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Innovative Modular Approach to High Concentration CSP Systems. Results and Achievements From the First-of-its-Kind 300 kWt Semi-Fresnel Fixed Mirror Module Prototype Up and Running

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Abstract. This paper presents the successes achieved during the construction, commissioning and testing of an innovative approach to stationary reflector/tracking absorber (SRTA) systems that demonstrate the viability of this kind of solar thermal solution. This novel approach is based on a Fresnel concept of a classical SRTA, which leads to cost reductions thanks to reducing the height reached by the solar field. In addition, it provides the SRTA systems with another extra layer of adaptability to different climatic, orographic and even economic situations. In order to demonstrate the feasibility of this solution, the MOSAIC project has constructed and commissioned a prototype based on this approach, surpassing challenges such as the flexible piping and showing new improvements that could be introduced in the future MOSAIC modules. The first tests have been conducted on this prototype demonstrating, still under suboptimal operational conditions, an efficiency of up to 18.6 % and the possibility to operate this system using molten salts for high output temperatures that could make the most of the 3D concentration. The modularity, versatility and adaptability demonstrated by this concept all along the project development lead to a wide portfolio of opportunities to integrate the MOSAIC concept in a variety of scenarios, free space availabilities, and different applications, while maintaining a reduced cost of energy production.

Keywords: MOSAIC Project, Fresnel Solar Field, SRTA System, Solar Thermal Power Plant, SHIP Plant

1. Introduction

1.1 SRTA Systems

Spherical concentrators allow configurations based on fixed solar fields and mobile receivers, known as stationary reflector/tracking absorber (SRTA) systems. This allows several advantages while raising important challenges when implementing large power systems.

Solar bowl systems can be combined forming huge plants of hundreds or even thousands of modules creating a solar mosaic in the terrain that can be adapted to cover and make the most of all free spaces with modules, whatever the available terrain would be.

Regarding the solar field, a solar bowl able to produce a good amount of energy during the first and last hours of the day, especially in winter, is a solar bowl whose structure reaches high altitudes. That means that its construction costs would also be high due to the need of a structure able to maintain a certain degree of optical quality, so it has to be quite robust.

To curb the cost, a Fresnel approach can be applied to the solar field, additionally providing versatility and flexibility to adapt the concentrator to the orography of each specific site [1]. This “fresnelization” consists of the collapse of the bowl into sections of different radii bowls that shares a common curvature centre, so all of them focus the light along the same straight line. In addition, this solution increases the flexibility to provide ad-hoc modular solutions to each specific application (heat or electricity, low or high output power, different solar radiation profiles, different terrain shapes, etc.) while keeping 3D high concentration ratios.

In order to explore and determine the real potential of the Fresnel approach to modular spherical concentrators, it is mandatory to gain practical experience designing, building, and testing a representative module, which has been done in the MOSAIC project. After several years of development, this project has come to an end with the construction, commissioning, and successful performance of the first operational tests of the proposed prototype, which is based on a semi-Fresnel configuration and a light cable-driven tracking system. This article shows the first results that demonstrate how this concept makes the construction and operation of SRTA systems viable.

1.2 MOSAIC system description

Figure 1 shows the system, erected in CENER facilities in Sangüesa (Spain) and already in operation, comprising a central bowl, and two spherically curved partial outer rings made of 1 m^2 mirrors (1x1 m^2) installed in 5x5 and 3x3 mirror modules respectively. The receiver tracks the concentrated flux actuated by 8 cables pulled from 4 towers.

Figure 1. Solar field saw from the top of the central tower (left) and a global view of the system during operation (right).

The aperture diameter of the prototype MOSAIC solar field is 30 m and peak thermal power is close to 300 kWt [2]. The southernmost section of the concentrator has been deleted from the construction plan, and then not erected in the prototype, due to the low cost-efficiency ratio shown during the optical analysis process for the latitude where the prototype is placed.

2. Achievements and test results

2.1 Challenges addressed during the construction of the prototype

2.1.1 Solar field and structure

Following and deepening more in the modularity principle, the Mosaic prototype has been designed to be formed by 2 different types of mirror modules. This provides the means to standardize the structures that form the whole solar field, leading to a reduction of the structure fabrication costs through economies of scale.

Then, the assembly of the whole solar field has been carried out following two different assembly procedures that were previously developed, tested and presented in [3], corresponding to each module type: the mirror assembly using a jig (Figure 2 left) whose surface can be adapted to the needed module curvature, and the on-site mirror assembly. The maximum normal error estimated from partially characterized solar field has been lower than 1 mrad, which is low enough taking into account the focal distance (between 7.5-9 m, depending on the curvature radius) and the receiver diameter (30 cm, up to 50 cm in the cone section), so the spillage losses derived from this geometry are negligible.

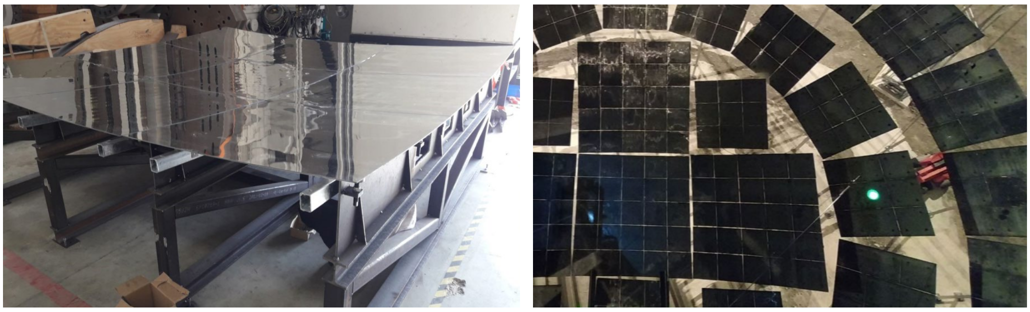

Figure 2. A mirror module assembled using the developed jig (left) and the canting process, at module level, being applied to a 3-by-3 module placed in the inner ring (right).

On one hand, 3-by-3 modules have been assembled with the aid of a jig placed at ground level that has assured good quality of the mirror canting of each module. In addition, the fact that the module is at ground level and the mirrors can be left resting on spheres has led to an easy and safe assembling procedure. The canting of these modules was evaluated once they were lifted atop of their corresponding pillars on field, and the high quality module canting achieved using the jig was then confirmed, having a mean error along the solar field, compounded by both canting and contour errors, of 2.33 mrad.

On the other hand, due to the complicated logistics involved in lifting such large assembled modules, 5-by-5 modules have been assembled directly on the field, and in a two-step assembly procedure. This begins by preassembling the mirrors in a favourable position on the solar field, using ad-hoc tooling, and then lifting the module in two parts to its final position on the solar field. Once there, the second step is performed, where the canting of each mirror is adjusted in a precise way. This procedure reaches high levels of quality due to the fine adjustment performed during the second step, but without this last step could be prone to high surface errors, mainly dominated by its canting component.

This two steps procedure has ended up in a more time-consuming, and even less practically implementable, task than the jig procedure. Another fact to take into account, in terms of construction time, is that these 25-mirror modules have to be assembled outdoors, which means that this task lasts much longer and could even produce delays in the construction of the solar field when unfavourable weather conditions occur.

An issue that was raised during the production of the 5-by-5 modules, in comparison with the lower-size modules, is the fact that they cannot be easily transported by road and lifted in a cost-economical way due to their size, so when they are produced in a far workshop they have to be produced in two different pieces. This in part converts the modules into lower-size modules but needs to design and build a new different structure and apply another assembly methodology. Additionally, 3-by-3 modules, and even 4-by-4 modules can be placed over a single pillar, so the assembly and canting process is easier and cheaper to perform.

All the aforementioned reasons and experiences clearly show that having a solar field composed only of one type of standardized structure would be easier to design, manufacture, transport, assemble, and cant, leading to a great cost reduction in the final construction cost of the solar field. In addition, a study on logistics, assemble and lifting of the modules based on the construction and commissioning experience concluded that the ideal module size would be a 4-by-4 module. In this way, collecting energy using the MOSAIC module would be cheaper thanks to making the most of economies of scale. Besides, security issues could introduce some restrictions that increase costs and construction times, so reducing dangerous activities in the assembly procedure will contribute to construction cost reduction.

Furthermore, thinking about a commercial implementation, the design of the template, with 4 pulling towers and a central tower to support the thermal loop, piping and parking oven would be reviewed. The central tower would disappear, or at least reduced in size and rigidity needs, because the thermal loop would be shared by different modules, further reducing the metal structure cost. Then, the piping and flexible hose could be held in place by cables from the pulling towers.

2.1.2 Flexible hose system

In such a complex thermal loop where the receiver tracks the sun, a flexible hose is mandatory in order to connect the receiver and the rest of the thermal loop. So, in order to connect the moving receiver with the skid where the main elements of the thermal loop are located, a bespoke flexible hose has been designed and manufactured, taking into account the singularities of the application and the future use of molten salts as HTF. The hoses have been extended to a complete system by adapting an additional cable protecting hose which acts bridging in a safe manner the cables, connecting from the skid to the receiver. The behaviour of this flexible hose was tested prior to its installation on the field by performing sagging tests and measuring the forces that appeared in the system to take them into account when designing the tracking system.

2.1.3 Tracking system

The prototype operation is based on the fact that the receiver is the moving part. This is a disruptive approach characteristic of fixed spherical concentrators that changes how the operation procedure has to be defined. For this, a cable-driven tracking system developed to position the receiver has been successfully implemented, and a vision system to close the control loop of the tracking. Different procedures have been carried out to improve the open-loop accuracy to values between 30-100 mm and a complete set of operation modes that cover different scenarios has been defined, implemented, and successfully tested.

For a massive implementation of MOSAIC systems, the tracking system might be used as a crane in the construction of the solar field thanks to the high precision required to place the receiver in the focal line, so the cable system might pick up the pre-assembled modules and lift them to their final position, which might lead to reducing the need for the use of cranes (which amounts to around 1 % of the cost of manufacturing and erecting the solar field). In this sense, during the receiver and flexible hose assembly manoeuvre, the ability to safely pick-up an object at ground level was satisfactorily tested, as shown in Figure 3.

Figure 3. Receiver elevation process using the tracking system to bring it from the ground level (left) to the position in which the flexible hoses were soldered (right).

2.2 Test results and discussion

The initial tests were carried out during October and November 2021 in two phases.

The first set of tests was oriented to prove the prototype operability. During those tests, the ad-hoc modes of operation and their transitions were tested to verify their convenience, as well as the capacity to control each subsystem during the proper operation.

The second set of tests, focused on the performance of the prototype, were performed under sub-optimal conditions, such as the latitude of the site where the prototype was erected (42.6°) and especially the time of the year, when both the optical efficiency, due to the low elevation of the sun and the solar field tilting, and the receiver efficiency due to the concentration footprint on its surface, were not close enough to their peak values. Those tests were performed operating at the maximum mass flow rate in order to verify that the whole system can be operated without taking risks of damaging any subsystem due to any error occurring.

Then, to calculate the efficiency, it has to be taken into account that the solar field does not track the sun, which means that the cosine effect of each module will vary a lot along the operation of the module and it is not the same for the entire solar field nor evolves in the same way. This is similar to what happens in the solar field of a central receiver power plant and the cosine effect impacting each heliostat. So the reference value of incident power will be estimated from the product of the DNI and the total mirror area. Then, the solar-to-heat efficiency of the MOSAIC module reached a preliminary value of 18.6 % (see Table 1).

Table 1. Results obtained from the efficiency test.

Input temperature [°C]	**Output temperature [°C]**	**DNI [W/m^2]**	**Mass flow rate [kg/s]**	**Power into HTF [kW]**	**Incident power [kW]**	**Total efficiency [%]**
191.5	303.4	788	0.314	75.5	406.1	18.6

It has not been possible up to now to characterize in a fine way the performance of the tracking system, the thermal efficiency of the receiver and the effect of working at a sub-optimal operating point. In order to estimate the actual losses that would be attributed to these uncertainties some theoretical simulations has been carried out. The optical power that is incident on the receiver of the prototype under the known conditions of the testing day (sun position, DNI = 788 W/m^2, mirror reflectivity = 0.94, soiling losses = 0.04, receiver absorptance = 0.944 and canting losses = 0.0025) was simulated and with this results the available solar power on the mirror surface obtained is 143 kW. Then, taking into account the optical losses characterized, the incident power on the receiver should be 130 kW while the estimated power that the HTF is absorbing is 75.5 kW. This means that the lost power that can be attributed to receiver, tracking, and sub-optimal operation amounts the 41.9 % of the theoretical incident power on the surface of the receiver.

Table 2. Comparison of the results obtained from simulations and tests.

Available solar power [kW]	Incident power on receiver [kW]	Theoretical power into HTF [kW]	Theoretical receiver efficiency [%]	Non-characterized losses [%]
143	130	88.1	68	14.3

From the thermal efficiency calculations performed during the project [4], a receiver efficiency of 68 % could be expected during the testing period of year, meaning that around 12-13 kW are lost due to non-optimal tracking and operation. At the sight of these results, it is expected that the receiver operation efficiency reached has been lower than in thermal simulations.

A new set of thermal studies and a deeper prototype characterization is needed to accurately obtain the receiver efficiency at this working point. But which is clear from the aforementioned results is that an optimised prototype operation resulting from the learning process derived from extended operating periodswould lead to a higher MOSAIC concept total efficiency. This would optimize the operating point for the receiver, so the MOSAIC prototype could achieve an efficiency of around 22 % at the same time of the year. By this reason, the MOSAIC team is searching for funding resources to optimize the operation of this concept.

Furthermore, some tests were performed to assess the time needed and the cooling of the receiver when it is taken from the oven to focus. All along them, the mass flow rate was set at maximum for receiver integrity reasons as during the previous tests, and the whole manoeuvre was performed manually. These tests were performed to assess the freezing risk possibility during this manoeuvre when using molten salts as HTF in future developments.

To obtain some conclusions, the physical properties of molten salts compared to thermal oil (Helisol 5A) were taken into account. During the test, the HTF cooled from 105.5 °C to 93.2 °C, that is, 12.3 °C. Although the density of solar salt is much bigger than the density of Helisol 5A and the thermal losses could be higher, it does not look likely that the molten salts would be cooled to the freezing point (240 °C) during this manoeuvre if they are properly preheated up to 290 °C. Moreover, the test took 17 minutes, a time that could be reduced with experience and automatic operation. In conclusion, it seems that there would not be a freezing risk in the case of using molten salts during that critical manoeuvre.

3. Adaptability to fit an evolving market

The adaptability underlined before can be used to advantage in different ways to reduce even more the cost of the solar field. One option is the use of the natural terrain slopes, which usually can be an issue, to our advantage by adapting the solar field to their shape.

In a typical solar thermal power plant, rough terrains suppose several problems such as possible shadows for central receiver power plants or the inability to install complete parabolic trough loops. For a MOSAIC system, this kind of terrain can allow to cut the solar field structure cost by adapting it to terrain slopes and irregularities (Figure 4).

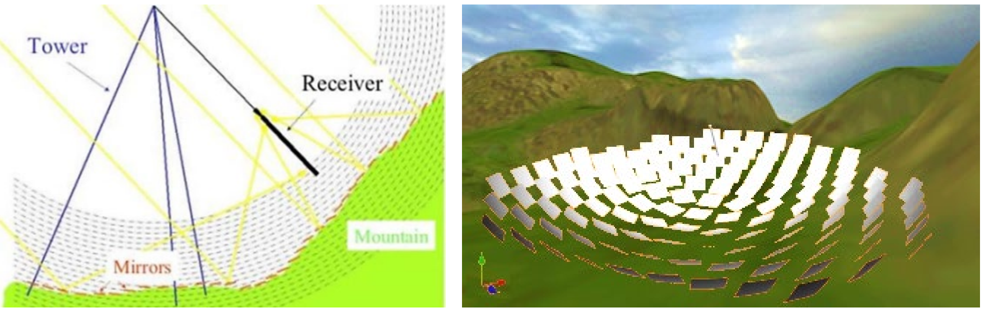

Figure 4. (Left) Illustration of adaptability to terrains and (right) an artwork depicting a solar field adapted to terrain irregularities.

That solution would place each mirror module at the same height from ground level, following the topography of the terrain, so construction costs are low while mirrors can be placed at more convenient heights to make the most of their annual energy collection capability, provided that all mirrors are oriented to the common centre of spheres. This can be implemented as spherical bowls using a spherical rings configuration or one similar to a heliostat field.

4. Conclusions

The erection and operation of a large SRTA system have a number of challenges that have been addressed and overpassed during the MOSAIC project. The success and conclusions obtained from this project open a new path to be further explored in the field of solar thermal technologies: a new contester equipped with characteristics as modularity, versatility and adaptability while taking advantage of 3D concentration for efficient high concentration ratios.

The geometry of the Semi-Fresnel SRTA configuration allows an easy canting procedure that will guarantee a high-quality surface shape while the cable-based tracking system allows the development of large tracking systems at affordable costs as well as offering other advantages like the possibility to reduce the need for cranes during the lifting of the solar field.

The developed and erected prototype has reached solar-to-heat efficiencies up to 18.6 % during the preliminary tests performed, under sub-optimal conditions, so it is expected to reach better performances once optimized the operation of the system and the tuning of the different subsystems.

The modularity and versatility demonstrated by the semi-Fresnel concept opens a wide range of applications where SRTA systems can be implemented. From huge CSP plants composed of thousands of standard-shaped modules that could even grow in capacity by adding more modules if the power needs rise, to Solar Heat for Industrial Processes (SHIP) applications where the solar field can be adapted to fit free spaces in industrial parks, to natural terrain slopes or building integrated, the adaptability of MOSAIC concept makes it a proved and advanced alternative to cope with green energy integration in different scenarios. In the future, different economic scenarios could be faced, meaning that adaptable systems like MOSAIC can be shaped to make the most of possible future cost reduction opportunities.

Data availability statement

The data showed in this paper is part of a preliminary analysis performed from the first series of tests obtained from the suboptimal operation of the MOSAIC prototype. This data has not been uploaded to any repository but are planned to be shared in repositories such as Zenodo OpenAIRE (Open Access Infrastructure for Research in Europe) (https://zenodo.org/), when they would be more complete, to a public repository for reaching a further dissemination of the results and the system possibilities.

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Competing interests

Authors have no conflicts of interest to declare that are relevant to the content of this article.

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References

1. M. Sánchez, M. Romero, V. Fernández, “Potential of optimized non-tracking mirror concentrators for distributed solar applications” 12th International SolarPaces Symposium. October 6-8, 2004. Oaxaca, ISBN 968-6114-18-1
2. C. Villasante et al., “Low-Cost Solar Electricity Using Stationary Solar Fields; Technology Potential and Practical Implementation Challenges to Be Overcome. Outcomes from H2020 MOSAIC Project,” Energies 13, no. 7: 1816, Apr. 2020, https://doi.org/10.3390/en13071816
3. I. Pagola et al., “MOSAIC: the First Prototype of a Semi-Fresnel Spherical Concentrator,” AIP Conference Proceedings 2445:1, 060004, May 2022, https://doi.org/10.1063/5.0085891
4. M. Cagnoli et al., “Design methodology for a prototype helical receiver adopted in the MOSAIC solar bowl system”, Solar Energy, Volume 208, 2020, Pages 905-916, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2020.08.012.