State of the Art in Heliostats and Definition of Specifications

Survey for a low cost heliostat development

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Executive Summary

The concentrator system in Central Receiver - Concentrating Solar Power (CR-CSP) technologies consists basically of a field of heliostats each with mobile reflective surface to maintain "stable" point of rerouting of the direct sunlight and a tower that supports a receiver or reactor. This concentrator system can represent up to 50% of the investment costs of the CR-CSP, so that the cost reduction of this element is clearly one of the strategies to make this technology competitive.

Specific heliostat costs are a function of its size, with various factors favoring the choice of small heliostats and others who seek to reduce specific costs by developing heliostat of increasing sizes. Since the market of CR-CSP is still young it does not offer optimal solutions for heliostats that fits-all projects but, on the contrary, each project and / or promoter faces the choice of a design and size suitable or optimal for each particular case. This is reflected in the wide variety of designs and sizes of heliostats developed as prototypes and the diverse selection of prototypes for implementation in R&D, demonstration and / or commercial CR-CSP plants.

The optimum heliostat size — if in fact one exists — will be better understood as the power tower industry continues to deploy and operate more systems. Power tower industry is forced at least by market and commercial constrains to design and produce optimum (cost-effective) heliostats, in the near, medium term to significantly reduce capital cost of CSP becoming more and more competitive in the energy market, CR technologies have the potential of leading Solar Power through effective cost reduction to competitiveness.

Starting with initial heliostat efforts in the early 1970s up to today, there has been a general tendency to increase the heliostat size from about 12 m^2 to approximately 150-200 m^2, with several counter-examples of much smaller heliostats, primarily in the past several years. So that, currently, there is no consensus among CR-CSP developers regarding the optimum size of a heliostat.

The tendency to favor larger heliostats during this period has apparently been based more in local experiences while building and testing the first prototypes than in a holistic analysis of the problem, leaving aside the benefits of mass production, lean manufacturing processes in terms of quality control and cost reduction both demanded by CR technologies in part on the assumed advantages of “economies of scale”. An expected benefit with larger heliostats was that the fixed cost of some components that are needed per each unit of heliostat could be spread over a larger area, thus reducing the specific cost per unit area. Other factors may have played a role in this general trend, such as availability of commercial drive units potentially offering high performance and low cost, or relaxing design criteria to achieve lower costs by increasing the reflector area to the maximum allowable for a given drive unit. In efforts to reduce the cost of the drive, a number of customized drive products have been developed by companies such as Sener [Lata2010], Flender Siemens [Siemens2008, Teufel2008, Kunert2009], Winsmith [Kolb2007, Winsmith2003] and Cone Drive [ConeDrive2013]. For smaller heliostats, the cost of the control and communication system also becomes an important cost driver favoring larger heliostats.

On the other side, a number of R&D institutions are presently developing very small heliostats: NREL ~6 m^2, DLR 8 m^2 and CSIRO 4.5 m^2 [US-DOE2013b, Pfahl2013, Schramek2009]. However, as size is reduced to a scale equivalent to other volume manufactured commodity items, a number of drivers relating to manufacturing and assembly become more relevant, such as:

- **Production volume**: smaller size means more heliostats, hence higher production volumes for components

- **Use of products that are ready-made and available for sale to the general public**: similarity to a wider breadth of industries helps when sourcing high volume manufactured components e.g. motors, gearboxes, bearings, etc.

- **Feasibility of a wider range of manufacturing processes**: specialized components are of a size more likely to take advantage of low-cost manufacturing processes e.g. casting, stamping, roll forming, etc.

- **Feasibility of standard assembly processes**: components better suited to automate assembly e.g. using robots, materials handling systems, smaller assembly buildings or even transportable assembly systems, such as the process for the assembly and installation of heliostats – called the Flexible Assembly Solar Technology (FAST) and proposed by BrightSource – to substantially reduce the costs and construction time of the solar field in solar power tower projects, [Koretz2013].

- **Simpler transport**: results in simpler logistics and more feasible off-site manufacturing.

These cost drivers all favor reduced scale, and have the impact of lowering specific cost for small sized heliostats. For example, a high volume ready-made and available component is the linear actuator used in smaller heliostats. They are relatively inexpensive at small scale as they are mass-produced for a wide variety of industrial and domestic applications. There are a number of other drivers favoring smaller heliostats that are unrelated to manufacturing and assembly, including a lower design wind speed, due to the wind velocity gradient and the closer proximity to the ground, and improved optical performance [Kolb2007].

This report on the heliostat state of the art aims to introduce the opportunities for cost reduction (with the objective of reducing the cost to €100/m² by developing small size heliostats), in consistence with required functional specifications and to review the actual heliostats deployment worldwide.

1 Introduction

The context for this review report on “heliostat’s state of the art and specifications” is the Concentrating Solar Power industry, (CSP), which is taking off since 2007 and has achieved a total power in operation of 3957 MW_e (as of March 2014, [CspToday2014]).

However, for the CSP industry, in 2013 began a phase of uncertainty – with strong competition in the solar sector from PV, a moratorium on renewable energy plants in Spain, and a slow recovery from the global financial crisis – and, at the same time remained a promising deployment, with 1.2 GW_e under construction and 2.8 GW_e under development.

At present, strongly funded research programs are in place, with aggressive levelized cost of energy (LCOE) targets, such as the U.S. SunShot program, with a 0.06 USD/kWh target [SunShort2013], and the Australian Solar Thermal Research Initiative (ASTRI) program, with a 0.12 AUD/kWh LCOE target [CSIRO2013], both by 2020.

Two technologies cover almost the entire world STE capacity currently in operation: Parabolic Trough (PT-STE), with about 87 % of the total capacity and Central Receiver (CR-STE), with about 12 % of the total STE capacity (as March 2014). Although the current deployment of the CR-STE is less than PT-STE, looking to the projects under development or planned, the relative deployment of the CR-STE is more balanced (almost equal) to the PT-STE. The main reasons of this trend are the higher potential to attain lower costs of electricity by designing more dispatchable, efficient and modular technology as the CR-STE with respect to PT-STE.

The CR-STE system consists of an array of tracking mirrors, or heliostats (in a number that ranges from a few hundreds to hundreds of thousands, depending on the nominal power of the plat or facility, on the capacity factor, the heliostat size, etc.), which are spaced in a field to avoid mechanical or optical interference with one another as they pivot to reflect incident direct-beam sunlight onto an elevated receiver or secondary reflector. The receiver is designed to effectively intercept the concentrated incoming sunlight (solar energy) and (usually) absorb it as heat at an elevated temperature. This energy is collected by a working fluid and stored as thermal energy, used to drive an electrical generator, or used as process heat.

According to [*Wikipedia-heliostat*], a **heliostat** (from *helios*, the Greek word for sun, and Latin *status*, stationary) is a device that includes a moving mirror surface, as a function of the apparent movement of the sun, so as to keep reflecting sunlight toward a predetermined target, usually a receiver or reactor supported on the ground by a tower. To do this, the reflective surface (usually one or several mirror facets) is kept perpendicular to the bisector of the angle between the directions of the sun and the target as seen from the reflector aperture surface. In almost every case, the target is stationary relative to the heliostat, so the light is reflected in a fixed direction.

Major heliostat system components include the reflection module, drive mechanism, foundation, structure and controls.

The movement of most modern heliostats employs a two-axis motorized system, controlled by a computer. Almost always, the primary rotation axis is vertical and the secondary horizontal, so the mirror is on an altitude-azimuth mount.

Heliostat sun tracking is usually implemented as a distributed control system which includes a local control for solving the heliostat positioning and a central control for assigning the aiming strategy. The processor or microcomputer included, usually, in the local control is given the latitude and longitude of the heliostat's position on the earth and the time and date. From these, using sun position equations, it calculates the direction of the sun as seen from the mirror, e.g. its compass bearing and angle of elevation. Then, given the direction of the target, the computer calculates the direction of the required angle-bisector, and sends control signals to motors, often stepper motors, so they turn the reflective surface of the heliostat to the correct alignment. This sequence of operations is repeated frequently to keep the mirror properly oriented.

The heliostat structure and foundation must withstand any load that can appear in any operating condition during its operational lifetime, estimated in the order of 20 to 30 years, and under the full range of temperature and environmental site conditions, without permanent damage. Usually the loads to withstand are due to wind, that imposes moments over the heliostat mechanical structure in accordance with the so-called “area to the three-halves law” for uniform wind speed[1]. Moreover, wind speeds are smaller for short heliostats that are closer to the ground. Therefore, this mechanical specification is more easily achieved by small size heliostats. So that, as the heliostat size increases the higher loads on a per unit area increase the weight and cost of the heliostat’s load-dependent components.

Nowadays, most heliostats are used in concentrating solar power plants (either demonstration or commercial) to generate electricity. A few are used experimentally in research facilities for other applications. Section 3 includes a list of projects that incorporate heliostats worldwide. As a summary, Table 1 shows the total number of heliostat identified by purpose and status of the project or facility (as of March 2014).

Besides these heliostats a number of prototypes have been designed and tested since the 70s, many of which have not led to mass productions (either small or large), but left a number of lessons learned that have served for the development and improvement of the state of the art. Some articles in the literature survey many of these developments ([Pfahl2013], [Mancini2000], [Kolb2007]).

Table 1: Number of heliostats by purpose and by deployment status[2]

Purpose/Status of the Project	Decommissioned	Operational	Under Construction	Development	Planned*	With-drawn	TOTALS
Commercial		181,851	238,730	357,170*	10,600*	21,222	809,573
Demonstration	1,926	41,120		510*	(*)		43,556
R&D facilities		3,881		50*	(*)		3,931
							857,060

[1] Both strength and stiffness requirements are typically considered in heliostat designs. Both can be shown to be dependent on the so-called ‘three-halves power law’. For a constant wind speed with height the imposed wind load force, F, on the heliostat is proportional to the wind pressure, P, times the reflector area, A. Assuming a characteristic moment arm can be associated with the square root of the area, a representative moment is this force times the square root of the area. Thus, a characteristic moment is given by: $M = FA^{1/2} = PA^{3/2}$ and the moment per unit area, M/A, is: $M/A = PA^{1/2}$. This law also applies to drive units, motors, pedestals, foundations, etc.

[2] Several of the projects under development or planned have not published the selection of heliostat design (size, number, etc.). Thus these figures are only accounting for the projects that have already placed and published that heliostat selection.

This report on the state of the art surveys the actual heliostats deployment worldwide and introduces the functional specifications both for generic heliostats and the particularities for a small heliostat that may cost below 100 €/m^2.

2 Heliostat Optional Designs

It should be noted, that the component called “heliostat” itself is very much independent from the rest of the key components of a central receiver system, taking into account overall system considerations; that is, unique heliostat designs are not required for each type of receiver heat transport fluid, receiver configuration, or end use application of thermal energy. Furthermore, different designs can be merged sharing a single heliostat field. This independence permits designs emphasis to be placed on mass production as a means of reducing the unit cost of the heliostat, recognizing that the collector system represents a major portion of the overall system cost. The heliostat cost can be reduced by taking more profit of each component (e.g. moving bigger reflecting areas with the same drives) or by reducing specifications and thus the costs of the components (e.g. loads on small heliostats are much lower thus leading to simpler and cheaper mechanical structures).

The **history of design and deployment** of heliostat fields is well documented ([Falcone1986, Kolb2007], etc.). First experiments were in the 1960s by the University of Genoa, including construction of a field of 121 heliostats. During the 1970’s six power tower plants were constructed worldwide, from 500 kW_e to 10 MW_e. This period also originated the azimuth-elevation tracking glass/metal pedestal design, which had extensive research, development and testing throughout the 1980s, and is the most common heliostat type operating in commercial power towers today.

Over the last several decades, heliostat designs have used conventional glass and steel, pedestal-mounted elevation-azimuth designs, but alternatives include ”ganged heliostats”, carousel heliostats on tracks, stretched membrane reflectors, inflatable (bubble) enclosures, shared support, venetian blinds, etc. Various examples are listed in Table 2 and some are shown in Figure 1**.**

Table 2: Selected heliostat development programs 1970-2010 (taken from Blackmon in [Lovegrove2012] with additions)

Year (approx.)	Program	Prime contractor or location	Size (m^2)
1970	Trombe Heliostats	France	45
1973-1974	National Science Foundation	University of Houston/McDonnell Douglas	13.4
1975-1977	Pilot plant	Boeing	48
	System Research	Martin Marietta	41
	Experiment	Honeywell	40
		University of Houston/McDonnell Douglas	31.4
		University of Houston/McDonnell Douglas	37.5
1977-1979	Central Receiver Test Facility (SNLA)	Martin Marietta	37.2
1978-1979	Pilot Plant Prototypes	Martin Marietta	39.9
		University of Houston/McDonnell Douglas	44.5
1979-1981	Second Generation Heliostat	Boeing	43.7
		Martin Marietta	57.4
		University of Houston/McDonnell Douglas	56.9
		Arco (Northrup)	57.8
1980-1981	Pilot Plant (Solar One)	Martin Marietta	39.9
1980’s	CESA-1 (PSA-facility-Spain)	CASA	40
		ASINEL	65
		SENER	40
1981-1986	Large Area Heliostat	University of Houston/McDonnell Douglas	90
		Arco	95
		Arco	150
		Solar Power Eng. Co.	200

Year (approx.)	Program	Prime contractor or location	Size (m^2)
1984-1986	Stressed Membrane (SM)	Solar Kinetics Inc	150
		Science Applications	150
1990	Stressed Membrane (SM)	Science Applications International Corp.	100
mid-1990s	SM, but with glass	Solar 2/Spain	150
	GM-100	CIEMAT	105
mid-1990s	USISTF High Concentration Solar Central Receiver	University of Houston/McDonnell Douglas/HiTek Services	9.2
mid-1990s	ASM-150	Steinmüller (Germany)	150
1995-2000	Gher S.A. Hellas 01	Gher S.A. (Spain)	19.2
	Colon-Solar	Inabensa	70
	Sanlucar90	Inabensa	90
	Sanlucar90-Hydraulic drives	Inabensa	90
2006	Existing Amonix PV Tracker Converted to a Heliostat	APS (proposed)	320
2006-2007	PS-10 and PS-20 (Sanlucar 120)	Planta Solar (Abengoa, Spain)	121
2006-2008	Carpe Diem HelioCA 16	DLR	16
2006-2009	SHP (Australia)	DLR-Julich, Germany	8
2007	CSIRO (Australia)	CSIRO National Solar Energy Centre Solar Towers	4.5
2009	BrightSource	Solar Energy Development Center, Rotem, Negev, Israel	14.4
2010	eSolar Sierra SunTower	eSolar, Inc (Five 1 sq. meter)	5

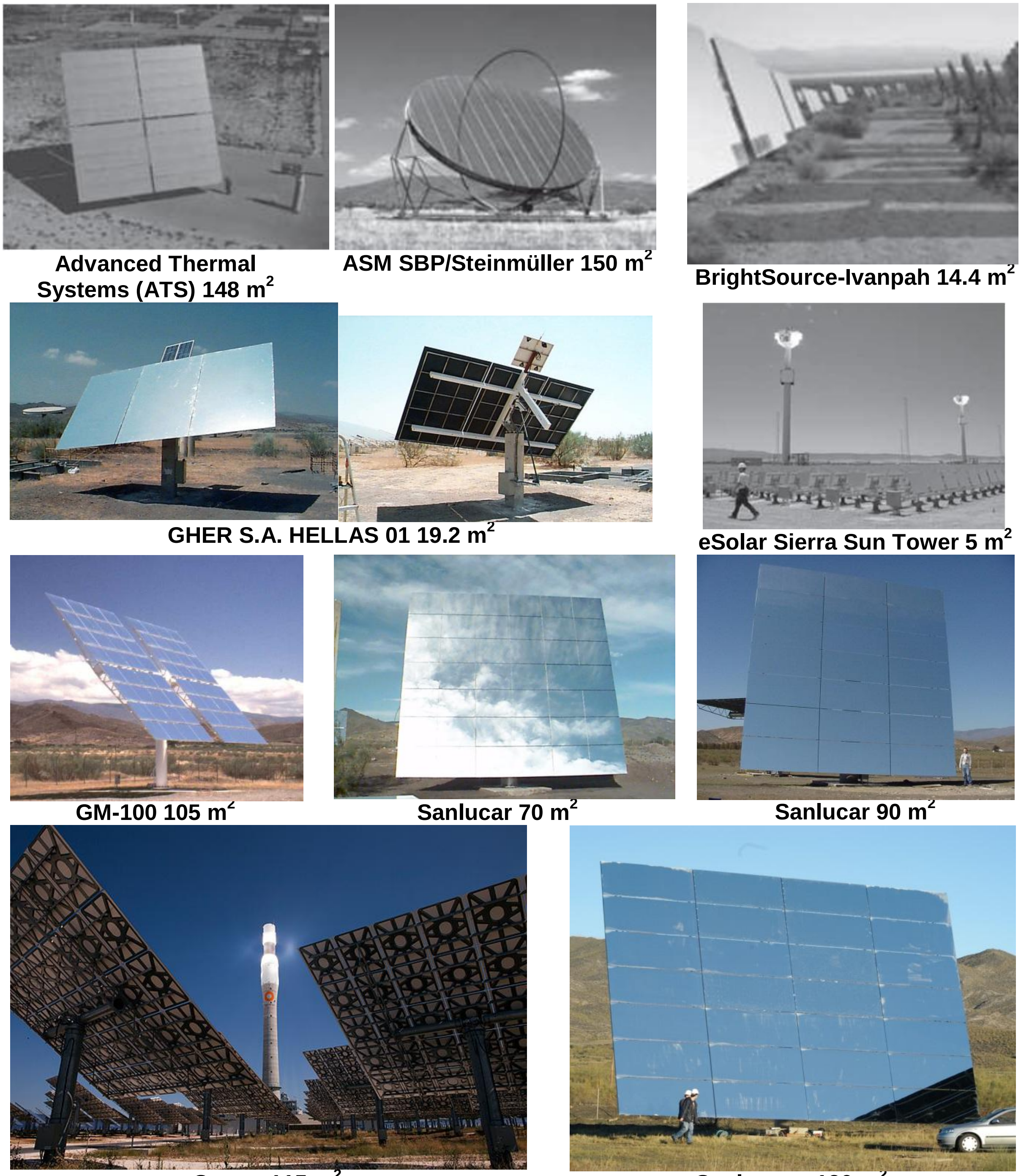
SAIC 50 m^2 Stretched Membrane

Martin Mariettta Solar One and Solar Two (39.9 m^2)

CSIRO National Solar Energy Centre Solar Towers, 4.5 m^2

SAIC Stretched Membrane 145 m^2

APS PV Concentrator 320 m^2 (Plan was to convert to Heliostat)



Advanced Thermal Systems (ATS) 148 m^2

ASM SBP/Steinmüller 150 m^2

BrightSource-Ivanpah 14.4 m^2

GHER S.A. HELLAS 01 19.2 m^2

eSolar Sierra Sun Tower 5 m^2

GM-100 105 m^2

Sanlucar 70 m^2

Sanlucar 90 m^2

Sener -115 m^2

Sanlucar – 120 m^2

Figure 1: Representative heliostat designs and sizes (adapted from [Kolb et al., 2007]).

While Abengoa Solar, Sener, Pratt Whitney and others are developing large heliostats, eSolar, BrightSource Energy and other are focusing on small scale heliostats of less than 20 m². Almost in parallel (since 2007), and as a potential cost reduction option by mass production of components, some demonstration plants deployed small heliostats, such as Cooma Tower (6 m^2), BrightSource SEDC (7 m^2), Sierra Sun Tower (eSolar, 1 m^2), Jülich Solar tower (8.2 m^2), etc.

Determining trends from industry is difficult. Some technology developers have recently upsized their existing heliostats – Abengoa from 120 m^2 to 140 m^2 [Abengoa2012], BrightSource from 15.2 m^2 to 19.0 m^2 [Koretz2013], and eSolar from 1.14 m^2 to 2.2 m^2 [Tyner2013] – perhaps to lower cost through less conservative use of customized components (such as the drive system).

In recent years research groups and commercial contractors have started to exploit the potential of small size heliostats, using components whose basic parts are widely available and, therefore, can leverage the advantages of mass production. Further advantages of small size heliostats are also from their reduced size itself. Wind loads and therefore mechanical stresses on the heliostat structure and drive mechanism are much lower and allow for simpler components with less material. Furthermore, due to the reduced size, larger parts of the heliostat can be preassembled at well-established factories thus assuring high quality control while still being easy to transport to the construction site. Also on site construction is simplified, as the whole construction is more accessible. For instance the pedestal height of a 150 m^2 heliostat is about 6 m above ground, requiring special equipment and security measures. Moreover, systems can be tested at real scale with affordable costs since the cost per unit is much lower.

As a matter of fact, currently, heliostats ranging between 1 m^2 and 150 m^2 are being developed following two separate trends (summarized in Table 3) both with the final goal to reduce the specific costs of the solar field collector.

Table 3: Advantages and drawbacks appearing when heliostat size is varying.

Heliostat size	PROs	CONs
Increasing	▪ Benefit from the economics of enlargement ▪ Reducing the number of heliostat leads to reducing the cost by: ▪ taking as much advantage as possible from expensive high-tech components mainly high precision tracking systems, ▪ Lowering the specific operation and maintenance costs.	▪ Increase of torques from wind loads, resulting in higher specific weight and higher specific drive power. Thus the level of demand in the technical specifications of the heliostat's tracking system increases with the size. ▪ On-site heliostat assembly is difficult (facilities not well-equipped, not easily automated and time consuming processes are involved such as canting); ▪ Canting accuracy becomes critical for a large heliostat. (For large heliostat fields where last row of heliostats could be placed at several kilometers from the solar tower, to be able to concentrate, large area heliostat need to keep their theoretical curvature). ▪ Land use might be worse with large heliostats and the long distance heliostats provide worse optical efficiency. ▪ Strong limitations when applying mass productions and lean manufacturing processes

Heliostat size	PROs	CONs
Decreasing	▪ Greater number of pedestals, controls, actuators, etc. may benefit more from learning/experience curve effects ▪ Wind loads decrease and therefore the technical specifications on structures and driving mechanisms can be relaxed ▪ Cost reduction may be reached: 1. on components with high volume manufacturing in mass production factories and, 2. on installation and set-up by well controlled factories with efficient calibrating procedures. ▪ The required automatic calibration procedures will help to relax driving mechanisms specifications. ▪ Cheaper testing facilities or test benches for system characterization and quality assurance ▪ Smaller sizes facilitate ad-hoc robotized systems and new approaches for cleaning and O&M can be developed at potential lower prices	▪ Greater number of pedestals, controls, actuators, etc. implies that control/wiring may become excessive ▪ Heliostat fields made of small area heliostats will require a more sophisticated control system since the number of heliostat units to be controlled will be multiplied by 10 or 100 ▪ Achieving required tracking accuracy for low cost drives becomes more difficult. ▪ Automatic calibration procedures are required. ▪ Standard systems/vehicles for cleaning and other O&M operations are not suitable and new approaches must be developed

2.1. Heliostat Components

Heliostats are made up of, but not limited to, mechanical structure, foundations, mirrors, facets, tracking system, control system, and all the required associated fixings, components and infrastructure to ensure correct performance and operation in all conditions (Figure 2, Table 4). All these items have several design options. And the final choice requires “optimizing” a combination of technical specifications and costs.

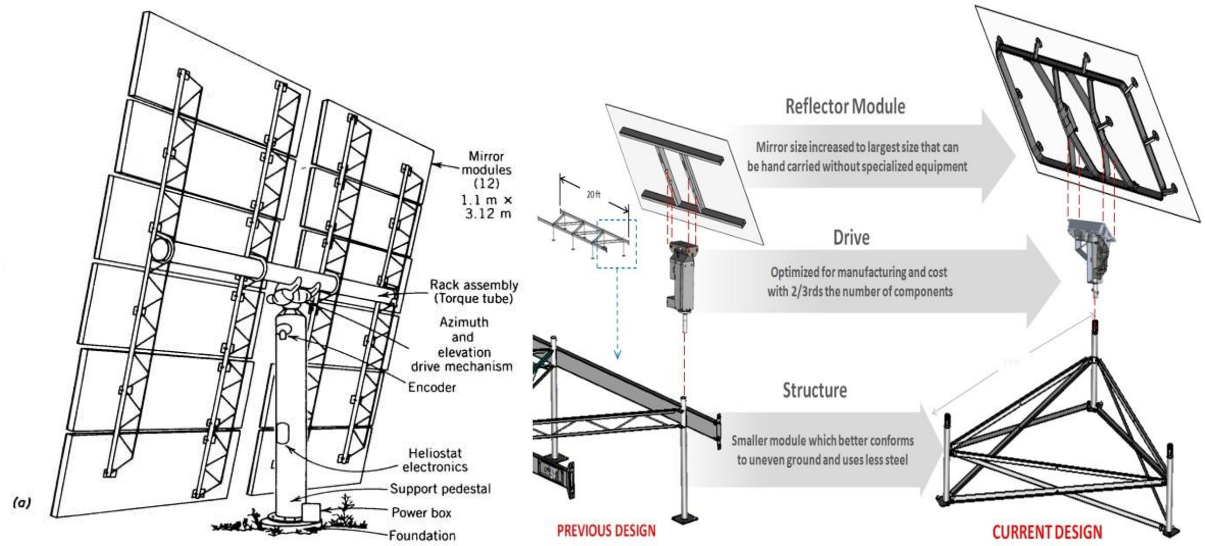


Figure 2: Examples of typical elements in large (left) and small (right) size heliostats (Source: Left: Southern California Edison Co. / Right: eSolar).

Table 4: Heliostat Components

Heliostat component	▪ Sub-elements
Reflecting module	▪ Mirror modules / facets ▪ Frame / rack assembly
Foundation	▪ Foundation / Ground anchorage
Structure	▪ Support structure
Drive mechanism	▪ Azimuth and elevation drive ▪ Gear box ▪ Cabling
Control	▪ Position sensor ▪ Interface with power system and heliostat field controller ▪ Drive controller ▪ Wiring ▪ Master control interface electronics for heliostat local control ▪ Time base, computers, software
Support equipment	▪ Handling equipment ▪ Maintenance trucks and equipment ▪ Heliostat washing equipment ▪ Operating procedures (including offset error corrections, …) ▪ Maintenance Procedures

Taking into account the influence of the choice of one or other configuration at each component level in the following choices, in the rest of the components and in the total cost of the final heliostat, a holistic approach is needed when facing the difficult task of defining heliostat specifications aiming to develop an innovative low cost heliostat

The **size** and the **optical design** of a heliostat are the main parameters considered for specifying a heliostat:

- The size (e.g. area of reflective surface) directly impacts other critical parameters for the design and for the cost such as the weight, wind load, time of construction and installation.
- The optical design covers the general design of the heliostat: nature of the reflective material (e.g. silvered glass, aluminum, polymer-based silver film, etc.), number of facets, shape (e.g. curvature), and orientation (e.g. elevation-azimuth vs. tilt-azimuth, target-aligned vs. zenith axis).

In dependence of these two factors follow the solar field layout, i.e. the positioning of each heliostat within the field.

While facing the task of choosing **the size and optical design** of a heliostat, to reach the most cost-effective option, it is important to bear in mind also which options are available to choose the subcomponents of the heliostat like:

- Mechanical structure and pedestal
  - General design (mast anchorage to the ground, beam, girder, box vs. truss…)
  - Material (steel, aluminum, concrete…)
  - Assembly (welding, bolts, rivets, glue…)
- Motors and drives
  - Main power supply (electric vs. hydraulic or pneumatic)
  - Type of motor (DC motors, synchronous motors, asynchronous motors, stepping motors)
  - Reduction step (direct drive, gear box, drive belt, chains, cable)
  - Actuator type (linear vs. rotating)
- Tracking controls, security systems
  - Open-loop vs. closed-loop
  - Local controller vs. central controller
  - Wireless communication vs. wired system
  - Heliostat concept connections (autonomous vs. grid connected)

In the following sections the technical options of these items will be (quickly) surveyed.

2.2. Reflecting Module

The reflective module of a heliostat is generally composed of one or more mirrors (also called facets) arranged in a usually spherical pattern (canting) to concentrate the reflected light onto the receiver surface. Additionally each mirror is often mounted in a slight concave form to aid in concentrating the reflected beam. However, to ease construction also flat mirrors, like the one used by eSolar, are used. Dividing the reflective surface into facets is not only for technical reasons during fabrication but also eases handling during construction and allows easier control over the curvature for larger heliostats. Typical facet sizes are between 1 and 10 m^2.

The module must perform accurately under a wide range of operating conditions such as varying wind speeds and ambient temperature. An ideal reflector should provide the following properties:

- High optical performance (e.g. reflectance/transmittance, specularity, geometrical configuration)
- Low specific weight
- Long Lifetime & Low Maintenance costs

Traditional heliostat designs rely on what is referred to as glass/metal structures for the reflective module. This consists of a sandwich-construction, where a second surface mirror (i.e. the reflective material is covered by a transparent material, which is placed between the sun and the reflecting surface) is connected via an adhesive to the support structure. Additionally, an environmental seal is used on the edges to protect against moisture and other corrosive species [Mar1981]. The silver reflective surface is therefore protected from one side by the glass, but requires protection from the other side as well. For monolithic mirrors, a copper layer is used with a layer of protective paint for the copper. Laminated glass mirrors use glass on both the front and rear layers, therefore, the reflective film lies between two glass layers. In any case a further edge seal is required to completely isolate the reflective layer from moisture or other corrosive substances in the environment.

A typical second surface mirror consists of silver or aluminum as the reflective agent, however any other reflective metal can be used. Silver is of greatest interest due to its high reflectivity (0.95-0.97) over a wide range of wavelengths, as compared to aluminum which exhibits both lower reflectivity (0.88-0.92) and an undesirable absorption band around 800 nm [Mar1981].

The transparent cover is typically made of glass, due to its almost inert nature, abrasion resistance, surface uniformity, low cost, large availability, and physical strength. The type of glass used is also an important parameter. Glass, aside from silica, can contain various filler materials depending on the mechanical properties desired. One such filler is iron oxide, a substance that strongly absorbs long visible wavelengths, reducing the overall reflectivity of the silvered mirror. Also, poorly made glass may contain captured air bubbles, which diminish the specularity of the mirror [SERI1985].

Current state of the art reflectors of this kind have a specular energy reflectance of 0.93-0.94 and exhibit a useful lifespan of 20-25 years without excessive corrosion or UV degradation. The targets for 2025 for reflectors consist of increasing specular reflectance to 0.95-0.96, eliminate heavy metals from the final product, include low maintenance anti-soiling coatings, and reduce the overall reflector costs.

While glass/metal mirrors provide a highly reflective surface and a proven long lifetime they have the disadvantage of a rather high specific weight. A common 3 mm mirror weights about 7.5 kg/m^2. This weight has to be supported by the mechanical structure and moved by the drive mechanism with very high precision, even under severe wind loads. Alternatively thin mirrors (< 1 mm) may be used, which have a much lower specific weight and due to the thinner glass layer also a higher reflectivity. However, the stability of these mirrors is lower causing them to deform easier due to gravitation and wind loads. To compensate for this either these thin mirrors are glued/laminated onto a support structure made of other materials (polymers, metals etc.) to reach the minimum stiffness or the support frame need to be reinforced compensating at least partially the weight reduction achieved. An alternative technology first pursued in the 1980's was the stretched membrane, where a highly reflective membrane was stretched over a frame. A parabolic shape is given to the membrane with the application of vacuum, to allow for further light focusing. Although this approach leads to significant material and weight savings, no large scale commercial development of this technology has been pursued mainly due to the following reasons:

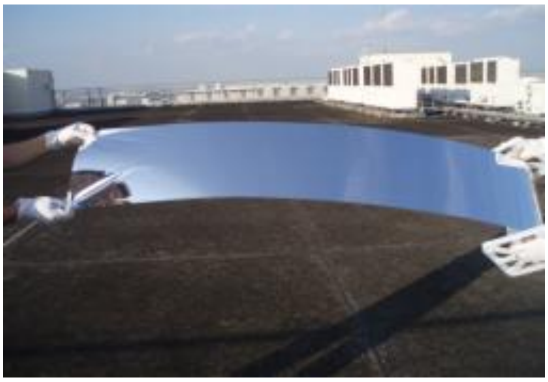
- High degree of planeness required on the heliostat frame
- High complexity during assembling of the system
- Higher Capital Cost than classical glass metal technology
- Higher Operational Costs (e.g. self-consumption for maintaining vacuum)


Figure 3. Prototypes of Stressed Membrane and glass/metal heliostats (Source: Left: PSA / Right: Abengoa)

The state-of-the-art at R&D level in reflector modules is the polymer film technology, where multiple layers of polymers with alternating refractive indices are laminated onto a support structure. The silvering is sealed in place by the polymer film, eliminating the need for glass. Polymer film has the advantage of being lightweight and easy to transport, flexible, has good optical properties, and is nearly unbreakable [Sansom2014]. The main drawbacks of the polymer film technology are the following:

- Final cost of the reflector modules once the polymer film is laminated onto the support structure
- Loss of specularity due to the lamination process and /or support structure smoothness
- Outdoor durability, (UV, abrasion- scratches under sand storm).

It is important to remark that, although some R&D programs on Reflectors modules are aiming to reduce the weight of the modules, in heliostat developments it is not the weight of the reflecting module what is driving the technical specifications of the structure and the tracking mechanism of the heliostat but the wind loads.



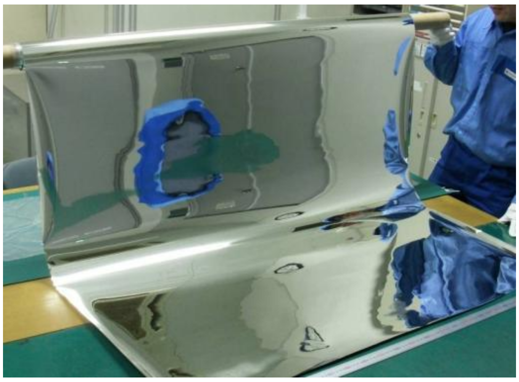


Figure 4. Film mirror from Konica Minolta (Source: Konica Minolta)

2.3. Foundation

The foundation anchors the heliostat to the ground. This is done with a concrete foundation as usually found in solar power plants using large heliostats

Concrete foundations are currently the most widespread solution. They provide a good foundation with reasonable costs. A concrete foundation can consist of a concrete base buried in the ground to which the heliostat pedestal is attached. Alternatively a hole is drilled into the ground into which the pedestal is inserted and the hole filled with concrete. Such foundations are usually used for large heliostats.

Such solutions might easily get prohibitive when used for small heliostats, as the amount of required construction work might become excessive for the large number of heliostats. In such cases the use of ground anchors might be an option. For these types of foundations the pedestal is drilled more or less directly into the ground. This method, however, requires a solid ground to provide enough stability for the heliostat under severe wind loads throughout a lifetime of 20 – 25 years. Resembling to only drilling a hole and inserting the pedestal facilitates the deployment of large number of heliostats within short time. This technique has recently been proven during the construction of “Ivanpah Solar Electric Generating System”, where about 170,000 heliostats have been mounted in such a way. To provide enough stability for the expected torques, the depth of the hole depends on the heliostat size. In order to avoid digging deep holes, this method, is limited to rather small heliostats. Furthermore, material costs for a longer pedestal might be higher than for concrete, which might prevent the application of this method.

Figure 5. Pylon insertion at Ivanpah (Source: BrightSource)

For very small heliostat sizes (< 2 m^2) even this method might be too expensive. In this regard eSolar has demonstrated in their “Sierra Sun Tower” plant that for certain configurations of the heliostat field a fixed ground attachment is not necessary. In their plant a large number of heliostats are mounted onto the same support structure (sacrificing the optical efficiency of the solar field) which in turn is just placed onto the ground and will maintain its position solely due to its own weight.

The latter two methods (ground anchor and heavy support structure) also have the big advantage of a smaller environmental footprint as less ground is destroyed. For concrete foundations often all vegetation around the heliostat will be removed in order to build the socket. Ground anchors on the other hand only require a rather small hole and allow leaving all vegetation around the heliostat untouched.

2.4. Structure

For many classical heliostats the structure can be divided into two parts:

- **Pedestal tube**: Provide ground clearance
- **Frame assembly**: Give rigidity to the facets

Figure 6. Heliostat with pedestal and frame assembly (Source: PSA)

This configuration (as depicted in Figure 6), also called **T-type**, is the most commonly used for medium or large size heliostats. The pedestal provides the necessary ground clearance for the reflection module. The frame assembly supports the array of mirror modules or facets. The modules are connected to the assembly using adhesives or other mechanical fasteners. Each mirror module usually has a slight concave curvature and is also canted (aligned) with respect to the plane of the support structure, to better focus the reflected sunlight on the receiver and thus improve performance. Usually this structure consists of a torque tube with several cross beams. The torque tube is attached to the drive system while the mirror modules are attached to the cross beams. Truss type beams are the preferred option especially for larger heliostats, because their depth can be varied to provide the required stiffness, with little weight penalty. For some designs the beams connected to the mirrors are substituted by perforated pressed metal plates. The azimuth/elevation gear drive unit is installed at the junction between the pedestal and the torque tube. The objective of the design is to give the necessary rigidity to the heliostat structure and to minimize deflections from wind loads. For large heliostat sizes this implies a heavy torque tube, increasing the specific weight, material and cost of the heliostat structure. In smaller heliostats, wind and other loads are much smaller, allowing for a lighter frame structure to be used. For instance the heliostat design from eSolar (see Figure 7) is quite different from these classical approaches. It only has a very small pedestal attached to a ground structure which is shared between many heliostats to avoid the costly foundation.

Figure 7: Low cost support structure for small heliostats (Source: eSolar)

Also due to its small size, no real frame assembly (especially no torque tube) is needed. Furthermore, only a simple structure to give rigidity to the mirror is used.

One of the great advantages of the T-type design with multiple facets is the possibility to allow the heliostat to face down (Figure 8). This safety position prevents damage to the reflection module during hailstorms or similar conditions. However, this comes at the cost of a slightly reduced optical efficiency due to its reduced effective area.

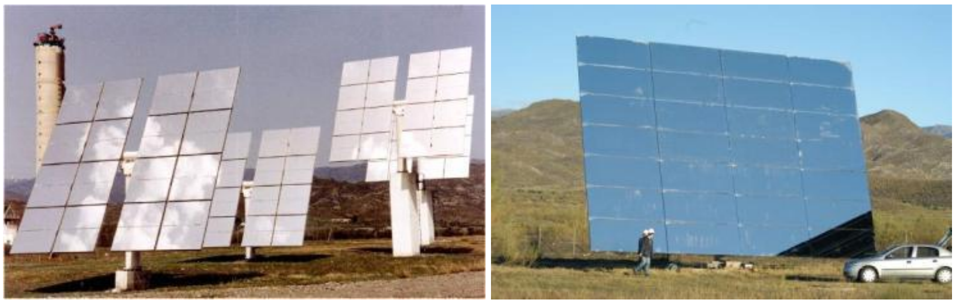


Figure 8: Opened T structure with complete turn down position (left) and Closed T structure without complete turn down position (right). (Source: Kolb2007)

2.5. Drive Mechanism

The drives are responsible for controlling the attitude of the frame assembly, in other words, they are responsible for applying the necessary rotations to the structure such that the solar irradiation is redirected onto the fixed target. A rotation about two axes is required, with usual configurations allowing for azimuth and elevation rotation.

The drive mechanism considers the power source on the one hand and the transmission on the other hand. Depending on the characteristics of the power source, the transmission solutions differ considerably in order to fulfill velocity and torque requirements of the heliostat.

In relation to power sources, there are two technologies being applied to heliostats: rotary electromagnetic motors and hydraulic actuators.

Rotary electromagnetic motors: An important fraction of the actuation solutions that need for some kind of motion control are nowadays supported by rotary electromagnetic actuators. During the last decades electromagnetic motor technologies and associated power electronics have evolved considerably. Among the advantages we can mention the possibility to provide from very small to large power capabilities, decentralized and independent solutions and very good motion control performance. On the other hand, lifetime and maintenance characteristics are advantageous as well. Finally, mass-production of these components allow for reduced costs. There are different types of rotary electromagnetic motors that are being used in heliostat actuation solutions. DC motors and asynchronous AC motors cover the lowest cost solutions while synchronous AC motors are also used in some trackers.

Hydraulic actuators: Hydraulic actuation solutions are usually associated to high power applications. The systems consist on a hydraulic pump, servo-valve and associated control electronics and a telescopic cylinder or rotary hydraulic motor. Due to the cost and complexity of the pressure generation system, it is usually shared among a large number of actuators, preventing this technology from being competitive when individual or a low number of actuators are required. Lifetime of the solutions can be comparable to that of electromagnetic actuators. However, maintenance becomes much more critical as far as fluid characteristics, sealing and wear are factors that compromise the performance of the solution. In the case of heliostats only two axes have to be driven but these kind of actuators have been considered for large heliostats which require high power.

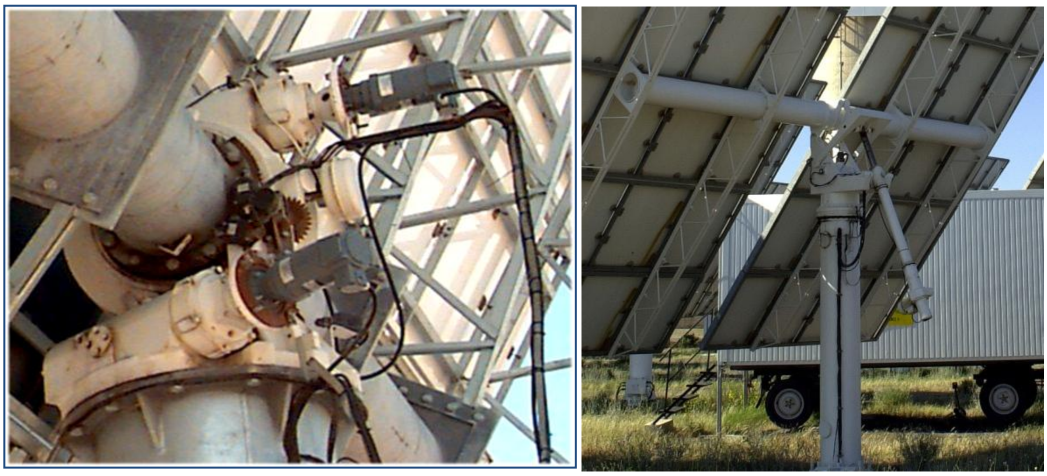


Figure 9. Rotating and linear actuators based on rotary electromagnetic motors as power sources.

The mechanical transmission of forces and movements from the previous power sources to the rotary axes of the heliostat can be coupled be means of different solutions. The critical aspects to consider in relation to the transmission solutions are the transmission ratio, the transmission accuracy and stiffness. Compared to the previous aspects, efficiency of the transmission is secondary. The back driving or reversibility characteristic is also important for the application as far as it can simplify the overall system by means of avoiding the need of a brake; however it is necessarily linked to efficiency losses.

The power source characteristics and the transmission ratio should be chosen so that heliostat requirements with regard to velocity and torque are optimally achieved. Heliostat axes require very low velocity and large torque, therefore high transmission ratios are usually required when rotary electromagnetic power sources are used which is not practical to provide without compromising other characteristics, such as accuracy and efficiency. In some solutions, linear movement is part of the transmission chain from the power source to the heliostat axes, which introduce some difficulties. The most relevant difficulties are the limited rotational stroke capability and the variable transmission ratio along the stroke of the actuator. In heliostat fields, they are sometimes applied to elevation axes, Figure 1 (b), which require smaller strokes than azimuth axes.

The accuracy of the transmission is relevant to the heliostat performance in different ways. When feedback sensors are used in the final stage of the heliostat, absolute accuracy is not so relevant. However, implementing these solutions is not cheap and only big heliostats include them. Therefore, accuracy of the transmission it is of outmost importance in many cases. On the other hand, backlash introduces issues in both scenarios.

There are a number of different driven solutions that have been used in different industrial applications depending on the power, speed and accuracy required. Among them different solutions and mechanical components that have been considered to achieve the required transmission in heliostats (worm drives, spur gears, screw and nut, chain, harmonic drive, …) while others do not fit this application (rack and pinion, friction wheels, linear actuators, …)

Worm gears: This gear configuration provides high transmission ratios in each stage, between 10 and 30 is usual. However efficiency characteristics are worse than other solutions. By proper design, back driving of the stage can be avoided if required. Backslash can be reduced by means of preloading the gears; however, wear due to aging of the components negatively affects this. Some solutions allow for wear compensation by means of adjustment of the gears.

Spur gears: Spur gears provide smooth mechanical transmission. The achievable transmission ratios are in the 2 to 5 range, therefore a large number of stages can be necessary. Some configurations such as planetary arrangements provide larger transmission ratios in each stage. Efficiency is usually high. On the other hand, it is not possible to guarantee irreversibility of the transmission.

Screw and nut: When linear movement is part of the transmission chain, screw and nut solutions can be considered in order to achieve large transmission ratios. If ball screws are used the smoothness and efficiency are considerable but the costs will be higher and the system will be reversible. On the other hand, friction screw and nut solutions allow for irreversible stage designs.

Chain and pinion: Chain and pinion solutions offer the possibility to implement low cost transmission. As in the case of the previous solutions this one relies on contact forces, however due to the chain not being fixed to the associated piece continuously, as it happens with the gears, achievable stiffness is lower. On the other hand, usually accuracy is also lower because the chain is composed of a large number of parts that need to be assembled together. Finally, achievable transmission rates can be considerable because the chain solution allow for pretty large diameter components compared to the pinion. Efficiency is also high.

Harmonic drive: Harmonic drive configuration gears, also known as “strain wave gears”, rely in contact and deformation to provide high transmission ratio, up to 100, high accuracy, high efficiency and backlash free rotational motion transmission. It is profusely applied in high accuracy solutions such as machine tool auxiliary devices and robotics. However, the high cost prevents it use in some applications.

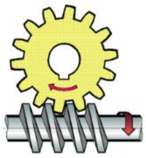
Capstan drives: These drives rely on cables to couple the movement of two elements, usually two pulleys. Unlike conventional pulley and belt solutions, capstan drive cable is fixed to the pulleys at its end. Compared to the previous solutions that rely on contact forces and are composed of discrete elements, except in the case of the screw and nut, capstan drives provide a uniform and smooth transmission. The transmission ratios can be comparable to those achieved with spur gears. As it happens with chain and pinion solutions, the stiffness is limited due to the axial stiffness of a considerable large cable being part of the transmission, even if the friction between the cable and the pulleys improves the scenario a little bit. This solution is free of backlash.

Planocentric drives: were suggested in [Kolb2007]. These drives provides extraordinary gear reduction (over 30000:1) in an extremely compact package. Unfortunately, heliostats seem to be the only application for this concept and they cannot benefit from systems massively produced for other applications. Kolb2007 also reports that a planocentric drive survived a severe wind event (breaking the wind meter at 113 mph) that destroyed other concentrators at Sandia labs, and suggests that it could be the lowest-cost option for big heliostats azimuth drive.

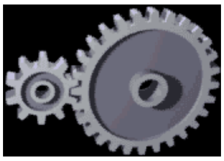
Rack and Pinion: This configuration provides high efficiency but small transmission ratios and back driving the stage is always possible so it is rarely part of a heliostat transmission solution.

Linear drives: achieve direct transmission of motion magnetically (e.g. without gears). Therefore, forces are very limited. Moreover, these systems are expensive thus heliostat application is not clear.

Friction wheels: can provide high accuracies but torque is limited and they are not applied to heliostat drives.



Worm gear

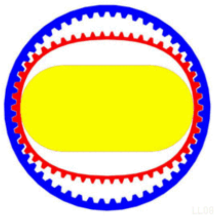


Spur gear

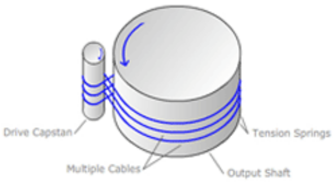
Rack and pinion

Screw and nut

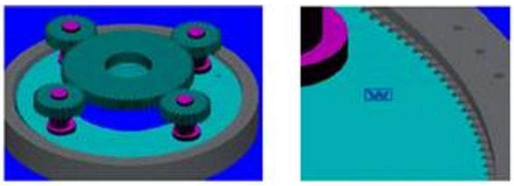
Chain and pinion



Harmonic drive



Capstan drive



Planocentric drives

Figure 10: Transmission solutions

Nowadays, the drive mechanism is most of the times the single **most expensive heliostat component** since azimuth/elevation drive mechanism for first commercial tower plants are based on big heliostats (100 – 150 m^2) moved by worm drives that cost about 5000 €. That is why there has been a trend in heliostat technology development to larger-area designs that lower the specific price per heliostat m^2. In the last years, some developers have included linear movement as part of the transmission chain for elevation axis.

2.6. Heliostat Control

The heliostat control system contains all necessary controllers, sensor, encoders, limit switches, processors to give the appropriate signals such that the drive positions the heliostat in the desired position. It assures the heliostats is following the commands issued by the central control system, i.e. focusing or defocusing, moving into stow position, etc. There are several types of control strategies depending on the technology of the drive mechanism and the tracking mode: step by step, continuous current, asynchronous, synchronous, hydraulics, etc. The motion control can either be controlled in torque or current mode, depending on the type of inverter used. Some parameters such as gains can be modified on site by the operator according to the desired performance: peak current, robustness, steady state, etc. The algorithm can either be implemented as closed-loop, using a sensor system to control the position of the heliostat or as open-loop, with an accurate solar position calculation.

In commercial plants this control is local to each heliostat and generally connected via field wiring to a central system. While this might be a viable solution for large size heliostats, field wiring quickly becomes an important cost factor for small size heliostats. Not only does is require a huge amount of cable trenches between all the heliostats but also the costs for the cables itself become an important factor.

One solution is to use independent heliostats, i.e. heliostats which are not directly connected to the central system. By using a photovoltaic panel, enough power can be generated to move the heliostat. The communication with the central control system is performed via Wi-Fi or similar (Figure 11).

Figure 11: Photovoltaic panel for power generation and antenna for communication.

Due to lack of practical experience at large scale it is unclear, whether or not, this solution will become commercial in the near future. Practical problems include taking care for situations of prolonged absence of sun and communication interference for huge numbers of heliostats. Another factor to consider is the cost of the control board, while representing only a small fraction of the costs for large heliostats, it might become an important factor, as its price is mostly independent of the actual heliostat size. Possible solutions include building groups of heliostats which are controlled by one system, thereby reducing the costs for local heliostat control. This approach might become more competitive when large heliostat fields are needed, then cost of trenches and wiring will increase thus wireless solution will become more convenient.

In any case the heliostat local control should be in close collaboration with the central control, as it has impact on the total plant performance, most notably on the parasitic power consumption. Moving all heliostats at the same time can lead to undesirable current peaks during tracking or while moving from/to stow position in the morning/evening. A reliable communication with the central receiver system is also crucial to assure a homogeneous flux distribution onto the receiver. This requires a fast correction of the heliostats (i.e. defocusing / refocusing) to avoid hotspots and, therefore, possible damage of the receiver.

2.7. Canting

The term canting refers to the alignment of the individual mirror facets of a heliostat on the support structure. The canting process can be applied whether the individual facets are curved or not, and it is used in order to maximize the energy obtained from a particular field (see Figure 12). For small heliostats of single facet construction, the curvature of the facet and the applied canting become the same thing, leading to a continuously canted surface.

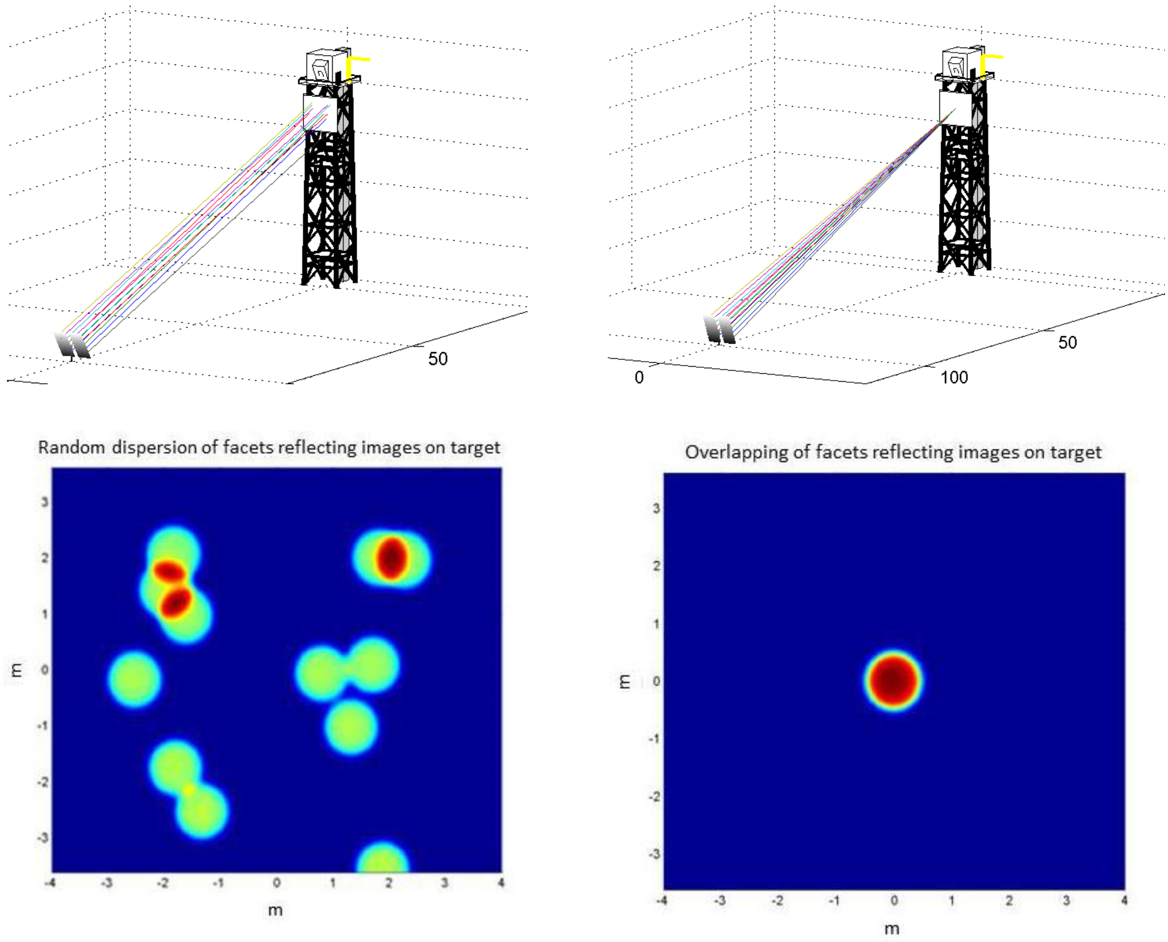


Figure 12: Simulation of heliostat image on target before (left) and after (right) canting (Source: [Monterreal2014]).

Several canting methods have been employed, and a comprehensive review of these methods is provided in [Yellowhair2010]. In general, the canting methods can be split into two broad categories, mechanical and optical. Mechanical methods (such as through the use of gauge blocks or inclinometers) involve pre-calculation of the facet canting angles required and manual measurement and adjustment of each facet to attain the desired angles. These processes are labor intensive, tedious, and prone to several sources of error, primarily due to structural gravity sag and local slope errors at the point of measurement.

Optical methods (such as photogrammetry, fringe reflection or reflection of a known image) typically rely on applying a correction to the mirror facets such that a non-distorted reflection of a known image is obtained. Optical methods are not only able to correct facet canting, but also measure focal length errors, and in general provide higher accuracies.

Applying the canting procedure requires precision and labor, thus is a factor contributing to the overall cost of the heliostat during the manufacturing and installation stages.

Literature studies have shown that the radius of curvature of the heliostat along the tangential and sagittal planes should be different, in order to reduce aberrations in the reflected image [Zaibel1995, Igel1979]. Therefore, one way of maximizing the energy obtained by a particular heliostat field is by applying the correct canting technique.

The canting technique applied depends also on the tracking method used on a heliostat. Most heliostats in field include two perpendicular axes of motion, which, allow rotation in azimuth and elevation, as in Figure 13a. The most common approach uses a first vertical axis (azimuth) and a second horizontal axis, although a first horizontal axis is also possible.

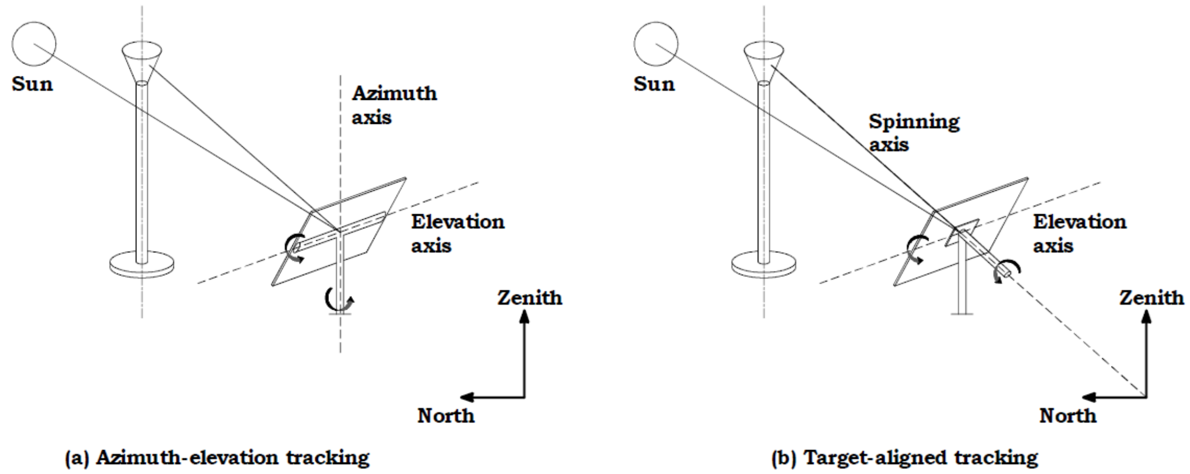


Figure 13: Schematic representation of the rotations in two heliostat tracking modes: (a) azimuth-elevation tracking and (b) target-aligned tracking.

The methodology chosen for this process is, however, not unique, but can be classified into two groups: on-axis and off-axis. For on-axis canting the facets are aligned to give a perfect image, when the heliostat center, the target and the sun are collinear, i.e. are on a line. For off-axis canting, the facets are arranged to optimize the convergence of all images on the solar receiver for a particular time and day of the year [Monterreal2014]. In CR-CSP plants usually an on-axis canting is employed and off-axis is used for optimizing the concentration ratio of some heliostats for certain times of the day.

In recent time target aligned canting [Ries1990, Wei2011] has grown some attention. The target aligned heliostats allows for a rotation along the axis connecting the center of the heliostat to the target, such that the surface normal vector and the vectors from the heliostat to the target and to the sun, all lie in the same plane. A second rotation in the elevation rotation allows for correct placement of the reflected image in space, as illustrated in Figure 13b. Although this method could reduce astigmatic effect when using rectangular heliostats, it has not been commercially applied since it forces to an additional specific alignment of each and every single heliostat to face the target, therefore, increasing time and cost of installation.

Some canting methodologies developed, summarized below [Buck2009, Chen2006, Chen, 2001, Bonanos2012]:

- **On axis**: Refers to the perfect alignment shape when the center of mirror, the target, and sun are co-linear, e.g. when the vectors from the heliostat center to the sun and from the heliostat center to the target are parallel.
- **Off-axis**: Refers to the perfect alignment shape for a particular instance in time. As the sun constantly moves throughout the day, a shape can be found where for a particular instance in time, the sun is perfectly focused.

- **Parabolic**: The mirror segments follow a parabolic profile. The normal vector at the center of each mirror facet and the normal vector at the corresponding location of a paraboloid are parallel.
- **Target aligned**: Is similar to off-axis canting, but applied to a heliostat that employs target aligned tracking.

3 Heliostat Deployment Worldwide

Heliostat technology development begins with the design, manufacture and characterization of an experimental prototype and/or some variants that allow validating its performance in operation. Only a small part of the prototypes designed, manufactured and tested have been selected for implementation in central receiver facilities whether for R&D, demonstration or commercial purposes.

Although it is difficult to extract lessons learned from those references its revision can provide useful information for one of the ultimate goals of this STAGE-STE task (WP 12.1.1): "Development of a small heliostat which can be manufactured at a cost lower than 100 €/m^2".

Since the goal has a technical-economic character the first step needed to carry out is to sort the information published related to cost and size in current references based on previous experiences to try to analyze if it is possible to establish a pattern or a reference case.

Since heliostat costs depend heavily on the type and quality of the heliostat and especially the number of units requested, this creates uncertainty in the assessment of costs, which are difficult to solve systematically (for different types of heliostats).

As a first approach to profile references and market trends in terms of sizes of heliostats, etc., the tables in the following sections list the current deployment and ongoing projects (June 2014) heliostats in facilities with different purpose (R&D, demonstration, and commercial). These tables allow to infer some trends in the heliostat size evolution with time and to summarize the heliostat deployment worldwide:

- There are now 226,852 heliostats in operation (Table 5) with a total mirror surface of about 3.3 millions of square meters. The figures for the heliostats to be implemented in the plants (and/or facilities) under construction are very similar: about 238,000 heliostats with a total surface of about 2 million square meters.

- The total number of heliostats by adding the plants under development and planned to the operational and under construction plants, amounts to 835,838 heliostat units with a total mirror surface of about 17 million square meters.

Table 5: Summary of heliostats deployment worldwide

Item\Status of the Project	Decommissioned	Operational	Under construction	Develop-ment*	Planned*	Withdrawn	TOTALS
Total Number of Heliostats	1 926	226,852	238,730	357,730	10,600	21,222	835,838*
Total Mirror Surface (m^2)	155,700	3,312,610	2 083,088	8,777,733	2,724,000	1,280,682	17,053,131**
Mean Number of Heliostats per project	963	9,074	79,577	56,853	227,000	426,894	22,554
Mean Heliostat Surface (m^2)	80.8	14.6	8.7	24.5*	140.0*	60.3	20.4
Max. Hel. Surface (m^2)	95	121	140	25*	140*	62.4	140
Min. Hel. Surface (m^2)	40	1.14	2	4.5*	140*	51	1.14

Note (*): Several of the projects under development or planned have not published the selection of heliostat design (size, number, etc.). Thus these figures are only accounting for the projects that have already placed and published that heliostat selection.

Note (**): Excluding withdrawn projects

As it may be seen in Figure 14 and Figure 15 the actual trend is both to build larger plants (with larger number of heliostats) and smaller sizes per heliostat. This may also be appreciated in Figure 14 by comparing the mean surface per heliostat between operational and "under construction" status.

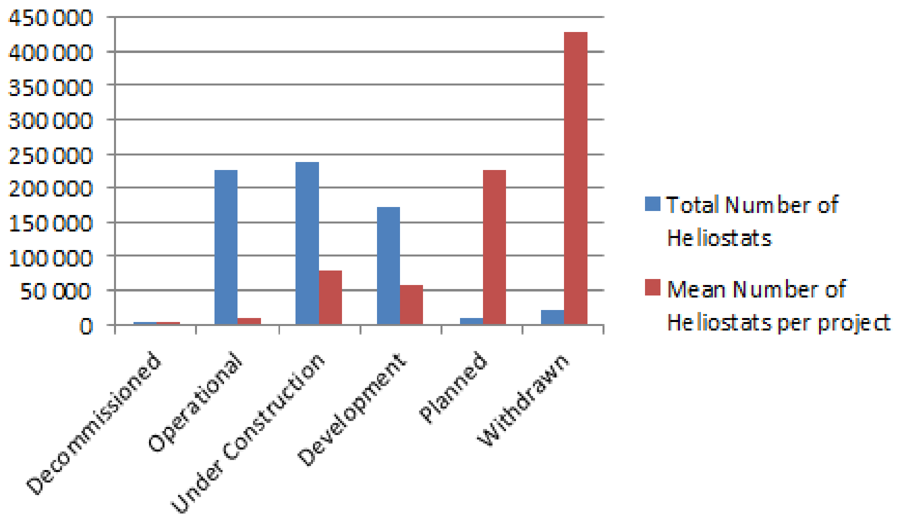


Figure 14. Deployment by project status.

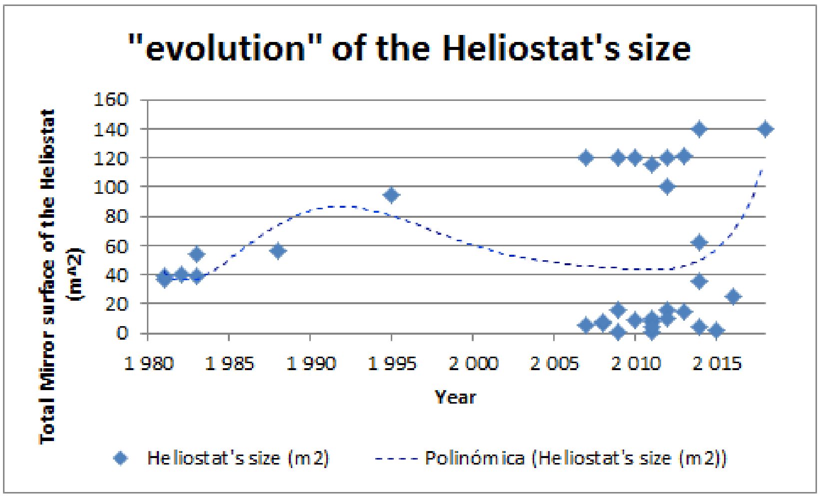


Figure 15. Temporal evolution of the size of the heliostats deployed commercially.

Nevertheless (Figure 15) the unambiguous trend toward increasing size of the heliostats during the period 1980-1995, has been unfolded (from 1995 to present) in two clear trends: on the one hand continuing a trend toward larger heliostats and, on the other hand, there is a new trend toward heliostats of reduced size.

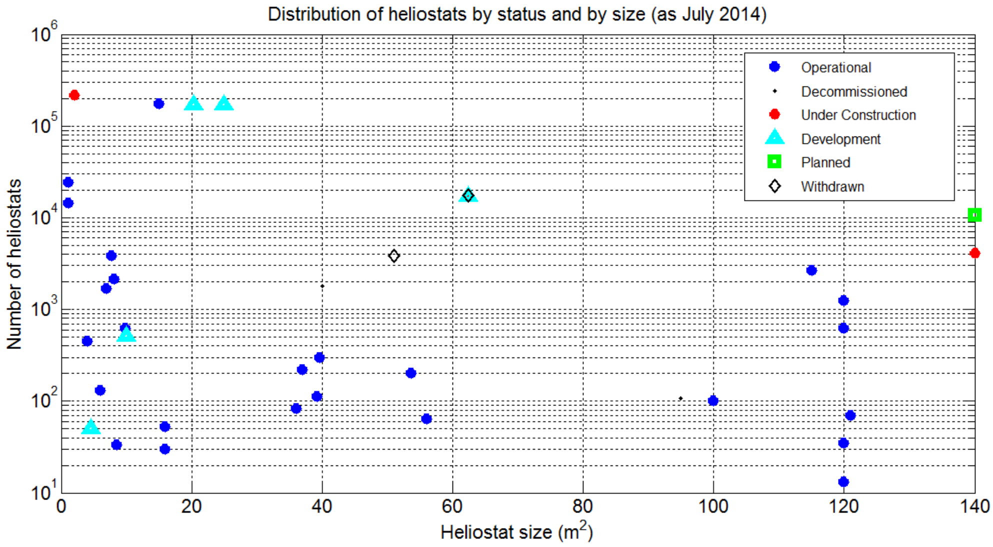


Figure 16. Distribution of number of heliostats deployed worldwide by project status and heliostat size.

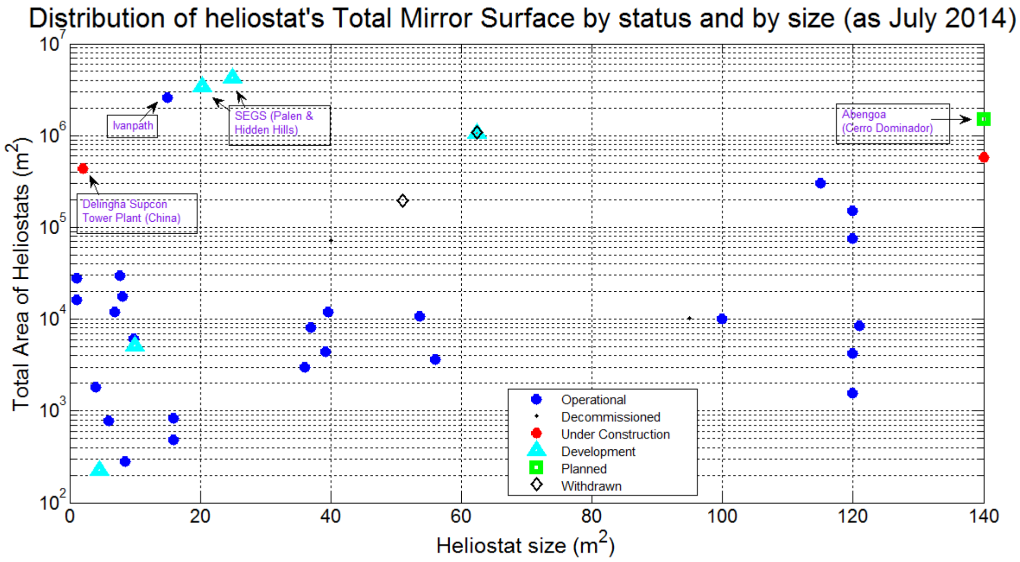


Figure 17. Distribution of total Heliostat mirror surface deployed worldwide by project status and heliostat size.

Figure 17 shows, in a logarithmic scale, the number of heliostats and the total heliostat mirror surface as a function of its size and the project status. It can be seen, for instance, that the size of heliostats in operation with most deployed total area is 15 m^2 (due to Ivanpah BrightSource plant) and the largest number of heliostat units under construction is associated with a 2 m^2 heliostat (Delingha Supcon Tower Plant in China).

Weighting the number of heliostats with the heliostat surface per unit it may be calculated an average heliostat surface and its deployment evolution may be observed in Figure 15 and Table 5.

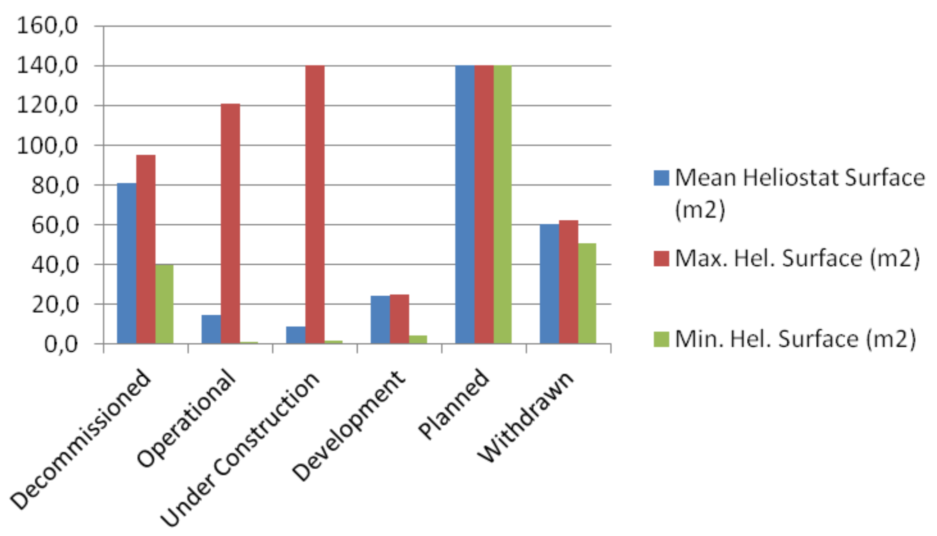


Figure 18. Heliostats sizes by project status.

Thus, the mean heliostat surface in the operational plants is about 14.6 m^2 while the mean surface of heliostats for the plants under construction is smaller (about 8.7 m^2). For the plants under development or planned the information about the heliostats to be implemented is scarce or not yet available so that the conclusions about trend are less reliable. The average heliostat surface for all the CSP-Central Receiver projects for all the status (excluding withdrawn) is about 20.4 m^2.

3.1.1. Heliostat Deployment in Commercial CSP Plants

Table 6: Heliostats deployment for commercial power plants.

Id_Nr	Project/Facility Name	Owner/s	Country	Status	Year (operation)	Power (MW)	Purpose	Heliostat's size (m2)	Number of Heliostats	Reflecting Area (m2)	Heliostat's type	Heliostat's provider
Comm_1	**PS10**	Abengoa Solar	Spain	Operational	2007	11	Commercial	120	624	74,880	"T" type	Abengoa Solucar 120
Comm_2	**PS20**	Abengoa Solar	Spain	Operational	2009	20	Commercial	120	1,255	150,600	"T" type	Abengoa Solucar 120
Comm_3	**Coalinga**	Chevron	US	Operational	2011	29 MWth	Commercial	7.8	3,822	29,826	"T" type	Chevron Brighsource
Comm_4	**Gemasolar**	Torresol Energy	Spain	Operational	2011	20	Commercial	115	2,650	304,750	"T" type	SENER
Comm_5	**Ivanpah SEGS**	BrightSource Energy, Google, NRG Energy	US	Operational	2013	377	Commercial	15	173,500	2,602,500	"T" type	Guardian EcoGuard Solar Boos
Comm_6	**Crescent Dunes**	SolarReserve	US	Under construction	2014	110	Commercial	62.4	17,170	1,071,408	"T" type	Pratt & Whitney Rocketdyn
Comm_7	**Khi Solar One**	Abengoa, Industrial Development Corporation	South Africa	Under construction	2014	50	Commercial	140	4,120	576,800	"T" type	Abengoa Solar
Comm_8	**Delingha Supcon Tower Plant**	Zhejiang SUPCON Solar Energy Technology	China	Under construction	2015	50.00 MW	Commercial	2	217,440	434,880		
Comm_9	**El Borma ISCC**	SITEP, STEG	Tunisia	Planned	2015	5	Commercial			40,000		

Table 6: Heliostats deployment for commercial power plants.

Id_Nr	Project/Facility Name	Owner/s	Country	Status	Year (operation)	Power (MW)	Purpose	Heliostat's size (m2)	Number of Heliostats	Reflecting Area (m2)	Heliostat's type	Heliostat's provider
Comm_10	**Palen SEGS**	BrightSource Energy	US	Development	2016	500	Commercial	25	170,000	4,250,000		Abengoa Solar / Rioglas
Comm_11	**Ashalim CSP plant 1**	Alstom, BrightSource Energy	Israel	Development	2017	121	Commercial			0		
Comm_12	**Planta Solar Cerro Dominador**	Abengoa	Chile	Planned	2018	110	Commercial	140	10,600	1,484,000	"T" type	Abengoa
Comm_13	**Cloncurry Solar Thermal Plant**	Lloyd Energy Systems	Australia	Withdrawn		10	Commercial	51	3,822	194,922		
Comm_14	**Rice Solar Energy Project**	SolarReserve	US	Development		150	Commercial	62.4	17,170	1,071,408	"T" type	Pratt & Whitney Rocketdyn
Comm_15	**Termosolar Alcazar**	Preneal, SolarReserve	Spain	Withdrawn		50	Commercial	62.4	17,400	1,085,760		
Comm_16	**Crossroads Solar Energy Project**	SolarReserve	US	Planned		150	Commercial			0		
Comm_17	**EOS Cyprus**	Alfa Mediterranean Enterprises, Vimentina	Cyprus	Planned		25	Commercial			0		
Comm_18	**Eskom CSP plant**		South Africa	Planned		100	Commercial			1,200,000		
Comm_19	**Gaskell Sun Tower**	eSolar	US	Planned		245	Commercial			0		
Comm_20	**Hidden Hills SEGS**	BrightSource Energy	US	Development		500	Commercial	20.3	170,000	3,451,000		

Table 6: Heliostats deployment for commercial power plants.

Id_Nr	Project/Facility Name	Owner/s	Country	Status	Year (operation)	Power (MW)	Purpose	Heliostat's size (m2)	Number of Heliostats	Reflecting Area (m2)	Heliostat's type	Heliostat's provider
Comm_21	**North Midlands Solar Thermal Power Project (Solastor Western Australia)**	Carbon Reduction Ventures, Solastor	Australia	Planned		3	Commercial			0		
Comm_22	**Ouarzazate 2**	MASEN	Morocco	Development		100	Commercial			0		
Comm_23	**Planta Termosolar Maria Elena**	Ibereolica	Chile	Planned		400	Commercial			0		
Comm_24	**Quartzsite**	SolarReserve	US	Planned		100	Commercial			0		
Comm_25	**Rio Mesa SEGS**	BrightSource Energy	US	Withdrawn		500	Commercial			0		
Comm_26	**Saguache Solar Energy Project**	SolarReserve	US	Planned		200	Commercial			0		
Comm_27	**Solastor Mejillones**	Safe Earth Energy, Solastor	Chile	Planned		5	Commercial			0		
Comm_28	**TAQA Concentrated Solar Power Plant**	TAQA Arabia	Egypt	Planned		250	Commercial			0		
Comm_29	**TuNur**	Glory Clean Energy, Nur Energie, TOP Oilfield Services	Tunisia	Development		2 000	Commercial			0		

3.1.2. Heliostats Deployment at Demonstration Plants

Table 7: Portfolio of heliostats installed in central receiver CSP demonstration plants

Id_Nr	Project/Facility Name	Owner/s	Country	Status	Year (operation)	Power (MW)	Purpose	Heliostat's size (m2)	Number of Heliostats	Reflecting Area (m2)	Heliostat's type	Heliostat's provider
Dem_1	**Solar One**	Sandia National Laboratories	US	Decommissioned	1 982	10	Demonstration	40	1 818	72 720	"T" type	
Dem_2	**Solar Two (Refurbishment of Solar one by adding...)**	Sandia National Laboratories	US	Decommissioned	1995	10	Demonstration	95	108	82,980	"T" type	
Dem_3	**Cooma tower**	Solastor	Australia	Operational	2007		Demonstration	6	130	780		Lloyd Energy Systems Pty Ltd
Dem_4	**BrightSource SEDC**	BrightSource Energy	Israel	Operational	2008	6	Demonstration	7	1700	11,900		
Dem_5	**Sierra SunTower**	eSolar	US	Operational	2009	5	Demonstration	1.14	24,360	27,649		eSolar. Flabeg (Mirrors). Victory Energy. Babcock & Wilkox
Dem_6	**AORA Solar Tulip Tower - Samar**	AORA	Israel	Operational	2009	0.1	Demonstration	16	30	480	"T" type	AHORA Solar
Dem_7	**Lake Cargelligo**	Graphite Energy	Australia	Operational	2011	4	Demonstration	9.8	620	6,076		Lloyd Energy Systems
Dem_8	**Acme solar thermal tower**	ACME	India	Operational	2011	3	Demonstration	1.14	14,280	16,222		eSolar

Table 7: Portfolio of heliostats installed in central receiver CSP demonstration plants

Id_Nr	Project/Facility Name	Owner/s	Country	Status	Year (operation)	Power (MW)	Purpose	Heliostat's size (m2)	Number of Heliostats	Reflecting Area (m2)	Heliostat's type	Heliostat's provider
Dem_9	**Mersin 5MWyh Solar Tower Plant**	Greenway CSP	Turkey	Development	2012	1	Demonstration	10	510	5,100	"T" type	Greenway CSP
Dem_10	**DLR - Algeria CSP tower pilot plant**	DLR	Algeria	Development	2013	7	Demonstration			0		
Dem_11	**MINOS CSP tower**	Nur-Moh Heliothermal SA	Greece	Development		50	Demonstration			0		
Dem_12	**PTC50 Alvarado**	Acciona Energia	Spain	Development		50	Demonstration			0	"T" type	Pratt & Whitney Rocketdyne

3.1.3. Heliostats Deployment at R&D Facilities

Table 8: List of heliostat installed in R&D facilities

Id_Nr	Project/Facility Name	Owner/s	Country	Status	Year (operation)	Power (MW)	Purpose	Heliostat's size (m2)	Number of Heliostats	Reflecting Area (m2)	Heliostat's type	Heliostat's provider
R&D_1	**CRTF**	Sandia National Laboratories	US	Operational	1981	5	Research & Development	37	218	8,066	"T" type	
R&D_2	**SSPS-CRS (PSA)**	CIEMAT-PSA	Spain	Operational	1981	2.7 MW_{th}	Research & Development	39.3; 52; 65	111	4,995	"T" type	SENER / CASA / Asinel / Martin Marietta / MBB

Table 8: List of heliostat installed in R&D facilities

Id_Nr	Project/Facility Name	Owner/s	Country	Status	Year (operation)	Power (MW)	Purpose	Heliostat's size (m2)	Number of Heliostats	Reflecting Area (m2)	Heliostat's type	Heliostat's provider
R&D_3	**CESA 1 (PSA)**	CIEMAT	Spain	Operational	1983	7 MW_{th}	Research & Development	39.6	300	11,880	"T" type	SENER / CASA / Asinel
R&D_4	**Themis solar tower**	CNRS	France	Operational	1983	4.6 MW_{th}	Research & Development	53.7	201	10,794	"T" type	PROMES - CNRS
R&D_5	**Weizmann Insttute of Science**		Israel	Operational	1988	2.5 MW_{th}	Research & Development	56	64	3,584	"T" type	
R&D_6	**Jülich Solar Tower**	DLR	Germany	Operational	2008	2	Research & Development	8.2	2153	17,655		DLR / Kraftanlagen München
R&D_7	**Eureka**	Abengoa Solar	Spain	Operational	2010	2	Research & Development	120	35	4,200		
R&D_8	**Solar Beam Down Plant**	Cosmo Oil, Masdar, Tokyo Institute of Technology	UAE	Operational	2010	0	Research & Development	8.5	33	280		
R&D_9	**Daegu Solar Power Tower**	Daesung Energy	South Korea	Operational	2011	0.20	Research & Development	4	450	1,800		
R&D_10	**Yanqing Solar Thermal Power (Dahan Tower Plant)**	IEE-CAS	China	Operational	2012	1	Research & Development	100	100	10,000	"T" type	Himin Solar (heliostats)
R&D_11	**CTAER variable geometry solar test facility**	CTAER	Spain	Operational	2012	8 MW_{th}	Research & Development	120	13	1,560	Heliomobiles	Abengoa Solar
R&D_12	**AORA Solar Tulip Tower - Almeria**	AORA	Spain	Operational	2012	0.1	Research & Development	16	52	832	"T" type	

Table 8: List of heliostat installed in R&D facilities

Id_Nr	Project/Facility Name	Owner/s	Country	Status	Year (operation)	Power (MW)	Purpose	Heliostat's size (m2)	Number of Heliostats	Reflecting Area (m2)	Heliostat's type	Heliostat's provider
R&D_13	**Solugas**	Abengoa Solar	Spain	Operational	2013	5	Research & Development	121	69	8349	"T" type	Abengoa Solar
R&D_14	**Pentakomo Research Facility**	The Cyprus Institute	Cyprus	Development	2014	0.1	Research & Development	4.5	50	225	small	CSIRO
R&D_15	**Sonora Heliostat Test Field**	UNAM - CONACYT - UNISON	Mexico	Operational	2014	2 MW_{th}	Research & Development	36	82	2,952	"T" type	

4 Heliostat's Cost

The solar field costs represent 30-50% of the initial capital investment in the central receiver or power tower solar thermal electricity technologies, CR-STE. Thus it is important to reduce the cost of heliostats as much as possible to improve the economic viability of power towers.

Besides cost, the heliostat performance (reflectivity, tracking accuracy, mechanical strength, etc.) and environmental durability are factors that largely determine the economic feasibility of the CR-STE-PP and should be considered when comparing heliostat designs.

Typical specifications for heliostats are given in Section 5.

The cost of heliostats is presently estimated in the range 150-200 USD/m^2 [Kolb2011, Sunshot2013] and target costs are generally in the range 75-120 USD/m^2 [US-DOE2013, Sunshot2013, Abengoa2013], indicating that there is an expectation within the industry for large cost reductions.

For this WP12 of the STAGE-STE project the challenge is identifying scenarios and small heliostat design solutions that may cost below 100 €/m^2.

The pretension to identify innovations and designs for heliostats to achieve costs below a certain threshold is faced with the difficulty of knowing the actual costs of said heliostats as it is a sector that is in the beginnings and it is driving hugely diverse designs (both typology and sizes per unit). Virtually every new plant proposes a new type of heliostat and the costs are not usually designated accessible. This makes it difficult the drawing of a learning curve that can be extrapolated from plant to plant. In fact, the learning curve is usually incorporated in each new plant from the number of heliostats that incorporates.

One study that is helping set the reference cost of the heliostats is [Kolb 2007].

As shown in Table 9, the current cost of the solar field is dominated by four components for both large and small heliostats. For large heliostats, the major cost drivers are drives (24%); manufacturing facilities / profit (21%); mirror modules (20%); and pedestal / mirror support structure / foundation (17%). For small heliostats, the major cost drivers are drives (33%); manufacturing facilities / profit (25%); field wiring and controls (20%); and mirror modules (18%). It is interesting to note that "pedestal / mirror support structure / foundation" costs impact large heliostats more than small heliostats, as large heliostats experience higher wind loads and require more structural steel (per m^2 of surface area) to maintain a rigid structure and survive worst-case wind storms. It is also interesting to note that "field wiring and controls" costs impact small heliostats more than large heliostats, as small heliostats require more complex field wiring and controls due to the increased number of heliostats in the field.

Table 9: Cost of Heliostat Solar Field subsystem [$/m2] expressed in 2011 dollars (taken from [Kolb2011] with update to 2011-$).

Heliostat Component	30 m², 235 000 m² - 7800 heliostats one time		148 m², 235 000 m² - 1600 heliostats one time	
	2011-$	%	2011-$	%
Mirror area of heliostat (m2)	30		148	
Cumulative production (m²)	235000		235000	
Units	7 833		1 588	
Mirror modules (Facets)	40	(18%)	44	(20%)
Drives	73	(33%)	54	(24%)
Pedestal, mirror support Structure, Foundation	18	(8%)	39	(17%)
Controls and wired connections	28	(12%)	8	(4%)
Field wiring	19	(8%)	8	(4%)
Manufacturing facilities and profit	56	(25%)	46	(21%)
Installation and checkout	11	(5%)	4	(2%)
Total capital cost (2011-$/m2)	**244**	**(100%)**	**204**	**(100%)**
O&M Cost (life-cycle cost) ($/m2)	16.5		7.2	

Cost breakdown of a large heliostat

According to Table 9 the initially selected size for the commercial CR plants was in the order of 115-120 m² (installed in PS10, PS20 and Gemasolar) and about 4646 units(or 544,339 m²) of this heliostats (built by different companies) are in operation in different commercial and demonstration plants and in R&D facilities.

A simplified breakdown of costs for this type (and size) of heliostat is shown in Table 10.

Table 10: Approximate cost breakdown for large (~120 m2) heliostat

Concept		Reference item cost (€-2011)	Specific cost (€-2011/m²)	Specific cost for reference plant size ($-2011)	Percentage of the total
Total mirror surface (m²)		305000		**1000000**	
Heliostat mirror size (m²)		**120**			
Support structure & mirror facets		6520	54	48	31.0%
	Facets	3796	32	28	
	T-tube	1550	13	11	
	Beams structure / press plate	934	8	7	
	Mechanical mounting	240	2	2	
Drive system		6600	55	48	31.4%
	Flender	6600	55	48	
	Winsmith (*)	6500	54	47	
	Sener(*)	7000	58	51	
	Hidraulic - 120(*)	5130	43	37	
	Hidraulic - 140(*)	6930	58	51	
Pedestal and foundation		2401	20	18	11.4%
	Pedestal	1716	14	13	
	On-site mounting	165	1	1	
	Foundation	520	4	4	
Field wiring (trenching and cabling)		1518	13	11	7.2%
	Trenching	1268	11	9	
	Field wiring	250	2	2	
Local control & electrical mounting		805	7	6	3.8%
	Electrical mounting	80	1	1	
	Local control box	725	6	5	
Other installation & checkout		180	2	1	0.9%
Manufacturing facilities and profit		3000	25	22	14.3%
O&M cost (life-cycle cost) (€/year)		1379	11	10	
TOTALS		**21024**	**175**	**153**	**100.0%**

(*) Optional

4.1. Cost Reduction Potential

Heliostat cost minimization challenges are driven by the issues of market entry. The first plants must bear most, if not all, of the startup costs, of which a major factor is associated with the heliostat factory as well as the installed cost of the heliostats.

Thus, the decision process for commercially successful market entry involves numerous heliostat cost aspects. Among these are the basic design concept; production rate; intrinsic cost of the heliostat **as a function of its size**; manufacturing learning curve effects; optical performance as a function of size; trade-off of custom designs against commercial off-the-shelf components; degree of assembly conducted in the field vs. in the factory; trade off of performance vs. cost; and use of low-cost labor vs. investment in automated production, to list a few.

Heliostat performance issues include factors such as tracking accuracy, stiffness, wind loads, gravity bending, and optical performance, such as reflectivity and reflector surface slope error or ‘waviness’, together with mirror module design and size. Higher performance should lead to improved capture of solar energy at the receiver, but above some level, the associated heliostat cost increases lead to a diminishing return. The operations and maintenance issues must also be factored into the heliostat cost, using e.g. the net present value, to comprehensively determine the optimum design and its initial cost. Typically O&M costs are treated separately from the heliostat installed cost and these are combined to determine the levelized cost of energy (LCOE), but the net present value approach allows O&M to be included in the comparison of heliostat designs and sizes.

Some qualitative considerations for small size heliostats related with the design, construction and O&M are listed below:

- **Cleaning**: It is more complex to clean a field of small size heliostats due to their number; however, due to their small size cleaning each of them is easier. A 150 m^2 heliostat is around 13 m high, requiring special trucks for cleaning. A 15 m^2 heliostat is about 4 m high making it easier to clean it. However the number of operations increase dramatically when the heliostat size is reduced what makes mandatory the development of automated cleaning systems for large solar fields made out of small heliostats.

- **Design errors**: Making a design error will lead to very high costs for small size heliostats due to the number of components involved. E.g. error in local control system might require the operator to change all boards.

- **Mirror support structure**: Allow for much saving as small size heliostat would have a specially designed structure. It is possible that rather small heliostats do neither require a torque tube nor truss beam. Due to the small size it might also probably easier to design for the actual loads and require less safety margins.

- **Control** capabilities are bigger and cheaper each day. Besides, control strategies normally involve a central system defining the azimuth and elevation angle for each heliostat. Therefore, control requirements for each heliostat can be provided by simple and cheap electronics. Moreover, this control can be easily integrated into motor drives control system thus reducing the total costs. On the other hand, small heliostats lead to a huge number of elements and therefore, wireless solutions will be not only favorable but probably compulsory. This wireless communication could/must be linked to local PV supply integrated into the heliostat to avoid completely wiring costs. Some configurations like that showed in Figure 2 (current eSolar design) involve a number of braced heliostats that could share some control, supply systems and back-up (batteries) without big additional wiring costs.

- **O&M Costs**: The amount of moving parts and spares increases for the small heliostat concept. When facing O&M tasks in those large heliostat fields additional costs may arise. Therefore, to reduce costs it is imperative that an important number of O&M operations need to be automated. This needs to taken into account during the design process and be reflected in the O&M protocols.

- **Optical Performance**: Is a critical point as the low costs heliostats might have problems at very large distances to assure the required performance. However, using small heliostats might allow designing a solar field with higher efficiencies due to less blocking and shadowing. If small heliostats share a common foundation, large heliostats have the advantage at large distances where the spreading of heliostats needs to be larger due to possible blocking. Canting lowers overall optical efficiency as canting is only optimal for one position. Small heliostats require less canting and might have an advantage over large heliostats.

The optimum heliostat area is hard to define as it involves a trade-off between many effects such as reflector support deflections under gravity and wind load, spillage (beam size at the receiver), and number of control systems, etc., to be built and maintained. Several analysis aimed to identify optimal heliostat sizing have been conducted ([SargentLundy2003, Kolb2007, Blackmon2013, Coventry2013], etc.).

Sargent & Lundy LLC Consulting Group [SargentLundy2003] conducted an independent analysis of power tower solar technology cost and performance. Some studied design improvements for collectors are listed:

- Improvement of mirrors should be reached by the use of higher reflectivity thin glass or films, and additional support structure would be made cost-effective in stable markets where high volume, low-cost production approaches would become practical. Higher volume capabilities for thin glass mirrors (low-iron glasses) should be reached to approach the price-point of the mass-produced conventional glass. High reflectivity (>94%) films have been demonstrated but the durability of these mirrors exposed to long-term outdoor conditions and frequent cleaning must be proven (including breakage, corrosion, manufacturing and maintaining cleanliness).

- Cleanliness can improve with the development of contact cleaning tools for heliostats and adaptation of "self-cleaning" glass for use with solar mirrors.

- Novel heliostat designs like stretched membrane (drum-like) or inflatable/rolling concepts that are lower in weight than traditional glass/metal designs.3

- Drive mechanisms can be simplified. Presently the drives use complex gearing.

- New flux monitoring and management systems that will permit higher solar flux levels on the receiver.

Kolb in his “Heliostat cost reduction study”, [Kolb2007], suggests that a price of about 90 $/m^2$ can be achieved through additional R&D and learning. Increasing the production rate of heliostats provides the ability to the manufacturer to add more automation in the factory and to decrease the costs (mainly costs for drives). A detailed analysis of capital, O&M, and installation costs concludes that large heliostats are more cost-efficient than small ones, the optimum heliostat area for a molten-salt power tower is between 50 and 150 m^2. However, more recent studies like [Blackmon2013] conclude that the actual value might be much lower.

The power tower roadmap written by Kolb et al. [Kolb2011] shows that a decrease of 10% on the drive, manufacturing and structure costs of a heliostat may lead to a LCOE reduction of 0.5 cents/kWh each.

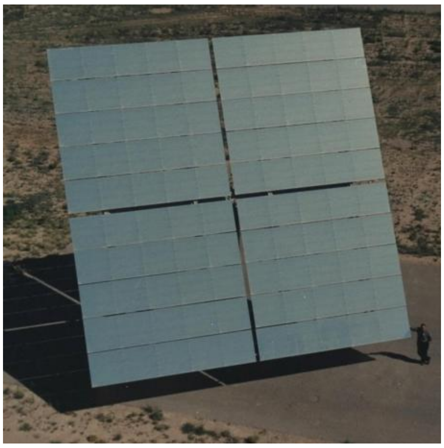


Figure 19: Advanced Thermal Systems H150 heliostat on test at Sandia's NSTTF (Source: [Mancini2000]).

The revolutionary approach of eSolar has started in 2008 [Schell2011] when they designed and build the Sierra SunTower demonstration facility with two towers having each north and south subfields. The heliostat size is 1.14 m^2 allowing the majority of construction and assembly to take place at factories (minimizing on-site labor cost). Widespread and inexpensive hybrid stepper motors were used to power the heliostat drives. Reflector modules are produced with an assembly line on site (125 modules per hour). RMS beam pointing error of 1.4 +/-0.1 mrad was measured. The structure comprises a truss to link many heliostats together and ballast weights are used to stabilize it under wind load. The heliostat small size keeps them close to the ground where wind load is reduced. The

3 It is important to remark that, although some R&D programs on Reflectors modules are aiming to reduce the weight of the modules, in heliostat developments it is not the weight of the reflecting module what is driving the technical specifications of the structure and the tracking mechanism of the heliostat but the wind loads.

heliostat density reduces also the wind load. The steel requirement is 15 kg per square meter of reflector compared to 30 for the ATS heliostat. Despite the need for water, the cleaning system is an automated machine in a row that should help a technician to clean about 12,000 heliostats in about 3 hours. During the first year, a problem was detected concerning fast corrosion of printed circuit boards. At the beginning of 2014, a new eSolar heliostat of 2 m² was commercially available and presented by Tyner [Tyner2013] for Molten Salt solar power plant.

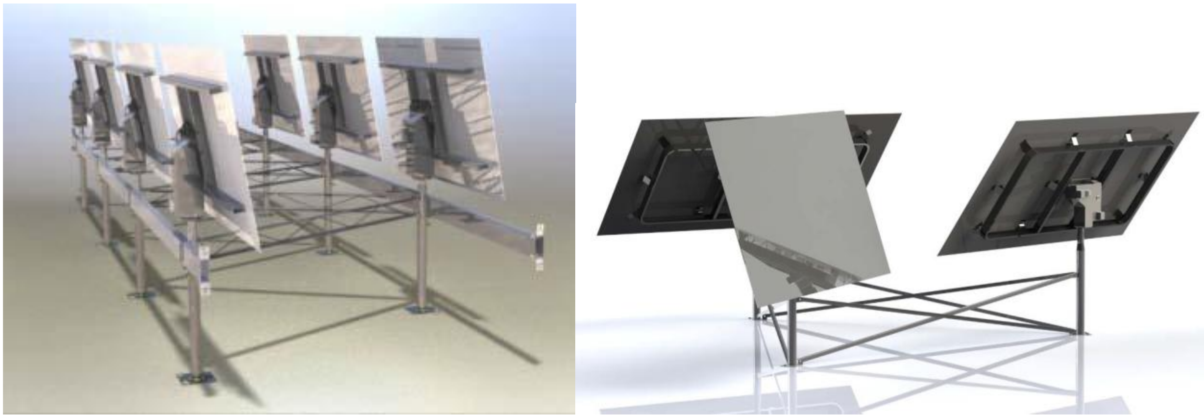


Figure 20: eSolar solar collecting system generation 3, 2011 (left), and 5, 2014 (right) (Source: eSolar).

The company Hitek Services Inc. has published two presentations [Kusek2011, Kusek2013] about the development of low cost heliostat. The objective is to find a heliostat having a minimum cost for a 100 MW_e base load solar electric power plant. The project includes two tasks: (1) Analysis tools will be developed to determine the heliostat cost as a function of size, and (2) a novel heliostat with the optimal size will be designed fabricated and tested.

- In the **first presentation**, the cost analysis starts by dividing in 3 categories the cost: **(1) Constant $ per unit area, (2) size dependent and (3) fixed per heliostat**. It is said that the cat. 2 represents the major part of the cost, cat. 1 is important, and cat. 3 becomes important when small heliostat are involved (depends on the number of heliostats which increases when the size of each decreases). Based on the cost data of Kolb [Kolb2007], the initial cost analysis shows an optimal heliostat size between 20 to 40 m². They defined a heliostat size of 28 m² (about 97,000 heliostats for 100 MW_e base load plant sized) and initiated the development of azimuth drive (az/el heliostat), control architecture and hardware.

- In the **second presentation**, they present some innovations: Use of small heliostat, elimination of field wiring, reduction of the effects of cumulative fatigue damage in drives. In addition some key results are given: Small heliostat cost is very dependent on fixed costs (cat. 3); Resistance to impulse loads is critical for the time-to-failure; Low-cost radiofrequency and PV technologies (autonomous controller) should be used instead of wires.

Blackmon [Blackmon2013] (Hitek Services Inc.) studied the heliostat cost dependency on size assuming the materials, performance requirements and configuration are the same for all the heliostat areas analyzed. The cost was divided in 3 categories: (1) costs that are constant on a per unit area basis (mirrors), (2) costs dependent on the area (structures, etc.), (3) costs that are fixed per heliostat (controllers, sensors, processors, etc.). The parametric (partial) study illustrates the important leveraging effect of reducing the costs from category 3, i.e. independent of size (if category 3 is 1% of

$200/m² DOE Total, optimum size is about 10m²). If the cost of components in category 3 is reduced, an important source of gain is expected by reducing the cost of mirrors (cat. 1). This partial study supports the conclusion of developing cost effective small size heliostat fields.

Two approaches are examined to reduce the heliostat installed hardware costs. The first approach is to decrease the size of the current base line heliostat in the DOE program, but retaining its basic design; this involves a parametric analysis of Category 2 for size, and Category 3 for the number of heliostats for a particular field size. The decrease in size reduces the loads, primarily from wind, expressed as the imposed moment (e.g. product of force due to wind or gravity times a characteristic moment arm). It is shown that the lower load for the smaller heliostat decreases the hardware weight and cost, on a per-unit area basis, and the higher numbers of smaller heliostats increases the Category 3 costs. In general, the Category 3 costs are much lower than those for Category 2.

Following this approach, *[Blackmon2013],* concludes that appropriately allocating the cost of the various components of the base line heliostat used in DOE studies and considering the cost and weight dependence on the imposed moment result in a reduced cost per unit area, and a substantially smaller heliostat, even without reducing the Category 1 constant cost per unit area or the Category 3 fixed cost of hardware required for each of these base line heliostats, irrespective of their size. However, as the size is reduced even further, to very small heliostats, the Category 3 fixed costs become dominant, and the cost per unit area increases, but in between these two extremes lies the minimum cost per unit area. The size reduction also improves the optical performance, and the larger number of heliostats allows substantial learning curve cost reductions as well.

The second approach is to reduce Category 3 fixed costs that are attributable directly to an individual heliostat, irrespective of its size, and by appropriately allocating a part of these costs into the other two categories. These costs are composed primarily of the electronics, such as processors, position sensors, limit switches, motor electronics, etc. **The challenge is to develop heliostat designs with much lower Category 3 costs**. By reducing these fixed costs, it is seen [Blackmon2013] that there is not only a reduction in the total cost, but there is also a leveraging effect that increases the cost reduction by further reducing the optimum heliostat area, and thus gaining additional benefit in terms of decreased moment and weight per unit area, additional learning curve benefits, and additional optical performance. This leveraging effect leads to a lower cost per unit area and it leads to a somewhat smaller overall field reflector area, and somewhat greater cost reduction through the learning curve effect. Successfully employing these two approaches can decease the hardware installed cost of the heliostat design on a per unit area basis.

Finally, there is another issue: operations and maintenance (O&M) costs, and how these are allocated to the heliostat. The observation of the importance of fixed costs per heliostat, irrespective of size, points to a means for reducing the total installed cost of the heliostat, including O&M, when it is treated together with heliostat installed cost. Similarly, some of the O&M costs are associated with Category 1 and 2 costs. The key is to appropriately allocate the heliostat hardware installed costs and the NPV O&M costs into the three major cost categories.

Pfahl et al. [Pfahl2013] proposed an autonomous light-weight heliostat with rim drives with a cost goal of 120 $/m². A cost reduction is proposed by developing new laminated mirror concepts and optimizing the size of the heliostat using better wind load determination.

Figure 21: Commercially available 6 m^2 low cost heliostat (Source: SAT CONTROL).

Aside from the typical suppliers for solar power plant, there are also companies commercially offering small sized heliostats, like the one in Figure 21. Prices are around 150 - 200 €/m^2 for single units, although significant reductions are expected for production of mass quantities. While the heliostats itself are usually not suited (and designed) for operation in large scale plants, due to limited precision of the drive mechanism, some of the employed concepts for the structure and drive mechanism might be interesting.

Coventry and Pye [Coventry2013] studied the state of the art of heliostat designs (as well as *unconventional* designs) and identified some of the more promising design concepts for cost reduction:

- Wind fences that reduce both stow and operational loads.
- Aerodynamic features mounted on the perimeter of heliostats that decrease static overturning moment.
- Durable, highly reflective film bonded to shaped, structurally optimized panels of various materials.
- Highly reflective thin glass sandwich panels, with minimal auxiliary supporting frame.
- Autonomous heliostats using wireless mesh communications and a PV power supply.
- Horizontal primary axis tracking with linear drives for both axes of movement, and dense field spacing close to the tower.
- Hinged mirror panels designed to deflect in high winds, and then return to the correct position.

In addition, they recommended that a novel cost-effective heliostat design should accommodate polar and surround fields (i.e. north or south and circular fields). Moreover, they pointed **out the use of either focusing or small heliostats are likely to be dictated by the optical requirements of high efficiency power tower plants** (uniform high flux concentration and low spillage). Cheap components such as common-off-the-shelf (COTS) components are more likely to be used for small size heliostat.

However, based on the Sandia cost analysis they believe heliostat smaller than 10 m² appear difficult to justify and the size increase should be a good design principle. As a conclusion, a tradeoff should be found between the size increase principle for heliostat and the use of COTS components dedicated to small heliostat.

The SunShot Concentrating Solar Power conference reviews the main developments in CSP for the SunShot Initiative. Below, a summary of US studies related to low cost heliostats is given.

- Design by eSolar of 50 MW_{th} modules (molten-salt tower receiver, 285-565°C) with a hexagonal heliostat field (92,000 ST3, 1.1 m² heliostats) calibrated and controlled (Spectra software system).

- A Flexible Assembly Solar Technology (FAST) system is studied by BrightSource to reduce the construction cost. The objective is to assemble mirrors with their structural support elements at a centralized off-site facility supplying multiple CSP projects, and to use an automated, transportable FAST platform to perform the final assembly on-site.

- Solaflect Energy studies Suspension Heliostats™ design which enable to reduce steel and assembly costs.

- 3M company studies Multilayer optical films (MOF) and optically accurate reflector panels. The best MOF mirrors have almost a perfect reflectivity between 420 and 750 nm, but very low otherwise.

- JPL (Jet Propulsion Lab.) and L'Garde are starting a project to develop low-cost, light weight, thin film solar concentrators (silverized polymer film bonded onto a light weight structural polyurethane rigid foam support).

- NREL is developing a low cost heliostat to meet the SunShot Initiative of 75 $/m². A small heliostat of 6 m² with flat mirrors was found to reach 72 $/m² (50,000 units/year). The use of wireless mesh networks (locally PV powered control station with a RF transceiver for communication) and a reduction of heliostat-mounted components for sun-tracking was found to lower the heliostat cost.

- Hitek Services Inc. found the optimal heliostat size is between 10-15 m², the drop of PV and RF communication prices have enabled the development of cost-effective autonomous heliostat and the staged azimuth chain drive, which has a good damping coefficient, should be further enhanced to reduce the cumulative fatigue damage leading to longer drive life.

- Otherlab is developing a polymer-based new actuator design (new kind of pressure controlled mechanism) to reduce the control and drive costs that become prohibitive per m² when small heliostat are considered.

5 Heliostat Functional Specifications

5.1. Heliostat Typical Specifications

Heliostats are the main component in the collector system configuring the solar field of the CR-TE power plants. **Heliostats' function consists of collecting the solar radiation and concentrating it into the solar receiver according to a specified aiming strategy and allowing its integrity during its lifetime by adequate mechanical and control designs**.

Heliostats are made up of, but not limited to, mechanical structure, foundations, mirrors, facets, tracking system, control system, and all the required associated fixings, components and infrastructure to ensure correct performance and operation in all conditions. All these items shall be designed, manufactured, transported to site, provided, assembled and commissioned, usually by a Contractor.

The heliostat arrangement in the solar field is quite independent on the heliostat type and size[4]. It basically requires to maximize the annual optical efficiency (by balancing the several optical loss processes, such as mirror reflectivity, cosine loss factor, shadowing and blocking losses, atmospheric attenuation and spillage in the target aperture) and to provide adequate space for access to all the heliostats for cleaning and maintenance.

In general (and not just for CR systems but also for PT and LFR) conventional focusing optics have dominated solar concentrator designs. In the future these systems might evolve and result in much more sophisticated solutions efficiency wise as well economical wise. It should be noted, however, that, although, many of the new developments involve innovative optical approaches, from today's viewpoint it is difficult to predict whether they will become economically viable or not.

The arrangement of heliostats in a Solar Field shall have enough accuracy, reflecting surface, availability and necessary characteristics to produce a granted energy production and adequate performances. Thus, typical figures of merit and/or criteria for optimization are: Maximize the annual solar field optical efficiency; optimize the land use as a compromise between the solar field optical efficiency and the allowance for operation and maintenance of the heliostats in the field; the optimum sizing and location of the tower, switching station, access road and water supply, etc.

The final layout of the field has a huge impact on the overall performance of the power plant and needs to be done accordingly. To offer the same electrical output, a solar field using small sized heliostats might need a greater number of heliostats. Introducing more heliostats to the field makes the layout optimization more challenging as the number of optimization variables (namely the position of the heliostat) increases. However, it allows finding a more efficient layout, as overall blocking and shading can be reduced. Going to very small heliostat sizes additional constraints might be introduced

[4] For current commercial CR plants, heliostat arrangement is in general independent of heliostat type and size, however, there are some configuration options where this is not true such as the concepts of ganged heliostats or those multi-tower systems in which the heliostat field that feeds a single power block is shared by two or more towers.

to the optimization algorithm, as cost effects for each heliostat change and for instance field wiring becomes more important.

Typical specifications on heliostats usually cover:

- Heliostat performance
- O&M costs
- Heliostat Mechanical requirements
- Heliostat operation modes
- Reflecting surface (usually mirrors) specifications and fixing system
- Tracking system requirements

5.1.1. Typical Specification on Heliostat Performance

Typical parameters **in relation with the granted energy production and performance** usually specified are:

- Mean reflectivity, reflectivity of clean mirrors and losses due to the dirt as a function of the time and the number of washes.
- Azimuth rotation range.
- Elevation rotation range.
- Maximum time to achieve the stow position from the farthest position.
- Electrical energy self-consumption and electrical power.
- Total accuracy during the normal and special operation modes.

The total accuracy shall take into account the following:

- Load induced as well as thermal induced deformations of the structure, mechanism, mast, foundation and mirrors.
- Backlash. The backlash must include the wear after (about) 25 years of operation.
- Canting and focus errors.
- Geometric errors due to manufacturing, assembly, etc. including the axis error.
- Non continuous tracking errors (or errors due to discontinuous monitoring step by step)
- Errors due to the control system and the position indicators.
- Heliostat calibration error.

5.1.2. Operation and Maintenance Costs

In order to assure a minimum LCOE, not only technical performances and capital costs must be analyzed but also operation and maintenance costs and even dismantling, disposal or recycling after service life of the plant. Thus:

- The heliostats shall be designed, installed and commissioned based on the painting and corrosion resistance requirements
- Reflectors must assure good reflectivity after frequent cleaning operations and long-term outdoor conditions exposure
- Cleaning operations must be easy and cheap.

5.1.3. Heliostats' Mechanical Requirements

Heliostats shall stand any load that can appear in any operating condition of the Plant during its lifecycle and under the full range of temperature and environmental Site conditions, without permanent damage.

The main loads affecting the heliostat mechanical specification are wind load and loads due to starts and stops:

Wind loads

- Heliostats shall withstand basic wind speed at the plant site.
- The turbulence and terrain category shall take into account the presence of the buildings and heliostats at the solar field of the Plant.
- Terrain topography shall be taken into account.
- Wind loads shall take into account the dynamic response for the wind gust.
- The heliostat at stow position shall withstand any wind condition. If the heliostats do not require the stow position then they must withstand any wind condition at any position.
- The maximum wind speed that the heliostat can withstand in any position (maximum operating wind speed) shall take into account the time to go to stow position and the wind condition changes during this time.

Start / Stop loads

- If heliostats require "starts and stops" several times during the sun tracking, then they shall withstand the loads and vibrations during these "starts and stops".

5.1.4. Operation Modes

Heliostats shall be able to operate, without permanent deflection and with the accuracy granted by the Contractor, in the following operational modes:

- **Normal operation mode**: Heliostats shall be able to operate on a continuous basis with the maximum accuracy, under specified conditions by the contractor.

- **Reduced operation mode**: Heliostats shall be able to operate on a continuous basis at reduced accuracy, under specified conditions by the contractor.

- **Standby mode**: Heliostats shall keep a specific position to be described by the contractor.

- **Survival mode**: Heliostats shall be able to withstand, without permanent deflection or damages, the loads set at the mechanical requirements.

5.1.5. Mirrors and the Mirrors Fixing System

Mirrors goal is to reflect sunlight along its life time. Therefore, apart from performances at installation time that are related to **reflectivity** as well as reflector **surface slope** error or '**waviness'**, durability issues are a main concern in order to keep mirror performances along time. Mirrors will be exposed to long-term outdoor conditions thus:

- Mirrors and the mirrors fixing system shall take into account corrosion consideration such as the minimum silver content

- Heliostats' mirrors shall be able to withstand hail impacts

- Heliostats' mirrors shall withstand sand abrasion

- Mirrors must withstand frequent cleaning operations

- Mirrors should withstand certain loads (shocks, wind loads, etc.) and should break in a safe manner for the personal and for the other mirrors.

5.1.6. Tracking System Requirement

- The tracking system shall be (usually) a 2-axis tracking system.

- The tracking system shall be designed, justified and commissioned to be able to achieve the survival position from the worst position at the maximum wind condition required by operational modes and to withstand, without deflection, the maximum wind speed at the stow position.

- The tracking system shall assure that speed is enough to reach this stow position in a certain time and that emergency defocusing is also quick enough to assure receptor survival.

- Each drive unit shall be capable of withstanding the torques developed during start, acceleration, and deceleration.

- Drive system's starts/stops shall be softened and reduce the vibration off the heliostat.

- Environmental seals for sensitive systems.

If a gear drive unit is used, the following requirement shall be applied:

- The tracking system shall have irreversibility. The drive will be resistant in both axes. A fail safe brake at the electrical motor can be used.

If the system requires lubrication the following requirements shall be applied:

- Lubricant seals shall be designed to comply with the working life under the operating conditions including UV resistance.

If a hydraulic drive system is used the following requirements shall be applied:

- The oil tank shall avoid the accumulation of dust, rain and water condensation. The oil tank shall have a level indicator with electric alarm and a filter or breathers plug and thermal switch. The filter or breather plug shall removes debris of 10 µm and larger.

- If there is a leakage or hose break, the hydraulic drive system shall keep the pressure at the hydraulic cylinder to avoid any movement.

5.2. Minimal Functional Specifications for Small Heliostat

The final goal of any heliostat designer regardless of heliostat size is to develop a functional heliostat that reflects the light to defined point with the **required precision** along its **service life** and at the minimum cost.

Of course, the overall requirements (accuracy, lifespan, etc.) are similar for big and small heliostats. Nevertheless, small heliostat require a different approach in order to get these requirements in the most cost-effective way so that we can take as much profit as possible of small heliostat advantages.

Therefore, understanding of error sources, their effects on the final performances (pointing accuracy and spot light characteristics) as well as the costs involved is the key point in order to identify which parts of the heliostat must be improved and which component requirements must be relaxed.

Error sources can be related to manufacturing accuracy, loads, thermal deformations, assembly process, etc. and therefore, they can be either random or systematic. At the end, errors from all component and processes must be added in order to get the global accuracy. Total error can be assumed to be the root square sum of all errors.

$$\varepsilon_t = \sqrt{{\varepsilon_1}^2 + {\varepsilon_2}^2 + {\varepsilon_3}^2 + \cdots + {\varepsilon_n}^2}$$

It is clear that loads (wind, weight, etc.) are lower for small heliostats than for big ones. Therefore, higher accuracies (low deflections) can be reached at lower prices. Regarding manufacturing and assembling processes; small heliostats manufactured, assembled and checked at well established off-site factories can also get higher accuracies at lower prices. Canting errors can also be reduced or avoided. On the contrary, small heliostats must use low cost drives thus getting high accuracies is harder and, therefore, drive requirements must be softened.

In order to define the required accuracy for each component and process in an optimum way and therefore, to reach the most cost-effective design, it is interesting to define an “error budget”. That is, a list of error sources and their effect on heliostat accuracy. In this way, the “error budget” is used to allocate errors to components and processes.

This approach is common for precision machine design [Slocum2001, Lacalle2009] or electronic equipment but it is seldom shown in heliostat design literature. R. Osuna proposed the following error budget for the Colon 70 heliostat design [Osuna2000].

Table 11: Common errors and magnitudes from different sources (F.i., Source: Abengoa).

Error type	Error source	Error (mrad)
General	Mirror surface error (curvature, waviness, etc.) at 25 °C	1.5
	Canting	1.2
	Adjument of rotation axis (non orthogonality, horizontallity of foundation, etc.)	0.5
	Electronic control (encoder, resolution, sun algorithm, …)	1.0
	Thermal deformation of structure	0.3
	Partial sum	**2.24**
Mass forces for elevation axis motions (between 30 ° and 90 °)	Beding of pedestal	0.6
	Support structure deformation	1.55
	Mirror deformation	0.4
	Elasticity of drive mechanism	-
	Partial sum	**1.71**
Wind load (18 km/h)	Bending and torsion of pedestal	0.4
	Support structure deformation	0.1
	Facet deformation	0.2
	Drive mechanism tolerance	0.3
	Elasticity of drive mechansim	0.4
	Partial sum	**0.68**
	Total	**2.9**

This error budget was proposed for a T-type 70 m^2 heliostat including an electro-mechanical drive. Later on, the same design evolved to a bigger heliostat (120 m^2) including the same drive unit. Of course, using the same drive to move a larger reflecting area implies bigger loads on the drives, and consequently shorter lifetime and bigger deflections. Therefore, the total error will be bigger and of course the error due to each source will be different.

As reducing each error source has a different cost depending on the size and the configuration, a different error distribution must be defined in order to reach enough accuracy at a reasonable price. For example, wind loads grow quickly with size, so bigger drive units, motors, structure, pedestals, foundations, etc. are necessary, thus, leading to much heavy and expensive systems.

On the contrary, small heliostats can assure much lower structural deflections even with light, simple and cheap structures. Thanks to this reduced deflection, error “allocated” to drives can and must be enlarged in order to allow that cheap off-the-shelf motors massively produced for less demanding sectors can be used.

It is also likely that foundation requirements have also to be softened in order to keep costs low since we cannot afford strong foundations for such a big amount of heliostats. Even structure stability along time could be relaxed if the rotation axis position can be determined often in an easy and cheap manner. In this way, new offsets for the tracking system would be introduced each time the system is calibrated.

We can say that small heliostats try to replace strong, heavy and expensive structures with lighter structures that include “smarter” tracking and calibration systems. That is, small heliostat reduce “hardware” costs but increase “software” costs that are supposed to be reduced along time since computing, data analysis and communication capabilities are larger and cheaper every day.

As a result, designing small heliostats imply a completely different “error budget” than designing a large one.

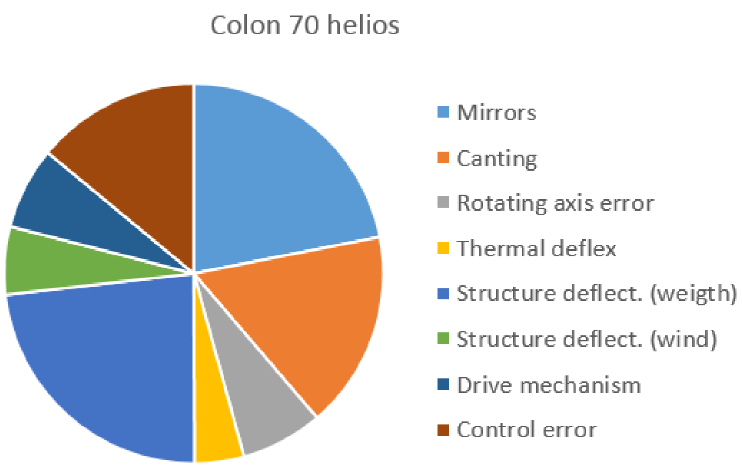


Figure 22: Balanced “error budgets” for different heliostat configurations.

5.2.1. Requirements not Directly Related to Accuracy

Apart from accuracy requirements pointed out before, designing small heliostats must take into account other requirements in order to take as much profit as possible from their advantages and get the more cost-effective design. Main points to be taken into account would be:

- Common-off-the-shelf (COTS) components can and must be used in the design. Specially, drive units used in other sectors must be reviewed so that the most suitable ones can be adapted and used.
- Take advantage of automation and quality control in the factory and assure that majority of the construction and assembly tasks take place at factories thus assuring high quality and minimizing on-site labor cost.
- Optimize the design in order to assure easy transportation from the factories to the plant and to assure easy and precise assembling, installation and commissioning processes in the field.
- Reduce or avoid canting processes.

- Reduce wiring and control costs. If heliostat size is very small it will be compulsory to develop wireless solutions for communication, control and heliostat power.

- Analyse O&M operations (cleaning, repairing, replacement, etc.) and assure that access to the heliostats is possible and easy. Moreover, O&M protocols and the automatization of processes (like in Figure 23) must be taken into account during the design process. If required special robots, vehicles or tools must be also designed.

Figure 23: eSolar's automatic cleaning robot (Source: eSolar).

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List of abbreviations and definitions

AUD	Australian Dollars
CR	Central Receiver
GWe	Giga Watt electrical
kWh	Kilo Watt-hour
LCOE	Levelized Cost of Electricity
NPV	Net Present Value
O&M	Operation and Maintenance
PSA	Plataforma Solar de Almería
PT	Parabolic Trough
PV	Photo Voltaic
STE	Solar Thermal Electricity
USD	United States Dollars
LFR	Linear Fresnel Reflectors