Review on Carousel Heliostat Designs

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Abstract

An overview of carousel heliostats is given. The general advantages and disadvantages are explained first. To distinguish between the different designs, possible variants of the carousel architecture and of the main components are described. Most of these variants can be found in the designs published so far, which are briefly presented. Finally, the cost efficiency of carousel heliostats in general is discussed.

Keywords

Solar Tower Plants, Heliostats, Carousel, Cost.

1 Introduction

To achieve low heliostat cost, many fancy concepts were developed so far which significantly differ in architecture and size [1] - [7]. The architectures of heliostats are characterized mainly by the orientation of their axes. The main orientations (in order of occurrence) are (Figure 1):

- Az-El: The axes correspond to the azimuth and elevation movement of the sun. The vertical azimuth axis is fixed and the horizontal elevation axis is pivoted about it. The main Az-El type heliostats are:
    - T-type: A torque tube is mounted on the top of a pylon which together form the shape of a T.
    - Carousel: The azimuth movement is realized by a carriage running on a horizontal circular raceway.
- Fixed horizontal axis: With a fixed horizontal axis (or at least close to horizontal), the maximum needed angle range is reduced. By this, linear drives are sufficient for both axes and extensive slew drives can be avoided.
- Target aligned: The first fixed axis of rotation is aligned to the receiver or target. By this, the optical astigmatism error can be reduced somewhat [8][9].

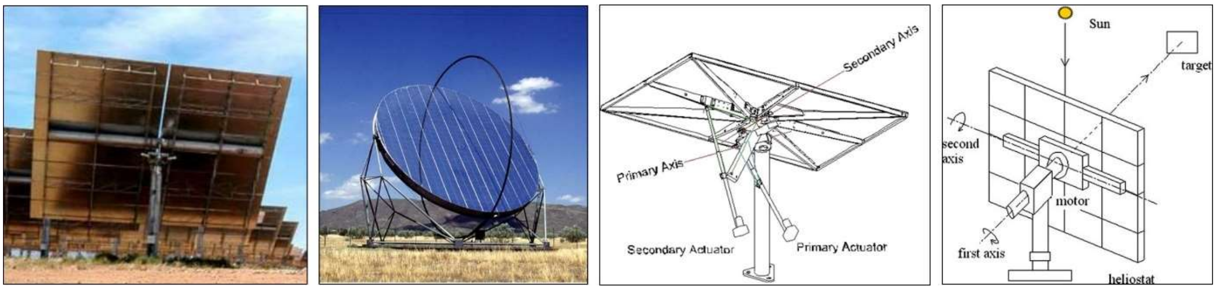

Figure 1: Main heliostat architectures (left to right): T-type [10], carousel [11], fixed horizontal axis [12], target aligned [13].

In this paper, different types of Az-El carousel architectures are investigated to estimate their potential to reduce heliostat field cost.

2 General Advantages and Disadvantages of Carousel Heliostats

The main principal advantage of carousel heliostats are their short load paths to the ground. Short load paths promise low material need [14]. For heliostats with pylons, all wind and gravity loads on the concentrator are first transferred to the pylon top and from there vertically into the ground. The average load path is comparably long and it leads to bending moments in the pylon which increases the material need. For carousel heliostats, the loads are transferred directly from the concentrator to the runway. Such, bending moments can be reduced and besides the concentrator, all components are almost only loaded by compressive and tensile forces for which comparably small cross sections are sufficient.

Another advantage of a carousel architecture is the possibility of having the elevation axis close to the ground. This enables a low stow height with very short load paths. Furthermore, the wind speeds are reduced. This is partly compensated by the higher turbulence intensity close to the ground [15]. However, closer to the ground, the turbulence structures are smaller and cover the concentrator by a smaller portion which all in all leads to lower stow loads [16]. But, lowering stow loads is leading to lower cost only if the stow loads (before reduction) are significantly higher than the wind loads during operation. This depends on the maximum possible wind speed of the site and on the maximum wind speed at which the heliostat field is operated.

A disadvantage of the lay-down option is the additional energy needed to lift the concentrator's center of gravity for operation, i.e., when moving the concentrator towards vertical orientation. But, this energy need is low compared to the energy gained by the heliostat during a complete day. However, the elevation drive system including energy supply must be dimensioned for higher loads which leads to some additional cost.

The main principal disadvantage of carousel heliostats is that, for each instance in time, the runway is loaded only for the short section that supports the carriage. Such, the instantaneous material usage of the runway is very low. If the runway can be realized at low cost or if it has a second function like providing weight against lifting, this drawback can be reduced.

3 Principal Design Variants

Carousel heliostat variants can be distinguished by:

- The height of the second (horizontal) axis of rotation.
- The size of the concentrator.
- The design of the main components.

The main mechanical components of a carousel heliostat are:

- The base that fixes the heliostat to the ground.
- The azimuth-drive for the rotation of the concentrator about the carousel's vertical axis.
- The elevation-drive for the rotation of the concentrator about the horizontal axis.
- The concentrator with its specific shape.

In this paragraph, known possible designs of all these points are described.

3.1 Second Axis' Height

The orientations of the axes of rotation characterize the different general heliostat architectures (see paragraph 1). For a carousel, the axis of rotation is vertical (= azimuth axis). Therefore, carousel heliostats are always of Az-El type.

Typically, at stow position, the azimuth axis runs through the concentrator's center to achieve maximum field density. Then, the minimum elevation axis height is half of the concentrator's chord length minus the distance of the second axis to the first axis to avoid mirror contact with the ground for upright concentrator (Figure 2). Figure 10, right, Figure 11, and Figure 13 show heliostats with the second axis close to the first one and a resulting second axis height equal to half the chord length. The heliostats of Figure 10, left, and Figure 14, left, have the second axis near the ground and the one of Figure 14, right, somewhat raised. The runway can be placed on the ground (Figure 2, a, b, c) or raised up to the height of the second axis (d). If the distance of the second axis to the first axis is close to zero, a "runway" of small diameter can be at a height equal to half the concentrator's chord length (e). But then the heliostat is not a carousel heliostat anymore, but a T-type heliostat.

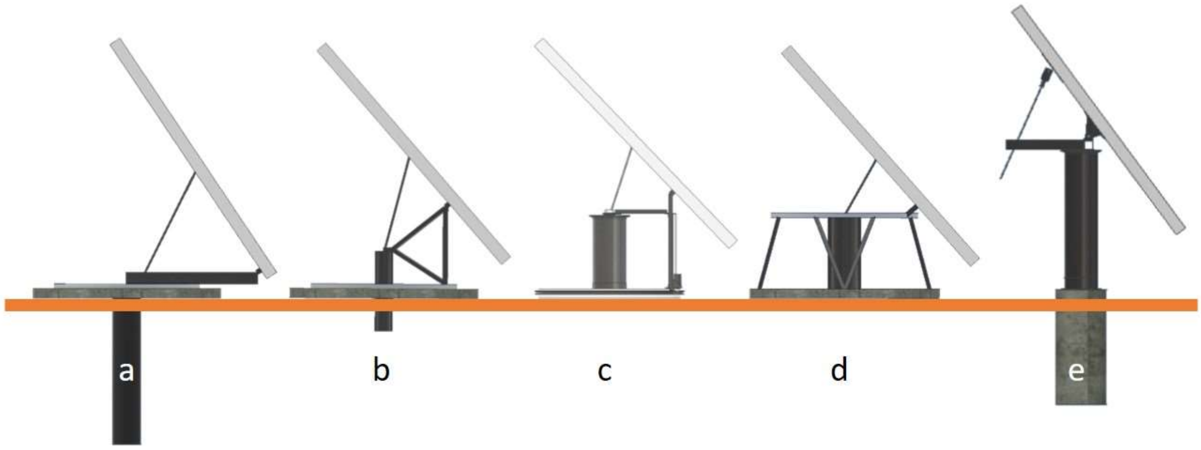

Figure 2: Second axis height: a) Near ground level, b) ¼ chord length, with lower elevation drive pivot point, c) ¼ chord length, with elevation drive pivot point at same height, d) ¼ chord length, with runway at same height, e) ½ chord length, with small "runway" at same height = T-type heliostat

3.2 Concentrator Size

Besides axes orientation and position, the size of a heliostat is an important characteristic. Because of the short load paths, carousel heliostats seem to be advantageous especially for large heliostats with high gravity and wind loads. However, in general, larger concentrator sizes lead to higher specific weight [17]. This means, that the disadvantage of the low material usage of the runway with the resulting high specific weight is even more pronounced for heliostats of larger size.

3.3 Main Components

Not only for the runway, but for all components, low-cost solutions are required. In this section, known solutions for each component are presented.

3.3.1 Base

Concrete

Concrete is an extremely low-cost material and it can be easily formed to the desired shape. But, molds are needed in which the concrete hardens. Since it is not cost effective to prepare only small quantities of concrete at a time, many molds are needed to be filled with. To avoid mold cost for foundations, holes can be dug or drilled into the ground at the heliostat positions that are filled with concrete. An automated solution is not trivial because ground conditions can vary significantly. Furthermore, using holes only allows a foundation up to ground level whereas carousel runways should be somewhat above ground level to avoid that obstacles that could block the carousel's wheels can be blown onto it by wind (Figure 1, mid-left, Figure 11, left, Figure 12, left, Figure 13).

A drawback of concrete foundations follows from the fact that solar sites are often in the outback and far from concrete factories. Then, transportation cost can be significant. It could be reduced by producing the concrete at site. But, automated cement production is complex and therefore usually not cost effective for comparably small quantities as needed for one single solar tower plant. However, production of concrete foundation elements for many solar power plants at one location is usually economically not feasible either because of the resulting very high transportation cost.

Stakes and Screw Piles

Stakes as ground anchors provide a cheap solution if the ground conditions are suitable. But, the ground conditions can vary significantly for different heliostat field sites and even within the same site. This makes it difficult to develop a low-cost standard solution. Screw piles are less sensitive to the specific ground conditions but significantly more expensive. The runway ring would also be rather expensive because it has to be quite stiff since it would be supported only punctually (Figure 11, right).

Container

Instead of fixing the runway directly to the ground, it can also be fixed to something of sufficiently high weight like a concrete ring. To avoid the shipping cost, instead, also material at site could be used as weight like sand, gravel, or stones filled into a container (Figure 3, Figure 14, right). The surface area of a container large enough to support the runway and to contain enough weight is comparably large. Therefore, steel sheets as container material would be rather expensive. Polymers could be an option, but, it would have to be UV resistant for 20 to 30 years lifetime and of enough strength to support the runway [18].

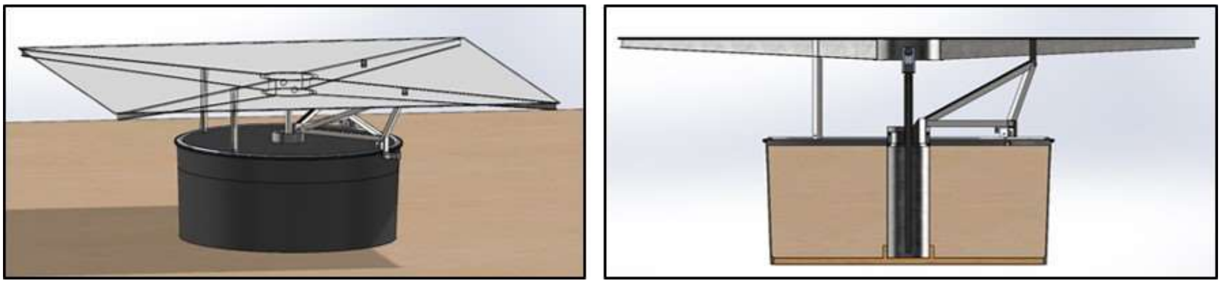

Figure 3: Carousel heliostat with polymer container base filled with sand.

Consolidated Soil

A very cheap runway would be the consolidated ground itself (Figure 4, left). Because of the remaining unevenness of the ground, only large wheels would be suitable. So, this idea is only feasible for large heliostats. A low-cost solution for the wheels could be disused car wheels [6]. To prevent up-lifting by wind, additional weight would be needed. With the wheels directly on the ground and an additional wheel, a heliostat that can be moved to different positions could be realized [7] (Figure 4, right).

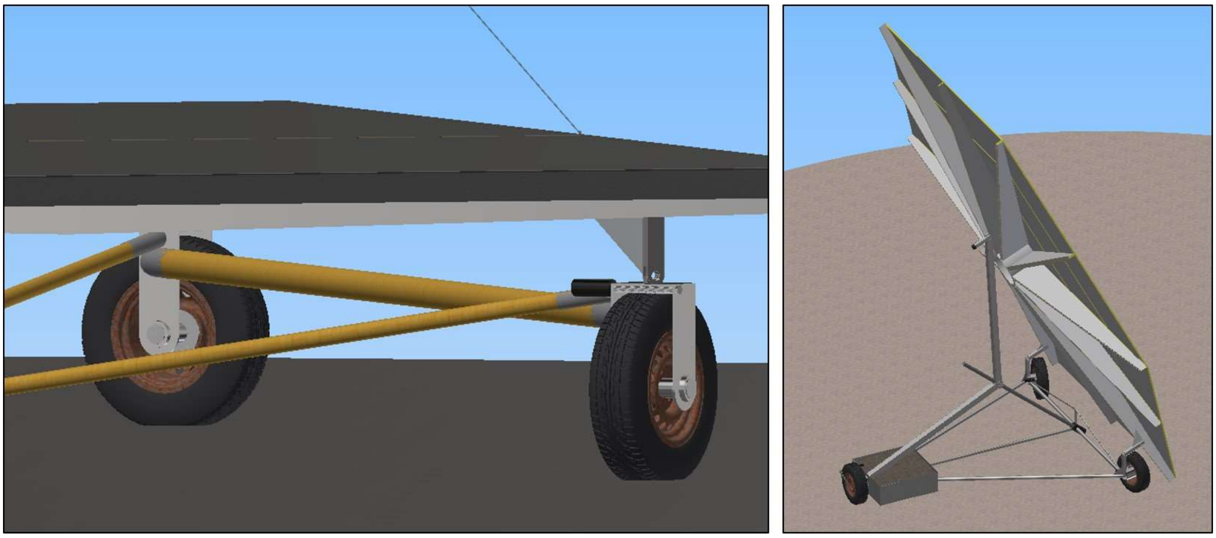

Figure 4: Heliostat wheels running directly on consolidated ground (left), movable heliostat with ballast on the rear wheel against uplift by wind (right).

3.3.2 Azimuth Drive

For all azimuth-drives, uplift must be excluded. This can be achieved by sufficient weight of the carriage or by a kind of hook that grips under the runway.

The moment of the azimuth drive must be transferred to the runway. In the following, several options are presented.

Friction Wheel

In principle, a friction wheel is a cheap solution but it can be sensitive to dust and sand on the runway. For high friction, soft rubber material would be most suitable. However, exposed to UV and for the needed lifetime of 20-30 years, hardening with time would be an issue.

To be able to carry the concentrator's weight, the wheel would have to be wide. But a wide wheel leads to different speeds at the inner and at the outer side of the wheel. The resulting slippage would lead to increased wear. This can be avoided by conical wheels. But this would result in a significant extra effort. Anyway, for friction wheels, slippage cannot be completely excluded. Therefore, a closed loop control would be needed.

A wheel running directly on consolidated soil (see 3.3.1) is also a kind of friction wheel. The small contact area of the wheel to the ground results in comparably high pressure. Therefore, a ground consolidation is mandatory to avoid subsidence at rain periods.

Chain

With steel wheels on a runway, less wide wheels would be sufficient and slippage would not lead to significant wear. But, friction would be too low, so an extra measure to transfer the moment to the runway is needed. This can be realized by a chain drive which can be very precise because it is almost backlash free when pretensioned [19]. But, due to the polygon effect, the sprocket must be of sufficient diameter which limits the maximum gear ratio.

When fixed around the runway or the carriage, a chain can serve as a large gear wheel. This option is not back lash free, but extra ordinary high gear ratios can be realized as for example with the ASM 150 heliostat (Figure 5, left). A significant cost factor would be the housing of the chain to protect it against sand and dust.

Figure 5: Gear wheel made from a chain (left) or bent sheet metal (right)

Toothed Wheel
A large tooth wheel can be made from bended sheet metal (Figure 5, right).

Cable
The runway or carriage can serve as a circular rim for a cable drive system as well [20][21] (Figure 6). For the cable, no protection against dust and sand is needed, but for the cable drum [4]. In principle, a cable drive is back lash free. But, the minimum diameter of the drum is limited by the minimum bending radius of the cable. So, with cable drives no large gear ratios can be achieved.

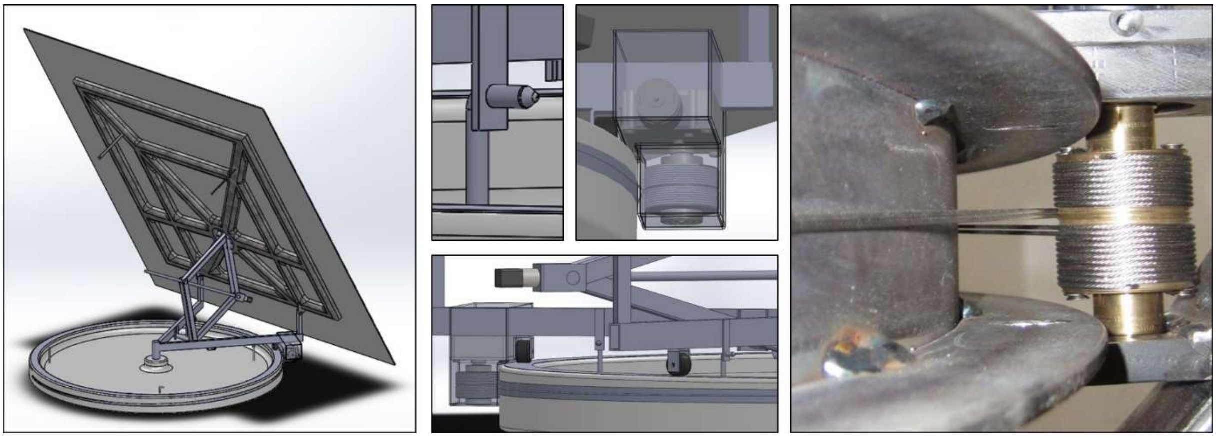

Figure 6: Carousel heliostat with scissor mechanism and locking at stow for elevation and cable drive for azimuth.

3.3.3 Elevation Drive

An advantage of carousel heliostats is that at stow the elevation drive can be easily locked by a rotation of the azimuth drive, without the need for an extra actuator. For this, hocks can be fixed to the runway, for example, which run into holes in the carriage when rotated to a certain position (Figure 6, middle). Then, in the stow position, the elevation drive is protected from the storm wind loads and it can be dimensioned according to the operating loads only.

In the following, several options for the elevation drive are given.

Rim Drive
The elevation drive can be realized by a rim on which a chain (Figure 11, left) or cables run or which is driven itself (Figure 11, right). For the azimuth drive, the runway can serve as a rim

while for the elevation drive an extra rim is needed. It cannot simply be laid on the ground but requires additional measures to fix it in an upright position.

Linear Drive
Linear drives are a very low-cost option for the elevation. The spindle gear provides an extremely high gear ratio which allows for a small motor of low cost. Another important advantage is the self-locking for sufficiently low spindle pitch. The resulting low efficiency of 20-30% is not critical because the additional energy consumption is negligible since usually the concentrator has to be elevated only once a day. The drive can be pretensioned by the gravity force of the concentrator. Thus, backlash of the spindle nut is of no relevance on the tracking accuracy.

For commercially available standard linear drives (Figure 7, right), the spindle nut moves a tube that runs in an outer tube at which the motor is fixed to. The surface of the inner tube must be sufficiently smooth for the cylinder sealing. To avoid the costly tubes with sealing, the spindle nut and the motor can be directly connected to the concentrator and the carousel’s carriage respectively (Figure 7, left). If the spindle-nut system needs a protection for outdoor applications, a sheathing tube or a bellows is needed. The sheathing tube can be of plastic and therefore low-cost. But, a UV resistant bellows for 30 years lifetime would be a significant cost factor. If necessary, then only for the section between concentrator and carriage because it varies in length with the elevation. This section is closed for the stow position. So, if protection of the spindle is only required for the high stow winds with possible sand storms, no bellows would be needed.

Spindle drives are designed for pressure and tensile forces. Loading by moments must be avoided because they cause the threads of the spindle nut and the spindle to be loaded asymmetrically, which leads to local overloads in the thread and thus to a reduced lifetime. To exclude moments on the spindle, the spindle drive can be connected to the concentrator and carriage via gimble joints, with the spindle axis running through the two axes of rotation of the gimble joint (Figure 7, left). If the spindle axis does not run through the gimble joint axes (Figure 7, right), the spindle is still subjected to a torque when loaded by an axial force. The gimble joints also reduce the required manufacturing accuracy.

Figure 7: Gimble joints with (left) and without (right) spindle axis running through the gimble joint axes.

For heliostats with the second axis close to the ground, a linear drive would need a very long stroke when connected to the upper end of the concentrator (Figure 10, left, Figure 12, right). Possible solutions for linear drives connected to the back side of the concentrator for shorter required stroke lengths are multi-stage telescopic linear actuators (e.g. [22]), an opening in the concentrator with the spindle nut connected to it (Figure 14, left), or an opening into the ground (Figure 2, a and b) with the spindle nut connected to the carriage. The disadvantage of multi-stage telescopic drives is that the outer spindles are larger in diameter than necessary for the loads so that the inner spindles fit into them. Therefore, material usage is low. With waterjet cutting with added particles, openings can be cut into the glass mirrors. But, the spindle would disturb cleaning when in stow and would have to be protected against sand storms by a bellows. The disadvantage of an opening in the ground is the significant extra effort for it.

Scissor Mechanism
With a scissor mechanism, a large ratio of stroke to minimum height can be achieved. Thus, a low height of the secondary axis can be realized (Figure 6, left). When retracted, at a low height, the angle between the legs of the scissors is small which leads to a load amplification on the spindle. The motor and the spindle must therefore be dimensioned for a multiple of the load of a directly loaded linear drive. For this reason and because of the additional costs for the scissor, a scissor mechanism drive is far more expensive than a simple direct linear drive. Furthermore, a scissor mechanism leads to additional backlash. But, when pretensioned by the gravity load of the concentrator, this is of no impact on the tracking accuracy.

3.3.4 Concentrator

Shape
Usually, heliostat concentrators are rectangular as to this shape the mirrors can be cut to easiest. A round shape (Figure 11, left) enables the highest heliostat field density but can result in much offcut. A good compromise seems to be mirrors cut into triangles which are assembled to a polygonal shape as with the Stellio heliostat [2].

Face-Down
Mirror cleaning and hail risk can be reduced for concentrators that can be turned face down (Figure 10, right, Figure 11, left). With the scissor mechanism shown in Figure 8, a face-down option can be realized for a heliostat with low concentrator height at stow [23]. However, the benefits did not seem worth the effort, so this approach was not followed up.

Figure 8: Carousel heliostat with lay-down and face-down concentrator at stow.

Instead of turning the concentrator upside down, it could also be folded up. Figure 9 shows a solution for a folding mechanism driven by the elevation drive [24] [25].

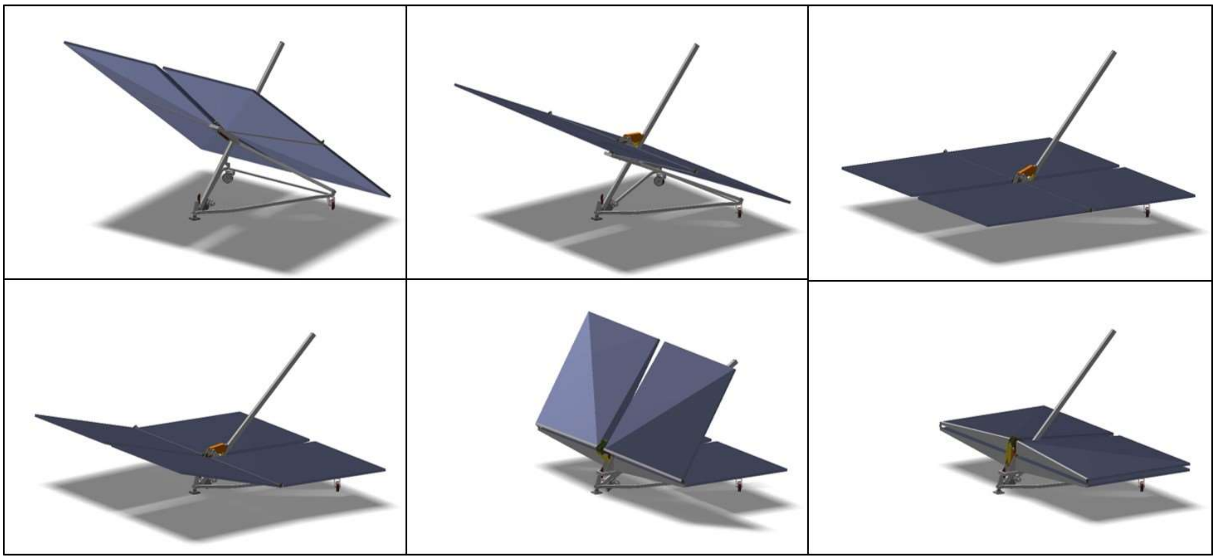

Figure 9: Carousel heliostat with concentrator folded up for stow by the elevation drive system [26].

Mirror Cleaning

For carousel heliostats, a comparably simple individual cleaning device can be realized [27] (Figure 14, mid-left). However, autonomous cleaning vehicles are probably the more cost-effective solution [28] [29].

4 Known Hitherto Carousel Heliostat Designs

4.1 Deflandre

Already in 1977, Deflandre et al. applied for a patent for a carousel heliostat [30] (Figure 10, left). The center of rotation is not central to the concentrator, but at one corner of it. This leads to a double as big diameter of the runway and to a significantly reduced field density. The linear drive for elevation is connected to the upper end of the concentrator which leads to a large length of the linear drive.

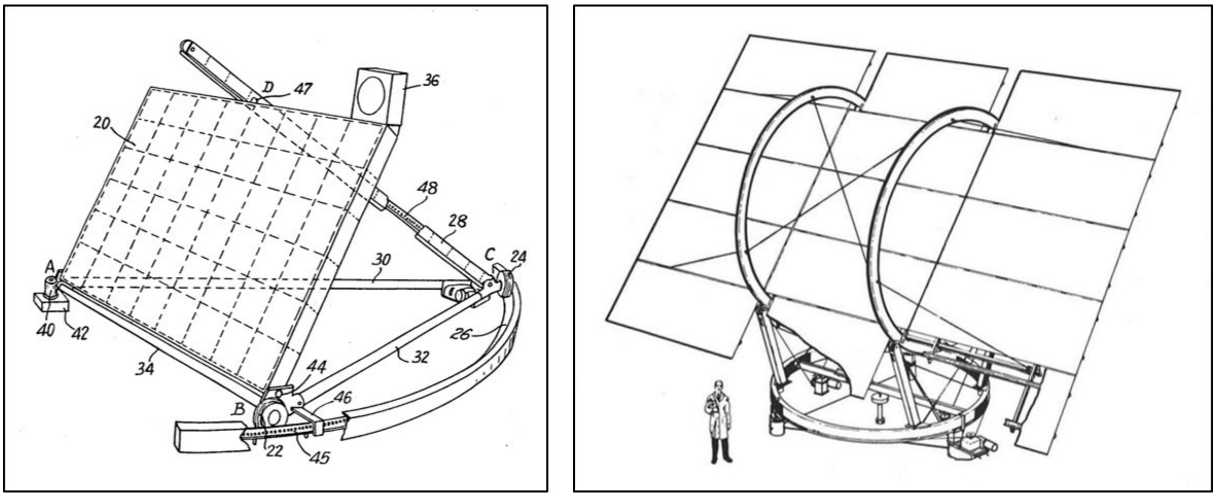

Figure 10: Heliostat of Deflandre et al. [30] (left) and Westinghouse [31] (right)

4.2 Westinghouse

The two rims that are directly driven for elevation make the Westinghouse heliostat unique [32] (Figure 10, right). The rims and the mirrors are stabilized by suspension cables.

4.3 ASM 150

The 150 m² Advanced Stressed Membrane Heliostat (ASM 150) of sbp (Figure 1, mid-left, Figure 5, left, Figure 11, left) is a highly efficient heliostat [33] [34]. Because of the long lever arms of the drives realized by rims of large diameter, a high tracking accuracy was achieved. Thin glass mirrors of high reflectivity were glued to a prestressed steel membrane that was kept in shape by a ventilator that regulated the pressure inside the concentrator.

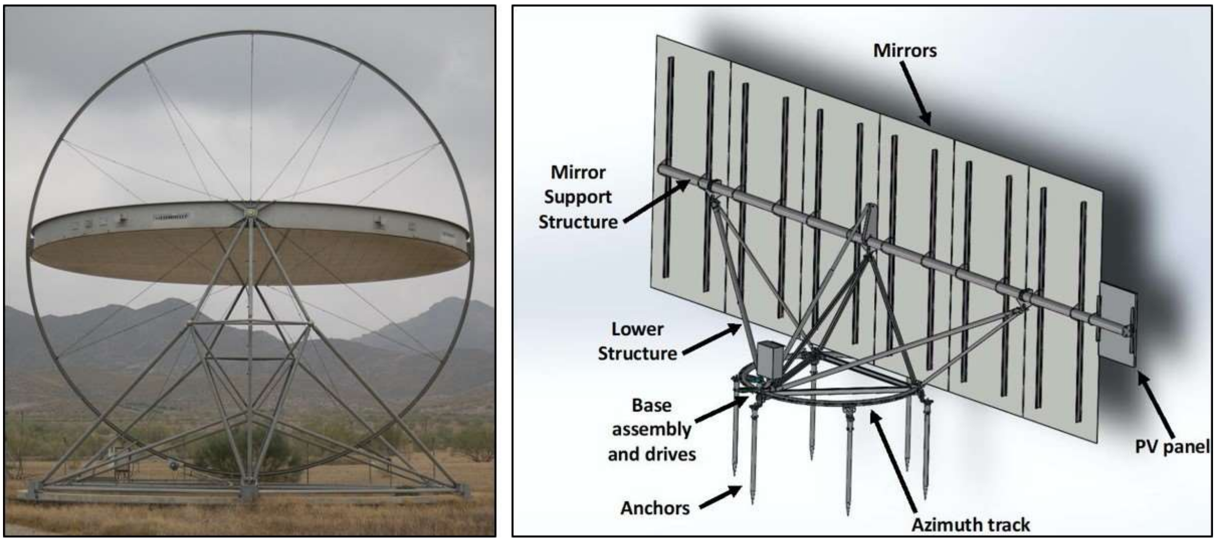

Figure 11: ASM 150 [33] (left) and Sunring [35] (right).

4.4 Sunring

Figure 11, right, shows the 27 m² Sunring heliostat [5] [36]. The disadvantages of the large aspect ratio of the concentrator are the higher astigmatism error and the reduced field density.

4.5 Pquadrum

With the 4 - 7 m² heliostat of pquadrum, almost all structural components are made from concrete [37] [38] (Figure 12). The high resulting weight prevents from uplift by wind. However, for a ground soaked with water after heavy rain, it is not clear if the heliostat would not sink in. For the advantages and disadvantages of using concrete, see 3.3.1, section “Concrete”.

Figure 12: Pquadrum's concrete heliostat (left) and Edisun's heliostats with the runways mounted on a grid of rods (right).

4.6 Edisun

The runways of the Edisun heliostat is mounted on a grid of rods (Figure 12) [39]. It is not clear, how ground and mirror cleaning would be realized.

4.7 Titan-Tracker

The Titan Tracker was offered for 150m² and 264m² mirror area (Figure 13) [41]. The tracker has a patented mechanism which allows for adaptations to possible irregularities in the runway.

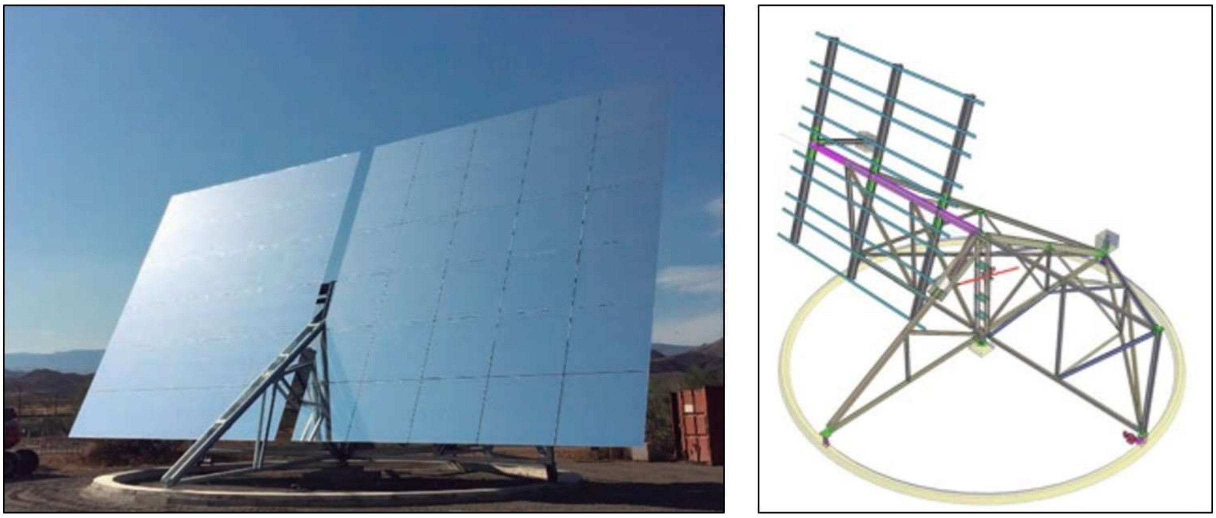

Figure 13: Titan Tracker [40] [41]

4.8 KOSMOS

The KOSMOS heliostat of DLR has a concentrator made of triangular sandwich facets [27][42]. The elevation drive runs trough the concentrator which can hinder mirror cleaning. Automated mirror cleaning can be realized with a wiper lip system (cf. 3.3.4, section "Mirror Cleaning"). A first 8 m² prototype was build (Figure 14, left). However, the drives and cross sections of the profiles of this prototype are dimensioned already for 50 m² heliostat size.

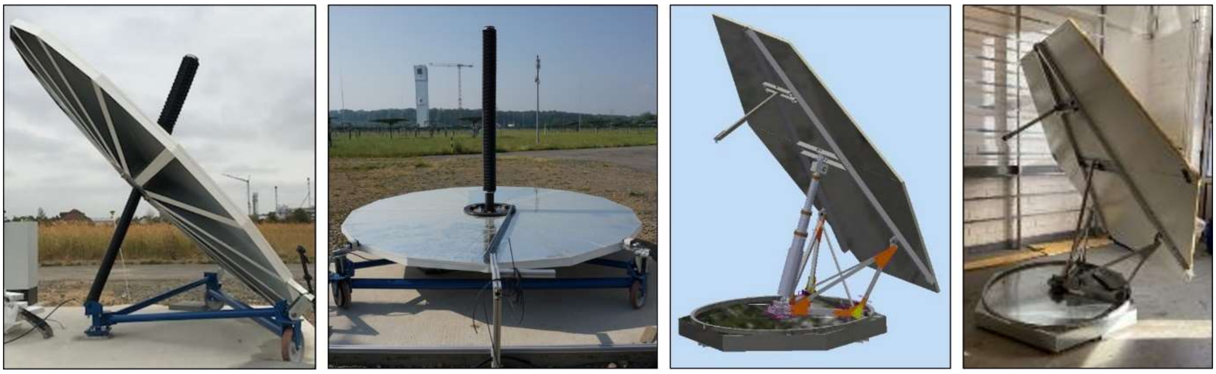

Figure 14: KOSMOS heliostat with wiper lip for mirror cleaning (left) and SAHEL heliostat (right).

4.9 SAHEL

As ballast and base for the runway, the 5 m² SAHEL heliostat of DLR has a container made of steel metal sheets to be filled with sand or gravel at site [43] (Figure 14, right). The elevation is realized by a telescopic linear drive [22] (cf. 3.3.3, section "Linear Drive").

5 Discussion and Conclusion

Many smart approaches have been developed to bring carousel heliostat cost down. But, are they sufficient to overcompensate the additional cost for the runway?

Particularly for large heliostats, the runway cost is high. The cheapest runway would be the consolidated ground. However, the required wheels would be rather expensive. The usage of disused car wheels could be a solution. But, it is not clear whether the cost of organizing the wheels and adapting them individually to the carriage's interface would exceed the cost savings and if a sufficiently high level of reliability could be guaranteed.

However, large heliostats are not economical anyway due to their high specific weight [17], their low suitability for high-volume production, the higher wind loading, and the significant reduction in electronics costs in recent decades. In addition, for high temperature applications like solar fuel production, which are getting more and more important, small heliostats are needed because of their lower astigmatism losses [18].

By comparing the carousel designs with the T-type design in Figure 2, it's questionable whether a carousel heliostat can compete against a simple T-type heliostat for small sizes. The pylon of the T-type heliostat can be of small wall thickness and for the foundation a simple hole can be drilled into the ground to be filled with cement or pile driving of the pylon could be used. In contrast, for a carousel heliostat the runway must be thick enough to keep the wheels form uplift by wind and for the on-ground foundation at least a simple additional mold, a consolidated ground, and reinforcement of the concrete is needed to prevent fractures. So, both components seem to be more expensive for the carousel heliostat. Pfahl et al. tried to find solutions for a low-cost runway and base, but for all cases, the T-type benchmark heliostat was of lower cost [18].

So, all in all, with the approaches found so far, it seems by a carousel architecture, no cost reduction for heliostats can be achieved.

6 Summary

Carousel heliostats can be seen as a special kind of an Az-El heliostat type. They can be distinguished by the height of the elevation axis, the size of the concentrator, and the design of the main components which are the base, the azimuth and elevation drive, and the concentrator.

Design variants of the base are concrete rings, stakes, screw piles, containers, or just the consolidated soil. Solutions for the azimuth drive found so far are friction wheels and chain, toothed wheels and cable drives. The elevation drive can be realized by a rim, a linear or a scissor mechanism drive. Square, polygonal, or round are shapes concentrators have been built so far, some with face-down option or even foldable for the stow position.

Most of these design variants can be found in known hitherto carousel heliostats from Deflandre and Westinghouse, the ASM 150 from sbp, the Sunring from Solar Dynamics, the concrete heliostat of pquadrum, a heliostat of Edisun, the Titan-Tracker heliostat, and the KOSMOS and the SAHEL heliostat of DLR.

In recent years, the trend has been towards smaller heliostats, as they are more cost effective, particularly for high temperature applications. For small heliostats, however, the comparison with T-type designs showed no cost advantage for carousel architectures. Unless new breakthrough approaches are found, it is therefore recommended to focus on other heliostat architectures.

7 Acknowledgements

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References

[1] A. Pfahl, Survey of Heliostat Concepts for Cost Reduction. Solar Energy Engineering 136, 2014, https://doi.org/10.1115/1.4024243.

[2] A. Pfahl, J. Coventry, M. Röger, F. Wolfertstetter, F. Vasquez, F. Gross, M. Arjomandi, P. Schwarzbözl, M. Geiger, P. Liedke, Progress in Heliostat Development. Solar Energy (152), pp. 3-37, 2017, https://dx.doi.org/10.1016/j.solener.2017.03.029.

[3] B. Gross, Beyond CSP – A Trillion Dollar Opportunity. SolarPACES 2020 conference.

[4] D. Schulte, C. Gregory, Design, Analysis, and Testing of Cable Drive Heliostat Actuator. SolarPACES 2020 Conference.

[5] K. Kattke et al., SunRing Heliostat: Minimizing Slope Error with Smart Design and Assembly. SolarPACES 2023 Conference, Sydney.

[6] A. Pfahl, H. Bouzekri, A. Djdiaa, D. Benitez, V. Nettelroth, J. Rheinländer, A. Krause, Heliostat Innovation in Detail to Reach Challenging Cost Target. AIP Conference Proceedings, 2022, https://doi.org/10.1063/5.0086922.

[7] A. Pfahl, A. Rong, Low-Cost Movable Heliostat. AIP Conference Proceedings, 2022,

[8] R. Zaibel, E. Dagan, J. Karni, H. Ries, An Astigmatic Corrected Target-Aligned Heliostat for High Concentration. Solar Energy Materials and Solar Cells, 37, pp. 191-202, 1995, https://doi.org/10.1016/0927-0248(94)00206-1.

[9] R. Buck, E. Teufel, E., Comparison and Optimization of Heliostat Canting Methods. Journal of Solar Energy Engineering, 2009, 131(1), doi:10.1115/1.3027500.

[10] Silva, J, New York Times, https://www.nytimes.com/2016/11/14/world/africa/south-africaenergy-solar-windnuclear.html?_r=1, accessed January 2017.

[11] T.R. Mancini, P. Heller, S. Jones, M. Romero. Catalog of Solar Heliostats, SolarPACES report No. III-1/00, 2000.

[12] CSIRO, http://www.scienceimage.csiro.au/mediarelease/mr10-124.html, accessed June 2012.

[13] X. Wei, Z. Lu, W. Yu, H. Zhang, Z. Wang, Tracking and Ray Tracing Equations for the Target-Aligned Heliostat for Solar Tower Power Plants, Renewable Energy, Volume 36, Issue 10, 2011, Pages 2687-2693, https://doi.org/10.1016/j.renene.2011.02.022.

[14] F. von Reeken, G. Weinrebe, T. Keck, M. Balz, Heliostat Cost Optimization Study. SolarPACES 2015 conference.
[15] M. Emes, A. Jafari, A. Pfahl, J. Coventry, M. Arjomandi, “A Review of Static and Dynamic Heliostat Wind Loads,” Solar Energy (225), 60-82, 2021, https://doi.org/10.1016/j.solener.2021.07.014.
[16] A. Pfahl, Wind Loads on Heliostats and Photovoltaic Trackers, PhD Thesis, DLR, TU Eindhoven, 2018, https://pure.tue.nl/ws/files/99010995/20180621_Pfahl.pdf.
[17] G. J. Kolb, S. A. Jones, M. W. Donnelly, D. Gorman, R. Thomas, R. Davenport, R. Lumia, Heliostat Cost Reduction Study. Paragraph A.3, SANDIA Report SAND2007-3293, Albuquerque, New Mexico, USA, 2007.
[18] A. Pfahl, V. Dohmen, Low-Cost Materials for Heliostats. SolarPACES 2023 Conference, Sydney.
[19] P. Liedke, A. Lewandowski, A. Pfahl, E. Hölle, Precise Low Cost Chain Gears for Heliostats. Procedings SolarPaces 2015 conference, Cape Town.
[20] A. Pfahl, M. Randt, C. Holze, S. Unterschütz, Autonomous Light-Weight Heliostat With Rim Drives. Solar Energy 2013, 92, pp 230–240.
[21] A. Pfahl, M. Randt, F. Meier, M. Zaschke, C.P.W. Geurts, M. Buselmeier, A Holistic Approach for low Cost Heliostat Fields. Energy Procedia, 2015.
[22] https://www.neff-ballscrews.com/products/telescopic-screw-drives.
[23] P.C. Prahl, A. Pfahl, M. Röger, Heliostat für Solarkraftwerke oder Solarkonzentratoren. DLR, German patent DE102015202084A1, 2015.
[24] R. Preßmair, A. Buchroithner, The FLAP Heliostat – A Novel Low-Cost Heliostat Design Featuring a Mirror Protection Mechanism Based on Dual-Use of the Elevation Drive. SolarPACES 2023 conference.
[25] R. Preßmair, A. Buchroithner, Foldable and Tiltable Device for the Conversion or Deflection of Solar Radiation. Technische Universität Graz, European patent, EP3916319B1, 2020.
[26] R. Preßmair, A. Buchroithner, Concept Animation FLAP-Heliostat. DOI:10.13140/RG.2.2.26722.81602, 2022.
[27] A. Pfahl, J. Rheinländer, A. Krause, R. Buck, S. Giuliano, J. Hertel, K. Blume, T. Schlichting, N. Janotte, A. Ries, First Lay-Down Heliostat with Monolithic Mirror-Panel, Closed Loop Control, and Cleaning System. SolarPACES 2018 conference, Casablanca.
[28] Supcon, Cleaning Vehicle. https://www.solarpaces.org/wp-content/uploads/1-1-page-description-of-the-innovative-idea-and-its-impact-and-the-role-of-the-applicants.pdf, accessed November 2023.
[29] Heliogen, Introducing Heliogen's ChariotAV, Our Field-Tested Autonomous Cleaning Vehicle. https://www.youtube.com/watch?v=WtVmEo3Tw9k, accessed November 2023.
[30] J. Deflandre, P. Matarasso, J.-P. Traisnel, Heliostats. U.S. Patent No. US4129360, 1978.
[31] Heliostat Development Division, Second Generation Heliostat Evaluation Executive Summary. SAND81 -8033, Sandia National Laboratories, 1982.
[32] R.K. Sayre, Heliostat Assemblies. U.S. Patent No. US4209231A, 1980.
[33] G. Weinrebe, M. Schitz-Goeb, W. Schiel, On the Performance of the ASM 150 Stressed Membrane Heliostat, Journal of Energy Resources Technology, 1996.
[34] G. Weinrebe, Technische, ökologische und ökonomische Analyse von solarthermischen Turmkraftwerken. PhD Thesis, Institut für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart, 2000.
[35] P. Kurup, S. Akar, S. Glynn, C. Augustine, P. Davenport, Cost Update: Commercial and Advanced Heliostat Collectors, Technical-Report NREL/TP-7A40-80482, 2022.
[36] N. Stegall, K. Kattke, R. Sommers, Systems and Methods for Mounting a Heliostat, Solar Dynamics, Patent WO 2021/231453A1, 2021.
[37] https://pquadrum.com/, accessed November 2023.
[38] A. Pedretti-Rodi, Method and Device for Producing a Concrete Workpiece. Pquadrum Engineering SA, international patent WO2019/183737A1, 2019.
[39] J. Baker, N. Syssoev, A. Fyke, Heliostat Array. Edisun Microgrids Inc., Patent US9477065B1, 2016.

[40] L. B. Soriano et al., Titan Tracker. In: La Propiedad Industrial y su Influencia en el Éxito Empresarial, Volume 2, 2018, pp 85-87.
[41] Titan Tracker, 2017a, http://www.titantracker.es/v_portal/apartados/apartado.asp?te=699, accessed January 2017.
[42] A. Pfahl, P. Liedke, Kostengünstige Spiegelsandwichfacetten für Heliostaten. Schlussbericht zum BMWi-Projekt SPACE, DLR, https://doi.org/10.2314/KXP:1677724579, 2019.
[43] G. Weinrebe et al., Wirtschaftlichere Heliostaten mit Sandwichkonzentrator, Karussellnachführung und optischer Closed-Loop-Regelung. Schlussbericht zum BMWi-Projekt SAHEL, https://doi.org/10.2314/KXP:186030950X, 2022.