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Low-Cost Materials for Heliostats

Cost Comparison of Extensive or Moderate Use of Timber, Concrete, and Polymers

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Abstract. To achieve significant cost reduction, four heliostat concepts with extensive use of timber, concrete, or polymers of 2 m² mirror size were developed. For cost comparison, a heliostat of same size with mainly steel components was designed and built. This benchmark heliostat was found to be of lowest cost. It seems that the specific disadvantages of low-cost materials are particularly strong for small heliostats. So, the result confirms the common practice to build heliostats mainly from steel. It can help other heliostat developers to shortcut their attempts to find the lowest-cost heliostat design.

Keywords: Point Focus Systems, Heliostats, Material

1. Introduction

The challenging cost targets for heliostats seem to be in contradiction with the highly demanding requirements which are mainly high optical accuracy, high efficiency, high wind loading, long lifetime, and suitability for many different ground conditions [1]. An important way to reduce costs nevertheless is to leverage high-volume production [2]. At high production rates, material costs are the main cost driver [3], besides shipping and installation. For this reason, it is desirable to use low-cost materials.

Possible low-cost materials include polymers, concrete, and timber/bamboo. But, compared to steel and regarding the requirements, they have significant shortcomings:

- Timber/bamboo: Sensitive to moisture and UV, deforms with time, and vulnerable to insects, especially termites.
- Concrete: The high weight leads to high shipping cost of precast elements; processing is expensive, especially because many molds are needed due to the long curing time.
- Polymers: Low strength, low UV resistance, and possible creep.

In this study, it is analyzed whether these materials could be an alternative to steel components despite these disadvantages. For this, designs that are favorable for these materials are compared to a standard heliostat with mainly steel components.

2. Method

For the comparison, the following steps were taken:

1. A heliostat size to be used in this study was chosen.
2. Heliostat variants of intense usage of low-cost materials were designed.
3. For comparison, also a benchmark heliostat with mainly steel components of same mirror size was designed.
4. The cost of the low-cost material components were determined as well as the cost of the substituted steel components and compared to each other.

It is assumed that the heliostats are manufactured in high-volume production. So, material costs are the main cost factor. For them, the following is assumed:

- Fabricated timber beams: $200/m³
- Stainless steel mesh: $7.00/m²
- Concrete: $0.05/kg
- Injection molding plastic with 20% glass fibers: $6.80/kg
- Fabricated galvanized steel: $2.60/kg

3. Heliostat Designs

3.1 Heliostat Size

In terms of specific weight (kg/m²) and thus material cost [1, 3.1] and regarding high volume production [2], small heliostats are advantageous. Therefore, and because small heliostats getting more cost effective with ongoing decreasing electronic cost, heliostats of only 2 m² size are compared in this study.

Another reason for assuming such a small heliostat size is that high temperature applications for e.g. solar fuel production are getting more important. They require a small aperture to avoid high thermal radiation losses which again requires a small focal spot and therefore small heliostats. With large heliostats, also small focal spots can be achieved, but only for times when the sun’s position in the sky is close to the direction of the optical axis of the parabola of the concentrator. For sideward insolation, which is most the case in the early mornings and late afternoons, the reflected beam is significantly widened which is called the astigmatism error. This error is increasing with the ratio of the mirror size to the distance to the receiver [4].

For illustration, in Figure 1, two simple heliostat field layouts calculated with HFLCal [5] are compared. The right field is optimized for 50 m² heliostats while the left one for 2 m² heliostats. The aperture of the receiver is 1 m in diameter and in 25 m height. The flux density shall be 2.5 MW/m² on 21st of March at 9 am (since solar fuels shall be produced during most of the day). The result shows that 50 m² heliostats are not suitable for such small plants because they would need more than 4 times more mirror area to yield the same flux density as 2 m² heliostats. The reason is the strong astigmatism at the design point. Using a 50 m² heliostat for such a small field is an extreme example but it well demonstrates the need for small heliostats for high temperature applications.

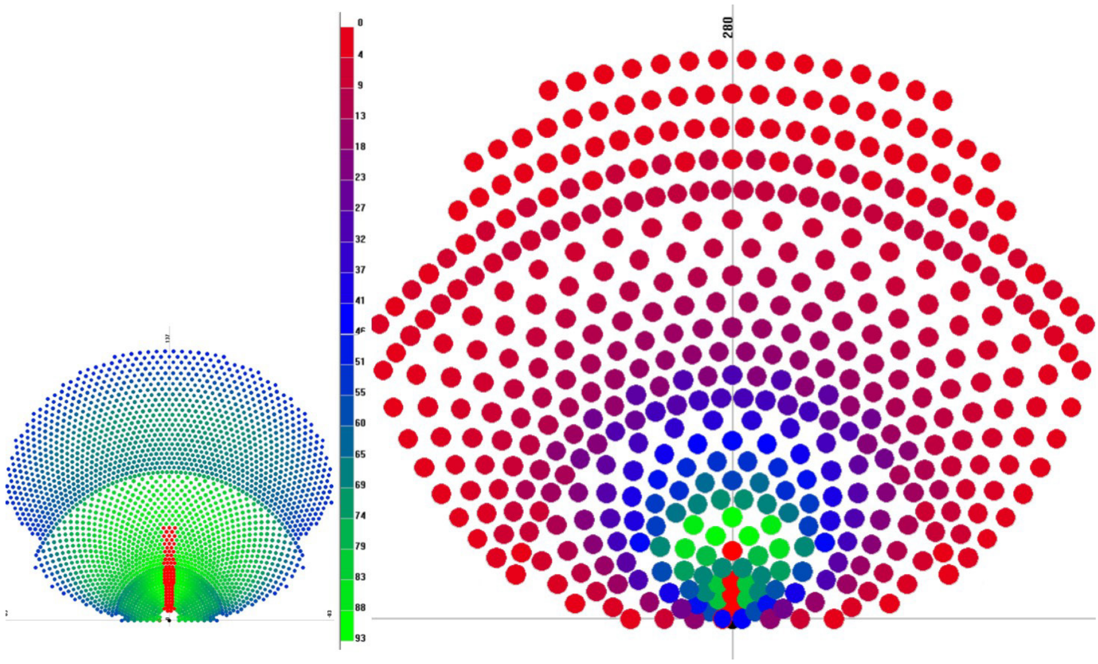

Figure 1. *Heliostat field layouts for 2 m² (left) and 50 m² (right) heliostats for an application with receiver aperture of 1 m in diameter. With a design point at 9 am, the field with large heliostats requires 4 times more mirror area due to astigmatism.*

3.2 Timber/Bamboo

Especially in dry areas, timber can have a long lifetime even if used outdoors, e.g. for electricity poles. The same is valid for bamboo which is a fascinating alternative to steel tubes if available close to the site. But, also for regions with frequent raining, long lifetime can be achieved if the timber is protected from rain and from too much sunlight. With heliostats, all these favorable conditions are given since CSP plants are located in sunny and rather dry areas and because the heliostat's concentrator acts like a parasol and an umbrella [6]. Because of possible deformations with time, timber is not suitable for the concentrator itself which must be of high form stability. But, it could be used for other components like the pylon because slight deformations can be well compensated by frequent calibration.

It is assumed that the heliostat shall be suitable for all potential solar sites, so also for regions with termites and that insecticides, and fungicides are not an option. But, to protect the timber, a fine woven stainless-steel mesh can be wrapped around it. The timber components would have to be of simple geometry to allow for easy attachment of the mesh.

For standard T-type heliostats, the pylon, the torque tube, and the cantilever arm for the elevation drive are components of simple geometry that are large enough to possibly make the wrapping worth the effort. For carousel type heliostats, the base is of simple geometry too. But, if made from timber instead of e.g. concrete, it would be too lightweight to prevent lift-off at high wind speeds. Therefore, a ground anchor would be required or the timber base would have to be designed as a container to be able to carry additional weight such as stones or sand. For the comparison, the T-type heliostat with timber pylon and the carousel type heliostat with timber container are considered (Figure 2).

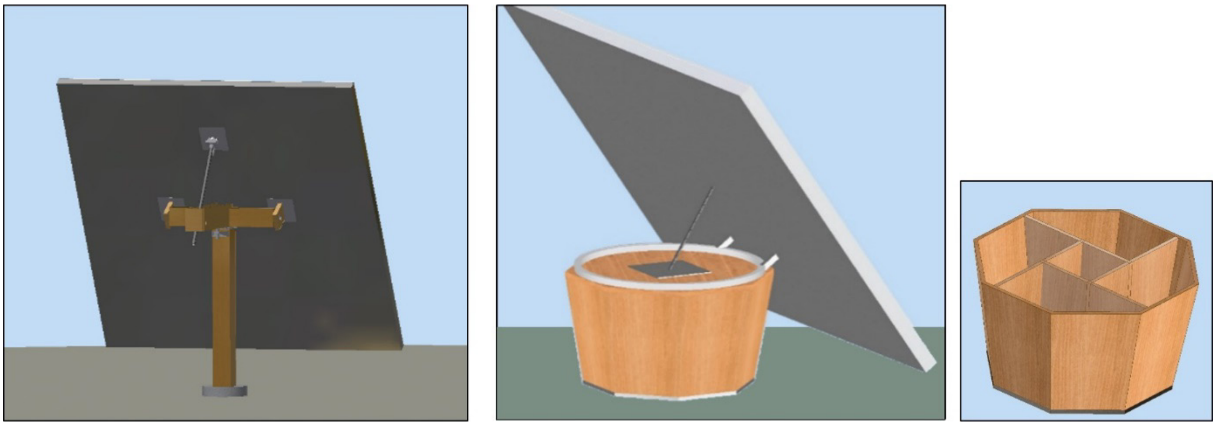

***Figure 2**. T-type (left) and carousel (middle, right) heliostats with timber components.*

3.3 Concrete

The raw material cost of concrete is extremely low. Another advantage is the high compressive strength, but the tensile strength is low. That's the reason why the weight of concrete components is much higher than comparable steel components (Figure 3, left). To avoid resulting high shipping cost, it is desired not to use precast elements but to manufacture concrete components on site.

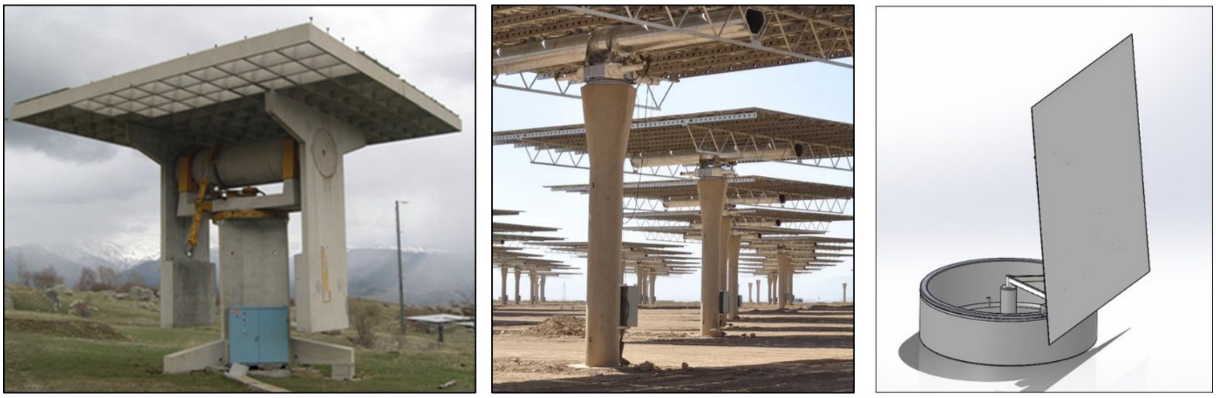

***Figure 3**. Concrete heliostat (left) [7], concrete pylon of a 178 m² heliostat (middle) [8], and carousel heliostat concept with concrete base.*

Especially for large steel components, the substitution by concrete can be cost effective because the weight to surface area ratio is high and thus the material cost reduction to mold cost ratio. For that reason, the concrete pylon of the 178 m² large Sener heliostat for Noor3 [1, 5.1.9] lead to a cost reduction (Figure 3, middle). There were also attempts to build mirror support structures from concrete [9] but yet without a proof of being cost effective.

With small heliostats and common molds, the long curing time of concrete would lead to uneconomically high manufacturing cost, as a very large number of molds and space for intermediate storage would be required to achieve the necessary production rate. However, with the immediate demolding method, the amount of molds could be significantly reduced. This method is often used in the production of concrete pipes and is only suitable for simple geometries.

Using concrete as the base of a carousel type heliostat seems to take most advantage of the benefits of concrete (Figure 3, right). The well manufacturable tubular shape can serve as the runway and the weight would make any foundation or ground anchoring redundant. Therefore, a carousel type heliostat with concrete base was chosen for the comparison.

3.4 Polymers

Polymers can be used for outdoor applications especially if they are not exposed to direct sunlight. This is the case for most heliostat parts, as the concentrator serves as a large sun shield. However, the low strength of polymers and the creep behavior only allows to use it for low-loaded components such as housings or containers or if strengthened by other materials. Closed containers are of remarkable high strength. Therefore, a carousel heliostat with a container base made from polymers with 20% glass fibers added is considered for the comparison (Figure 4). The polymer container could be filled with sand or stones to prevent uplift. Alternatively, ground anchors could be used.

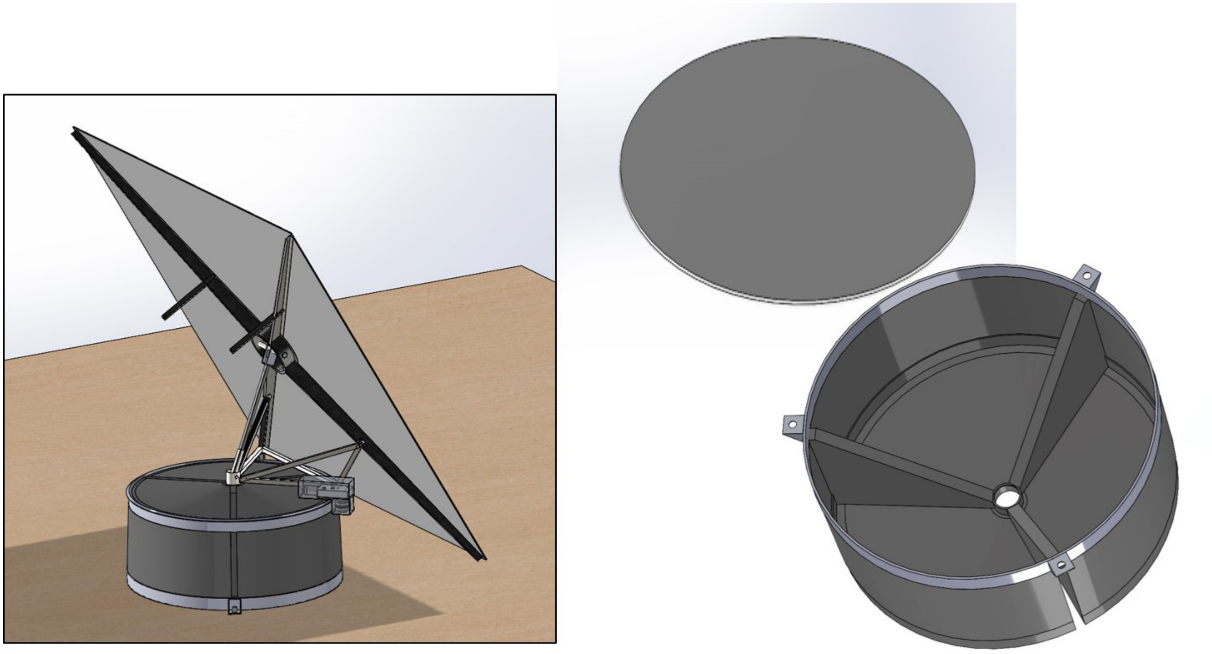

***Figure 4**. Carousel heliostat with polymer container base.*

With sandwich concentrators, also a significant material share of polymers can be obtained. Polymer sheets and hard foams could be used as back layer and core material, respectively. To reduce creep, the concentrator would have to be lightweight, which can be achieved by using reflective polymer films instead of glass mirrors. The load on the sandwich structure could also be reduced by adding support beams.

3.5 Benchmark: Moderate Usage of Low-Cost Materials

As a benchmark, a heliostat with only moderate usage of the before mentioned low-cost materials was designed. For concrete and polymers, components were identified that would allow for their usage in a moderate way while for timber or bamboo this was not the case. The main reason is that a termite protection would be required which particularly for small parts can hardly be realized in an economic way.

The main disadvantages of concrete are the expenses for the molds and the long curing time which would make the realization of the needed short production cycle times expensive. But, for ground foundations, holes in the ground can serve as molds, so sufficient cycle times can be achieved without the need of a high number of molds and a lot of storing space for curing. Since for small heliostats no deep holes are needed, the effort for the hole drilling is expected to be low for most of potential ground conditions. This makes it quite feasible to have the foundations built by autonomous machines, which enables low construction costs.

Polymers are used for the plain bearings (bushings) and as housings e.g., for the azimuth drive system. Because of the low weight of the small concentrator and because of the extraordinary low rotational speeds and the comparably low amount of total rotations during lifetime, ball bearings seem to be dispensable.

The support structure for the 4 mm mirror is built from spot welded C-profiles of 1 mm wall thickness (similar to CSIRO heliostat [1, 5.1.4). For high temperature applications with the need for higher optical quality, a sandwich mirror as described in section 3.4 can be used instead.

As heliostat architectures, standard ones were chosen which are the T-heliostat (or Az-El heliostat) and a heliostat design with two linear drives for which a close to horizontally oriented primary axis is advantageous in terms of maximum angle range. While many fancy heliostat architectures have been developed so far, some of which have the potential to reduce the weight and cost of the heliostat [1], [2], [7], they usually result in greater complexity with a larger number of parts and connections required and often lower reliability and/or functionality. Because for small heliostats the potential for such a weight reduction is rather low, this potential seems to be more than outbalanced by the mentioned disadvantages. For these reasons, only a T-type concept and one with horizontal primary axis were developed as benchmarks. Both seem to have similar cost. To enable a detailed bottom-up cost analysis, the T-type heliostat concept was designed in detail and a prototype was built to prove its functionality (Figure 5).

***Figure 5**. 2 m² T-type benchmark heliostat.*

For the benchmark heliostat, innovations developed for the other designs were also used. Thus, a solution of high accuracy and durability gained. Nevertheless, very low costs were achieved. The main reasons for the high accuracy are the following:

- Small mirror size: Low astigmatism error
- Single facet: No canting error
- Pretensioned drives: Effectively no backlash
- Optional sandwich facet: Low slope error

The low cost is achieved mainly by the following points:

- Small size: Lower wind loading and low weight/m²
- Simple heliostat architecture: Low part count and high reliability
- Plain bearings: No costly ball bearings
- Mostly spot-welding
- Automated installation well possible
- Multiple functionality of some components

The controller and the energy storage were not developed yet. Therefore, their cost could be only estimated based on own experience and information from other companies. However, if the cost should turn out to be higher, its impact on the total cost per square meter can be reduced by increasing the mirror size.

4. Cost Comparison

For the heliostats with extensive use of low-cost materials, the cost of the components from these materials are compared to the cost of the corresponding components of the benchmark heliostat. In Table 1, an overview of the comparison is shown with lowest cost for the benchmark components for all cases. In the following sections, details for each material and heliostat type are given.

Table 1. *Overview of cost comparison of low-cost materials heliostats with benchmark.*

Material	Heliostat Type	Components	Cost [$]	Replaced Benchmark Components	Cost [$]
Timber	T-type	Timber pile + beams + steel mesh	5.9	Pylon	3.6
		Complex joints	» 0.6	Torque tube + cantilever	2.9
Timber	Carousel	Steel ground plate + runway	5.2	Foundation	10.1
		Steel mesh	12.0	Pylon incl. collar + foot	7.4
		14 timber parts + joining	» 0.3		
Concrete	T-type	Molds, process cost	> 3.6	Pylon	3.6
Concrete	Carousel	Steel runway	1.9	Foundation	10.1
		Cost of similar concrete tubes	» 15.6	Pylon incl. collar + foot	7.4
Polymer	Carousel	Steel runway	1.9	Foundation	10.1
		Polymer + 20% glass fibers	20.7	Pylon incl. collar + foot	7.4

4.1 Timber/Bamboo

4.1.1 T-Type

With the T-type heliostat, the pylon and the torque tube with cantilever arm are made of timber or Bamboo. For the 2 m² benchmark heliostat, these components are of steel and can be of small 0.5 mm wall thickness for the pylon and of 1 mm for the torque tube and the cantilever arm. Thus, the weight of the pylon tube is only 1.4 kg which leads to only $3.6. The weight of the torque tube with cantilever arm is 1.1 kg, so the cost is $2.9. Material cost of the timber pile, torque tube, and cantilever arm would be $2.4. However, timber or bamboo would have to be protected against termites by a woven stainless-steel mesh of 0.5 m² and $3.5 cost. Additionally, joining elements for bamboo or timber beams are quite complex, because they must compensate for any shrinkage. It is impossible to realize them for the remaining $0.6. So, no cost reduction was achieved with this timber solution.

4.1.2 Carousel with Container Base

The wooden container filled with sand or stones available at site would substitute the concrete foundation and the pylon including pylon collar and foot of the benchmark heliostat which sums up to $17.5. The timber container is sealed against moisture from the ground by a 0.5 mm steel sheet. As runway for the carousel wheels or sliding blocks, a steel ring is foreseen. Its contour is shaped so that hooks on the carousel can hook into the ring to prevent the concentrator from lifting off in windy conditions. Therefore, for the ring, a minimum thickness of 1.5 mm is assumed. The weight of the steel sheet and the steel ring is 2.0 kg at least which corresponds to $5.2. For termite protection, 1.7 m² woven stainless-steel mesh is needed with total cost of $12.0. The ground would have to be levelized and compacted to prevent settlements and the container would have to be filled with sand, gravel, or stones which is assumed to be at least the same effort as the hole drilling and filling it with concrete for the benchmark heliostat. So, no budget would be left for the material, manufacturing and joining of the 14 wooden parts of the container. Furthermore, the volume of the container is significantly larger than that of the pylon of the benchmark heliostat which leads to additional shipping cost. Therefore, all in all, also the carousel heliostat with wooden container is of significantly higher cost than the benchmark heliostat.

4.2 Concrete

4.2.1 T-Type

The material cost for a pylon made of concrete would be negligibly low. However, the reinforcement, the molds, and the on-site labor cannot be realized by the low cost of only $3.6 of the thin-walled steel pylon.

4.2.2 Carousel

As the wooden one, a concrete carousel base would also substitute components of the benchmark heliostat of $17.5 cost. Since it also needs a $1.9 steel runway, a budget of $15.6 remains. To resist uplift forces and overturning moments caused by strong winds, the weight is 130 kg with $6.5 material cost. However, by comparing the allowed budget with cost of similar concrete sewage pipes, the budget seems to be by far not sufficient. So, although the material cost is very low, it seems that the process cost is comparably high, even with the immediate demolding method.

4.3 Polymers

4.3.1 Carousel with Container Base

A carousel heliostat's base made from polymers would also have to be of costs below $15.6 since it would also need a runway made of steel. It is assumed, that at least a wall thickness of 2 mm would be required. To have sufficient strength and creep resistance, the polymers would need e.g. additional glass filaments. With a weight of 3 kg of the polymer container base, $20.7 result. Hence, also the polymer design does not beet the benchmark heliostat.

4.3.2 Sandwich Concentrator

For the benchmark concentrator, a 4 mm glass mirror with a support structure of 1 mm spot welded C-profiles with a weight of 4 kg and $9.6 material cost is used. As front layer of the sandwich concentrator, a 1 - 2 mm thin glass mirror is foreseen, as core material a polymer hard foam, and as back layer a 0.5 mm steel sheet of $13.5. The steel sheet cost alone is above the mirror support structure material cost of the benchmark concentrator. Since the 4 mm glass mirror is of same cost as the 1 - 2 mm thin glass mirror because of easier handling, the sandwich concentrator is by far more expensive than the benchmark solution. However, for high temperature applications with small receiver apertures, a sandwich concentrator might be all in all the most cost-effective solution because of the high slope accuracy and the higher reflectivity due to the thin glass mirror [10].

5. Conclusions

The low cost of the benchmark heliostat could not be undercut by the investigated heliostat architectures with extensive substitutions of steel. It turned out that the specific disadvantages of low-cost materials are particularly strong with small heliostats:

- Timber/bamboo: Especially for small components, protection with a steel mesh is filigree and therefore of relatively high cost per mirror area.
- Concrete: Providing many small molds and processing concrete and filling them with it is more challenging then for some few large mods.
- Polymers: For small structures, reinforcement with steel elements would result in too many parts. With polymer containers, this results in a thick wall thickness and a large amount of material required.

Only for high temperature applications, significant amounts of polymers would be needed for the core material of sandwich mirrors which might be the most cost-effective solution for the required high slope accuracy. However, because of the polymers, sandwich structures can hardly be recycled which is also an important disadvantage of concrete. This is a further argument for steel.

The 2 m² benchmark heliostat with moderate usage of low-cost materials confirmed the cost reduction possible with small heliostats [2]. A field of small heliostats requires more control and energy supply units and more ground anchoring. However, with large-scale production of the electronic components and automated installation these disadvantages are reduced and by far outweighed by the advantageous in terms of wind loads, specific weight, low astigmatism, and suitability for high-volume production. Furthermore, it turned out that the amount of different parts can be lower and that plain bearings are sufficient. With this and some further innovations in detail (which actually were found during the development of the low-cost material designs), extraordinarily low overall costs were achieved. Thus, the overall goal of designing a low-cost heliostat was accomplished, although not by extensive use of low-cost materials as expected, but by a moderate one and some further innovations (to be published separately).

6. Summary and Outlook

It was investigated, how heliostat cost can be reduced by the low-cost materials timber/bamboo, concrete, and polymers. For this, heliostat concepts were designed that allow extensive usage of these materials. The costs of these heliostats were compared to a heliostat design with only moderate usage of low-cost materials as a benchmark. All heliostats were designed with a size of 2 m² because small heliostats are of lower specific weight and astigmatism and are advantageous in terms of high production volumes.

For the heliostat with only moderate use of low-cost materials, an extraordinary low-cost solution was found. It takes advantage from simplifications that are possible because of the small size and by some additional innovations in details. The heliostats with extensive usage of low-cost materials could not compete with it. In general, the reason is that the specific disadvantages of low-cost materials are particularly strong for small heliostats. Specifically:

- Timber/bamboo: The design should be suitable for all main potential solar sites. Therefore, termite protection by a woven stainless-steel mesh would be needed if insecticides and fungicides are not an option as assumed here. The material cost of the steel mesh and the extra cost for mounting and for the generally more complex joints required for wooden components are higher than the cost savings.
- Concrete: Material cost is extremely low. However, the cost savings are too small compared to the process cost including concrete mixing, molding, demolding, and

storage during curing time, particularly for the comparably small components of small heliostats. Another disadvantage is the low recyclability.

- Polymers: To substitute loaded steel components, comparably large structures made of injection molded plastic strengthened with e.g. glass fibers are needed. The resulting large amount of that material leads all in all to higher cost than the compact steel components. Also, sandwich mirrors are more expensive than mirrors with a steel support structure. However, in terms of total heliostat field cost, sandwich mirrors can be an economic solution, particularly for high temperature applications, if the creep issue can be solved. However, sandwich facets can hardly be recycled which is an important drawback.

Thus, the overall goal of designing a low-cost heliostat was not accomplished by an extensive use of low-cost materials, but by a moderate one with some further innovations. The advantage of this result is that proven and reliable components are used by the benchmark heliostat and that a market ready solution can be expected sooner. In this respect, also the small mirror area is helpful, as it facilitates the construction of several heliostat prototype generations in a short period of time. Potential for further cost reduction is seen in the following points:

- For the given cost figures, manufacturing in high labor-cost countries is assumed. High local content in many countries of the sun belt would lead to significantly lower cost.
- In this study, only 2 m² heliostats were assumed. With a cost optimization of the size (up to 8 m² as maximum size for shipping of a single facet), the cost could be further reduced.
- A large cost factor are the mirrors. Here also a significant potential for further cost reduction is seen.

Data availability statement

All relevant data is given in the text or the referenced literature.

Author contributions

Volkmar Dohmen: Parts of the investigations (building of benchmark heliostat), Andreas Pfahl: Conceptualization, methodology, validation, formal analysis, parts of the investigations, writing.

Competing interests

No competing interests.

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