SolarPACES 2023, 29th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Receivers and Heat Transfer Media and Transport: Point Focus Systems

https://doi.org/10.52825/solarpaces.v2i.777

Published: 16 Sep. 2024

Testing and Validation of Innovative on-Site Solar Field Measurement Techniques to Increase Power Tower Plant Performance: The LEIA Project

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Abstract. LEIA project aims to contribute to the development of the next generation of central receiver power plants focusing on validating a combination and integration of pre-commercial solar field control and O&M solutions for the central tower receiver technology using molten salts, as the most promising cost-effective solution with the highest market penetration potential. To effectively remove the existing technical and industrial barriers to optimize central receiver and heliostat field operation & maintenance and thus to improve overall CSP performance, the following innovations are being developed: 1) Smart heliostat field control, 2) Smart control systems, 3) Solar Field Operation and Maintenance control strategies. These developments will be tested and demonstrated in three flagship operational environments: a) Cerro Dominador (Chile), b) CIEMAT – PSA (Spain), and c) CENER – Tudela (Spain).

Keywords: Solar Power Tower Plants, Smart Solar Field, Smart Receiver Control, Operation and Maintenance Control Strategies

1. Introduction

The European Union (EU) has established challenging targets for making a transition to a sustainable energy system in Europe, including that the EU's electricity supply achieve essentially zero emissions of greenhouse gases by 2050. Solar Thermal Electricity (STE) is positioned to play a significant role in the future global generation mix, being one of the key technologies to contribute the Net Zero Emissions scenario, providing the 2% of the world electricity generation by 2050, according to International Energy Agency [1].

STE is expected to experience great growth potential in the coming years, up to 32% compound average annual growth rate to 2030 and 17% to 2050 according to the IEA World Energy Outlook 2021 [1]. It will become a cost-competitive option ready to replace carbon-emitting technologies as an effective and dispatchable renewable energy source (RES) as a result of its ability to provide a firm base-load and/or peak supply of energy [2]. Furthermore, by providing flexibility for grid services, STE can facilitate the integration of other variable RES, such as PV or wind, thereby contributing to the reliability of the transmission grid.

The sooner this transition is achieved, the smaller will be the environmental changes and social impacts in a world that is increasingly affected by ongoing climate change. In this general energy context, the *soLar field mEasurements to Increase performAnce* (LEIA) project aims to contribute to the development of the next generation of central receiver power plants. The project focuses on validating solar field control and operation and maintenance (O&M) solutions for central receiver systems using molten salts, as this is the most promising cost-effective solution with the highest market penetration potential.

LEIA aims to innovate in the core components of this technology and to remove existing technical and industrial barriers. By bringing these innovations to a commercial scale, the competitiveness and reliability of the Concentrated Solar Power (CSP) technology as well as confidence in the market will be improved. This will allow the project to reach the two strategic targets of the Strategic Energy Technology (SET) Plan at the same time [3]:

- Short-term: More than 40% reduction in energy costs to reach a price lower than 0.10 €/kWh.
- Long-term: Development of the next generation of STE technologies.

The presence of STE plants and the interest in further commercial investments in this dispatchable renewable energy technology will only be boosted through innovations like the ones pursued within LEIA. These innovations aim at increasing performance and reliability.

2. LEIA Objectives

LEIA will combine and integrate innovative smart control and O&M solutions on a pre-commercial level for Solar Power Tower Plants (SPTP). By removing technological and industrial barriers, LEIA will improve not only the competitiveness and reliability of future central receiver technology, but also its attractiveness for investors, as well as developing solutions that could also be implemented in current commercial SPTP.

Moreover, the LEIA project centralises development, robustly and effectively combining and integrating the innovations developed by the partners from two leading STE European countries: Spain and Germany, which will help to maintain European technological leadership, as well as to keep the EU at the forefront of RES usage; the project uses three flagship operational environments in Europe and in Chile, one of the latest countries to deploy SPTP with very favourable solar conditions:

1. Cerro Dominador (Chile): The first commercial tower STE plant in South America.
2. CIEMAT – PSA (Spain): The largest concentrated solar technology research, development and test centre in Europe, and a European Large Scientific Installation. Testing will be done at the iconic CESA-I tower.
3. CENER – Tudela (Spain): The test facility for testing heliostats at the largest distances from the tower in the world, up to 1200 meters.

LEIA aims at removing existing technological and industrial barriers regarding the central receiver and the heliostat field in order to reduce CAPEX (Capital Expenditure) and OPEX

(Operational Expenditure). This will be achieved by developing the new solar field and control solutions summarised in Figure 1.

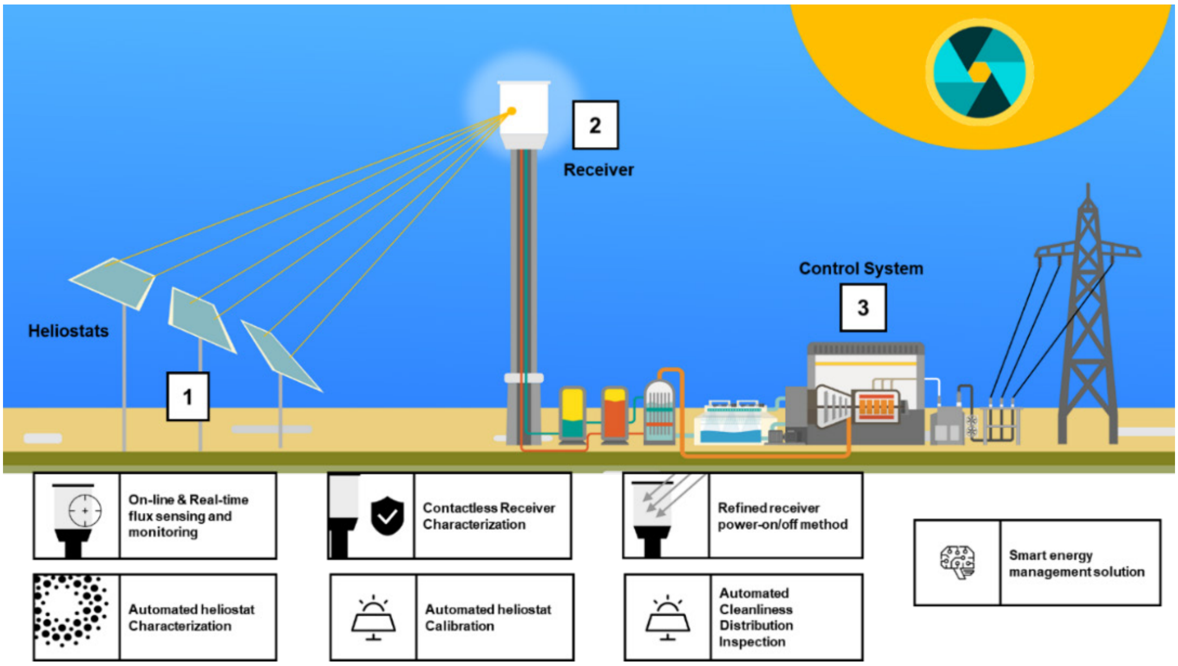

***Figure 1**. LEIA innovative solutions*

2.1 Smart heliostat field control solutions

The main goal of this task is to develop procedures to characterize the optical quality of the heliostat field in order to:

1. Reduces the labour needed significantly.
2. Minimises the time required to characterise the whole solar field.
3. Allows daily plant operation without interference.
4. Allows balanced computational efforts to monitor, control, improve and optimise plant logistics.

Optical quality is influenced by both offset and tracking accuracy, which change over time, and create uncertainty in the aiming strategy or require a very expensive recalibration process using the tower target. An automated characterisation process will allow:

1. Reliable prediction and control of the energy flux distribution on the solar receiver at all times during operation.
2. Screening of the optical quality of the heliostats related to the influence of changes in seasonal atmospheric conditions.
3. Ongoing measurement of the degradation of the optical quality of the heliostats with age.

The project proposes three cutting-edge solutions to characterise and control the heliostat accurately, as presented in the following sub-sections.

2.1.1 Online heliostat field characterization

CIEMAT-PSA will develop a system for sequential image capture of the different heliostats of a solar field on a Lambertian target placed at the tower, generating an image database without interfering with daily plant operation. Then, using computational optimisation algorithms, the optical quality of each heliostat will be inferred, and the information added to the database, which will be accessible to O&M operators.

This process will automate and enhance the state-of-the-art (SoA) of the heliostat characterisation and calibration method (target-camera) reducing the computational resources and time, in order to optimise the labour required by the process [4].

2.1.2 Direct heliostat characterization

Spain's National Centre for Renewable Energy (CENER) will use the Helioschar+ system it developed, patented and validated, which is based on an optoelectronic device with an array of light detectors and cameras distributed along a vertical pole. The system is a direct-beam measurement solution that reduces some of the problems encountered in the target-camera method. The system is parallelisable and can reduce commissioning time by at least 50%.

This solution aims to achieve accuracies of less than 0.1 mrad in slope deviation measurement, being able to provide facet-canting information and distinguish between slope deviations caused by either surface deformation and waviness or canting error. These requirements can be met by heliostats at distances greater than 1 km from the tower, regardless of the type, size or position.

2.1.3 Real-time calibration solution

Tewer Engineering will design a new solar sensor, SUNSEN, to perform offset calibration and tracking corrections on a heliostat by means of machine learning algorithms, in order to provide a real-time, online calibration system. A collimating-type, pinhole CMOS sun sensor will be used with a target cost under €30/unit with an accuracy of less than 0.1 mrad. The implementation of fuzzy logic in sensing the sun's position will be used to employ cheaper photo-sensors to reach the required accuracy and resolution. The use of this type of sensor greatly enhances the performance of the solar field and reduces the calibration cost, given that a large group of heliostats in the solar field could be calibrated simultaneously without using the target. The use of this sensor also provides information about the heliostat offset and tracking degradation.

2.2 Smart receiver control solutions

The aim of this task is to push the SoA technology regarding real-time receiver characterisation in order to enable smart receiver control that does not interfere with daily plant routines. The specific goals are the following:

1. Improve the existing techniques to measure, in real time, the flux density distribution on the receiver surface, and thus, to optimise the aim-pointing strategy in order to increase plant efficiency. Three measurement techniques with differences in their methodologies, but potential synergies, are presented in section 2.2.1.
2. Improve the measurement of the temperature and emittance of a receiver in order to increase its lifetime and efficiency.
3. Improve an existing method used to measure the receiver efficiency by increasing the information about the power from the field and the receiver to reduce uncertainties.

The project proposes different solutions to control receiver performance, presented in the following sub-sections.

2.2.1 Online & real-time solar receiver high solar irradiance measurement

The aim is to provide a quantitative high solar irradiance distribution measurement and monitoring procedure for solar receivers that can be used for large receivers at commercial

STE plants, one that can be implemented in a dynamic heliostat aim-pointing and receiver operation strategy. Three different methodologies and systems will be developed:

1. Quantitative receiver high solar irradiance measurement: CIEMAT will develop a new solution based on a hybrid method that uses a digitally calibrated camera at a protected area in the solar field and a radiometer close to the receiver [5].
2. Contactless quantitative flux density monitoring (QFlux): the DLR solar research centre and CSP Services company will further develop and demonstrate a system measuring the receiver flux distribution online and in real-time (with radiometrically calibrated cameras with elaborated corrections [6,7]). Furthermore, a long-term validation of the two-camera prototype system will be performed.
3. Indirect camera-based flux density distribution measurement (FLUXCAM): Tewer will develop a visual camera system to measure the front surface flux distribution in real time, taking advantage of the camera-based heliostat calibration and characterisation system, already in place at the Cerro Dominador plant.

The potential synergy between systems will evaluate the capacity of the monitoring systems to quantify how the flux distribution affects the thermodynamic and optical properties of the receiver surface.

2.2.2 Contactless receiver characterization

DLR developed a remote sensing method to characterize the surface temperature and spectral emittance of the coating on tubular receivers. This method relies on a multispectral infrared camera, radiometrically calibrated. As part of LEIA, they will improve the method for these measurements to be used on the Cerro Dominador receiver together with CSP Services.

The calibration and test procedures will be refined, and the measurement uncertainty analysed with respect to the parameters affecting the radiometric chain, such as coating emittance and atmospheric transmittance. The influence of atmospheric conditions and signal attenuation will be evaluated at the Cerro Dominador STE plant.

2.2.3 Refined power-on/off method

The power-on/off method [8] is used to calculate receiver efficiency without measuring the incident power in the receiver. DLR will enhance the SoA technique with a refined power-on/off method, thus facilitating insight into solar field performance, by reducing the uncertainty in the thermal loss assumptions, e.g. absorptance, infrared images, convection losses due to wind. Power-on/off data provided by Acciona will be analysed and compared to efficiency figures.

2.3 Solar field operation and maintenance control strategies

Solar field O&M is a difficult task due to the large dimensions of the fields, vast numbers of heliostats, their variations in beam shape, optical quality and calibration, and harsh ambient desert conditions. This task has the following objectives:

1. Making the characterisation of the solar field soiling more efficient and dynamic. Having more up-to-date information on solar field soiling can optimise the maintenance of the solar field, and also its operation.
2. Using the characterisation of the solar field and the receiver to improve energy management, considering both transient and steady-state situations.

The project proposes different solutions to control receiver performance, as presented in the following sub-sections.

2.3.1 Cleanliness distribution automated inspection methodology

DLR and CSPS will develop and test a method to measure the soiling level of the heliostat field using aerial images taken by Unmanned Aerial Vehicles (UAVs). This method is currently being developed for parabolic trough fields [9]. DLR will develop in LEIA enhanced image analysis methods on soiled heliostats to further improve method reliability using image data from selected heliostats in a PSA heliostat field, and CSPS will develop an optimised waypoint planning for efficient data acquisition from large-scale heliostat fields. They will develop pre-processing algorithms to deliver geo-referenced, orthogonalized images of the mirror surfaces with complementary information on UAVs and heliostat positions suitable for the soiling evaluation method. The methods will be applied in the demonstration campaign, and the results of the new method compared to reference soiling measurements taken in the Cerro Dominador solar field.

2.3.2 Smart energy management system (SEMS)

Acciona will develop a solar field SEMS predictive simulation tool to analyse the influence of the real-time characterisation of receiver and solar field performance. LEIA-developed solutions for transient and steady-state situations will be used to maximise plant production by recalculating aiming strategies and making predictions in order to have dynamic control over the plant strategy.

2.4 Control integration design and big-data management

Today’s STE plants use a Distributed Control System (DCS) that integrates the different control systems used in different plant areas such as heliostat field, receiver, etc. However, there are no control system solutions for all plant areas working in a closed loop where each system works to iterate the control strategy depending on the state of the plant. The control concept follows, in principle, the classic automation pyramid where the individual systems exchange data (e.g., from the heliostat field) with the superordinate system for monitoring and control of the entire plant. An exchange of data between the individual systems usually does not occur directly but only via the superordinate systems. Indeed, the amount of data and the number of exchanges are limited. The control system of the next generation of CSP plants will look different, as the world of direct control systems, including field (operation level) and internet (IT) solutions, continue to evolve.

The goal of this task is to first study the required data analysis based on computational requirements, as well as the detailed specifications and requirements for the real-time processing of each LEIA solution. Afterwards, a conceptual design of a new solar field control system will be developed.

Two main developments will be undertaken in this part of the project:

1. Data analysis and cloud computing: The implementation of the algorithm developed in section 2.3.2 is very demanding, especially when there is a need to evaluate the performance of a plant continuously. Therefore, for integrating a SEMS into the DCS of the plant, Siemens Energy and Acciona will analyse the data involved in the real-time operation of each control solution as part of the finalisation of a conceptual design for the control system.
2. New solar field control system: This research will address the New Solar Field Control System Design based on the previous results. The next generation of STE towers will be based on this control integration orientated toward a smart energy solution. This analysis will allow Siemens Energy to design a concept for a new control system taking into consideration the individual technical demands of the control concept.

3. Results

The proposed developments and solutions are to be implemented in the SEMS, affecting both the CAPEX and OPEX as shown in the following table:

***Table 1**. CAPEX and OPEX savings estimation*

	CAPEX	OPEX
Online Flux Distribution	0.05 %	0.30 %
Receiver Power-on/off method	0.0 %	0.0 %
Solar Field Characterisation + Calibration	0.0 %	-1.0 %
Contactless Receiver Characterisation	0.0 %	-0.2 %
Soiling Inspection	0.0 %	-0.2 %
Total	**0.05 %**	**-1.10 %**

After implementing all the solutions, CAPEX will need to increase by only 0.05 % in order to increase the total efficiency of the plant, which will lead to higher income as a result of the increase in electricity production. At the same time, total OPEX will be reduced by 1.10 %, due to the automatisation of the operating control systems.

The contactless receiver characterisation will save up to €50,000 on painting of the receivers over the lifetime of the plant. While improving the cleaning cycles based on the soiling inspection will lead to a savings of €50,000 in the total OPEX budget.

The heliostat field will be fully characterised more accurately and frequently to allow better flux control over the receivers and, therefore optimising the O&M of the plants. That is, the flux distribution will be more homogeneous, the receivers will always be operated very close to nominal peak flux conditions (maximum efficiency), but will never be operated beyond that point, thus avoiding accelerated material fatigue. To calculate the LCOE (Levelized Cost Of Electricity), two hypotheses have been made:

- The CAPEX is €5m/MW. So for a plant of 100 MW, total CAPEX would be 500m€.
- The OPEX is a third of the CAPEX over the lifetime of the plant (25 years).

The Key Performance Indicators used in the business model applied to a plant with dimensions similar to the Cerro Dominador STE (100MWe, 17.5h of storage and lifecycle of 25 years) would result in the following:

- An increase of 180 annual equivalent hours of operation and 1.5% in receiver efficiency.
- An increase in annual electrical production of 5% due to heliostat field characterisation and calibration solutions.
- An increase in CAPEX of 0.05% and a decrease in OPEX of 1.1% in the solar field due to the monitoring and measurement systems.
- An increase of 5.6% in the annual generation of the plant as a result of the improved control strategies.
- This results in a reduction of 5.5 % on the LCOE for a final LCOE of €72.8/MWh.

Data availability statement

The raw/processed data required to reproduce the above findings cannot be shared at this time as the data also forms part of an ongoing study.

Author contributions

A. Avila-Marin: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – original draft; **J. Fernandez-Reche**: Investigation, Funding acquisition, Resources, Writing – review & editing; **R. Monterreal**: Investigation, Resources, Writing – review & editing; **J. Ballestrin**: Investigation, Resources, Writing – review & editing; **J.F. Gallego**: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – review & editing; **M. Casanova**: Investigation, Resources, Formal Analysis, Writing – review & editing; **S. Escorza**: Investigation, Resources, Writing – review & editing; **A. Mutuberria**: Investigation, Resources, Writing – review & editing; **A. Kämpgen**: Investigation, Resources, Writing – review & editing; **A. Macke**: Investigation, Resources, Writing – review & editing; **M. Röger**: Investigation, Resources, Writing – review & editing; **J.J. Krauth**: Investigation, Resources, Writing – review & editing; **S. Schlau**: Investigation, Resources, Writing – review & editing; **A. Barenbruegge**: Investigation, Resources, Writing – review & editing; **J.M. Blazquez**: Investigation, Resources, Writing – review & editing; **A. Zurita**: Investigation, Resources, Writing – review & editing;

Competing interests

The authors declare that they have no competing interests.

Acknowledgement

This work is part of the action PCI2022-135015-2, funded by MCIN/AEI/10.13039/501100011033 and by the European Union “NextGenerationEU”/PRTR. The authors gratefully acknowledge the financial support of the German Federal Ministry for Economic Affairs and Climate Action (LEIA contract 03EE5134A and 03EE5134B). The authors furthermore like to thank Simon Caron, Kristina Blume, Tim Schlichting, José Escamilla, Christoph Happich.

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