High-Performance Stellio Heliostat for High Temperature Application

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Abstract..High-temperature energy conversion processes and the corresponding high surface temperatures of receivers increase thermal losses. This makes high-performance heliostats with increased optical and tracking quality interesting. Several improvement measures were investigated for the Stellio heliostat (Figure 1). Performance gains and cost effects were examined for each measure and for a combination of all measures. LCoE changes have been calculated to assess cost-effectiveness.

FIGURE 1. Stellio heliostats at Hami power plant

INTRODUCTION

For the upcoming generation of solar tower systems with high-temperature conversion process, high quality heliostats are even more required than for state-of-the-art molten salt receivers and power blocks. Main reason is that high-temperature processes mean high surface temperatures of receivers and absorbers which increases thermal losses. Especially the IR radiation increases with the 4th power of the absolute temperature. This requires cavity receivers with as small as possible apertures and heliostats with narrow beams and thus high optical quality. Tracking accuracy and aim point strategies must be adequate as well.

THE NEXT-CSP PROJECT

One such advanced high-temperature system has been developed in the Horizon 2020 project next-CSP [1, 2]. In this project, a fluidized particle-in-tube receiver for 750 °C particle temperature was designed by 10 European partners. The particles are also used as thermal storage. A 3 MW_{th} prototype receiver with storage, heat exchanger and gas turbine is installed at Thémis plant in Odeillo/France, to be completed in 2020 and operated by CNRS.

In this context, a high-performance heliostat has been investigated by sbp. EDF have performed LCoE calculations for this.

THE STELLIO HELIOSTAT

Stellio is one of the most precise heliostats on the market (Figure 2), characterized by innovative kinematics and drives, an effective structural system, highly precise assembly and sophisticated controls [3]. It has been awarded several times, prototypes have been built in 2014 and 2017. It is applied commercially for the first time the Hami solar tower project in China (Figure 1), with solar field completion in 2021 [4]. Stellio was selected as the basis for conceptual design of a high-performance heliostat.

Main characteristics of Stellio are its novel kinematic system with inclined axes (slope drive), the use of two linear actuators and a reflector substructure with high stiffness which enables high optical quality. It has a net reflective surface of 48.5 m², a slope error of 1.5 mrad (2D) and a tracking error of 0.6 mrad (1D).

FIGURE 2. Stellio Heliostat

HELIOSTAT QUALITY PARAMETERS

Heliostat quality is determined by two main components: slope error and tracking error. These are defined in the following to avoid the confusion occurring sometimes when different parameters are jumbled.

Slope error:

$$\sigma_{beam} = 2 \times \sigma_{slope}$$

$$\sigma_{slope,\,2D} = \sqrt{\sigma^2_{slope,\,x} + \sigma^2_{slope,\,y}}$$

For Stellio, the guaranteed slope error $\sigma_{slope,\,2D}$ (SD_{tot}) is 1.5 mrad at low wind speed up to 4 m/s. This value is used as basis even if the series heliostats in the Hami project have achieved clearly better values, typically between 1.2 and 1.3 mrad with the best heliostats around 1.0 mrad.

Tracking error:

$$\sigma_{pointing} = 2 \times \sigma_{tracking}$$

$$\sigma_{tracking,\,2D} = \sqrt{\sigma_{tracking,\,x}^2 + \sigma_{tracking,\,y}^2}$$

The standard Stellio tracking error $\sigma_{tracking,\,1D}$ *is* 0.6 mrad.

OPTICAL QUALITY IMPROVEMENTS

Mirror contour accuracy and thus slope error depend primarily on stiffness of the supporting steel structure, stiffness of mirror panels and accuracy of connection between mirror and support structure (canting, jig accuracy).

The principles applied to assemble standard Stellio heliostats already provide very good optical quality by using a highly precise mirror jig that ensures that the shape of the mirrors is close to perfect geometry before being glued to the support structure. This allows for compensation of steel structure imperfections without any kind of adjustment and with very good repeatability. Canting errors do not exist.

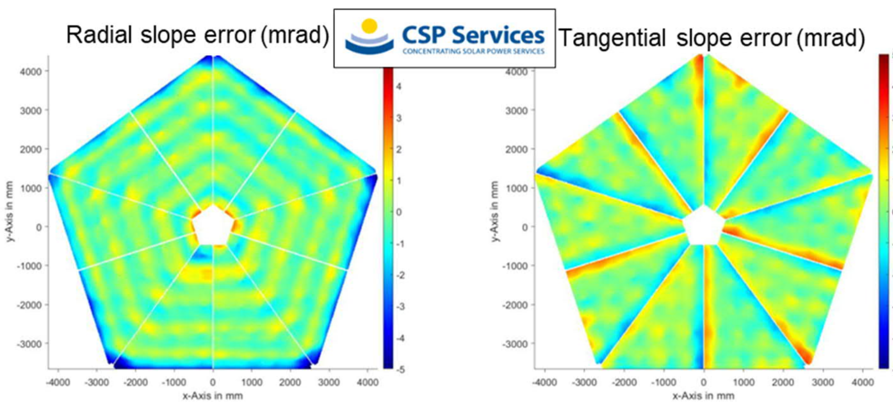

FIGURE 3. Typical slope error distribution of Stellio heliostat in Hami, from deflectometry analysis

Thus, the main contributors to slope error are support structure and mirror deformations (Figure 3). Table 1 lists the improvement measures investigated to identify the most promising ones in terms of technical and commercial criteria.

TABLE 1. Possible measures to improve optical quality

Measures	Potential	Engineering effort	Cost increase
Increase of purlin stiffness	++	medium	low
Increase of cantilever arm stiffness	+	medium	low
Increased number of mirror supporting points	+++	high	medium
Modification of supporting point details	+	medium	medium
Increase of facet stiffness	+++	high	high

Additional mirror supports were finally selected as the most effective option. The Stellio reflector consists of 10 mirror facets and a central one, with 4 mm thickness. The supporting structure is composed of a central hub, 10 cantilever arms and 5 rows of purlins. Each mirror facet is connected at 13 points to the purlins (Figure 4).

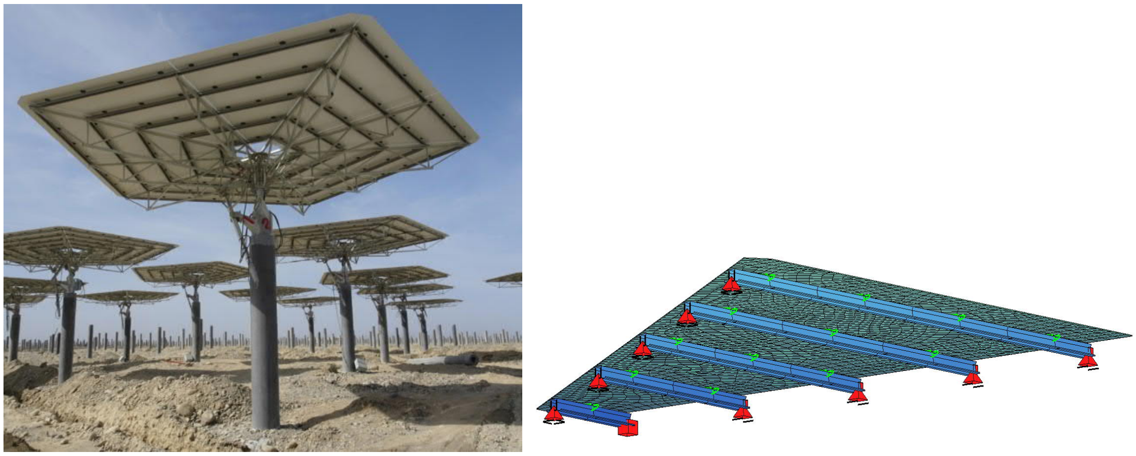

FIGURE 4. Stellio mirror supporting

A study was carried out to determine the best number of purlins and mirror supports, the exact positions of all supports were defined in a multi-parameter optimisation. The outcome was an improved version with 6 purlins and 17 supports (Figure 5). The slope error (2D) reduces from 1.5 to 1.3 mrad. This could be achieved with relatively low additional steel mass and increase in assembly effort.

The cost impact was estimated to 2 % of the total heliostat cost (wo. pylon and foundations).

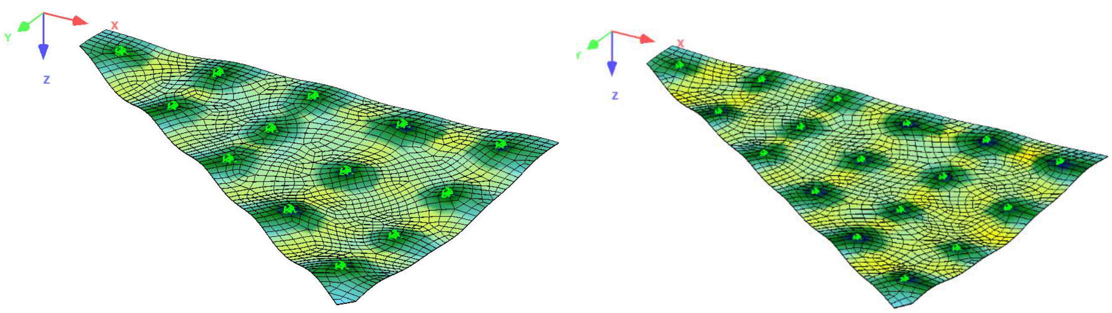

FIGURE 5. Mirror supporting and gravity deformation for standard Stellio (left) and improved version (right)

TRACKING QUALITY IMPROVEMENTS

Heliostat tracking errors consist of several components that are correlated with the actuators, structural stiffness and tracking control. Table 2 summarizes the measures for tracking error reduction we looked at.

TABLE 2. Possible measures to improve tracking quality

Measures	**Potential**	**Engineering effort**	**Cost increase**
Reduction of actuator backlash	++	medium	medium
Reduced tolerances of spindle pitch	+	low	medium
Increased actuator stiffness (ball screw)	+	medium	high
Increased limit switch precision	+	low	low
Improved actuator corrections by control (temperature, normal force, pitch)	+	high	zero
Increased pylon head stiffness	+++	medium	low
Refinement of heliostat calibration	++	high	low

Actuator backlash and stiffness and the pylon head stiffness were chosen as the most promising options and were further investigated.

Dead Weight and Wind Induced Tracking Errors

With Stellio control system, structure deformation by dead weight is largely compensated. Deformations depending on both axis positions were calculated by FEA to generate a matrix. With this matrix, deflection of actual heliostat orientation is compensated. In the same way, normal force in each actuator is computed by FEA for all axis positions. With measured elastic actuator length change vs. normal force, the actuator length change can be compensated. Also, thermal expansion of actuators is corrected using measured ambient air temperature.

Remaining tracking errors are further reduced by calibration: by application of a beam characterisation system (BCS), each heliostat is repeatedly directed to a large target at the tower. Photos are taken by cameras and the beam position is evaluated. By comparing actual vs. nominal position, correction data are generated. The procedure is repeated at different sun positions to develop a correction matrix.

While dead load deformations can be well reduced with this method, wind induced, deformations remain and cannot be compensated. These can only be decreased when stiffness of the complete structure and of the actuators is improved.

Actuator Improvements

For the linear actuators to bi-axially move the heliostat's reflector, besides of their stiffness another important parameter is their backlash.

One specific feature of Stellio is the unbalanced reflector which means pull loads on the drive in the very most positions. While increasing the maximum normal force for the actuator, this avoids actuator stability problems (buckling) under push load and substantially reduces frequency of situations where wind induced forces can overcome the preload and activate backlash. Even if Stellio is therefore much less sensitive to the effects of actuator backlash, calculating the annualized effect of backlash shows that its reduction reduces tracking error noticeably.

Standard Stellio heliostats are driven by an ACME (trapezoid) spindle/nut with brushless motors. These provide good performance at moderate cost. However, the plastic nuts, which are typically used because of their low maintenance requirements, have low stiffness. Furthermore, different thermal expansions of spindle and nut do not allow adjusting tight thread tolerances. This results in temperature dependent backlash and the plastic material is subject to wear. Over the service life, a backlash of 1 mm or more has to be accounted for.

For the high-performance heliostat, ball screw actuators were investigated instead (Figure 6). These have a nut equipped with steel balls that roll along the spindle groove during operation. This leads to high stiffness and considerably lower backlash, which furthermore increases less over lifetime and is temperature independent. The rolling instead of a sliding contact to the spindle means high efficiency and loss of self-locking, therefore either a low efficiency pre-stage gear or a motor brake is required to obtain self-locking.

Not surprising, the disadvantage of ball screw actuators is their higher cost. For the Stellio actuators, approx. 30-40 % increase have to be accounted for.

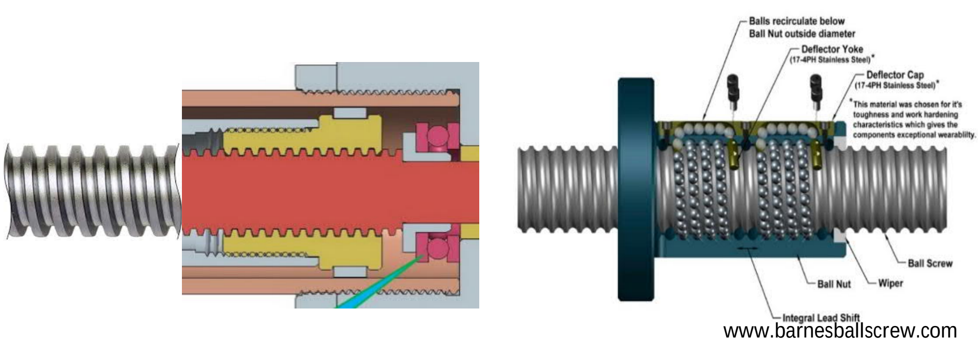

FIGURE 6. ACME (left) and ball screw/nut (right)

Pylon Head Reinforcement

The Stellio heliostat is mounted on a steel or concrete pylon. The upper part of the pylon (pylon head) is a separate component bolted to the lower pylon (Figure 7). It carries the main axis and a console for main axis actuator support. Deadweight and wind deformation of the upper pylon part was identified to be relatively high. A study compared several pylon head design variants, finally a relatively simple modification of geometry and optimisation of material thicknesses was found to significantly increase stiffness while keeping steel mass and component cost constant.

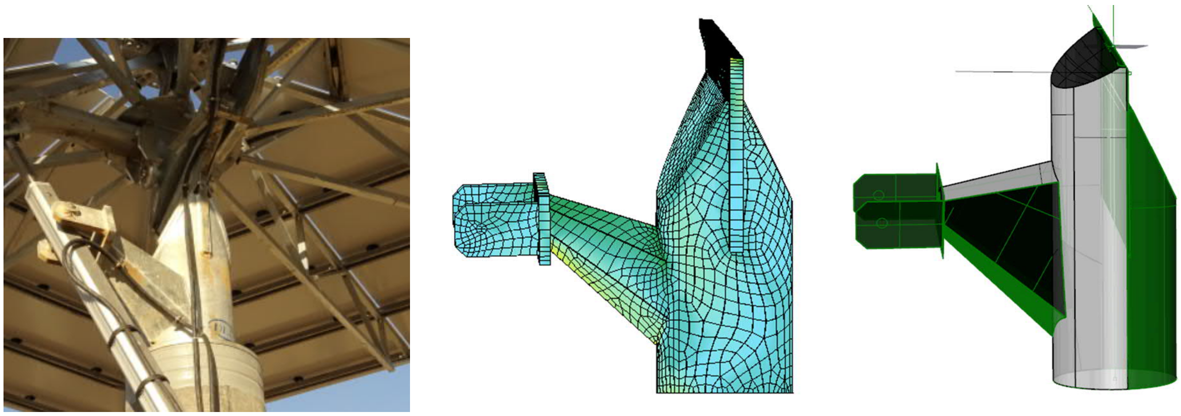

FIGURE 7. Pylon head of standard Stellio (left, middle), reinforced design (right)

Improved Calibration

The classic camera/target based BCS as described above is well proven but has some drawbacks: initial calibration of a large number of heliostats (the Hami solar field comprises 14’500 heliostats) has to be performed repeatedly at different sun positions. This takes much time as it is a sequential procedure, even if multiple beams can be evaluated simultaneously. Heliostats in the outer part of the solar field have low brightness beams, the reduced contrast on the target background increases uncertainty in beam position calculation.

Some innovative calibration methods are being discussed and developed to overcome disadvantages of the classic technique. Some of these advanced methods also promise to improve measurement accuracy. An advanced calibration method using UAVs is also being developed together with CSP Services and other partners in the project HelioPoint [5].

Computing all the above mentioned corrective functions for tracking error is a field of further development and it is expected that accuracy can be further increased.

The potential to increase tracking accuracy by improved calibration and compensation algorithms cannot yet be accurately quantified. It is assumed that related tracking errors can be cut by half.

Combined Tracking Error

Total tracking error is combined from the already mentioned components: structure stiffness, drive backlash, drive stiffness and accuracy of calibration and compensation algorithms. The errors are superimposed by RMS, as they can be considered linearly independent. Only backlash and stiffness related errors are added since they normally act in the same direction and are thus not independent.

Yet, especially for backlash error, RMS calculation of total error is not fully correct: small averaged backlash values almost disappear in RMS computed total and may seem insubstantial. Here it has to be considered how the control tries to compensate backlash. Based on the theoretical actuator normal force for the current heliostat orientation, the point is determined at which the force changes its sign and reverses the play. While this can be done fairly good for dead weight, wind forces result in shifting the point of sign change. Without direct measurement of actuator force or backlash, this means for heliostat angles with low forces that the resulting force sign cannot be predicted and therefore not be compensated reliably. Thus, full backlash offset can worsen tracking accuracy.

Since tracking error components are RMS superimposed, the tracking error from backlash may not be time-averaged before using in RMS calculation. The correct way is to split total error calculation in the two cases of cases of active or non-active backlash. For both, total RMS is determined and in second step, the time-average of the both total values is calculated. The weighting of the two variables is based on the probability of an uncompensated backlash. This results in considerably higher values if backlash error is large – which is the case for the ACME thread/nut.

Starting from the standard Stellio as reference with a combined tracking error of 0.63 mrad (1D standard deviation at low wind speed), combination of the studied improvement measures reduce it to 0.4 mrad. The by far most effective single measure is backlash reduction, see figure below.

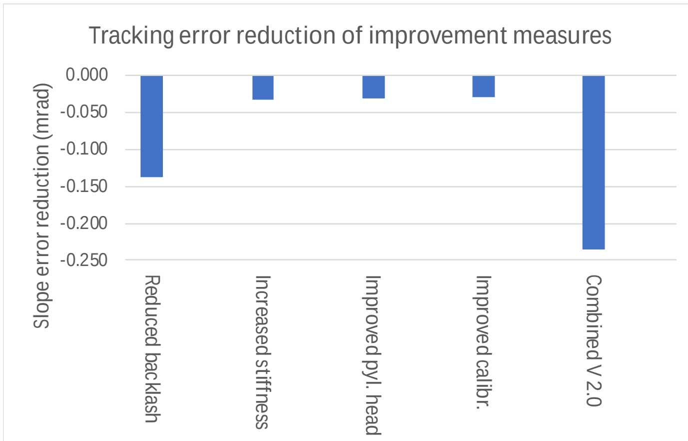

FIGURE 8. Tracking error reduction by different measures and in combination

TECHNO-ECONOMIC ANALYSIS

To evaluate economic viability of described measures, EDF used a relatively simple model for LCoE analysis. CAPEX (total investment cost of the plant) is divided by the discounted production of electricity during the plant's lifetime (Table 3). The result is the LCOE excluding the Operation and Maintenance costs. These have to be added in order to obtain the actual LCOE of the plant. However, it was assumed that the O&M costs do not depend on the design changes for the high performance Stellio, therefore they can be neglected here.

A discount rate of 4 % and a lifespan of 25 years were applied and a 150 MW_{el} peaker plant with next-CSP technology and 5 hours of daily full load was used as a basis.

TABLE 3. Reference plant data for LCoE calculation

Receiver outlet power	343	MW_{th}
Plant net electric power	150	MW_{el}
Daily thermal energy	1.6	GWh_{th}
Daily electric energy	0.75	GWh_{el}
CAPEX	340	M€
LCoE	95	€/MWh_{el}

The changes in CAPEX and net output caused by the improvement measures are small enough, thus a linear approach can be chosen and LCoE effects on CAPEX and output can be calculated separately and summed up then.

The specific LCoE changes for CAPEX and output were calculated by EDF:

+1 M€ in CAPEX results in LCoE change of +0.14 €/MWh

+1 MW_{el} in net output results in LCoE change of -0.628 €/MWh

The major share of the resulting LCoE decrease of 1.35 €/MWh_{el}, corresponding to 1.42 % of the reference LCoE, is from slope error improvements (Table 4). Even if reduced tracking errors increase thermal power output of the receiver more than slope error reduction, the cost penalty of tracking quality measures is considerably higher.

Looking into shares of the tracking quality measures, it can be seen that the ball screw actuators are not worth it due to their high extra cost (Table 5).

TABLE 4. Overall LCoE changes

Improvement measures	**CAPEX increase**	**Performance gain**	**LCoE change**
	(M€)	**(MW_{el})**	**(€/MWh_{el})**
Slope error	1.55	2.16	-0.93
Tracking error	4.16	2.53	-0.43
Combined	5.71	4.69	**-1.35**

TABLE 5. Tracking error LCoE changes

Improvement measures	**CAPEX increase**	**Performance gain**	**LCoE change**
	(M€)	**(MW_{el})**	**(€/MWh_{el})**
Ball screw actuator	4.16	1.82	0.02
Improved pylon head	0	0.54	-0.34
Improved calibration	0	0.52	-0.33
Combined	4.16	2.53	-0.43

CONCLUSION

Most of the investigated measures reduce the LCoE and therefore can be regarded technically and economically worthwhile. In contrary, ball screw actuators provide no benefit with the assumed extra cost. The total reduction in LCoE of approx. 1.5 % is relatively low.

It should be noted that the investigation was on a conceptual level with no or little optimisation, and that simplified calculations were applied. It is expected that a more in-depth study, which would cover more aspects of the design, could lead to higher savings.

ACKNOWLEDGEMENT

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