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MEMORIA CIENTÍFICO-TÉCNICA DE PROYECTOS INDIVIDUALES
Convocatoria 2021 - «Proyectos de Generación de Conocimiento»

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IMPORTANT – The research proposal cannot exceed 20 pages. Instructions to fill this document are available in the website. If the project cost is equal or greater than 100.000 €, this document must be filled in English.

1. DATOS DE LA PROPUESTA – *PROPOSAL DATA*

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TÍTULO DEL PROYECTO (ACRÓNIMO): Campos de Heliostatos mas Eficientes para Plantas Solares de Torre (HELIOSUN)

TITLE OF THE PROJECT (ACRONYM): More efficient Heliostat Fields for Solar Tower Plants (HELIOSUN)

2. ANTECEDENTES, ESTADO ACTUAL Y JUSTIFICACIÓN DE LA PROPUESTA - *BACKGROUND, CURRENT STATUS AND JUSTIFICATION OF THE PROPOSAL*

2.1 Background

Environmental issues and concerns about sustainability are constantly encouraging research and investment in renewable energy technologies. They are, by definition, the only way we can keep producing energy for a virtually infinite period of time. Solar energy is appealing due to its high potential; it is the most abundant energy source on Earth. As the International Energy Agency states[1], the development of affordable solar energy technologies will have huge longer-terms benefits in the enhancing of environment sustainability (clean energy which reduces pollution and mitigates climate change), social sustainability (indigenous import-independent resource) and economic sustainability (keeping fossil fuel prices lower than otherwise).

Affordable solar energy technologies would highly contribute to mitigating the climate change and achieve energy targets of the Europe 2020, 2030 and 2050 strategies, where the major issues to address are: reduction of the greenhouse gas emissions, improving the energy efficiency and increasing the energy coming from renewables. The two major solar energy technologies are solar photovoltaic (PV) and solar thermal. The most efficient way of storing heat in solar thermal energy makes it more appropriate for large-scale energy production. Optical concentration is used to achieve maximum conversion at little heat loss by reflecting and concentrating the solar flux onto a reduced-area receiver; this technology is known as Concentrating Solar Power (CSP).

The European Union (EU) adopted the agreement that 20% of its final energy consumption (FEC) be supplied by renewable sources by 2020, together with the commitment to reduce by 20% the greenhouse gas emmissions (GHG), in comparison with the values of 1990 (European Directives 2009/28/EC y 2009/29/EC). Afterwards, the Paris Agreement (2015)

[1] International Energy Agency, Market report series: Renewables 2020. Analysis and forecasts to 2025. https://www.iea.org/renewables2020/

was a breakthrough as it was the first global, legally binding agreement on climate change. The EU ratified it in 2016 and presented a package of measures (revised in 2018) that aims to achieve by 2030: a) at least a 32% share of renewable energy in the EU FEC; b) at least a 40% reduction in GHGs compared to 1990; and c) at least a 32.5% improvement in energy efficiency. Renewable energies therefore play a critical role in this energy transition. To ensure compliance with the Paris Agreement, the EU has required each Member State to draw up an integrated National Energy and Climate Plan (NECPs) 2021-2030. The Spanish NECP published in 2020[2] includes a set of measures, thanks to which renewable energies are expected to account for 42% of the country's FEC in 2030. This requires the promotion of several measures, as example it has just been known that the third auction planned by the Ministerio para la Transición Ecológica y Reto Demográfico during 2021 will include the tendering of 200MWe of new solar thermal power plants that will increase in the short term the installed power capacity of this renewable energy technology in the country from 2.3GWe[3] to 2.5GWe.

Among the different renewable energy sources (RES) available for power generation the role of **solar thermal power plants**, **including** those of **tower or central receiver**, **have demonstrated its** feasibility and **reliability to dispatch electricity during night or when the primary RES** (i.e. solar energy) **is not available**. The worlwide development of commercial solar power plants projects has increased significantly since 2009[4] and **Spain is at the forefront of the development of these technologies**.

A simplified scheme of a concentrating solar tower power plant with central receiver (STPCR) (see Figure 1) would be formed by a field of heliostats, a solar receiver and a thermal machine (i.e. steam turbine or gas turbine). These kind of power plants use concentrated solar radiation to heat a fluid at a temperature sufficient to operate a thermodynamic cycle in which at the end steam is generated, directly or through a heat exchanger, under conditions suitable to move a steam turbine, which is the tipical turbomachinery used in commercial solar power plants up to now. The efficiency in a plant of these characteristics will depend on the temperature of the receiver and on the concentration ratio. For each concentration there will be an optimum working temperature of the solar receiver and at the same time this optimum temperature will increase with the concentration of solar radiation achieved by the optical system (a heliostats field) onto the receiver surface. Thus, there is a clear and direct relationship between the concentration achieved and the theoretical efficiency of the system.

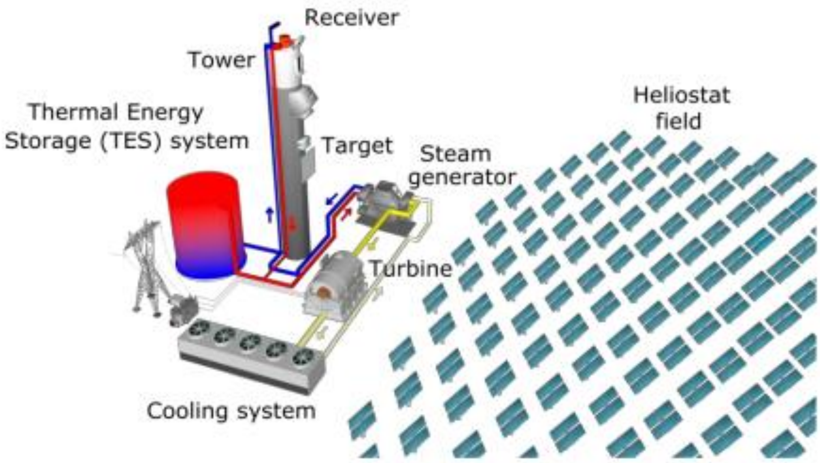

Figure 1 . Schematic of a central receiver solar tower power plant.

[2] Ministerio para la Transición Ecológica y el Reto Demográfico. Plan Nacional Integrado de Energía y Clima (PNIEC2021-2030, January, 2020.
[3] PROTERMOSOLAR, Asociación Española para la Promoción de la Industria Termosolar, https://www.protermosolar.com/la-energia-termosolar/el-sector-en-cifras/. (Accessed 05/12/2021)
[4] SolarPACES (IEA Programme Agreement). CSP Projects Around the World, https://www.solarpaces.org/csp-technologies/csp-projects-around-the-world/ (Accessed 05/12/2021)

The Plataforma Solar de Almería (PSA) is a Singular Technical Scientific Installation (ICTS, Instalación Científico Técnica Singular) of the Spanish system of Science and Innovation[5]. In PSA facilities different prototypes of solar receiver systems have been evaluated during the last thirty years[6,7]. Currently there are two experimental tower plants of these characteristics where different types of receivers have been evaluated: CESA-1 system and SSPS-CRS system, of 7 and 2.7MWt respectively. These **solar tower plants at PSA** have **allowed the execution of** several **projects for development and improvement of** components and procedures for **this concentrating solar thermal technology**, **contributing** significantly **to the commercial deployment** of the technology in the last decade.

In addition to the existing commercial Solar Tower Plants of Central Receiver currently in operation (for example, PS10 (11MWe), PS20 (20MWe) and Gemasolar (19.9MWe) in Spain, Ivanpah (392MWe) in EEUU, Noor III (110MWe) in Morocco, Khi Solar One (50MWe) in SouthAfrica,…)[8] there is **a growing interest in the development of higher capacity power plants** in the Solar Belt[9]. These new designs **involve large surfaces of the heliostat field**, **and** also **larger distances between the furthest heliostats and the receiver**.

The largest heliostat field up to date is at Ivanpah solar plant (Mojave Desert, USA), with 173,500 heliostats, three towers and a gross capacity of 392MWe. The heliostat field is estimated to be responsible from 30% up to 60% of the total plant cost[10]. Thus, **heliostat cost reduction** and its deployment on the solar field, as well as the **increasing of optical efficiency via the correct measurement of heliostat field optical performance can** dramatically **reduce the overall cost of a solar tower plant**. Some of the areas with improving heliostats cost reduction potential are the following:

- Industrial heliostats operate following open-loop tracking strategies with error models. This requires intensive-labour installation procedures and expensive hardware to reliably follow the control signals, as there is no feedback for error correction. **Closed-loop tracking strategies**, considering feedback, **could keep the same accuracy using less expensive hardware**. Other benefits of close-loop tracking are related to tracking drifts that can occur with the use of angular position encoders or possible ageing or deformation of the supporting structure of the heliostats.
- The reflected solar radiation missed in the receiver, known as spillage, highly influences the global solar plant performance. **More accurate tracking methods**, reducing or removing the calibration time **would decrease the spillage** and thus increase the plant performance.
- **Advanced aiming strategies**, which maintain a uniform temperature distribution in the receiver, **could reduce the receiver thermal stress and prolong its lifetime**.

On the same way, the **atmospheric extinction of solar radiation represents a source of energy losses in central receiver solar thermal power plants**. For the correct design of these power plants it is important to have prior knowledge of the solar radiation extinction in an eligible site. The **atmospheric extinction of the solar radiation is** of a markedly **local**

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[5] Ministerio de Ciencia e Innovación, 2021. Infraestructuras Científicas y Técnicas Singulares (ICTS). https://bit.ly/3lIa2GO (Accessed 05/12/2021)
[6] Téllez, F. M., Hoffschmidt, B., Valverde, A., Fernández-Reche, J., Romero, M., Monterreal, R., Ballestrín, J. Performance Evaluation of the 200 kWth 'HitRec II' Volumetric Receiver. XI SolarPACES International Symposium on Concentrated Solar Power and Chemical Energy Technologies. Zurich, Switzerland (September 4-6, 2002).
[7] Plataforma Solar de Almería-Annual Technical Report 2014-17. http://www.psa.es/en/techrep/index.php
[8] https://solarpaces.nrel.gov/by-technology/power-tower
[9] Romero, M., González-Aguilar, J. Chapter 3: Solar Thermal Power Plants: From Endagered Species to Bulk Power Production in Sun Belt Regions. In "Energy and power generation handbook: established and emerging technologies". 2013.
[10] G.J. Kolb, S.A. Jones, M.W. Donnelly, D. Gorman, R. Thomas, R. Davenport, R. Lumia. Heliostat cost reduction study, 2007. https://doi.org/10.2172/912923

character **and varies seasonally and daily in response to meteorological parameters**, mainly the humidity and the concentration of aerosols (any solid or liquid particle suspended in the air) in the lower layer of the atmosphere.

The greatest challenge posed by large solar installations is their integration into the power distribution networks, which, for STPCR, is conditioned by adequate knowledge of the fluctuations in direct solar radiation reaching the receiver, due to their dependence on patterns non-deterministic.

The **large sizes of the heliostat fields and the large heliostat-tower distances bring** with them **the need for** a better **knowledge of the real efficiency** of the furthest heliostats **in episodes of high atmospheric turbidity**. In the case of the evaluation of the solar radiation reflected from the heliostat to the receiver, it is a problem that, until a few years ago, with the growing expansion and success of the STPCR, has begun to arise. The vast majority of STPCR plants are found in areas with high probability of occurrence of episodes of high concentrations of aerosols or dust intrusions. That is why it is necessary to include the extinction factor for a correct evaluation of the values of concentrated direct solar radiation on the receiver.

2.2 Current Status

Tracking methods can be classified attending to different criteria: number of rotation axes, active or passive tracking and, open-loop or closed-loop tracking. Linear concentrating systems (parabolic troughs and linear Fresnel systems) use trackers with one rotation axis, whereas point-focus systems (parabolic dishes and STPCR systems) employ trackers with two rotation axes. An open-loop tracker uses only its current state and an algorithm to determine its control actions, without feedback. Therefore, it cannot determine if the actions taken have achieved the desired result. On the other hand, a closed-loop tracker uses feedback to mitigate errors and disturbances.

Passive trackers are only mechanical. This category includes clockwork trackers (open-loop) and trackers that take advantage of thermal expansion (closed-loop). Active heliostat trackers make use of sensors and/or actuators and include electro-optical sensor trackers (closed-loop) and trackers based on Solar Position Algorithms (SPAs) (open-loop).

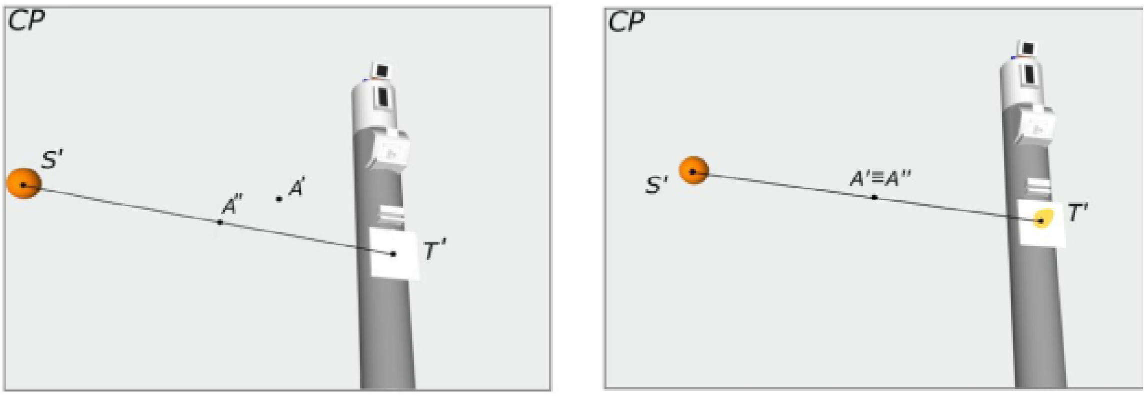
Active open-loop trackers rely on SPAs to estimate the position of the Sun and demand a strict heliostat installation procedure to ensure proper alignment. It is labour intensive and it is difficult to guarantee the desired accuracy. During operation, it is also required to estimate an error model per heliostat to minimize geometry misalignments. Geometry misalignments are constant aberrations such as pedestal tilt errors and bad references from sensors. Error models need to be periodically calibrated because heliostats can become slightly misaligned due to meteorological conditions and other disturbances, and they need to remain accurate at the milliradian level. The maximum desirable tracking error depends on the distance from the receiver to the farthest heliostat and on the receiver area. A 1mrad tracking error is only 10cm off-target at 100m, but it is 1m off-target at 1km.

Closed-loop methods use feedback to compensate error and disturbances, which is a clear advantage with respect to open-loop methods. However, current closed-loop solutions have been labelled as impractical, too complex or too expensive by the industry.

Commonly, the error model is determined by individually aiming each heliostat to concentrate the solar radiation onto a white Lambertian target, which is placed in the tower. Then, manual or automatic techniques are used to calibrate each heliostat. The calibration involves canonical and daily tracking movements and offsets. This calibration method is problematic at large distances since the reflected image could be bigger than the target or have a low power density. It is an expensive and time-consuming process since it has to be performed for each heliostat. This process can take several weeks or months in extensive heliostat fields.

The concept of Smart Heliostat Tracker proposed in this project is an active closed-loop tracker based on machine learning. The main hardware elements are a low-cost low-power consumption embedded computer plus a wide-angle camera. Software includes a neural network able to detect the Sun and the receiver. The general idea is to calculate the heliostat aiming position from detections of the Sun and receiver in the camera video frames.

The procedure to correctly focus a heliostat considering this proposal is defined in the next paragraph. It is assumed that the needed vision system is attached to the heliostat surface mirror's center point and moves with it; other positions are also possible. This example considers the target as the element where the concentrated flux is reflected; the same applies for the receiver.
The camera provides a plane view (CP, see Figure 2) of the scene. The neural network detects the Sun's (S') and target's (T') center points. The middle point (A") between S' and T' is the desired heliostat aiming point. The current heliostat aiming point (A') is the center point in the plane view (CP). The heliostat is then moved to place the current aiming point (A') at the desired aiming point (A"). Figure2a shows a camera view for an out-of-focus heliostat, whereas Figure 2b shows the same view for a focused heliostat.



a) b)

Figure 2. Smart heliostat tracking principle.

Preliminary feasibility results of artificial vision proposal for heliostat tracking have been published by members of the research team in Renewable Energy[11]. In this work, a Convolutional Neural Network (CNN) called AlexNet[12] was tuned and trained to detect the Sun, target, heliostats and clouds with a small subset of 300 images taken in the CESA-I STPCR facility, located at Plataforma Solar de Almería (PSA). The prototype HEL-IoT (heliostat with smart tracker, see Figure 3, left) was composed by a reduced board computer, a camera with a wide-angle lens, a small portable solar battery, the CNN trained and one of the farthest and scored heliostats in the CESA-I heliostat field (see Figure 3, right). The tested heliostat was controlled by the open-loop controller of the CESA-I facility, the system was only recording data. The Sun and target were properly identified during the whole experiment even though a low number of training images was used. The aiming difference

[11] J.A. Carballo, J. Bonilla, M. Berenguel, J. Fernández-Reche, G. García, New approach for solar tracking systems based on computer vision, low cost hardware and deep learning, Renew. Energy 133 (2019) 1158-1166. https://doi.org/10.1016/j.renene.2018.08.101
[12] A. Krizhevsky, I. Sutskever, G.E. Hinton, ImageNet classification with deep convolutional neural networks, in: F. Pereira, C.J.C. Burges, L. Bottou, K.Q. Weinberger (Eds.), Adv. Neural Inf. Process. Syst. 25, Curran Associates, Inc., 2012: pp. 1097–1105.

between the open-loop tracker and the so-called HEL-IoT concept was lower than 3mrad, which is a good starting point considering that the precision of the current open-loop tracker at CESA-I facility is 1.2mrad and smart tracker HEL-IoT was limited to a resolution of 2mrad, given that the camera was set to a low resolution mode (800x600 pixels) and the angle of view was 150º. Heliostats and clouds were identified in some cases, but the neural network needs to be improved since these classes of objects are subjected to more colour, shape and form changes.

Figure 3. Smart Solar tracker prototype and selected installation in the CESA-I heliostat field (PSA).

Concerning atmospheric attenuation measurement, under the project "Medida y modelización de la atenuación atmosférica en centrales termosolares de torre con aplicabilidad en la operación de la planta (ENE2014-59454-C3-3-R)", **a solar extinction measurement system has recently been developed at PSA and it is currently running daily**. The research and work teams of this application developed and implemented the aforementioned measurement system[13]. The aim of this measurement system is taking simultaneous images of the same target at very different distances using two identical optical systems with digital cameras (CMOS), suitable lenses and ND filters (Figure 4).

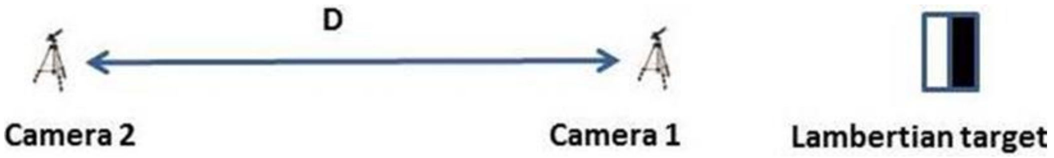


Figure 4. Layout of solar extinction measurement system.

In this procedure, it is necessary to work with diffuse solar radiation reflected by the target in order to avoid direct solar radiation and thus, minimize specular influences and directionality. For this reason, the target and the two cameras were placed in a north-south line; the target was situated south looking north, to avoid the direct solar radiation and the cameras were located north pointing towards the target. The intensity levels of the digital images are proportional to the diffuse solar radiance coming from the target and the difference of intensity between the images is due to the extinction of the solar radiation in the path between both cameras. Having Lambertian targets is important for this measurement system since the position of the cameras and the angles relative to the target can never be known for sure at such large distances. With a perfect diffuser surface, an image of the target taken from any viewing angle will accurately represent the same brightness or luminance. For this setup a target of appreciable dimensions (2m x 2m) was needed and its specific manufacturing was necessary. The target is supported on two pillars, approximately one meter above the ground. It has two side doors that remained closed when it is not used in order to protect it from rain, dust, etc. Two standard steel plates of 2m x 1m were used for their construction (Figure 5).

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[13] Ballestrín, J., Monterreal, R., Carra, E., Fernández-Reche, J. et al. "Solar extinction measurement system based on digital cameras. Application to solar tower plants". Renew. Energy 125 (2018) 648-654. ISSN: 0960-1481. https://doi.org/10.1016/j.renene.2018.03.004

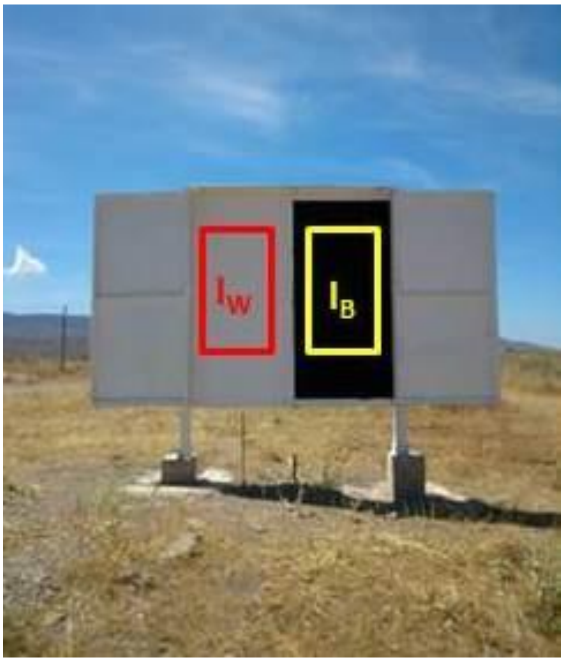

Figure 5. White and black Lambertian target for extinction measurement. Black (IB) and white (IW) zones of interest.

Both were sandblasted to achieve diffusivity on their surface. Unfortunately, this treatment was not enough and it was necessary to apply a special coating for this purpose. A number of different paints were tested and it was found that white Amercoat®741 and black Zynolyte® had suitable diffuser properties. For this study, one of the steel plates was painted in high reflectance white and the other was sprayed in black. The white part of the target had a weighted solar reflectance of 76% after being painted. The black part of the target had a weighted solar absorptance of 95% and the image taken from this part is considered as the airlight contribution or light scattered in the air by dust, haze, etc. This light contribution, I_B, is suppressed from the light input of the images taken of the white part of the target I_W (Fig. 5).

The research team of this project proposal has published several articles about the development and application of this solar extinction measurement system[14,15,16].

In terms of simulation tools of optical performance of solar energy systems, through the ENE2015-68339-R project, "Desarrollo de una herramienta computacional de alta resolución para el análisis óptico de captores solares-OTSun**", the OTSun source code was developed in Python programming language**. This made it possible to use libraries that are already freely available, such as FreeCAD package used both for the definition of the optical geometry and for the calculations of ray-scene intersections. Thus, a ray tracing tool was developed where the solar harvesting system is drawn with typical CAD tools using standard files. In OTSun, a consolidated, rigorous and verified optical model was implemented based on the Fresnel equations implemented in their original form without

[14] Ballestrín, J., Monterreal, R., Carra, M. E., Fernández-Reche, J., Barbero, F. J., Marzo, A. “Measurement of solar extinction in tower plants with digital cameras”. American Institute of Physics Conf. Proc. 1734 (2016), 130002-1–130002-8; https://doi.org/10.1063/1.4949212

[15] Ballestrín, J.,Carra, E., Enrique, R., Monterreal, R., Fernández-Reche, J., Polo, J., Casanova, M., Barbero, J., Marzo, A. “Diagnosis of a Lambertian target in solar context”. Measurement 119 (2018) 265–269. ISSN: 0263-2241. https://doi.org/10.1016/j.measurement.2018.01.046

[16] Ballestrín, J., Monterreal, R., Carra, E., Fernández-Reche, J. et al. “Solar extinction measurement system based on digital cameras. Application to solar tower plants”. Renewable Energy 125 (2018) 648-654. ISSN: 0960-1481. https://doi.org/10.1016/j.renene.2018.03.004

additional simplifications. The optical model was complemented with the thin-film Transfer Matrix Method (TMM) in order to consider coating layers. As for the absorption of the light produced in the materials, it considers the Beer-Lambert Law as a function of the optical path traced inside them. The code was hosted in the GitHub repository: https://github.com/bielcardona/OTSun. The developed tool allows to optically analyze both solar thermal and photovoltaics regardless of their geometry, an example can be seen in Figure 6 with the simulation of a STPCR plant based on the PS10 power plant located in Sevilla. All these achievements represent important milestones compared to previously available open-source tools (i.e. Tonatiuh and SolTrace). The OTSun source code has been made available to the scientific-technical community under a permissive free software license, the so-called MIT licence, thus contributing to the development of free software in accordance with the HORIZON 2020 strategy on Open Science. In this way, the code can be inspected, modified, and extended to achieve new capabilities by the scientific community. The scientific description of the tool has been published in the multidisciplinary Plos One journal[17].

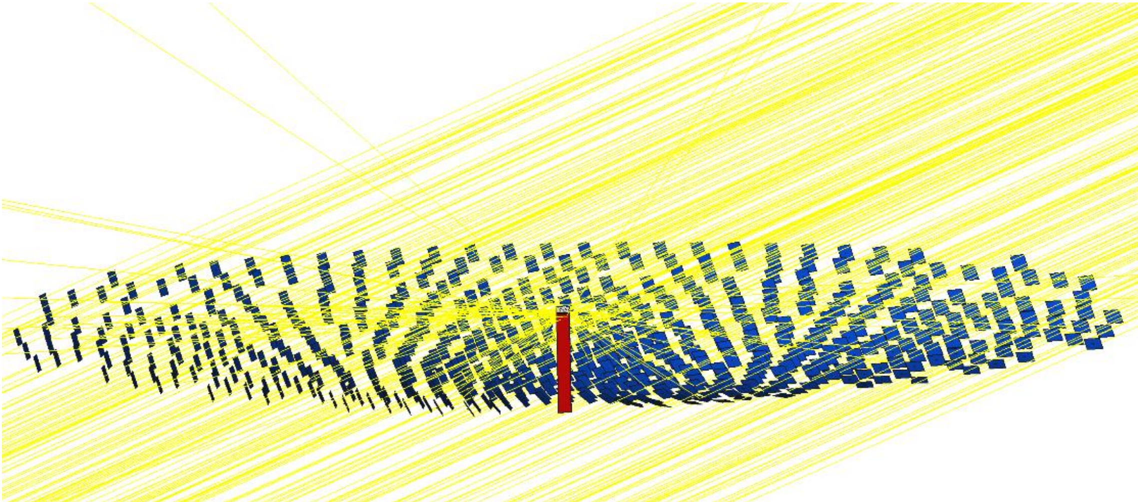

Figure 6. Solar tower power plant based on the PS10 power plant simulated with OTSun.

2.3 Justification

As mentioned, preliminary developments have been carried out to apply artificial vision and machine learning techniques for the control of heliostats in solar tower systems, but these works have been conducted with budget and technical limitations and further investigations have to be done at pilot scale to demonstrate the feasibility, reliability and benefits of this control tracking solution for the future development of heliostat fields. The HELIOSUN project would be the framework to give a step forward on the development of a low-cost smart tracker for heliostats. The same occurs with the application of the solar extinction system developed at PSA, which has demonstrated its reliability but further improvements can be achieved with the incorporation of some innovations on the measurement hardware, that would be investigated during the HELIOSUN project. And finally, the OTSun simulation software to study the optical performance of solar energy systems presents a high potential of application in concentrating solar thermal energy systems that has not been exploited up to now in particular for the study of solar tower plants. The HELIOSUN project will provide the opportunity to bring together in the same framework the individual results of each of the

[17] Cardona, G. and Pujol_Nadal, R. OTSun, a python package for the optical analysis of solar-thermal collectors and photovoltaic cells with arbitrary geometry. PLoS ONE 15(10)(2020), e0240735. https://doi.org/10.1371/journal.pone.0240735

proposed activities in such a way that the feedback between them is effective and mutually beneficial.

3. OBJETIVOS, METODOLOGÍA Y PLAN DE TRABAJO - *OBJECTIVES, METHODOLOGY AND WORK PLAN*

The main goal of this proposal is to **reduce costs and improve the efficiency of heliostat fields in solar tower thermal plants through** the following specific objectives:

- The **development and testing at heliostats' 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. The

- **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[18].

[18] Sallaberry, F., Pujol-Nadal, R., Larcher, M., & Rittmann-Frank, M. H. (2015). Direct tracking error characterization on a single-axis solar tracker. Energy Conversion and Management, 105, 1281-1290. https://doi.org/10.1016/j.enconman.2015.08.081

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

ACTIVITY 1. Development of the Smart Heliostat Tracking System

A closed-loop heliostat tracker based on machine learning with the industrial-standard aiming accuracy of 1mrad will be completely developed. Deep learning will be applied to train a CNN for object detection. Images from the Plataforma Solar de Almería 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.

<u>Task 1.1. Deep learning for Smart Heliostats</u>. The goal of this task is to collect data (images of 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.). A deliverable (D1.1: Guideline to obtain and process data for HEL-IoT development for any STPCR plant) providing guidelines about how to obtain and process data from any STPCR plant will be available at the end of this task.

<u>Task 1.2. Tuning, training and evaluation</u>. 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 will be given in Deliverable 1.2 (Smart Tracker development applied to CESA-I STPCR plant).

<u>Task 1.3. Embedded software</u>. 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.

<u>Task 1.4. Smart trackers testing & validation</u>. 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.). Test field results will be included in Deliverable 1.3 (Report on testing and validation of smart trackers applied to CESA-I STPCR facility).

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 helisotat soiling, with this information it can be kwon the amount of energy lost by soiling and optimize the heliostat field cleaning tasks.

ACTIVITY 2. Solar Extinction type year determination

A reliable system for measuring atmospheric extinction of solar radiation has been recently developed at Plataforma Solar de Almería (PSA) by CIEMAT researchers of the proposal. 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 and 82.88m 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 duration of 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.

Sandia methodology[19] 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[20,21]. 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 at any site. 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.

[19] Hall I, Prairie R, Anderson H, Boes E. Generation of Typical Meteorological Years for 26 SOLMET Stations. SAND78-1601, 1978. Albuquerque, Sandia National Laboratories
[20] Vignola F, McDaniels K. Value of long-term solar radiation data. Proceedings of the solar '93 conference, American solar energy society 1993. Boulder, CO: American Solar Energy Society (ASES).
[21] Festa R, Ratto CF. Proposal of a numerical procedure to select reference years. Solar Energy 1993;50(1):9-17.https://doi.org/10.1016/0038-092X(93)90003-7

Task 2.1. Start-up of the solar radiation atmospheric extinction measurement system at PSA.
After almost three years of operation, this system needs improvements such as:

- Digital camera refurbishment (acquisition)
- Painting and characterization of the Lambertian target
- Improvement in measurement uncertainty
- Spatial calibration of the camera system
- Image acquisition and processing software enhancements

Task 2.2. Daily operation and maintenance of the extinction measurement system, acquisition and filtering of extinction measurements and calculation of uncertainties. Likewise, the most relevant meteorological variables for the phenomenon will be measured simultaneously, such as ambient humidity and the concentration of particles in the atmosphere, in order to analyze the dependence or correlation of these magnitudes on solar extinction.

Task 2.3. Obtaining a solar extinction type year at PSA based on five years of solar extinction measurements. Analyze the variations of this parameter daily, seasonally and annually.

Task 2.4. Validation of models for the calculation of solar extinction using as input the local atmospheric parameter AOD of the same five years of the solar extinction type year. The statistical agreement between the models and the solar extinction measurements of the type year will irrefutably validate the models.

Task 2.5. Selection of sites in Spain and obtaining AOD databases for them from AERONET stations or from satellite. Generation of an extinction map of Spain from the extinction calculation in the selected sites with the validated models.

ACTIVITY 3. Development of specific simulation tools for Smart heliostat fields into OTSun software.

To incorporate the results from activities 1 and 2 on the current OTSun software, 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.

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.

Table 1 shows the Gantt chart of the proposed activities and the personnel dedication to each one.

Table 1. Gantt chart

Activity	Task	Researchers	1st year				2nd year				3rd year			
1. Smart Heliostat Tracking System	1.1 Deep learning for Smart Heliostats	**JF**, JC, LV, JBo, RM							IR					FR
	1.2 Tuning, training and evaluation	**LV**, All							IR					FR
	1.3 Embedded software	**JF**, JC, LV, JBo, RM							IR					FR
	1.4 Smart trackers testing & validation	**JF**, LV, JC, JBo, RM							IR					FR
	1.5 New inputs for Smart Heliostats	**LV**, All							IR					FR
2. Atmospheric Extinction	2.1 Start up of the measurement system	**JBa**, EC, AM, RM							IR					FR
	2.2 Daily operation & Mainteinance	**JBa**, EC, RM							IR					FR
	2.3 Solar extinction type year	**JBa**, All							IR					FR
	2.4 Models validation	**JBa**, All							IR					FR
	2.5 Spain's extinction map	**JBa**, EC, AM							IR					FR
3. Ray-Tracing Modelling and Simulation	3.1 Development of OTSunGrid	**RP**,GC, JC, JF, LV							IR					FR
	3.2 OTSun-CAD interaction	**RP**,GC, JC, LV							IR					FR
	3.3 Optical Charact. of technology materials	**RP**, GC, JF, LV, NE							IR					FR
	3.4 Implementation of act. 1 & 2 Results	**RP**, All							IR					FR

Research Team:	Jesús Ballestrín (JBa), Loreto Valenzuela (LV), Ramón Pujol (RP), Gabriel Cardona (GC) and Jesús Fernández (JF)
Working Team:	Jose Antonio Carballo (JC), Javier Bonilla (JBo), Elena Carra (EC), Aitor Marzo(AM), Rafael Monterreal (RM), Noelia Estremera (NE)
	IR & FR: Intermediate & Final Reporting

4. IMPACTO CIENTÍFICO-TÉCNICO - *SCIENTIFIC-TECHNICAL IMPACT*

Related to Activity 1, it is expected the development of a low-cost low-powered closed-loop solar tracker based on machine learning. Preliminary results established the high possibility of greatly improving current systems. This **smart solar tracker** will reduce the costs of current systems and improve efficiency, and by extension reduce the cost and improve de efficiency in STPCR. This technology **is expected to have a relevant impact in the development of self-calibrating and cheaper heliostats**.

In addition, as Smart tracker system is not limited to detect the Sun and the receiver placed at the top of the solar tower, it can also detect other relevant objects in STPCR plants. Furthermore, **its autonomous design adds** more **capabilities that can be exploited afterwards**:

- The system will contribute to the **development of the Autonomous heliostat**, as it is also compatible with autonomous heliostats[22,23]. Autonomous heliostats remove all the electrical wires and related components. The communication is performed by radio or Wi-Fi. Autonomous heliostats are powered by batteries and PV panels. HEL-IoT contributes to this concept giving more autonomy to the heliostat, since the automatic control system is embedded. Wireless communications are only needed to receive supervision and to send local data.
- Internet of Things (IoT). Smart tracker **can include IoT capabilities**, since collected data can be processed and sent to be stored in a cloud database. Detailed information can be checked in real time and historical information can be analysed to study and improve the process.
- Industry 4.0. Some of the main Industry 4.0 design principles[24] are included in this project: **virtuality** (STPCR plant dynamic model), **real-time capability** (real-time optimal control of STPCR plants) **and decentralization**.
- SMARTCSP. It contributes also to the emerging concept of SMARTHELIOSTAT in the scope of SMARTCSP. The main features of SMARTCSP components are autonomous intelligent control, **lean manufacturing concepts** and **plug-and-play** approaches[25].
- Other applications. Finally, it will **provide insight or data for improving CSP processes**, such as concentrated solar flux measurements on the receiver, atmospheric attenuation, soiling in the solar field, etc.

Concerning Activity 2, the proposal aims to achieve significant milestones not previously achieved anywhere in the world. In this sense, the scientific-technical impact of this project would be:

- One objective of this project is to obtain a **solar extinction type year at PSA** measuring solar extinction **for at least five years** to analyze the variations of this

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[24] C. Santos, A. Mehrsai, A.C. Barros, M. Araújo, E. Ares, Towards Industry 4.0: an overview of European strategic roadmaps, Procedia Manuf. 13 (2017) 972–979. https://doi.org/10.1016/j.promfg.2017.09.093

[25] C. Villasante, J. Mabe, I. Les, A. Peña, M. Sánchez, S. López, SMARTCSP: The Industry 4.0 approach for an effective CSP cost reduction, in: 24th SolarPACES Annu. Conf., Casablanca, Morocco, 2018.

parameter daily, seasonally, and annually. To date there is **no record** of a solar extinction typical year **at any location in the world**.

- Based on this solar extinction type year, **models** for PSA based on the AOD (Atmospherical Optical Depth) atmospheric parameter **can be reliably validated and applied to other sites** since this parameter can be obtained from the ground (AERONET: Aerosol Robotic Network) and failing that from a satellite.
- In this sense, another objective of the project is **to obtain an extinction map of Spain** with the previously validated models **that will serve as a guide for CSP promoters of solar tower thermal power plants** (SENER, ABENGOA, ACWA, SHOUHANG, BRIGHT SOURCE,…) in the correct choice of the most favourable locations in our country. This map will allow having information of the energy losses due to extinction in STPCR plants during extended periods of time in a site.

Finally, **Activity 3 will offer** to the scientific community a simulation software that will include the results extracted from activities 1 and 2 and will allow evaluating the impact of the proposed solutions in terms of enhanced efficiency in real solar tower heliostats fields. Thus, the scientific-technical impact of Activity 3 would be:

- A highly parallelized and computationally powerful **distributed grid application for the spectral characterization of solar tower plants**. Its applications can be used both in the design of new plants and in subsequent phases of technological development and experimentation. The application, being of public use, will be of great interest to the entire research, academic and industrial sector, both nationally and internationally.
- Optical characterization in a CAD mechanical design environment, which will allow the **optical response** of the system being designed to be known at the design stage.
- **Prediction of the power generated** by the plant using high-precision simulations, **considering spectral analysis and optomechanical features**.

5. IMPACTO SOCIAL Y ECONÓMICO - *SOCIAL AND ECONOMIC IMPACT*

Social and economic impacts of this project will be due both, to reduce the cost of heliostats fabrication and of the deployment of heliostats in the solar field, and to provide valuable information on the economic losses due to losses in thermal energy/electricity production in solar tower plants due to solar radiation extinction in any location in the Spanish territory. The results obtained from this project can be a great help for the control and operation of existing solar power plants, as well as for the more efficient energy supply and integration into the electricity grid. At the same time, they will offer, with greater reliability, a prediction of production in a certain moment, assuming an important help in the design of new solar plants. In addition, methodologies applied and results obtained will contribute to the emerging concept of virtual power plants (VPP). VPP is a network of decentralized medium-scale power generating units that would combine different energy technologies, mainly RES plants considering the existing energy market prospects. With the improvement in the operation of solar tower power plants and thanks to its dispatch-ability, because the use of medium-to-long term thermal energy storage capacity, and with the application of industry 4.0 aspects to this energy technology, the project would have a relevant contribution to challenges of the current energy and digital transition. All contributions in this context are clearly included in thematic priority number 5 of the call: Climate, energy and mobility.

The main advantages of the proposed smart heliostat tracker with respect to current industrial heliostat trackers are:

- It reduces the installation and maintenance cost. The hardware is low cost (<135€) and it is cheaper than current control system hardware in industrial heliostat trackers (>780$≈ 675€)[26,27]. Furthermore, there is room for further cost reduction, for instance bulk purchases or using less-powerful custom-tailored hardware. It does not require a strict and labour-intensive heliostat installation process. Since it is a closed-loop approach, the installation cost could be further reduced by employing less expensive heliostat equipment. Fixed cost reduction could also lead to a reduction in the optimal heliostat area from an economic point of view. This will also translate into a cost reduction in the heliostat structure.
- It decreases the operation cost. It is autonomous and does not require calibration which reduces the spillage, thus increasing the overall plant performance.
- It provides additional information to detect plant design issues, i.e. blocking and shadowing due to surrounding heliostats. Moreover, cloud detections provide data to optimally control STP plants.

On other hand, solar extinction phenomenon decreases the efficiency of the electricity production in STPCR plants. As an example of this, the economic impact that solar extinction could have on a site like PSA is shown below. For this, solar extinction models have been obtained from the LibRadTran radiative transfer code, using average AOD values obtained from the PSA AERONET station as an input parameter. The extinction model levels are introduced in the solar thermal electric code SAM (System Advisor Model)[28] to study the impact of extinction in the energy production, as well as the impact in economic terms in a STPCR plant with similar characteristics as Gemasolar solar power plant (Sevilla, Spain) but with the atmospheric scenario of the PSA: solar plant power is 19.9MWe, 2650 heliostats of 10.9mx10.9m each one, tower height is 140m and maximum distance heliostat-tower is 1120m.

Table 2 shows that solar radiation extinction could produce at PSA up to 4.40% of annual energy generation losses. These losses due to extinction – translated into economic terms - involve losses over 645k€ per year.

Data in Table 2 point out that neglecting extinction, non-viable projects could result wrongly viable. Some financial parameters as NPV (Net Present Value) and IRR (Internal Rate of Return) could be wrong if extinction losses are not considered. In Table 2, it is observed that NPV is higher when extinction is lower, in fact, the most elevated NPV takes place when extinction is zero (last column), thus, it is established that extinction can decrease the viability of a project. Considering zero extinction in SAM, it results a NPV over 29.3M while the NPV is over 15.4M€ for the PSA average extinction levels (ranging from 1% for short distances (150m) up to 9% for 3km distance). So, this clarifies that neglecting extinction results NPV much higher (over double) than it really is and this makes some projects seem feasible when they are not.

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[26] F. Téllez, M. Burisch, C. Villasante, M. Sánchez, C. Sansom, P. Kirby, C. Caliot, A. Ferriere, C.A. Bonanos, C. Papanicolas, A. Montenon, R. Monterreal, J. Fernández, State of the art in heliostats and definition of specifications (Survey for a low cost heliostat development), 2017. https://doi.org/10.5281/zenodo.834887

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[28] Dobos A, Neises T, Wagner M. Advances in CSP simulation technology in the System Advisor Model. Energy Procedia 2013; 49:2482-2489. https://doi.org/10.1016/j.egypro.2014.03.263

Table 2. Electricity production and economic losses due to solar extinction in a solar tower plant at PSA[29]

	Max Ext.	**Mean Ext.**	**Min. Ext.**	**Zero Ext.**
Annual Energy Production	166.26GWh	171.26GWh	172.42GWh	174.0GWh
Annual Losses	7.65GWh	2.65GWh	1.49GWh	-
Economic Losses (0.0834€/kWh)	645k€	223k€	125k€	-
% Production Losses	4.40%	1.52%	0.86%	-
NPV (Net Present Value)	15.392M€	15.393M€	15.394M€	29.288M€
IRR (Internal Rate of Return)	11.00%	11.00%	11.00%	12.49%
Year IRR is achieved	20	20	20	20

These specific contributions will have a significant impact on the existing and continuous development that concentrating solar thermal technology is living during the last decade because it has demonstrated its potential to be an important economic driver in many regions of Spain. In particular, it has become an important economic motor for depopulated rural areas, helping to fix the population in these areas, while contributing to the development of infrastructures such as the implementation of mobile networks, etc[30].

6. CAPACIDAD FORMATIVA - *TRAINING CAPACITY*

The members of the research team have extensive experience in training, tutoring and PhD and master theses supervision as accredited by the CVs of its members. The novelty of the subject and its complexity represent a good opportunity for the development of a new doctoral thesis on the subject, which will include the development of new knowledge and its experimental application in a pilot plant scale thanks to the complete installations available for testing at Plataforma Solar de Almería (http://www.psa.es/es/instalaciones/index.php). The University of Almería would be the ideal academic center due to its proximity to the PSA and the existing collaboration with some departments of this University. In any case, if a PhD contract is granted with the project, it will be advertised at the University of Almería but also in other universities of Spain with which there are close collaborations (UNED, University of Seville, Polytechnic University of Madrid, University Carlos III, Universidad de las Islas Baleares, etc.) for the search of candidates.

[29] Carra, E., Ballestrín, J., Polo, J., Barbero, J., Fernández-Reche, J. "Atmospheric extinction levels of solar radiation at Plataforma Solar de Almería. Application to solar thermal electric plants". Energy 145 (2018) 400-407. ISSN: 0360-5442. https://doi.org/10.1016/j.energy.2017.12.111
[30] PROTERMOSOLAR. "La industria termosolar como motor económico en España". Impacto económico en 2019 y potencial del aumento del almacenamiento y el cumplimiento de los objetivos del PNIEC. PwC. 2020.

1) Supervised PhD theses by members of the Research Team

Jesús Ballestrín:

- PhD Director of Marina Casanova. Plataforma Solar de Almería 2018-2021. PhD title: “Medida de Alta Irradiancia en Centrales Solares Termoeléctricas de Receptor Central”. Universidad de Almería, 2021.
- PhD Director of Elena Carra. Plataforma Solar de Almería 2015-2018. PhD title: “Medida de la Extinción Atmosférica de la Radiación Solar en Centrales Solares Termoeléctricas de Receptor Central”. Universidad de Almería, 2018. Elena Carra is a member of the project's working team.
- PhD Director of Aitor Marzo Rosa. Plataforma Solar de Almería 2009-2012. PhD title: “Medida de Temperatura en Entornos de Radiación Solar Concentrada”. Universidad de Almería, 2012. Aitor Marzo is a member of the project's working team.

Loreto Valenzuela

- PhD Director of Antonio Sanda Mera (Estudiante doctorado CENIDET, México). “Desarrollo de un código numérico para estudios del flujo bifásico agua-vapor en el tubo absorbedor de captadores solares cilindro-parabólicos”. Tecnológico Nacional de México, Centro Nacional de Investigación y Desarrollo Tecnológico (CENIDET), 2021.
- PhD Director of Diego Pulido Iparraguirre (Contratado Universidad Antofagasta, Chile). “Desarrollo de un prototipo de captador solar Fresnel lineal de media Temperatura”. Universidad de Almería, 2020.
- PhD Director of Mario Biencinto Murga (Contratado Tit. Superior CIEMAT). “Simulación y optimización de centrales termosolares de generación directa de vapor con captadores cilindroparabólicos usando un modelo cuasidinámico”. UNED , 2018.
- PhD Director of Juan José Serrano Aguilera (Beca FPI Ref. BES-2012-056876). “Thermal-hydraulic and optical modeling of solar Direct Steam Generation systems based on Parabolic-Trough Collectors”. Universidad de Málaga, 2017

Ramón Pujol

- PhD Director of Fabienne Sallaberry. Programa Oficial de Doctorado en Energías Renovables (UPNA). "Characterization of optical losses due to tracking systems on a linear solar thermal concentrator". Universidad de las Islas Baleares, 2015.
- PhD Director of Julian D. Hertel. Programa de doctorado en Física (UIB). "Study on the general applicability of the collector efficiency model to solar process heat collectors". Red europea SHINE (número de subvención: PITN-GA-2012-317085), 2019.

2) Master's final theses (TFM) and Final Degree projects (TFG) supervised by members of the Research Team

Jesús Ballestrín

- TFM: Elena Carra. Universidad de Almería, 2016. Title: “Transmisión de calor aplicada a la energía solar”.
- TFM: Alberto Flores Martínez. Universidad de Almería, 2016. Title: ”Medición de flujo en un sistema de concentración solar a partir de un método híbrido”.

Loreto Valenzuela

- TFM: Noelia Estremera Pedriza. Universidad de Almería, 2020. Title: “Optimización en la configuración de campos solares con concentradores Fresnel para aplicaciones industriales”.
- TFM: Ignacio Javier Arias Olivares. Universidad de Almería, 2020. Title: ”Estudio de producción de centrales termosolares en el norte de Chile y comparación de resultados con los obtenidos mediante SAM”.

Ramón Pujol

- TFG: David Gómez Sospedra. Universidad de las Islas Baleares, 2020. Title: “Caracterización óptica de un concentrador lineal Fresnel mediante el software libre OTSun”.
- Supervisor of 30 academic projects (TFG, PFC, TFM).

Jesús Fernández

- Hicham Boutoil. Universidad de Almería, 2021. Title: “Diseño de un sistema de limpieza autónoma para heliostatos”.
- Hector Herrada. Universidad de Almería, 2018. Title: “Adaptación del código DELSOL a sistemas de 64 bits. Diseño y simulación de una planta de torre central”.

3) Participation as teachers in courses and masters (only referred to members of the Research Team)

Jesús Ballestrín, Loreto Valenzuela, Jesús Fernández-Reche

- Teachers in the Master of Solar Energy “CIESOL”, Universidad Almería, 2006-2011, 2018-2021.
- Teachers in the course: “Sistemas Solares Térmicos de Concentración”, CIEMAT, Madrid, 2006-2011.

Ramón Pujol

- Teaching of the online seminar "OTSun: trazado de rayos para la simulación óptica de sistemas solares térmicos y células fotovoltaicas" in the Master of Solar Energy “CIESOL”, University of Almería, 2020. 4 hours duration.
- Participation in 12 different regulated subjects of different Engineering degrees and Masters at UIB (more than 1700 hours in 13 years).

7. CONDICIONES ESPECÍFICAS PARA LA EJECUCIÓN DE DETERMINADOS PROYECTOS – *SPECIFIC CONDITIONS FOR THE EXECUTION OF CERTAIN PROJECTS*

Do not apply.