SolarPACES 2022, 28th International Conference on Concentrating Solar Power and Chemical Energy Systems
Receivers and Heat Transfer Media and Transport: Point Focus Systems
https://doi.org/10.52825/solarpaces.v1i.627

The FLAP Heliostat

A Novel Low-Cost Heliostat Design Featuring a Mirror Protection Mechanism Based on Dual-Use of the Elevation Drive

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Abstract. Heliostats represent a major cost share of concentrating solar power (CSP) plants with central receiver. They are essential for system efficiency and strongly influence maintenance cost and service life. Since CSP facilities require direct solar radiation, suitable installation sites can eminently be found in desert regions. However, dusty conditions may greatly reduce the performance of the plant due to soiling of the heliostat's reflective surface and / or irreversible degradation caused by abrasive sand particles. A novel heliostat called FLAP, developed specifically for desert environments, is presented in this paper. It was designed with an emphasis on maximum manufacturing and maintenance cost reduction, yet improved service life in mind. The essential innovation of the FLAP heliostat is the patented foldable reflector support structure consisting of two panel sections that are oriented face-to-face when being in lay-down stow position. Folding of the panels is accomplished by means of a mechanism comprising a simple yet effective 4-bar linkage. To avoid costs for additional drives, the device is actuated by the one single central linear actuator that is also used for elevation tracking. Furthermore, wind loads are minimized due to the low profile of the heliostat structure in stow position, resulting in material and hence overall cost savings.

Keywords: Heliostat, Foldable Reflector, Desert Environment, Mirror Degradation, Anti-Soiling, Concentrating Solar Power, Central Receiver, Power Tower

1 Introduction

CSP power towers (aka *central receiver solar plants*) hold great potential in the context of the energy revolution, mainly due to their ability to provide dispatchable energy by means of economic thermal energy storage [1], [2]. In such plants, heliostats are arranged in arrays of up to tens of thousands of units around a central receiver (i.e. tower), typically accounting for approximately 40 to 50 % of the capital cost of the entire plant [3], [4], depending on the so called "solar multiple" (i.e. ratio between the capacity of the solar field and power block) [5]. Therefore, reducing the cost of a single heliostat is a huge lever for lowering the overall cost of the plant. However, regions with high direct normal irradiance (DNI) throughout the year, which are optimal for CSP applications, are generally arid, resulting in harsh environmental conditions. Swirling dust, or sand storms in an even more severe manner, can greatly reduce the performance of the heliostat (and consequently the CSP system as a whole) due to soiling and irreversible degradation of the reflecting surfaces [4, pp. 32-34]. The costs for mirror cleaning and / or maintenance can furthermore contribute significantly to increased levelized cost of electricity (LCOE) or heat [6], [7]. The innovative concept presented in this paper called FLAP heliostat (**F**ace-to-face **L**ay-down **A**nti-degradation **P**rotection) hence addresses three major design goals that are summarized in Table 1.

Table 1. FLAP design goal overview.

Strategic goal	Effect	Design approach
Reduce abrasion	Long heliostat service life / reliable operation	Face-to-face reflector
Reduce soiling	Reduced operation and maintenance cost	Face-to-face reflector
Reduce wind load	Low-cost, yet resilient lightweight design	Lay-down stow position

Different strategies to partly address the above mentioned objectives like “strategic stow orientation” or “dust avoiding technologies” have been proposed in literature (a review thereof is given e.g. by [8]) and may be capable to resolve some issues to a certain extent. However, the FLAP concept features a disruptive mechanical redesign with a significant improvement of the heliostat layout / geometry itself in mind. The following arguments underpin the choice of this approach:

- **Dust avoiding technologies:** Active dust repellent applications (e.g. using electrostatic methods, surface vibration, etc.) are generally costly and require an external power source. Passive anti-soiling mirror coatings often lack durability [8]. Hence, reliable protection of the mirror surface against irreversible abrasion is not provided in either case.
- **Strategic stow orientation:** Certain types of a conventional pedestal supported heliostat allow for strategically orienting its mirror surface “face-down” in stow position, which can help to reduce soiling. However, an effective protection against abrasion remains missing.
- **Improved heliostat layout / geometry:** The reduction of wind load during stow on a conventional pedestal supported heliostat is limited due to its exposed position above the ground (wind speed generally increases with height [9]). Therefore, further load reduction can be achieved by deploying a laydown heliostat geometry without a static tall pedestal.

2 Conceptual idea of the FLAP heliostat

The invention described in this paper offers a new strategy for protecting the reflective surfaces of heliostats against detrimental environmental conditions. Figure 1 illustrates the concept by showing a time series of the unfolding and tracking process. In case of heavy winds and/or during sandstorms, as well as during nighttime, the reflector surface can be stowed in a *face-to-face* position, i.e. the reflective surfaces protect each other. This is accomplished by means of a novel and patented folding mechanism [10], which uses only one single actuator for the (un-)folding procedure, as well as for sun tracking. The reflector structure can be lowered close to the ground during stow, which reduces wind load (this is referred to as "lay-down" or “low-profile”). Reduced wind loads also enable lighter and thinner mechanical structures, which results in reduced material use.

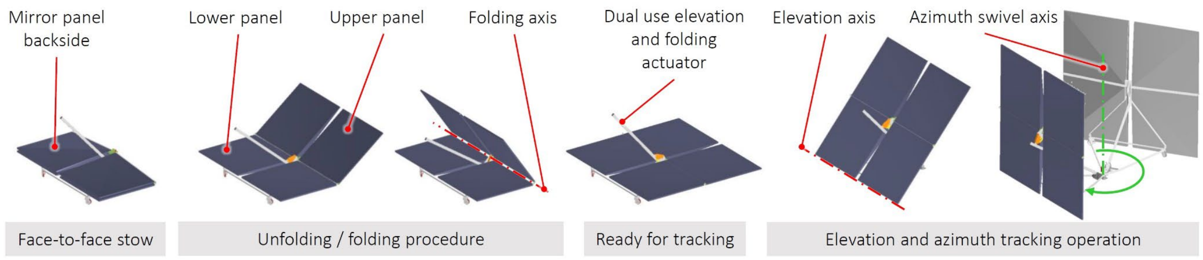

Figure 1. FLAP heliostat concept overview, showing the process from stow to tracking mode.

Before starting the development process of the FLAP heliostat, a thorough assessment of the state of the art in heliostat design, particularly an analysis of existing low-cost lay-down heliostat concepts was conducted and is summarized in the subsequent section.

2.1 Related work regarding lay-down (track-mounted) heliostats

The development of the FLAP heliostat was originally inspired by different concepts proposed by Pfahl et al. [11], [12] at DLR. All these concepts aim at reducing wind loads during storms by stowing the mirror structure close to ground ("lay-down" or "low-profile"), with the mirror surface facing either up- or downwards.

A "face-down" stow orientation has the advantage of potentially better protection against soiling, hail or bird dropping. This face down stow position could in theory be achieved by means of a scissor or linkage mechanism, which is actuated by the elevation drive. A scissor mechanism (Figure 2, left), however, usually offers only unfavorable kinematics as it enables rapid angular movement during tracking (i.e. when not needed), yet showing slow characteristics for moving into stow, when speed may be critical. A completely opposite behavior is desired though, which can be achieved e.g. by a rather complex linkage mechanism (Figure 2, middle). Although the ideas behind both designs are technologically valid, the mechanics (very long levers / bars) that have to carry / turn the entire load of the mirror structure result in rather bulky structures. Thus, the intended cost reduction potential due to reduced wind load will most likely be nullified. Beyond that, bulky structures and unfavorable kinematics also result in higher energy consumption while tracking. This might be a disadvantage in the case of autonomous heliostats as proposed in [13].

A quite radical cost reduction approach was pursued by DLR with the deployment of a "face-up" lay-down carousel heliostat with monolithic reflector structure. It was designed for very low specific heliostat field costs below 75 USD/m² [4]. The drawback of this concept is that the reflective surface is exposed to all meteorological hazards like hail or sand and dust accumulation when being in lay-down position. Bird dropping can also cause additional soiling of upward facing heliostats [14] (and PV modules for that matter [15].)

Figure 2. Lay-Down heliostat concepts proposed by DLR; Left: Face-down with scissor mechanism [11], Middle: Face-down with linkage mechanism [12], Right: Face-up [12]. (Images with kind permission by DLR).

2.2 The "face-to-face" lay-down concept

The state of the art analysis lets the reader conclude that all mentioned lay-down concepts presented in the previous subsection have one common challenge that hinders large scale deployment of these so called "next generation" heliostats (i.e. heliostats at very low cost): Ensuring sufficient protection against abrasion from swirling dust or sand near ground. Although the "face-down" layout could be equipped with an additional planar stow face to protect the reflecting surface, this would mean increased material use and hence higher cost. However, in the case of a "face-to-face" layout, this protective stow plane is provided intrinsically. This idea led to the design of the FLAP heliostat, which offers a number of further advantages, such as:

- Because the reflector surface can be fully covered from harsh weather conditions like hail and sand storms, more economic (cheaper) reflective layers (e.g. thin film reflective foil or anodized aluminum) could be deployed alternatively instead of silvered float glass mirrors.
- The FLAP concept can also be implemented into already existing (carousel type) heliostat designs relatively easily, due to its compact design.

- A self-actuating cleaning mechanism could also be triggered and powered by folding/unfolding of the FLAP heliostat. This is possible due to the relative motion of the two mirror facets during the unfolding process. E.g. a sliding cleaning lip that is attached to the lower panel could be continuously pushed from the center towards the edges of the reflector by the folding (shutting) upper panel. This cleaning lip could also act as a seal against dust in stow position.
- The ability of the reflector structure to be folded allows a certain "partial operation", with only half of the heliostat being focused onto the receiver and the other half being placed parallel and low to the ground. The wind speed limit could therefore be extended for such partial operating conditions, as the area exposed to the wind is smaller.
- The FLAP concept may also be adapted to other applications in solar power generation, such as PV trackers, where soiling, hail damage and even snow shedding play an important role. By exploring additional markets, production numbers could increase and costs could be reduced even further.

3 Design of the FLAP mechanism

The heart of the novel heliostat concept is the FLAP mechanism, which consist of three interacting subunits, namely (a) folding mechanism, (b) locking mechanism (incl. ground lock) and (c) dual-use elevation drive. These subunits are described in more detail below. Figure 4, left shows an entire (track-mounted) carousel heliostat with implemented FLAP mechanism. In this case, a square-shaped reflector is depicted. However, the reflector could have a different shape (round, polygonal) as well, depending on which mirror facets are available. Also, the linear elevation actuator could be of any suitable type (spindle, multi-stage telescope drive, etc.) and is not limited to the linear belt drive design which was chosen by the authors for their study. The upper panel of the reflector is rigidly connected to the swivel frame, which represents a tilting pedestal that elevates with respect to the base frame during tracking operation. The concept also comprises a carousel carriage (base frame with attached wheel drive) for rotation about the azimuth axis.

Note: The following subsections describe the mechanical relations within the heliostat. However, the 2-dimensional kinematics may in part be difficult to grasp with only static images at hand. The authors have therefore decided to provide an animation showing the folding and tracking procedure of the FLAP heliostat via a link that can be found in the "Underlying and related material" section. Furthermore, the patent offers a more in-depth description of the mechanisms [10].

a) Folding mechanism:

The basic principle of the folding mechanism is shown in Figure 3. The lower mirror panel (including the swivel frame) remains horizontal (i.e. close to the ground) throughout the folding procedure. Connected to the lower mirror panel, the folding lever actuates the coupling rod, which turns the upper mirror panel about the folding axis (the hinge, which connects the two panels). The folding mechanism hence represents a simple four-bar-linkage. Figure 4, right, shows a possible design realization of the folding mechanism (incl. locking mechanism, which is discussed below), relying mainly on simple rectangular steel tube and bent sheet metal parts.

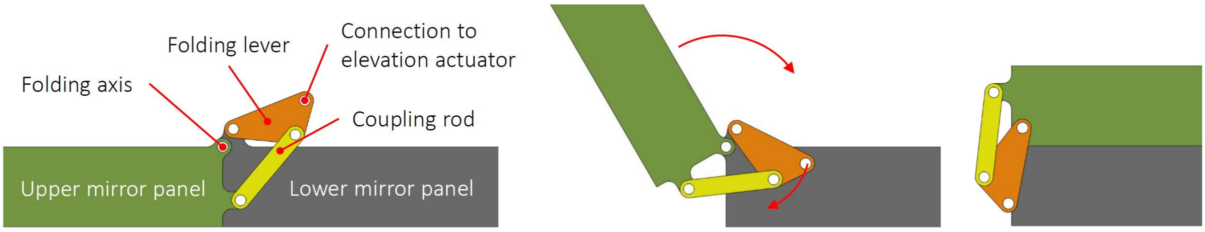

Figure 3. Simplified sketch of folding sequence, illustrating how the folding mechanism works.

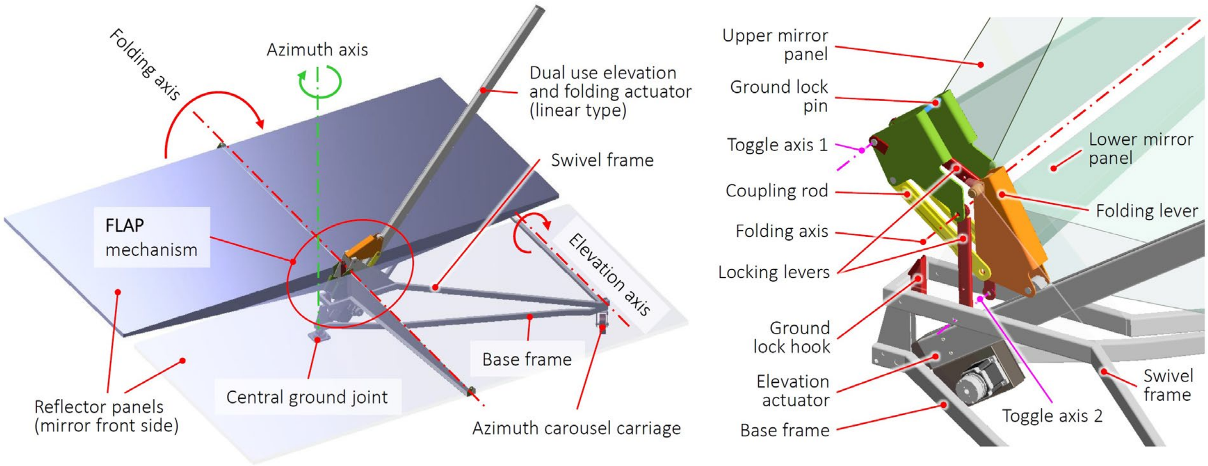

Figure 4. Left: Component overview of the FLAP heliostat (CAD model). Half of the rectangular reflector is displayed in a semi-transparent way to reveal the FLAP mechanism underneath; Right: Possible realization of the FLAP mechanism (CAD model). Only the relevant components are depicted, the bulk of the mirror panels are displayed in a semi-transparent way.

b) Locking mechanism:

Locking of the two mirror panels (i.e. in-plane alignment of the two foldable mirror facets) has to be accomplished providing zero backlash due to the high optical requirements of a heliostat [16]. Even a slight wobble or vibration might lead to significant optical errors [17]. The FLAP invention therefore deploys a toggle lever mechanism to lock the facets with respect to each other (see Figure 5). By establishing a slight offset between the two toggle axes of the toggle levers, pre-tensioning, and hence zero backlash, can be achieved. Locking and unlocking can be realized without additional drives, i.e. self-actuating, by using e.g. a simple trigger cam (not depicted here).

Figure 5. Simplified sequence illustration of the FLAP mechanism incorporating a toggle lever locking mechanism.

It has to be mentioned that the toggle lever mechanism is one possible implementation option which enables locking without separation of the related components, i.e. the locking levers remain connected to the reflector panels when unlocked. This might be advantageous regarding wear over the service life. However, the task of locking could eventually also be accomplished by other devices like some kind of hook or bolt.

In order to clearly separate the two operation modes tracking and folding, a ground lock is additionally required (see Figure 4 and Figure 5). The ground lock clamp is latched by a small tension spring, i.e. the default position of the ground lock is “locked”. Actuation is necessary only for the transition of “unfolding” of the reflector panels to “tracking” operation. Therefore, the clamp is actuated, also by a self-actuating ground lock pin, which is attached to the upper panel. The ground lock also fixes the reflector structure in stow position and therefore relieves the FLAP mechanics and the drive.

c) Dual-use elevation drive:

As already mentioned, the FLAP mechanism could be actuated by any kind of linear drive. Spindle drives generally require lubrication and in case of long free spindle length (and the absence of an additional guidance rail), gravity sag can cause severe skewing between spindle axis and spindle nut. Furthermore, long compression loaded spindles are prone to buckling, which has to be prevented by sufficient spindle cross section. The major inherent benefit of spindles is their general ability of self-locking. Toothed belt drives, in contrast, offer low specific weight and lubrication can be omitted. However, the main uncertainty of a toothed belt is the service life, as it depends on several factors, such as chemical degradation, UV embrittlement, maintenance, environmental conditions etc. Until now, only the simplest solution incorporating a fixed length linear actuator type was followed. Nevertheless, attempts to package all actuating components behind the mirror facets (to avoid shading and to close the gap between the reflector panels) are currently undertaken (e.g. multi-stage telescopic actuator or intermediate scissor mechanics). Furthermore, although not yet designed in detail, reliable sealing against sand and dust, will be addressed in the next design phase.

4 Structural assessment

Although the design of the whole heliostat concept is based on thorough structural assessment, only a short excerpt of the mechanical load analysis of the FLAP mechanism components, will be presented here. The underlying goal was to keep the forces required to put the heliostat into stow in the same range as the maximum mechanical load during tracking operation, which determines dimensioning of the dual-use elevation drive. The geometry of the linkage mechanism was therefore iteratively optimized to meet this goal. In Figure 6 the resulting load (reaction force) on the linear actuator for an exemplary 9-m² square heliostat (prototype) is graphed over the folding and tracking angle respectively.

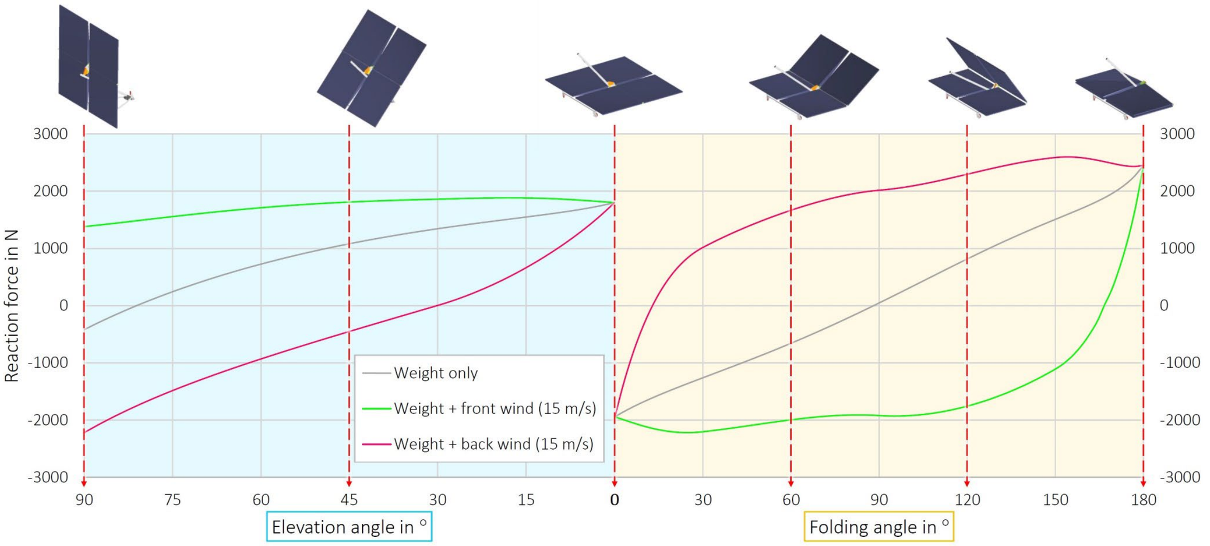

Figure 6. Progression of load on the linear elevation actuator due to wind and heliostat weight for a 9-m² square heliostat during folding / unfolding and tracking. Left: Reaction force over elevation angle; Right: Reaction force over folding angle; Positive reaction force corresponds to upward direction, negative force accordingly to downward direction; Wind direction expressions refer to the collector side being impinged.

Wind loads were estimated using the widely adopted approach established by Peterka et al. [9], whereby aerodynamic load components (drag / lift forces and bending moments) can be calculated by means of peak wind load coefficients and a mean wind speed. Both, for tracking and for moving into stow, a mean wind speed of 15 m/s (at 10 m above ground) was assumed. Load coefficients were taken from [18]. In contrast to conventional pedestal mounted heliostats, the height of the center of the heliostat area from ground for a lay-down heliostat varies with elevation angle. While the turbulence intensity increases closer to the ground (higher peak load coefficients at lower heights) the mean wind velocity decreases. As an approximation it was assumed that the effects compensate for each other, i.e. no adjustment of the height (and hence turbulence intensity and mean wind speed) for calculation of loads on the lay-down heliostat were made. Aspect ratio dependencies, as determined by [18] were taken into account for calculating loads during folding (only half of the heliostat area with rectangular shape is attacked by wind). In order to obtain a representative force distribution over the angle range, wind load coefficients were interpolated between known values at certain positions. Nevertheless, accurate coefficients on a heliostat without pedestal and (partially) folded collector structure still have to be determined by wind tunnel tests. It is also worth mentioning that actuator load during folding can be reduced by changing the azimuthal orientation of the heliostat.

5 Discussion of heliostat manufacturing and assembly

When designing the FLAP heliostat, great attention was paid to allow simple manufacturing and assembly, well suitable for industrial large-scale production. Inspired by methods and technologies used in mass production of chassis parts in the automotive industry, the tubular frame structures were designed to be manufactured via an in-line process of machining (notching), kinking and 3D laser welding. The necessary threaded holes in thin-walled frame parts could be realized by means of “flow drilling”, as suggested by the authors also in [19]. However, alternative manufacturing approaches, such as injection molding and the use of recycled materials (e.g. plastics) are also being investigated by the authors of this paper and may well allow significant cost reduction in the near future [20]. All moving parts of the folding and locking mechanism are designed as simple sheet metal components in a way to minimize scrap metal. In order to prevent backlash due to wear and tear occurring over the service life, economic plastic plain bearings can be used at the rotational joints between the moving parts, as this represents a well-established solution in the CSP sector [21], [22].

6 Cost consideration

Within the scope of this paper, only the cost of the FLAP mechanism in addition to the “baseline design” of a lay-down carousel heliostat are briefly discussed, as this is relevant for comparison with conventional designs. After all, the additional cost for the joints and moving parts need to be comparted to the savings in cleaning / maintenance costs and extension of heliostat service life. Based on a 9-m² design a rough estimate of additional costs was conducted. As presented in Table 2, additional costs of less than € 50 in total seem feasible, resulting in a specific cost increase of 5.56 €/m² for a small (9 m²) heliostat and 2.00 €/m² for a medium sized (25 m²) heliostat. Larger designs (> 50 m²) may require increased bearing and part sizes, hence altering the additional costs.

Table 2. Estimate of FLAP mechanism additional costs.

Component group	**No. of items**	**Retail price**	**Serial price**
Plastic gliding bearings	~ 10	€ 60	< € 10
Sheet metal parts (cutting, punching, bending, galvanization)	~ 5	€ 500	€ 35
Nuts, bolts, fasteners, springs, etc.	~ 20	€ 30	€ 2
Subtotal		€ 590	**€ 47**

Pinning down absolute numbers of specific cost of the entire heliostat would require an in-depth analysis of the underlying manufacturing processes including material and energy cost, to name but a few factors. Methods to perform these cost studies are for example described in [19], [3] and [23]. However, a study of this kind can be performed only after the suitability of a concrete design and realization has been confirmed by deployment of a full-scale prototype in a field test.

7 Conclusion and outlook

The heliostat concept developed by the authors allows for the first time a face-to-face arrangement of the reflector panels close to the ground, which is used in the event of excessively high wind speeds or during breaks in operation and is referred to as FLAP (**F**ace-to-face **L**ay-down **A**nti-Degradation **P**rotection). It is designed to substantially

- reduce soiling of the mirror surface,
- reduce risk of sand abrasion of the mirror surface,
- reduce wind loads on the heliostat structure during storms.

Besides lightweight design, and consequently lower material costs, potential savings in costs for operation and maintenance (O&M) and cleaning water consumption can thus be considered the most crucial benefits of the FLAP heliostat.

In terms of a more detailed design phase of the FLAP heliostat, there are a couple of aspects that still have to be elaborated. Research on solutions for following issues is currently ongoing:

- Choice and design of the most suitable linear elevation drive, incl. adequate sealing.
- Detailed design of the azimuth carousel carriage: traction wheel, geared track, etc.
- Determination of the optimum size and shape of the reflector (incl. choice of material) and detailed design of mirror facet attachment.
- Design of an (integrated) mirror cleaning device.
- Detailed design of panel sealing to prevent dust settlement in face-to-face stow position.

7.1 Alternative applications of the FLAP mechanism

PV trackers are becoming increasingly popular and their installation capacity is surpassing conventional static installations by now [24]. Several studies also underline the economic benefits of single axis PV trackers [25]. However, several issues remain using single axes tracking, but could be resolved with deployment of a FLAP-based PV tracker:

- Reduced surface degradation and soiling due to protective face-to-face stow position
- Eliminating snow coverage (“so called snow shedding”) to allow more effective energy production during winter
- Flattening of PV peak and increase of operating hours especially in high latitude regions (“harnessing the midnight sun”.)

In summary, the presented technology holds great potential for deployment in several industrial solar power sectors. The authors are currently looking for partners to manufacture and test full-scale prototypes and welcome serious requests for collaboration.

Data availability statement

The data (CAD and calculations) the article is based on are available from the corresponding author, (R. Preßmair), upon reasonable request.

Underlying and related material

An animation of the FLAP heliostat concept, showing tracking and folding mode, can be accessed via https://doi.org/10.13140/RG.2.2.26722.81602.

Author contributions

Rupert Preßmair: Conceptualization, Investigation, Methodology, Writing – original draft. Armin Buchroithner: Project administration, Conceptualization, Investigation, Writing – original draft

Competing interests

The authors declare no competing interests.

Acknowledgement

The authors would like to thank the *Research & Technology House* of *Graz University of Technology* for their support in filing the patent for the technology developed within this project, in particular *Mr. Andreas Ruplitsch*, MSc.

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