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James N. Larmuth, Willem A. Landamn, and Paul Gauché

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A Top-down Approach to Heliostat Cost Reduction

James N. Larmuth[1, a)], Willem A. Landamn[1] and Paul Gauché[1]

[1] *Helio100 project, CRSES, Stellenbosch University*

[a)]Corresponding author: larmuth@sun.ac.za

Abstract. The Technology Innovation Agency (TIA) has funded a South African central receiver collector technology development project, called Helio100. The project aims to provide South Africa's first commercially viable heliostat technology, which is both low in cost and offers high local content potential. A top-down approach is employed for heliostat cost reduction. This approach incorporates interlinked tools which move from high level cost analyses based on qualitative data during early stages of conceptual design, to detailed quantitative analyses in the final stages of design. Low cost heliostat designs are realized by the incorporation of both a top-down and bottom-up method. The current H100 design results in heliostat costs of $155/m^2 at 20 000 units p.a. while further industrialisation results in heliostat costs of $126/m^2 at 20 000 units.

INTRODUCTION

The Technology Innovation Agency (TIA) has funded a South African central receiver collector technology development project, called Helio100 [1] . The project aims to provide South Africa's first commercially viable heliostat technology, which is both low in cost and offers high local content potential. The technology is demonstrated in a 100 kW(t) central receiver collector pilot and research facility at Mariendahl in Stellenbosch. The overarching heliostat design philosophy used for design departure is listed below:

- High localization for South Africa
- Zero ground preparation required
- No foundations required
- Easily deployable field assembly by teams of two unskilled laborers
- Smart calibration using low cost wireless control systems powered by PV and batteries
- Modular design allowing for big or small solar field installations

FIGURE 1. An artist's Impression of the complete Helio100 system

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Understanding the effects of heliostat cost is complex and research on heliostat cost reduction is still in its infancy, with little knowledge available at the heliostat subcomponent costs level. Traditionally heliostat cost is measured on a cost per m^2 basis [2]. This measure of cost does not allow for impartial inter-heliostat comparison or sub-component comparison, as it does not consider heliostat or central receiver system performance. More recent studies include the cost effects of heliostat performance on the central receiver system LCoE, allowing for a holistic approach [3]. The DLR suggests that traditional heliostat designs will not be sufficient to allow significant cost reduction and novel approaches are required [4].

The aim of this paper is to describe the overarching cost reduction methodology used to guide low cost heliostat design within the Helio100 project. The emphasis of this paper is on the cost reduction method and how it operates in parallel to the heliostat design process by guiding design considerations, as heliostat designs move from abstract conceptual designs to the final quantitative designs. A heliostat component performance procedure is created which allows performance metrics to be measured in parallel to the cost reduction methodology by the creation of a heliostat sub-component error model. The details of the error and performance model are however out of scope for this paper.

COST REDUCTION METHOD

Top-down and bottom-up approaches are traditionally forms of information processing. These approaches are broadly used in engineering fields such as, product design, management and software development, amongst others. In a top-down approach a global system state is selected, that state is then decomposed to gain insight into its relevant subsystems [5]. The subsystems are typically treated as black boxes until they are better defined, this allows for easier system manipulation in a stepwise manner. Top-down methods do not require detailed knowledge of the sub-system and are therefore well suited to early stages of design particularly when limited data is available. A bottom-up approach starts with the detailed sub-systems and builds discrete elements which collectively make up the global system through their interaction [5]. Bottom-up approaches provide accurate details, but typically rely on detailed subsystem data for execution. If these methods are used together, the top-down and bottom-up methods can operate in contention, and may require iterative processing between them.

In this study elements of both the top-down and bottom-up approach are used to guide heliostat design towards a low cost solution. The top-down approach is used for strategic, high level cost analyses based on qualitative data during early stages of conceptual design and prototyping. The bottom-up approach is used for detailed quantitative analyses in the final stages of design. A key aspect is that both approaches of this method move in parallel to the design process. A flow chart for the cost reduction method is presented in Figure 2. The shaded cells represent the methodology while the un-shaded cells show the parallel heliostat design process as it moves from creative conceptual design and prototyping to detailed design.

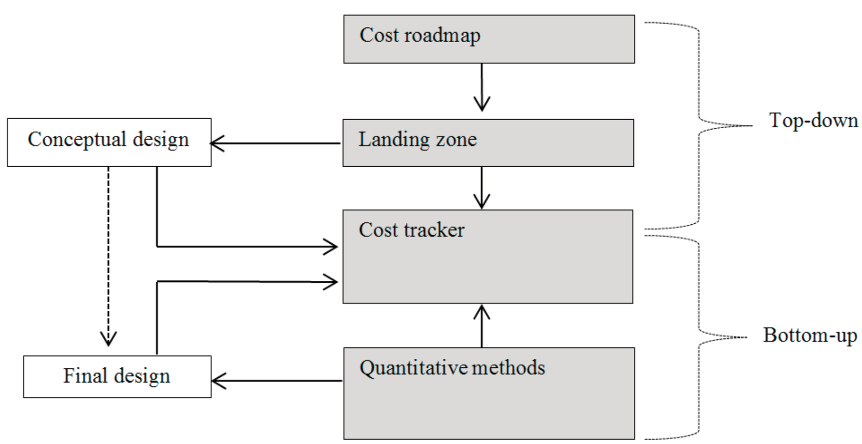

FIGURE 2. Top- down and bottom up cost reduction methodology

Each shaded cell shown in Figure 2 represents a discrete element in the cost reduction methodology. Each element is discussed throughout this paper.

Cost Roadmap

The cost roadmap represents the first step in the cost reduction process. It provides time bound cost goals for the global heliostat system. A five year cost road map is presented in Figure 3. This roadmap shows heliostat cost targets, as well as existing cost reduction goals [6] [7]. An existing heliostat, from a predecessor project called Helio40, is used as a physical dataset which represents the cost departure points for this study, and is abbreviated hereafter as H40.

The Helio40 heliostat is a small (2 m^2) un-optimized research heliostat which provides a useful physical cost and performance data set. Due to the nature of the Helio40 heliostat it represents a high cost and low volume design point. For this roadmap two data points were extrapolated from Helio40 data for 2014 (See Table 1). The first data point represents the invoiced cost for the production of 20 units. The second shows the estimated cost of the exact design, but at an increased volume production of 5 000 units.

TABLE 1. Helio40 cost departure points

Design:	Cost	Production volumes
Helio40 Low Volume	US$ 545/m^2	40 m^2 p.a
Helio40 High Volume	US$ 273/m^2	10 000 m^2 p.a

CSP is expected to follow a learning rate of 10% noting a ±5% uncertainty within this rate [8]. This learning rate is generically attributed to the entire CSP system which includes already developed power block systems currently experiencing much lower learning rates in the region of 5% [9]. Accordingly solar collector systems are expected to experience a higher learning rate in the region of 12% [9] for each cumulative doubling of collector aperture.

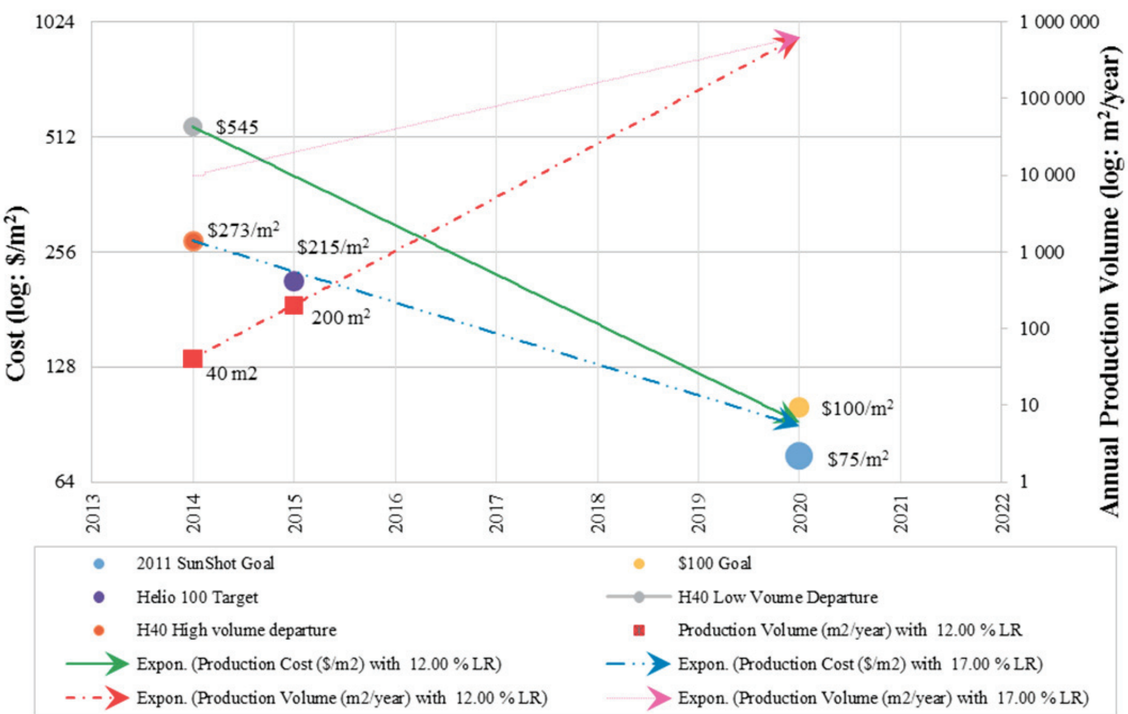

FIGURE 3. Cost roadmap

The result of the trends indicate that learning rates of between 12 and 17% need to be maintained with annual production volume increases of between 200 and 500% to achieve a sub $100/$m^2$ solution, noting the low volume departure point. The short term Helio100 target of $215/$m^2$ falls close to this feasibility area and can thus be considered an achievable short term project goal.

Landing Zone

The landing zone is a tool for establishing cost and performance targets at the heliostat subcomponent level. The landing zone incorporates a routine similar to those set out in existing target costing methods shown by Cooper & Slagmulder [10]. The roadmap cost targets are now decomposed into smaller cost proportions and allocated to the respective heliostat subcomponents in a budgetary manner. Here generic heliostat subcomponents are treated as "black box" cost centers the sum of which amount to the pre-defined cumulative heliostat system cost. Generic heliostat sub components were used to form cost centers a description of each cost center is shown by Table 2.

TABLE 2. Generic heliostat cost center descriptions

Cost center	Description
Mirror Module	Reflector and bonding/ fastening agent
Mirror Support Structure	Reflector backing, structural element
Tracking Assembly	Tracking mechanism linkages
Drive 1	Drive 1 – Primary axis
Drive 2	Drive 2 – Secondary axis
Controls and Cabling	Control system and drive cabling includes power electronics
Pedestal	Pylon onto which tracker and facet is mounted
Direct Heliostat Support	Inter pylon truss-work – if ganged pylons are used
Foundation	Ground works and foundation
Field Wiring	Trenching and cabling for Power and communication
Alignment and Checkout	Field alignment and canting

Some heliostat sub components are better suited to cost reduction when compared to others, as a result, determining sensible proportions of total cost to distribute among heliostat sub-components is complex. A review of existing component cost data from Sandia, NREL and DLR [2] [11] [12] as well as in-house cost estimations of known commercial heliostats using regression cost analysis methods is used to provide benchmark costs for the heliostat subcomponents. A comparative higher and lower cost bound is determined from these benchmarks for each subcomponent. These higher and lower bounds form the cost "landing zone" which provides a window within which a proportion of total cost can be allocated. The subcomponent targets are graphically represented in Figure 4 by a Pareto plot which uses the Helio40 high volume data as the departure point. The targets set out by the cost roadmaps are now iteratively allocated into the subcomponent cost landing zones which collectively amounts to the cumulative cost.

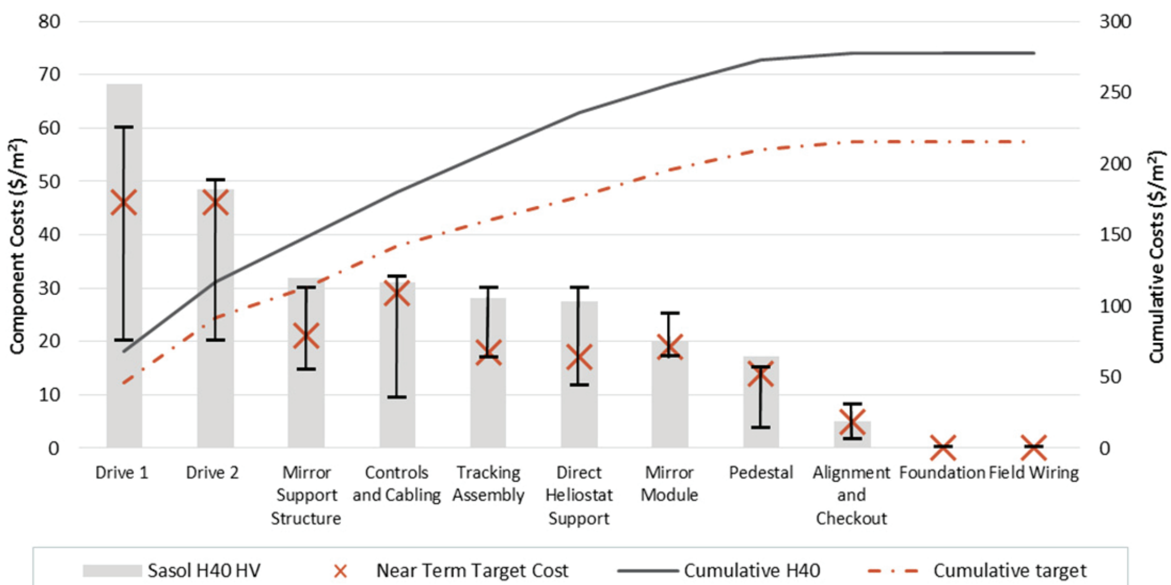

FIGURE 4. Cost Landing Zone

The landing zone strategically prioritizes improvements in heliostat drives since they are currently the worst performing components in the Helio40 system, as well as the largest total cost proportion holder. In terms of the reflector, float glass mirror is already a high volume product and therefore standard mirror module costs do not show significant scope for cost improvement within conventional design. The current cost departure point includes non-optimized structural components. Moderate cost reductions to these components are thus achievable through the use of structural optimization and design for manufacture and assembly (DFMA) techniques. Improvements in fixed cost items such as the control system have a significant leveraging effect on heliostat cost, as they allow for the use of smaller heliostats and therefore reduced wind loading [13].

Cost Tracker

The cost tracking template operates as a central, but simple tool which allows the top-down and bottom-up approaches to merge in an iterative manner. This tool is simply a table which holds the generic component cost centres. Table 3 shows an illustrative example of a cost tracker which excludes numerical values. This table forms a template for tracking cost and performance improvements from the conceptual design phase through to the detailed design phase. The cost template in combination with the landing zone benchmarks, allows for component level cost and performance comparisons to be made. These comparisons allow for the continuous identification of strategic improvements in holistic heliostat cost. In addition it allows for cost data to be collected and a database to be created. As the database grows the ability to understand cost sensitive design knowledge is improved.

TABLE 3. Cost Tracker

	H40 Departure Costs		Short term Target Cost	Mid-term Cost goal	Concept 1…	Concept 2…
Production Rate	20/yr.	20 000/yr.	20 000/yr.	20 000/yr.	20 000/yr.	20 000/yr.
Mirror Module	$	$	$	$	$	$
Mirror Support Structure	$	$	$	$	$	$
Elevation Assembly	$	$	$	$	$	$
Drive 1 (Azimuth)	$	$	$	$	$	$
Drive 2 (Elevation)	$	$	$	$	$	$
Controls and Cabling	$	$	$	$	$	$
Pedestal	$	$	$	$	$	$
Direct Heliostat Support	$	$	$	$	$	$
Field Costs	$	$	$	$	$	$
Foundation	$	$	$	$	$	$
Field Wiring	$	$	$	$	$	$
Alignment and Checkout	$	$	$	$	$	$
Total Installed Cost	$	$	$	$	$	$

BOTTOM-UP METHODS

A predominant aspect of the bottom-up analysis is a detailed techno-economic market review. By analysing heliostat component costs based on supplier data, new insight can be gained into the upper and lower bounds previously set in the landing zone (Figure 4). This market review focused on exploring common-off-the-shelf components (COTS) [14] as well as custom sub-assemblies for novel designs. Each component reviewed is logged into a component database and is tested against the limits set out by the landing zone. As data is accumulated more design limitations become more clearly visible.

Heliostat size models similar to those set out by [13] [7] [15] were also used. This also allowed for further identification of cost sensitivities. The optimum size of a heliostat is a function of the cost and performance of its sub-components [13]. Incorporating COTS components can result in a size and performance variation between different suppliers. Further standard size increments of one heliostat sub component may not be optimally compatible with another. For example a low cost drive supplier may not be able to supply an appropriate drive for a single faceted design, due to the standard size increments of glass and its corresponding loading. As a result the nearest size increment is selected or a custom design is pursued.

Within the techno-economic review, particular emphasis was placed on understanding the effects of increased order/manufacture volume on heliostat subcomponent cost. For each component reviewed supplier costs were solicited in increasing purchase volumes this allowed for the establishment of component and supplier specific volume cost curves. Order volume was found to be a significant driver of cost reduction. For smaller plants and pilot projects smaller heliostats are favoured due to their ability to immediately increase order quantities of subcomponents inducing significant cost reductions for the same filed size. Figure 5 shows a simplified relationship between heliostat size and production volumes for alternate plant sizes assuming constant total efficiency and solar resource.

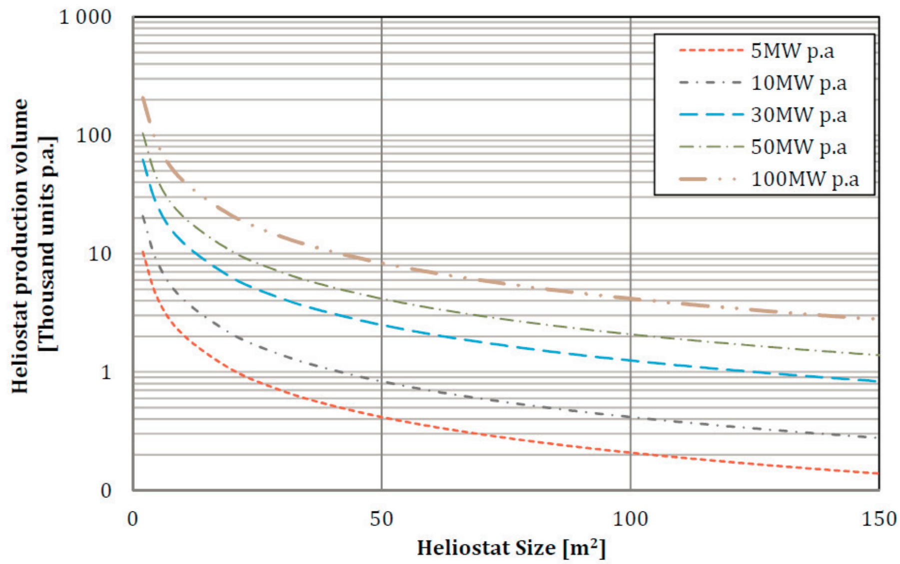

FIGURE 5. Production volume and heliostat size for varying plant capacities

KEY FINDINGS AND COSTS REALISED

In the case of the Helio40 departure point drives continue to be the largest contributor to heliostat cost. Cost reduction was found by the use of a fixed horizontal tracking mechanism which incorporated dual linear actuators. The use of dual linear drives allowed for a significant cost reduction in the primary axis of the departure heliostat design as well as improved pointing accuracy due to reduced backlash.

Linear drives are available for a wide range of domestic and industrial applications for a large variety of heliostat sizes. The proportion of drives suitable for use on heliostats is however smaller than previously expected. This is due to the stringent mechanical resolution and backlash performance required for accurate heliostat positioning.

A cost reduction in excess of 40% was seen from increasing linear drives in volumes from 1000 units p.a. to 20 000 units p.a. As a result the use of smaller heliostats further assist in this cost reduction by significantly increasing the production volume for the same field size. Further, drive suppliers were willing to customize products only for larger order quantities. The use of smaller heliostats to induce higher order volumes can allow for better scope on future drive customization, thereby potentially allowing optimum cost and size targets to be achieved on smaller central receiver systems.

Off-the-shelf slew drives were seen to be feasible on larger heliostats, however increasing the reflective area in order to cater for load bearing components, such as drives, also resulted in poor exploitation of the cost reduction potential of low fixed costs. Custom in house control systems provided low fixed costs with control clusters allowing for further direct cost reduction.

In some instances target cost allocation was too low and needed to be adjusted based on the bottom-up method. In particular glass costs were originally expected to be subject to some degree of cost reduction. However glass purchases were not subject to volume cost reduction due to the large size of existing glass markets relative to the CSP market.

The methodology realized a heliostat design which results in the cost improvements shown by Figure 6.

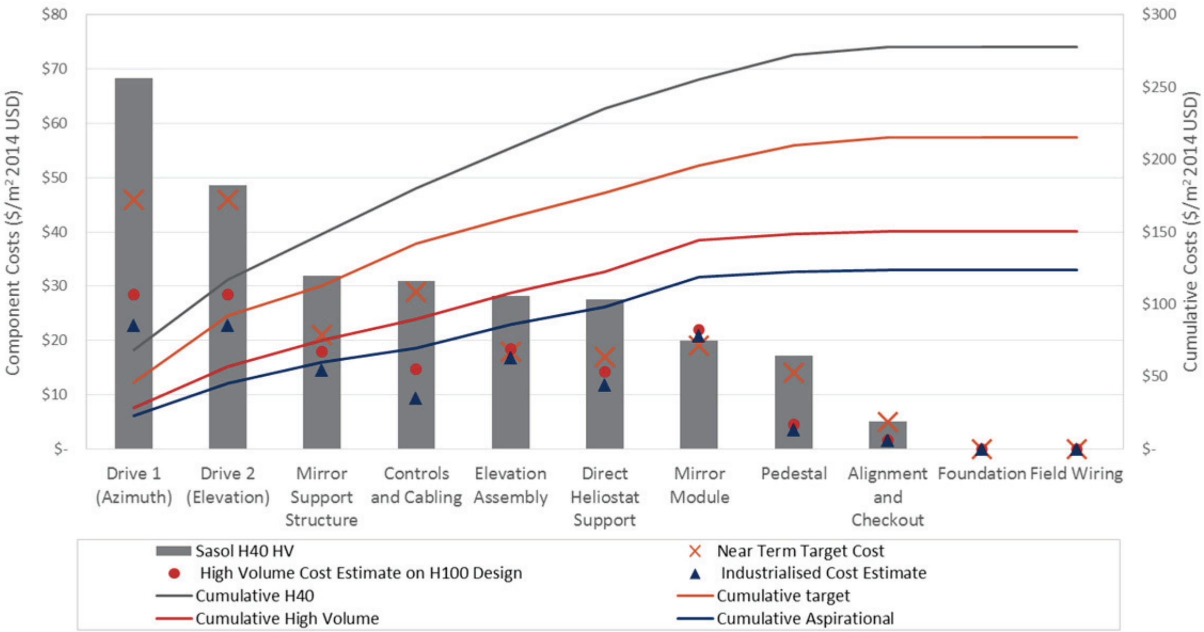

FIGURE 6. Heliostat cost reductions

CONCLUSION

This paper presents an approach to heliostat cost reduction which tracks cost from the early conceptual stages of design to the final quantitative stages. The top-down approach specifies a global system state for heliostat cost thereby creating cost targets which allow sub-components costs to meet the required global system state By operating in parallel to design it allows for novel design approaches to be measured with minimal effort. In this method a low cost heliostat design culminates at the iterative junction between a dual top-down and bottom-up approach. The current H100 design results in heliostat costs of $155/m^2 at 20 000 units p.a. while further industrialisation results in estimated heliostat costs of $126/m^2 at 20 000 units. Future cost targets using next generation heliostat designs aim to realise sub $100/m^2 values.

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