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More Efficient Heliostat Fields for Solar Tower Plants: The HELIOSUN Project

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Abstract. Heliostats could represent up to 60% of the investment cost for solar tower plants with more than 100 MWe of power, then reducing the cost of heliostats would have an important cost reduction of the plant. The Heliosun project approaches this cost reduction from three different perspectives. Firstly, an artificial vision system with object recognition is proposed, which allows the closed-loop tracking control of the heliostats. This system, consisting on the installation of a low-cost camera and processor in each one of the heliostats, will eliminate the positioning sensors and improve the tracking accuracy of heliostat, improving the concentrated solar radiation distribution on the solar receiver surface. Moreover, a correct measurement of the atmospheric attenuation suffered by the solar radiation concentrated by the heliostats on its way to the solar receiver, with distances greater than 1500m in large plants, will allow firstly, to perform an adequate selection of those sites with the best characteristics for the deployment of solar tower plants and to optimize the routine operation of the solar plant. Finally, a ray-tracing simulation software, based on OTSun, is intended to be developed, including a more accurate prediction of the behaviour of a solar tower plant with central receiver considering spectral analysis, as well as including all the experimental results presented above. These three approaches will allow to improve the operation of solar tower plants as a whole, optimizing the operation of the solar receiver and the solar field, increasing the technical and economic efficiency of these systems.

Keywords: SMART HELIOSTAT, SOLAR EXTINCTION, OTSUN, CSP, SOLAR TOWER PLANTS

1. Introduction

The HELIOSUN project (2023-2025), funded by the Spanish Ministerio de Ciencia e Innovación, is an ambitious and comprehensive initiative aimed at improving the efficiency and reducing the costs associated with central receiver tower technology in concentrating solar power (CSP) plants. Let's break down the key components and goals of the project:

- *Artificial Vision System for Heliostat Tracking:*

The project proposes the use of an artificial vision system with object recognition based on neural networks. This system will be implemented in each heliostat in the solar field. The artificial vision system aims to enable closed-loop tracking control of the heliostats, eliminating the need for positioning sensors. This can result in improved tracking accuracy of heliostats, leading to better concentration of solar radiation on the receiver surface. The installation of a low-cost camera and processor in each heliostat is part of the approach to reduce costs associated with heliostat control systems.

- *Measurement and simulation of atmospheric attenuation of solar radiation:*

The project aims to develop a method for accurately measuring atmospheric attenuation of solar radiation over the long distances (greater than 1500m) between heliostats and receiver. Accurate measurement of atmospheric attenuation is crucial for selecting optimal sites for solar tower plants and for real-time optimization of plant operation. The generation of an extinction type year for the Plataforma Solar de Almería (PSA) and the creation and validation of atmospheric extinction prediction models based on climatic variables are part of this aspect of the project. The project intends to use the generated models and satellite data to create an atmospheric extinction map for Spain. This map could be valuable for CSP promoters interested in developing central receiver tower technology at national level, providing insights into atmospheric conditions that affect the performance of solar plants.

- *Ray-Tracing Simulation Software OTSun:*

The project plans to develop a ray-tracing simulation software based on OTSun. This software is expected to offer a more accurate prediction of the behavior of a solar tower plant, considering spectral analysis. It aims to incorporate experimental results obtained from the project.

In summary, the HELIOSUN project addresses key aspects of solar tower technology, including heliostat tracking, atmospheric attenuation measurement and modeling, and ray-tracing simulation. The integration of artificial intelligence, data analysis, and simulation tools is a comprehensive approach to enhance the efficiency and reduce costs in concentrating solar power plants. If successful, the outcomes of this project could contribute significantly to the advancement of CSP technology in Spain and beyond.

2. HELIOSUN Objectives

The main goal of this project is to reduce costs and improve the efficiency of heliostat fields in solar tower thermal plants [1, 2] through the following specific objectives:

• The development and testing at heliostat solar field scale of a Smart Heliostat tracker (HEL-IoT). It is a low-cost low-powered closed-loop tracker based on machine learning. Its main components are an embedded computer, a wide-angle camera and a portable solar battery to power HEL-IoT low energy requirements. The camera live video stream can be analysed to detect objects of interest (Sun and receiver). With this information, heliostats can be automatically controlled. This approach does not require calibration and eliminates requirements during installation, with the consequent very significant cost reduction. Furthermore, HEL-IoT can provide new information that makes it possible to develop advanced control strategies that improve efficiency with the consequent reduction in costs.

For example clouds detection provides information to make short-term forecast about the near future collected solar radiation and the overall plant production. This information enables to optimally control the STPCR plant. Other inputs will be analized, for example blocks and shadows caused by nearby helisotat, soiling and the atmospheric extinction of solar radiation measured by Hel-IoT.

- The problem of the atmospheric extinction of solar radiation represents a challenge for the design of the future solar tower plants. Knowing the energy losses that these plants will have during the years of operation and amortization represents a crucial issue for their correct design. The answer to this question will undoubtedly be welcomed by the promoters and designers of the future plants. The sites for solar tower plants are usually arid areas with high atmospheric turbidity. If we add that the distances between heliostats and the receiver reach 1km, it is concluded that the development of a measurement system and procedure for knowing the extinction in the site of a future solar plant is fundamental by both the correct sizing of the heliostat field and the optimization of the future operation of the plant, increasing annual electricity generation and, consequently, revenues.

- Generalize the use of OTSun simulation software for solar tower plants, taking advantage of the wavelenght dependence of its results, and optomechanics features of the heliostat field. Knowing the optical behavior of the plant is crucial for maximizing its efficiency. However, to the best knowledge of the project research team, there are no known studies that provide an understanding of the optical performance of central tower plants as a function of wavelength. This fact, which has not yet been discussed, may reveal factors for improving the optical efficiency of the plant, either due to the materials that make up the plant or to the atmospheric attenuation of the environment. Other relevant aspects consist of improving efficiency using simulation tools that consider optomechanical aspects, such as heliostat tracking errors using non-standard functions based on a simple Gaussian distribution, which has already been shown to be far from reality in other systems such as one- axis tracking systems.

These main general objectives will be splitted in three diferent activities for the correct development of the project.

2.1 Development of the Smart Heliostat Tracking System

A closed-loop heliostat tracker based on machine learning with the industrial-standard aiming accuracy of 1 mrad will be completely developed [3]. Deep learning will be applied to train a Convolutional Neural Network (CNN) for object detection. Images from the PSA CESA-I facility will be stored in three datasets for training, testing and validating the CNN. They will be processed to make the CNN more robust (add noise, mimic dust in the camera, etc.). State-of-the-art neural networks will be studied, evaluated and tested in the CESA-I facility.

Smart Trackers will be installed in a representative set of heliostats of the solar field (which is composed by 300 heliostats) and will detect four kinds of objects: receiver, Sun, clouds and heliostats. It will receive supervision commands from the central control system and will send data about detected objects (clouds and surrounding heliostats). The system will also control the heliostat’s actuators to set the heliostat on focus. The precise aiming point on the receiver will be given by the central control system, since a uniform temperature distribution must be maintained to assure correct performance of the receiver and reduce its thermal stress. When then Sun is hidden from the heliostat point of view, trackers will work in open-loop mode. The system will estimate a Sun movement model from local time, a SPA and previous video frames (when the Sun was still detected). When the Sun is detected again, it will switch to closed-loop mode. This transition will be controlled by the central control system to manage the receiver temperature increase. Adding inputs for Activity 2 as direct normal irradiance (DNI) and atmospheric extinction, will allow to strengthen the CNN and to robust the close-control loop.

Task 1.1. Deep learning for Smart Heliostats. The goal of this task is to collect data (images from the CESA-I facility) for three datasets: training, test and validation sets. Images should be taken considering all possible scenarios. They will be processed to make the artificial neural network more robust (add noise, mimic dust in the camera, etc.).

Task 1.2. Tuning, training and evaluation. This subtask involves studying state-of-the-art neural networks for object detection and image segmentation. Neural networks must be tuned to detect objects at STPCR plants. Selected neural networks will be trained with CESA-I images and evaluated with the test and validation datasets. The trainings will be performed in a cloud computing platform. After this subtask, a neural network for object detection at the CESA-I facility will be available and details about why this neural network was selected and guidelines to train it in any STPCR plant.

Task 1.3. Embedded software. Smart tracker software will be developed in this task. The functionality includes: recording videos, taking pictures, processing frames, inferring results from neural networks, controlling the heliostat's actuators, receive commands and send data to the central control system.

Task 1.4. Smart trackers testing & validation. Selected neural networks will be tested in the CESA-I field in this task. It may require iteration over Task 1.2 to tune neural networks for proper detection, task 1.1 to gather data to better tune neural networks and task 1.3 to add features to the software or fix bugs. Once a neural network is selected in task 1.2 and the software is ready in Task 1.3, additional tests will be performed to provide metrics of the final solution (error, response time, etc.).

Figure 1. Smart solar tracker prototype and selected installation in the CESA-I heliostat field (PSA).

Task 1.5. Analyze new inputs to make control more efficient. In this task, some possible sources of additional information and the way to take advantage of them to improve the control of helisotat and STPCR will be analyzed. Cloud detection provides valuable information to be able to make short-term predictions about the availability of the solar resource. Block and shadows caused by nearby helisotat also provides information about the amount of energy lost at a particular time. Soiling in the apperture surface of the camera could be computed and extrapolate to the heliostat soiling, with this information it can be kwon the amount of energy lost by soiling and optimize the heliostat field cleaning tasks.

2.2 Solar Extinction Type Year Determination

A reliable system for measuring atmospheric extinction of solar radiation has been recently developed at PSA by CIEMAT researchers of the proposal [4]. This system is based on two high-performance digital cameras, located at a distance of 741.63m from each other and a Lambertian target at a distance of 82.88m and 824.51m respectively. This system measures solar extinction with an absolute uncertainty of ± 2%. This system has been developed by members of the research team of this project proposal and, although it is available, it still needs some improvements for its correct operation during the project. The acquisition of new high-performance digital cameras with high resolution and internal Peltier cooling will allow extinction measurements with less uncertainty. In fact, these tasks to improve the extinction measurement system represent one of the specific objectives, which is essential to obtain the general objectives of the project.

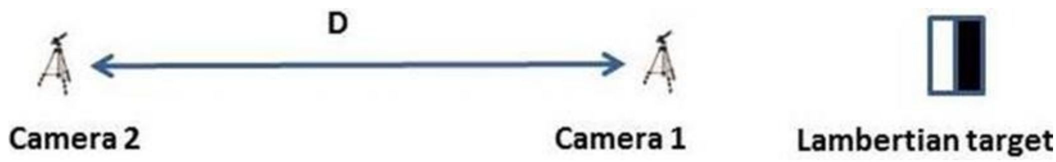

Figure 2. Layout of solar extinction measurement system.

Sandia methodology is used to produce Typical Meteorological Years (TMY). This methodology will be used to create a PSA solar extinction type year. The statistical analysis to configure the long-term or typical year or type year consists of the concatenation of 12 different months selected from the sample according to the values of the Finkelstein-Schafer statistic. Although this methodology recommends about 30 years of meteorological data and a statistical treatment of them to generate a TMY, some studies in the literature affirm that just only 5 years of meteorological data are sufficiently representative for any emplacement. In this way the statistical study of at least five years of solar extinction measures will allow to know the daily, seasonal and annual variability of this variable. The preparation of a solar extinction type year will provide information on the prediction of long- term losses in tower plants in an environment such as the one selected.

Based on this PSA solar extinction type year, the validation of models for calculating solar extinction at PSA will be carried out reliably, which will allow the application of these models worlwide. These models are based on the Radiative Transfer Code (RTC) LibRadTran and the local atmospheric parameter AOD (Atmospheric Optical Depth) is used as input.

A selection of sites in Spain will be made and AOD databases for them from AERONET stations and failing that from a satellite will be obtained. With all this information, the solar extinction maps of Spain will be generated by calculating with the models the solar extinction values at the previously selected sites. These maps could be based on the extinction coefficient or the percentage extinction for 1km slant range.

2.3 Development of Specific Simulation Tools for Smart Heliostat Fields into OTSun Software

To incorporate the results from activities 2.1 and 2.2 on the current OTSun software [5], the environment needs some improvements that are collected in the following tasks.

Task 3.1. Development of OTSun on a grid computing technology.

Ray-tracing simulations are time-consuming and computationally demanding. To provide an effective simulation tool for tower plants with a large number of tracking objects, a distributed grid computing architecture will be developed to run large simulations in OTSun. The architecture to be developed should allow moving, with the minimum of effort, to a cloud computing architecture in case of need. For this purpose, first of all, a state of the art of grid computing technologies will be elaborated, as well as the annexed modules for the correct operation. Once the best technology for the desired application has been identified, the

OTSun functionalities will be migrated and the distributed computing engine will be developed.

Contingency plan Task 3.1: developing the architecture for distributed computing at the beginning of the project is of paramount necessity for later stages of the project. However, it will be of utmost importance to implement control tests that will serve to check its correct functioning as functionalities are extended and resource-intensive simulations are run. It will also be necessary to expand the test controls as the project progresses.

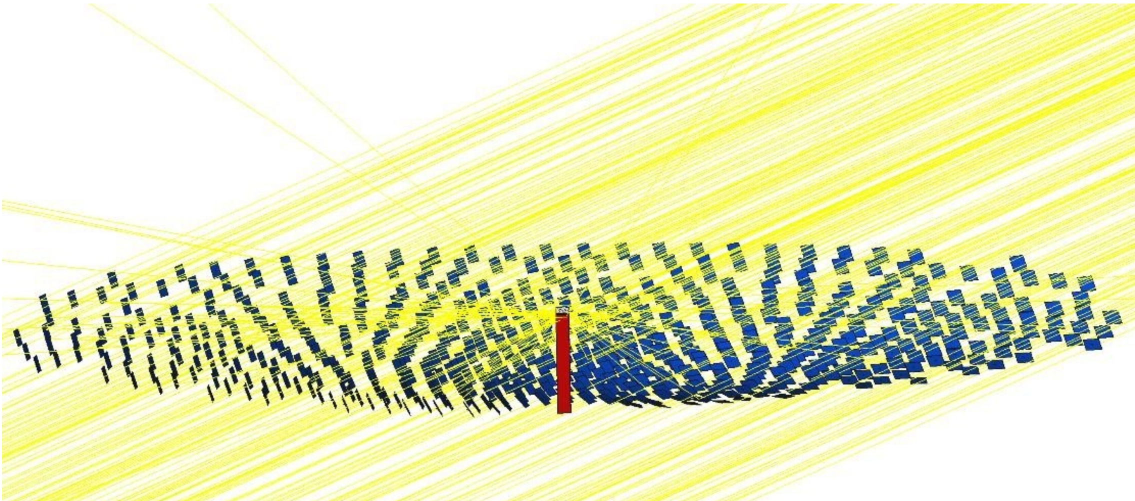

Figure 3. Solar tower power plant based on the PS10 power plant simulated with OTSun.

Task 3.2. Improvement of the current OTSun-CAD interaction for solar tower plants.

The OTSun calculation engine uses FreeCAD files to generate geometries. Although any mechanical design can be indeed generated with FreeCAD, it is of utmost importance to facilitate the creation of geometries to accelerate the use of the computational tool and thus achieve a greater scientific-technical impact in its use. A state of the art of solar tower plants technologies according to different existing typologies will be elaborated. The aim is to have a high diversity of pre-designed blocks that can be used for the design of the plant, updated for different applications and with different optical concentration systems. Subsequently, it will be determined how to reproduce these blocks, with their design parameters, through the use of the FreeCAD API, giving rise to a new Python library for the production of FreeCAD files with the geometric information and the optical labeling of the system. With all this, each of the pre-established geometries will be validated through the inspection of the CAD file itself and the expected optical result.

Contingency plan Task 3.2: some of the mathematical functions required for the geometric generation of a heliostat field may not be implemented in the FreeCAD API. In this case, neutral formats that allow the exchange of information between CAD systems, such as IGES and STL, will be used. If this happens, a substantial delay in the time required is not foreseen.

Task 3.3. Optical characterization of solar energy materials of solar tower plants.

This subtask proposes to characterize optical materials that are commonly used in central tower plants, both reflective and absorber materials. In this phase, it will be necessary to acquire optical materials for characterization in the laboratory. The aim is to obtain experimental measurements of the materials in order to be able to generate more accurate models of their spectral response. These models will be implemented in the OTSun simulation tool. For this purpose, the CARY 5000 UV-Vis-IR spectrophotometer and accessories available at the University of the Balearic Islands will be used. In this phase, it will be necessary to acquire samples of optical materials, calibrated materials, and small materials for the in-house manufacture of masks and clamps. Once the new optical materials have been implemented in OTSun, we will dispose of a ray-tracing tool that allows us to parameterize both geometrically and optically the heliostat field, leading to optimal results by means of spectral analysis.

Task. 3.4. Implementation of results from activities 1 and 2 in the new OTSun tool.

From Task 1, the tracking error of the heliostats will be determined using the newly implemented algorithm. Knowing the error probability distribution will be crucial to be able to model the plant under real operating conditions. The model of the error distribution will be implemented in the OTSun tool to be able to quantify the optical solar tracking losses of the heliostat field. On the other hand, the image of the mirrors at the focus will be determined in order to refine the smart solar tracking system according to the radiation distribution at the receiver. This will be done by means of spectral analysis in order to elucidate the importance of wavelength dependence in such systems. On the other hand, for atmospheric attenuation, the model obtained from Task 2 will be implemented in OTSun.This will allow us to know the real impact of attenuation on the concentration of radiation at the receiver, in order to detect the estimated power and thus be able to intervene in the management of the plant by being able to predict the thermal power as a function of atmospheric attenuation.

Contingency plan Tasks 3.3 and 3.4: It will be crucial to have all the information underlying the geometry and materials that form the solar concentrating systems. On occasions, however, this is not simple, as the manufacturers do not provide the necessary information on the material configuration of the systems. To mitigate this difficulty, experimental measurements of the materials that form the system will be carried out by means of spectrophotometry. These materials will be requested/acquired from the manufacturers themselves. Additionally, in-situ measurements will be carried out with a portable spectrometer (STN-BW-UVNB-Compact Spectrometer). Regarding geometrical specifications, ideal designs will be considered but modeled by means of positioning and/or tracking errors in the simulations.

3. Conclusions and Outlook

The HELIOSUN project's multi-faceted strategy not only addresses the cost concerns associated with heliostats but also seeks to advance the overall performance and feasibility of solar tower plants. If successful, these advancements could have a positive impact on the adoption and competitiveness of concentrating solar power technology.

Given that heliostats can constitute a substantial portion of the investment cost of a large solar tower plant (up to 60%), the three-pronged approach is expected to result in significant cost reductions for these plants. Improved heliostat tracking, solar atmospheric attenuation measurement and modeling, and simulation software collectively enhance the operation of solar tower plants. The optimization of both the solar receiver and the solar field contributes to increased technical and economic efficiency of the entire system.

Data availability statement

Images collected for the Heliot system and used for training the models are stored in the Heliot Web Server and will be available for the community on request.

Author contributions

J. Ballestrín: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – original draft; **L. Valenzuela:**

Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – original draft; **J. Fernández-Reche**: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – original draft; **R. Pujol**: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – original draft; **G. Cardona:** Investigation, system implementation, Resources, Draft review & editing; **J.A. Carballo**: Investigation, system implementation, Resources, Draft review & editing; **J. Bonilla**: Investigation, Resources, Draft review & editing; **N. Estremera**: Investigation, Resources, Draft review & editing; **E. Carra**: Investigation, Resources, Draft review & editing; **N. Simal**: Investigation, Resources, Draft review & editing; **R. Monterreal**: Investigation, Resources, Draft review & editing; **A. Marzo**: Investigation, Resources, Draft review & editing.

Competing interests

The authors declare that they have no competing interests.

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