection

Surface level wind characteristics are important to the design of systems subject to the open environment. Numerical modeling and wind tunnel testing cannot easily replicate the true conditions that exist in nature due to the significant impact that the local terrain plays in surface wind characteristics.

Geography plays a key role in wind formations, and as the flow visualization shows, turbulence and vortex formation have significant effects on heliostats. To gain a better understanding of wind speed and wind characteristics, we needed high-frequency sampled wind data. When we couldn't find any public data that met our needs, we decided to create our own.

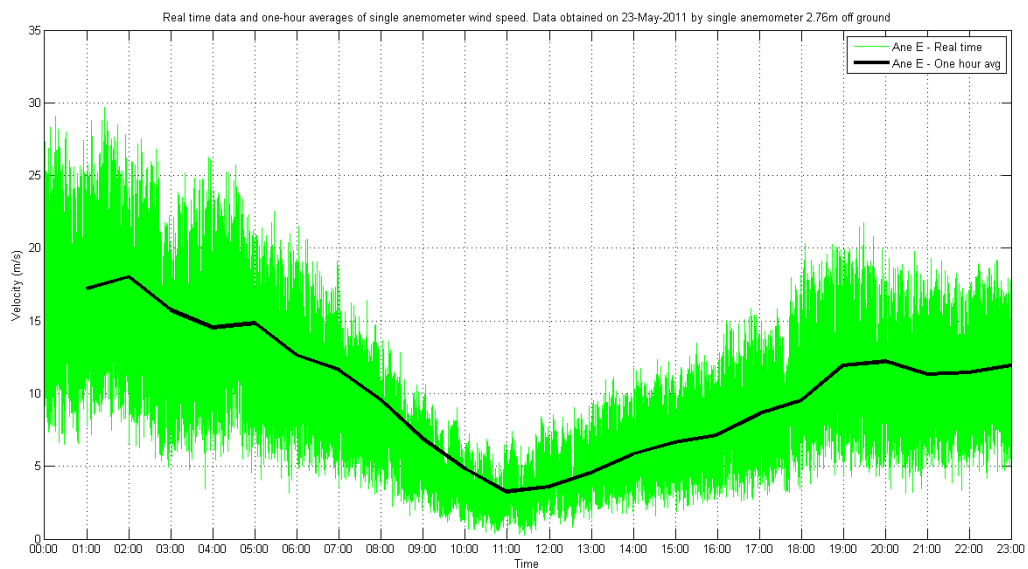
We set up an array of anemometers to measure the wind speed and direction for a period of one month at a location known for significantly gusty wind conditions, near Tracy, CA. This data was sampled at 7.6 Hz, or about 1 sample every 0.13 seconds.

For more details and the full data set, see [RE<C Surface Level Wind Data Collection](#).





**Google's anemometer array for measuring surface wind characteristics**

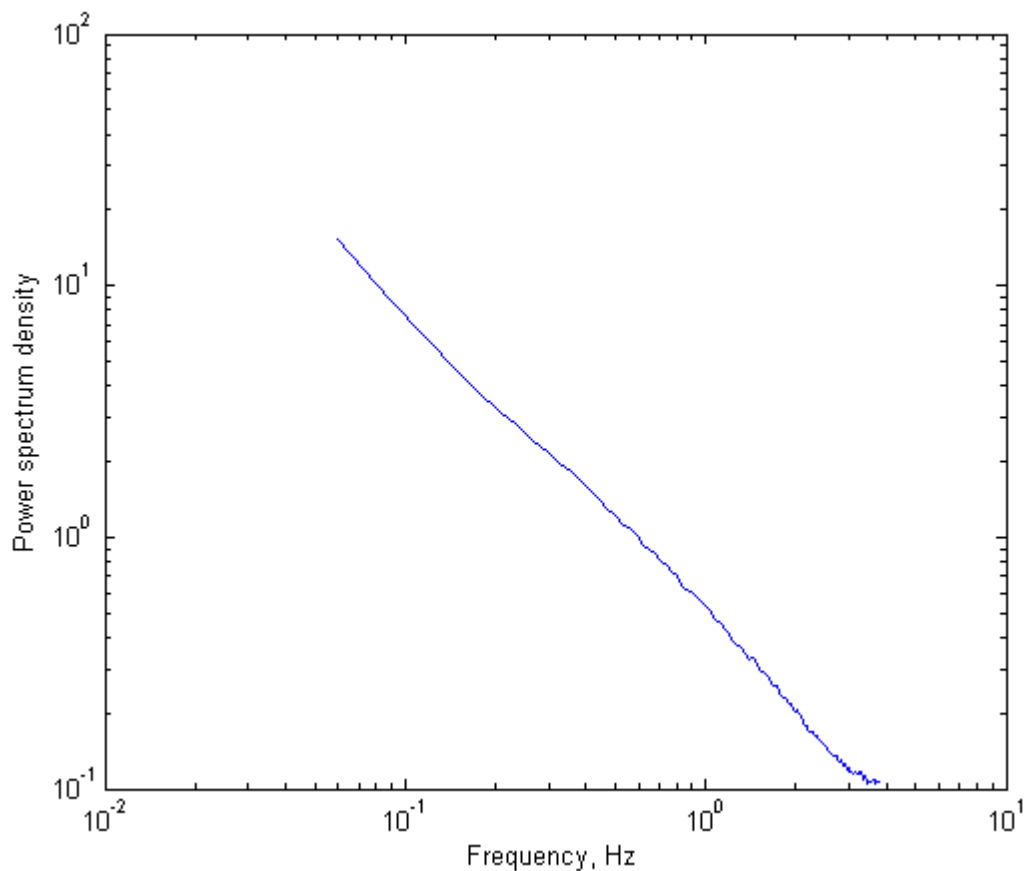


**Sample data from single anemometer from 23-May-2011: Green is real time wind speed and black is the 1 hour average wind speed.**

## Wind Implications for Targeting

The targeting control system we developed has limited ability to compensate for gusty wind. Realistically, its one-second response time limits it to compensating for heliostat deflections due to steady wind forces.

The wind, however, is clearly not steady and in fact quite gusty, as the green “noise” on the anemometer data graph above highlights. This gustiness, as well as turbulence and vortex shedding (as seen in our steady [flow visualization testing](#)) even from steady wind results in mirror vibrations. These mirror vibrations result in on-target reflected light spot oscillations at frequencies beyond which the control system can respond to. Of course, not all oscillations of light spots result in significant power generation reduction, but it is useful to understand what aspects of wind result in the biggest losses.



**Power Spectral density of wind, taken from a sample of the recorded wind data**

The above plot shows that the rolloff of power in the wind is roughly proportional to frequency. A wind speed change that takes 10 seconds (0.1 Hz) has ten times more power than a wind speed change that takes 1 second (1 Hz). Different frequencies of wind change affect different components on the heliostat and require different compensation strategies.

These frequencies can be broken up into three bands, shown in the chart below:

Frequency Band	Example	Compensation
Low-frequency: (less than 1 cycle/minute)	Steady wind from a fixed direction.	Feedback control system compensates directly for steady wind-induced spot position error.
Mid-frequency: (1/10 to 10 cycles/second)	Wind gusts, shifts in wind direction., and vortex shedding	Reflector motion could be dampened using passive viscous damping devices such as <a href="#">dashpots</a> .
High-frequency: (more than 10 cycles/second)	Turbulence and wind mixing.	The mass and inertia of the heliostat reflector dampens wind induced oscillation increasingly effectively with higher frequency.

The feedback control system compensates for low frequency wind changes, and the inertia of the heliostat prevents high frequency wind disturbance. This leaves the middle frequencies where neither the control system nor the mirror module's mass and inertia counteract the oscillating wind power.

Several options exist to damp these mid-frequency wind-induced vibrations without costly modifications to the heliostat control system or structure. We believe that the most effective strategy to damp these vibrations would be to develop a passive damping system using viscous dampers. Dampers could reduce heliostat reflector motion by connecting to stationary anchors, such as a damper connection from a heliostat corner to an anchor in the ground,. Alternately, damper connections can be to points that move in non-correlated or anti-correlated ways, for example the upper left corner of one heliostat can have a damper connection attached to the lower right corner of the one behind it.

## Conclusions

Close investigation of wind effects on heliostat behavior shaped our development of wind mitigation strategies. Operationally, heliostat reflectors need to be able to withstand 25 mph (11 m/s) winds and be able to orient into a stowed position within 20 minutes in order to collect 90% of the available solar energy. Anemometers can be installed around the field to predict approaching wind, allowing sufficient time for heliostat reflectors to reach stow.

At a field level, several simple strategies can be employed to reduce aerodynamic loading. Installing a porous perimeter fence similar to a snow fence around the field can easily cut aerodynamic loads in half. In addition, tightly packing heliostats can make the most effective use of a wind block, and heliostats in the middle of a field are protected from the wind by heliostats located near the perimeter.

Lastly, the closed loop control system can compensate for extremely low frequency wind induced deflection and the mass of the reflector can compensate for high frequency changes. However, there may be a frequency band in the middle that neither strategy mitigates. If this is



the case, viscous damping or dashpots may need to be incorporated into our heliostat design and installation to improve reliable light spot targeting.