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Heliostat cost reduction – where to now?

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Abstract

The Australian National University has been undertaking a review of state-of-the-art in heliostat design, as part of the Australian Solar Thermal Research Initiative (ASTRI). Deep cost reduction is required to ensure solar tower technology becomes competitive, and to achieve the aggressive LCOE targets of ASTRI and other programs like U.S. Sunshot. This paper is a case study for a new heliostat design, and aims to provide directions and identify opportunities for cost reduction.

The review examines trends at both a system level and at an individual collector level, to make sense of where the greatest potential for cost reduction lies. At a heliostat system level, we focus in particular on three factors critical to cost reduction: manufacturing and assembly, heliostat size and wind load analysis. A technological review of heliostat componentry highlights those areas we believe have most performance improvement and cost reduction potential, including mirrors, tracking systems, communication systems and structure. The review also identifies cost reducing design features of some recent unconventional heliostat designs, and provides a summary of those features we believe to hold the most promise.

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1. Introduction

This paper is a case study for a new heliostat design, and aims to provide directions and identify opportunities for cost reduction, i.e. where to now? The context is the CSP industry which has grown at 40% since 2005 [1], and is expected to reach installed capacity of 4.5 GWe in 2013 [2]. It is a year of unprecedented growth for power tower technology, with 500 MWe expected to become operational this calendar year compared to the 65 MWe presently in operation [3]. For the CSP industry it is a period 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 of promise, with 2.9 GWe under construction and 7.3 GWe soon to commence construction [2]. Strongly funded research programs are in place, with aggressive levelised cost of energy (LCOE) targets, such as the U.S. SunShot program, with a 0.06 USD/kWh target [4], and the Australian Solar Thermal Research Initiative (ASTRI) program, with a 0.12 AUD/kWh LCOE target [5], both by 2020. This review is the first step in a heliostat cost-reduction project to be carried out as part of the 8 year

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ASTRI program. We discuss technology trends and examine some of the best prospects to progress the state-of-the-art, to reduce heliostat solar field cost consistent with ASTRI goals.

The history of design and deployment of heliostat fields is well documented [6, 7]. 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 kWe to 10 MWe. 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.

The cost of heliostats is presently estimated in the range 150-200 USD/m² [8, 9] and target costs are generally in the range 75-120 USD/m² [4, 9, 10], indicating that there is an expectation within the industry for large cost reductions.

2. The key to LCOE reduction

We believe that the key to achieving LCOE targets is not a single ‘breakthrough’ development, but to bring together as many of the performance improving, cost reducing design concepts as possible into a single package, integrating design decisions at a solar field level, an individual heliostat level, and subcomponent level.

It is worth comparing the difference in leverage of heliostat performance and cost on the LCOE. For example in a recent report on CSP in Australia [1], sensitivity analysis about a 250 AUD/MWh baseline showed that a 10% improvement in annual generation, and a 10% reduction in capital cost have a similar impact on LCOE: 8% and 9% reduction respectively (in other words, the ‘steepness’ of the red and yellow lines in Figure 1 are reasonably similar when close to this baseline). However, the solar field makes up only about 38% of the direct capital cost in a power tower plant [9]. Therefore, in terms of LCOE reduction a design improvement that results in 1% performance improvement is equivalent to a design improvement that reduces solar field cost by about 2.3%, i.e. the leverage of performance vs. cost on LCOE is better by a factor of about 2.3×. The leverage of performance is important to consider at all times, and is probably finds most practical application for heliostat design decisions that relate to the optical performance, for example, selection of the mirror type, annual optical efficiency of the heliostat field, cleaning regimes, etc.

![Figure 1. Variation of cost against an LCOE baseline of a Nevada Solar 1 type system at Longreach, from [1].](image)

Despite these observations about the relative leverage of performance and cost reduction, capital cost reductions of around 50% are targeted by programs such as ASTRI and Sunshot. However performance improvement, in terms of energy delivered by the heliostat field, is probably limited to less than 10% through measures such as higher reflectance mirrors, better solar field efficiency, and higher optical capture at the receiver. Therefore, despite the leverage of improved performance, continued cost reduction of heliostats is critical to the future competitiveness of power tower systems.

We now examine design factors at a solar field level, an individual heliostat level, and subcomponent level, and give our opinions as which factors are most important to a new heliostat design.

3. Design factors at a solar field level

Current CSP research programs have ambitious performance goals, such as > 50% power cycle efficiency using working fluids hotter than 650ºC for the SunShot program [4]. For example, the supercritical CO₂ Brayton cycle is viewed by many as a good prospect to achieve this aim [11, 12]. Critical factors for receivers operating at such high temperatures are a high concentration ratio (i.e. high optical accuracy from the solar field)
and a low radiative view factor [13]. While both cavity and external receivers are feasible, better thermal efficiency may be expected by the use of a cavity [13].

The design requirements of individual heliostats influence, and are influenced by, the design of the solar field layout and the receiver type. The two most common field layouts are the ‘surround field’ (e.g. Solar Two, Gemasolar, Ivanpah, Crescent Dunes) and the ‘polar field’ (e.g. Thermis, PS10, PS20, Julich). LCOE analysis comparing surround and polar layouts should take into account all factors – blocking, shading, cosine losses, atmospheric attenuation, tower height, latitude, plant size, etc. The best option varies case-to-case, as evidenced by studies and continued commercial development of solar towers of both layout types [6, 14]. External-type receivers are suited to both field layouts. Cavity-type receivers are better suited to polar fields, although multiple cavities or downward facing cavities are feasible for surround fields [15, 16].

Assuming here a power tower optimized for high temperature, high efficiency energy conversion, we make the following observations regarding our new heliostat design:

- Heliostats deployed in >50% efficient power tower plants are more likely to be arranged in a polar field than a surround field, due to the compatibility with cavity receivers. However, surround fields are also feasible and it would therefore be unwise rule out this option at the start of the design process. The field layout impacts heliostat design factors such as the required range of movement, tracking type, and the required optical accuracy (as polar fields have a greater average slant range than surround fields of an equivalent size).
- Analysis of the optical requirements of the solar field for high efficiency systems suggests optically accurate focusing heliostats will be required (or else small heliostats relative to the receiver) to achieve high flux at the receiver with acceptable uniformity and light spillage [11].

4. Design factors at a heliostat level

In this section we address three design factors we think critical to cost reduction of heliostats: manufacturing and assembly, heliostat size and wind load analysis. As we will discuss, the three factors are interlinked and should be addressed at the beginning of, and throughout, the design life-cycle.

4.1. Heliostat manufacturing and assembly

It has been estimated that as much as 80% of the cost of product development and manufacture is determined by the decisions made in the initial stages of design [17]. Design of a solar field is highly multi-disciplinary, involving engineers in the fields of mechanical, structural, manufacturing, electrical, communications, aerodynamics, optical analysis, plus many more. In that context, it is inconceivable that a quality, low-cost outcome for a new heliostat design could result from a traditional sequential type design process. Concurrent engineering processes are essential, i.e engineers across disciplines working together from the earliest stages of product design, and throughout the design life-cycle.

We focus on an aspect of the concurrent engineering approach, known as design for manufacture and assembly (DFMA). Boothroyd discussed the results of a 1990 study of the automotive industry, that showed that there was a wide variation in automobile assembly-plant throughput, yet that the level of automation accounted for only one third of the difference in productivity between plants [18]. He suggested that the key lesson from this was that no improvements in operation can make a plant fully competitive if the product design is defective. We believe this is a lesson that is also true for heliostat design.

In order for heliostats to reduce costs in the order of 50%, their manufacture and assembly must be highly efficient. A key feature of the DFMA approach is simplifying the product by reduction of the separate number of parts and materials, and increasing the utility of subcomponents, perhaps using more sophisticated manufacturing processes. It requires a fundamental understanding of the capabilities and limitations of materials and manufacturing processes, which is why concurrent engineering – design and manufacturing engineers working together from the earliest design stages – is particularly important.

Make-buy decisions (driven by the lure of low-cost country sourcing) are important and are part of the concurrent design process. The make-buy decision is not simply about reducing cost, but a range of factors [19]. A “buy” strategy allows sharing of costs, including R&D costs, with suppliers and access to a wider range of new ideas and technologies, but this is balanced up by the benefits of “learning by doing” and gaining a competitive advantage through development of IP and in-house expertise. Supplier capability is a key issue, and original thinking suppliers with high expertise are typically those with a diverse range of customers across diverse industries. Additionally, supply chain growth will undoubtedly assist with cost reduction as the industry matures. There is a lack of consensus in literature about the best make-buy strategy for new technologies [20]; in general most commercial heliostat developers appear to be quite vertically integrated – i.e. the favour the
“make” strategy - offering their own technology from heliostat design through manufacture and assembly, specialised components, tracking and alignment software, and even in some cases mirror cleaning systems. However, despite the status quo, the potential cost reduction benefits of low-cost country sourcing of heliostat components cannot be overlooked, although savings may not be as great as expected as companies tend to underestimate the add-on costs [21, 22].

Strong long-term relationships based on trust between technology developers and their suppliers is generally considered critical to success, although there is some evidence this is less important where radical technologies are being developed [20]. Supplier confidence and trust has not been helped by instability in the CSP industry in recent times.

4.2. Heliostat size

It is noted in a number of recent reports [9, 23] that there presently appears to be no consensus regarding the optimal size of a heliostat. Operational heliostats range in size from 1.14 m² (eSolar) to 120 m² (Abengoa) with various sizes in between, e.g. 15.2 m² (Brightsource), 62.5 m² (Pratt&Whitney), 116 m² (Sener) [24-28]. Determining trends from industry is difficult. Some technology developers have recently upsized their existing heliostats – Abengoa from 120 m² to 140 m² [25, 29], BrightSource from 15.2 m² to 19.0 m² [26], and eSolar from 1.14 m² to 2.2 m² [30] – perhaps to lower cost through less conservative use of customised components (such as the drive system). However, the lack of a clear trend by the bigger technology developers is exemplified by Abengoa, who are simultaneously offering a 140 m² heliostat and developing an 18 m² heliostat [10]. A number of well-respected R&D institutions are presently developing very small heliostats: NREL ~6 m², DLR 8 m² and CSIRO 4.5 m² [8, 31, 32].

Throughout the 1980s, the prevailing view (at least in the US) was that heliostats should be very large to be cost effective. Sandia analysis in the year 2000 supported this view, indicating heliostats should be at least 50 m², and preferably 150 m² [7]. The main driver to large scale was the cost per m² of the heliostat drive system. In efforts to reduce the cost of the drive, a number of customised drive products have been developed by companies such as Sener [28], Flender Siemens [33-35], Winsmith [7, 36] and Cone Drive [37]. For smaller heliostats, the cost of the control and communication system also becomes an important cost driver favouring larger heliostats.

The Sandia study [7] used the 148 m² ATS heliostat as its reference, and explored a size domain of 53 m² to 214 m². Figure 2 shows what happens when the relationships developed in this study are extended for heliostats smaller than 53 m². While outside the original domain of the Sandia analysis, the general trends are clear: specific cost escalates strongly as size falls, with the impact particularly noticeable for sizes below about 30 m².

![Figure 2. Heliostat price dependence upon area, using the method of Sandia (Scott Jones) [7] to extrapolate to smaller sizes (solid line). Note that as the intention is to show the trend, the values remain in year 2000 USD as per the original Sandia data. The dashed line is indicative only, showing forecast impact of cost drivers relating to manufacturing and assembly of smaller heliostats.](image-url)

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 common-off-the-shelf (COTS) components: similarity to a wider breadth of industries helps when sourcing high volume manufactured COTS components e.g. motors, gearboxes, bearings, etc.
• Feasibility of a wider range of manufacturing processes: specialised 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 automated assembly e.g. using robots, materials handling systems, smaller assembly buildings or even transportable assembly systems, such as the FAST system proposed by BrightSource [26].

• Simpler transport: logistics simpler, and off-site manufacturing more feasible.

These cost drivers all favour reduced scale, and have the impact of lowering specific cost for small sized heliostats (with the trend indicated by the arrow and dashed line in Figure 2). For example, a high volume COTS 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 favouring 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 [7].

We believe that the combination of these drivers are behind the lack of consensus in the optimal size for heliostats, and perhaps also provide some guidance as to how to further reduce cost. The key trends in the specific cost curves (Figure 2) from the Sandia study are that the slope of the curve becomes steep as the heliostat size tends towards zero, and conversely, that the slope of the curve is gentler as the heliostat size becomes large. Based on these trends, we believe very small heliostats (say, less than about 10 m²) appear difficult to justify, and that looking for opportunities to increase size should be a design principle. However, we believe an equally important design principle is to seek compatibility with volume manufacturing and assembly processes, including the use of COTS components, which will have the tendency to reduce heliostat size. With these two equally important but competing design principles established, our answer to the question of optimum heliostat size is that, as long as a concurrent engineering / DFMA approach is adopted, the size will evolve naturally towards an optimum during product design.

4.3. Wind loads

The wind effects on the heliostats can be divided into two parts: the static wind load and the dynamic wind load. An in-depth understanding of both types of wind effects is important for targeting cost reduction measures. For static loads, a critical initial design decision for cost reduction is the determination of the peak wind speed. Static load depend on the square of wind velocity, hence even a small variation in the peak wind specification makes a significant difference to loads (and hence material cost), e.g. cf. 38 m/s [38, 39] and 40 m/s [6] peak wind, gives a load reduction of approximately 10%. As methods for determining peak wind loads relate to risk factors and are probabilistic in nature, a risk analysis for the specific site is warranted to remove conservative factors inherent in codes. Analysis of historic wind data can also help, where it is available [40].

Once the design wind speed is selected, static wind loads can be further reduced by improving the heliostat design. For example, a porous fence around the perimeter of the heliostat reflector can reduce flow separation, and has been shown to reduce overturning moment by as much as 40% [31]. This load reduction enables a 30% weight reduction of the mirror facet supports, the pylon, and the foundations. The impact of the fence on operational loads is yet to be investigated.

Another method of reducing cost is the use of heliostat field perimeter wind fences, which can reduce both the stow and operational loads compared to an isolated heliostat [41, 42]. The horizontal force and overturning moments are shown to decrease significantly using a wind fence that is ¾ as high as the heliostats with a porosity of 40% [41].

The dynamic wind load, caused mainly by large-scale vortex shedding behind the heliostat (as shown in Figure 35), is important in the heliostat design. The stiffness and damping of a heliostat structure must be high enough to avoid wind-induced torsional divergence, flutter, and resonance of the structure. Dynamic wind loading has the potential to cause structural failure, tracking errors, optical losses, and reduction of heliostat life.
One solution to controlling vibration is to increase the rigidity of the structure supporting the reflectors which, in general, will result in increased cost of a heliostat. An alternative and lower cost solution is to adjust the flow field to reduce the vortex formation using aerodynamic methods such as attachments to the heliostat reflector [31, 44].

Aerodynamic loads obtained in low-turbulence flow are inappropriate and unconservative for heliostat design [45] as turbulence has a significant influence on heliostat loads [38, 40]. Therefore, wind tunnel tests typically attempt to simulate the turbulence profile; however, the methodology has been shown to be important. Turbulence intensity matching in wind tunnels, to simulate an open country profile, can artificially increase the predicted dynamic effects [46]. A number of well-cited experimental studies of heliostats do turbulence intensity matching, and therefore potentially overestimate wind loads in the stow position [31]. Higher turbulence intensity than in codes has been measured for low wind speeds, which should be considered for estimation of operational loads [40]. A strong understanding of aerodynamic and wind tunnel methods is critical for heliostat cost reduction, to determine wind loads accurately, to avoid overly conservative design and to take advantage of load-reducing design features.

5. Design factors at a sub-system or component level

Glass-metal, faceted T-shaped heliostats have long been the dominant technology [7, 25, 26, 28, 47], and continue to have popularity for new heliostat designs, for example, NEM Energy’s 58 m² heliostat [48] and AORA Solar’s 16 m² heliostat [49], both under test at PSA. However, there are a number of other unconventional concepts under development with design features that could potentially lower costs:

- The DLR ‘autonomous light-weight’ heliostat [31] uses cable driven rim drives on both axes to improve the mechanical advantage, lower loads on bearings, the mirror panel, and the upper part of the pylon. Other cost-reduction features are a prefabricated concrete ground anchor, and a wind load reduction mechanism using a perimeter fence mounted on the heliostat.

- The Solaflect ‘suspension heliostat’ [50] has glass facets held in position by cables tensioned from a compression element perpendicular and central to the mirror panels. It is claimed that material use is as low as 35-40% of that of a conventional heliostat, by making the most of the favourable properties of steel in tension combined with using the mirror panels as structural members in compression.

- JPL & L’Garde are developing a large faceted heliostat, with one innovative feature that facets are designed to deflect in high winds (>35 mph), then re-latch with a magnetic latch system to return to the correct position [8, 51]. This potentially allows for a lower cost design by optimizing material use for more common wind conditions, rather than for infrequent wind gusts. Similar to the Solaflect concept, tension wires are used to minimise the mass of the structure and to impart curvature.

Other recent unconventional designs include those of TitanTracker [52], Google [53], CSIRO [54], NREL [8, 55], HelioTower [39], HydroHelio [56, 57], Heliosystems [58], and Solar Tower Technologies [59]. A recent DLR survey [60] of a wide range of heliostat designs categorised pros and cons of the various design features in a systematic way, to make a series of recommendations of promising concepts [60]. Similarly, we focus on those design features at a sub-system or component level that we believe have most performance improvement and cost reduction potential.

Referring back to the discussion in Section 2 about the leverage of performance on LCOE, the use of thin glass (~1 mm) for mirrors offers a useful reflectivity advantage of around 1% [61] compared to thick glass...
from the added complexity of this mode of tracking. Improved optical performance must be weighed up against a likely increase in capital cost. However, the benefits of this approach, annualized and averaged across the whole heliostat field, are significant.

The range found the secondary axis could be actuated by a linear drive, but a slew drive is required on the primary axis. Improving the uniformity of the reflected image from each individual heliostat. A study of the tracking angle curvature of each axis to minimise the average astigmatic aberration, which reduces the maximum spread and the sun, its sagittal and tangential directions do not change, and therefore it is theoretically possible to tune the tracking angle range for SunShot [4]). Some question marks remain, but nonetheless the use of reflective films would open up a range of cost reduction options not available to glass, for example, bonding film to lightweight and rigid fibre-reinforced plastic structures such as foam cored sandwich panels, or direct bonding to shaped, closed-cell foam structures [51], and therefore the continued development and improvement of reflective films is certainly of interest.

Development of autonomous heliostats has progressed markedly in recent years i.e. heliostats that do not require power or communication wiring. In 2004 PSA tested a field of 92 radio-controlled heliostats [70], and found capital cost savings of more than 50% were feasible compared to a conventional hard wired systems. A wireless mesh communication system has been tested at the solar tower plant in Julich by Trinamic [71], and a similar system is under development by NREL [55]. Advances to wireless communication technology and reduction in the cost of photovoltaic panels have made heliostat autonomy an attractive option for cost reduction.

Heliostats with a primary horizontal axis of rotation allow up to 80% denser spacing without collision [23, 39, 72], which is particularly useful in regions close to the tower. A number of small heliostats under development employ this type of tracking [31, 32, 39]. Furthermore, it is shown with optimal alignment of the primary axis, the range of motion for both axes can be brought within the feasibility limits of linear actuators [31, 39], allowing the use of cheaper components.

Another tracking type with some merit for a high concentration solar tower is the so-called ‘target aligned’ heliostat approach [74, 75], where the primary axis of rotation points to the receiver. As each heliostat tracks the sun, its sagittal and tangential directions do not change, and therefore it is theoretically possible to tune the curvature of each axis to minimise the average astigmatic aberration, which reduces the maximum spread and improves the uniformity of the reflected image from each individual heliostat. A study of the tracking angle range found the secondary axis could be actuated by a linear drive, but a slew drive is required on the primary axis [76]. However, the benefits of this approach, annualized and averaged across the whole heliostat field, are not yet clear [75]. Improved optical performance must be weighed up against a likely increase in capital cost from the added complexity of this mode of tracking.

Hydraulic drives are well suited to solar tracking as they can be very precise, do not develop backlash over their lifetime, and can incorporate a pressurized reservoir for backup in case of power failure [56]. Cost benefits of hydraulic drives are more likely to be realized for large heliostat designs, due to both fixed cost components and maintenance requirements.

For foundations, the pedestal is typically mounted on a steel reinforced concrete pier (e.g. Sener [28]) or set directly below ground into concrete (e.g. ATS heliostat [7]). It is interesting to note divergent approaches to reducing the cost of foundations in a number of recent heliostat designs. Brightsource have developed a method of augering, then vibration hammering a thin walled pylon directly into the ground [78]. eSolar’s heliostats are mounted on an above-ground ballasted frame [24], and Abengoa’s planned 18 m² heliostats will also have ballast type foundations [10]. DLR have opted for a pre-fabricated concrete ground anchor dropped in a hole, and further ballasted by natural site material [31].

6. Conclusions

The key to achieving LCOE targets is to bring together as many of the performance improving, cost reducing design concepts as possible into a single package. Through studying the state-of-the-art, and a range of ‘unconventional’ heliostat designs, we have identified some of the more promising design concepts for cost reduction including:

- 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 optimised 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, then return to the correct position

Heliostats deployed in high efficiency power tower plants are more likely to be arranged in the polar field orientation due to compatibility with cavity receivers, however surrounding fields are also feasible, and it is recommended that a new heliostat design should accommodate both options. The optical requirements of high efficiency power tower plants are likely to dictate either the use of focusing heliostats or small heliostats relative to the receiver size, to achieve high flux at the receiver with acceptable uniformity and light spillage.

We have developed two guiding design principles regarding optimal heliostat size. One principle is to increase size, which is beneficial due to cost drivers relating to the heliostat drive and fixed costs, such as the control and communication system. The other principle is to seek compatibility with volume manufacturing and assembly processes, including the use of COTS components, and the cost drivers to achieve this all favour reduced scale.

We believe that a concurrent engineering approach to heliostat design is key to achieving LCOE targets, with design and manufacturing engineers working together from the earliest design stage. Make-buy decisions are also important, as the potential cost reduction benefits of low-country sourcing of components cannot be overlooked.

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References


