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Optical simulation of a central receiver system: Comparison of different software tools

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ABSTRACT

Heliostat field layout design is a critical task in solar tower power plant construction due to its impact in the final plant efficiency and cost. The complexity of these systems and the high number of parameters to define during the field design stage demand the use of suitable simulation tools to compare different design options and evaluate the final performance of the heliostat field. This work concerns a comparison of some of the most common tools used for the heliostat field layout design and analysis, aiming to help Concentrating Solar Power researchers and industry by providing more information regarding the tools comparative results and features. A brief review of available tools is presented, including an extended description of some of them – Tonatiuh, SolTrace, TracePro and CRS4-2. A qualitative comparison of these four tools is performed focusing on functionality and usability. A quantitative comparison is done providing simulation results for a test-case, the SPSS-CRS facility located at Plataforma Solar de Almeria in Spain. In general, the results for total power and maximum irradiance are in good agreement across most tools. The total power values are very close for Tonatiuh, SolTrace and CRS4-2. Apart from the designer preferences, the choice of the most suitable tool depends on the specific application and requirements.

1. Introduction

Scientific research and technological development (RTD) enhances Concentrating Solar Power (CSP) systems, leading to improved efficiency and durability, and contributing to a decrease in CSP's levelized cost of electricity. Cost reductions coupled with CSP plants inherent capability to provide dispatchable power and ancillary services (by using thermal energy storage systems or through hybridization with other power sources [1]) are leading to an increased deployment of this technology.

Central receiver systems (CRS) are one of the main CSP technologies being deployed. Based on a matrix of flat or slightly curved reflectors, called heliostats, CRS concentrate the solar radiation onto a receiver placed on the top of a tower where it is absorbed and converted into heat [1–3]. An alternative configuration is the beam-down layout: where the heliostats focus the radiation on secondary optics, located on the top of a tower, which redirect the concentrated beam towards a receiver placed at the bottom of the tower [4–6].

Knowledge of the optical performance of the heliostat field is required for RTD activities and project development, from feasibility studies to detailed design. The total power incident on the receiver is one of the parameters required to characterize the heliostat field for research and during early stages of the project development, being used to compute heliostat field efficiency matrices used in plant performance simulations. Moreover it is also one of the relevant parameters during the detailed plant design, together with other information such as the maximum irradiance on the receiver surface and its position.

CRS optical design and simulation is complex and time-consuming, being a critical step to ensure the plant's feasibility and viability since the heliostat field represents a significant share of the plant's capital costs and energy losses [7].

Commercially available software packages for generic optical design, like Zemax/OpticStudio [8], TracePro [9], Code V [10], OSLO [11], ASAP [12] and others are conceived to simulate, develop and optimize optical components for disparate applications. Although the optical design of solar components can be one of such tasks, these

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software tools are not specifically developed to simulate solar plants, lacking dedicated methods for the design and optimization of CRS optical systems. The development of new software, to replace or complement the commercial packages, has the advantage of adapting the software to the needs of the solar plants optical design and optimization. However, this represents a considerable effort and resource consumption due to the complexity involved in creating an accurate and flexible tool suited to more than one application and configuration with all the needed functionalities, requiring a joint effort by a combined group of researchers and developers to be successful. It is also possible to develop simpler tools specific for a given application or configuration, however, such an approach will lead to the necessity for new developments every time a new configuration is to be simulated or a different analysis must be performed, increasing the amount of work and potentially leading to duplication of effort. Moreover, CSP technology is still not mature, with intense RTD activities underway, creating new requirements for the tools functionalities. Thus, software tools for optical design and analysis of CRS and other CSP technologies must be flexible and expandable since there is a strong drive for the development of new functionalities and demand for its application in new situations.

Over time, several tools have been developed by the CSP community, trying to achieve more accurate, faster and better suited tools to enable further development of this sector. Those efforts were (and to some extent still are) largely uncoordinated, arising from individual needs created by the research and development activities, having resulted in a large set of different software with distinct specificities and capabilities. A literature review, focused on publications where results from CSP RTD activities were presented, identified up to 37 different tools used for optical simulation of concentrating solar systems (see Table 1).

Brief descriptions and comments regarding the main characteristics and functionalities of several tools can be found in the following review papers [7,12,21,31]. These works result from a qualitative analysis of the software, performed by the authors based on their personal usage of the tools, literature review and a user/developer survey. Garcia et al. [21] surveyed the developers or heavy users of six of the most used tools at the time, presenting the main characteristics and features of the tools, dividing them between optimization and performance analysis codes. Moreover they quoted new generation codes that were under development. This article is still relevant since several of the reviewed tools are still being used today, ten years later. Cruz et al. [7] is built upon the work of Garcia et al. [21], presenting and briefly analyzing the features of a large subset of the available tools, reviewing the key aspects and availability of 18 software tools, categorizing them in two groups: precise-analysis tools and optimization-oriented tools. Additionally they present summarized information regarding “valuable discontinued tools, proofs of concept (even if they may not be used as stand-alone software) and not widely used/described tools that could also be of interest.” Ho [12] presents a general overview of the available software tools for the analysis of concentrating solar thermal systems, encompassing a wide range of tasks and technologies, including six tools for the optical design and performance assessment of heliostat fields. Bode and Gauché [31] briefly summarize and compare the main characteristics of ten tools.

None of these articles delves into an in-depth comparison of the software features, no one performs any kind of comparison of the results. However, comparative analysis of tool functionalities and simulation results are extremely relevant to the CSP community, namely to its researchers and engineers, who must choose the most suitable tool for their tasks in order to achieve fast and accurate results. The chosen tool can be different depending on the task at hand. For example, simulation or performance analysis requires tools able to perform accurate and precise simulations, representing as close as possible the real system. However, for optimization purposes it may be best to sacrifice some accuracy to achieve greater computational speed. Other authors [7,12,21] briefly discussed the choice of a suitable tool. Garcia et al. [21] present the choice problem from an industrial project point of view, suggesting two approaches for the CRS design. The first is a two steps approach, starting with the determination of the general layout of the plant from key parameters using an optimization code, followed by a detailed analysis with a performance analysis code. The second consists in using solar field efficiency matrices, obtained with one of the analyzed codes, in thermal performance simulations of the CRS system. Bode and Gauché [31] discuss this subject from the South African researcher point of view, defending the development of their own tool considering the mathematical models and algorithms already available and described in the literature. Garcia et al. [21] stress the need to separate from detailed heliostat field analysis and optimization when choosing a tool and to evaluate tool availability, support, documentation and expansion capabilities. For detailed optical analysis activities they recommend to consider first SolTrace, Tonatiuh and a commercial tool like STRAL. However, for heliostat field optimization there is no clear recommendation.

Considering that a large number of tools are available, it is necessary to know how the tools compare for a given application in order to help the users to decide which tool to use for each type of task. Moreover, these comparisons help to identify the requirements for further improvement of the tools and to understand which tools should be chosen for additional development, signaling to the community the best tools to develop, i.e., the ones where resources for improvement should be focused, helping to achieve a coalescence around a smaller set of tools in order to reduce dispersion of efforts while increasing the resource pool available for each tool.

Very few articles present direct comparisons of simulation results obtained using different software tools. One exception is [44] that presents a comparison between Tonatiuh and SolTrace for different solar concentration systems. However, this comparison was carried out

Table 1
Non exhaustive list of software tools used for optical simulation of concentrating solar systems.

Software	Reference	Software	Reference	Software	Reference
ASAP	[12]	LightTools	[27,28]	SolTrace	[36]
CAMPO	[13]	mcm3d	[20]	SOLVER	[31]
CAVITY	[14]	MIRVAL/SPRAY	[29]	SORISM	[23]
CIRCE	[15]	NSPOC/CAVISOL	[30]	STRAL	[37]
COSAC	[16]	OPTEC	[31]	Tonatiuh	[38,39]
CRS4-2	[17,18]	OptiCAD	[32]	TracePro	[9]
DELSOL/winDELSOL	[19]	Radiance	[33]	VeGas	[40]
EDStar	[20]	RADSOLVER	[14]	WELSOL	[41]
Fiat Lux	[21]	Raytrace3D	[34]	WISDOM	[42]
HELIOS	[22]	RCELL/TieSOL	[31]	Zemax/OpticStudio	[8]
HFLCAL	[23,24]	SCT	[31]	Tracer	[43]
HFLD	[25]	SENSOL	[31]		
ISOS	[26]	SoFiA	[35]		

during the initial stages of development of Tonatiuh and no longer reflects the current status of this tool. Another exception is the work developed by Osório et al. [45], where a set of optical simulations of Linear Focusing Solar Collectors were performed to compare the application of seven software tools (Tonatiuh, OptiCAD, OTSun, Raytrace3D, STRAL, SPRAY, SolTrace) to compute collector optical efficiency and incident angle modifier. Such a kind of comparison is yet to be performed for central receiver systems.

Other authors such Garcia at al. [21] mention "Comparing results of updated codes from both categories on one or various reference test cases should be a challenging work in partnership for research centers involved in CRS or other CSP technologies." A signal of the necessity of these comparisons.

This work intends to contribute to filling this gap by analyzing the application of different tools to the optical study of CRS, particularly the computation of the total radiative flux impinging on the receiver. The tools compared in this study and the problem of its choice are addressed in Section 2. Section 3 includes a qualitative analysis of the software functionalities and usability (Section 3.1), and a quantitative analysis, through a comparative study of the tools behavior and results for the simulation of the total flux production of the SSPS-CRS (Small Solar Power System - Central Receiver System) heliostat field, located at the Plataforma Solar de Almeria in Spain (Section 3.2). Additionally, a brief analysis of other relevant results is presented, including the receiver's maximum irradiance, its position and the position of the radiative flux distribution centroid (Section 4.1). It is important to know the capabilities of the software, the objective of the analysis and the accuracy of the results before selecting a software tool. For this reason, the qualitative and quantitative comparisons of the tools are a good starting point for researchers and designers to select the most suitable tool for their studies.

2. Tested new generation software codes and commercial package

From the wide range of available software, the authors focused on performance analysis codes, choosing to compare two new generation software codes, specifically developed for CSP applications and freely available to the community (Tonatiuh and SolTrace) with a commercial software (TracePro) and an in-house developed programme (CRS4-2). These four codes represent a small subsection of the available tools for optical simulation of CRS. Ideally a comprehensive set of the available software codes should be used in broad comparison studies; however, tool availability is a limiting factor, since not all tools are available to the authors, who tried to use a representative subset of the tools. Tonatiuh and SolTrace were chosen due to their widespread use among the CSP community and their freeware status. TracePro was chosen as an example of a commercial software successfully used for CSP optical simulations by research groups. CRS4-2 was chosen as an example of modern, non-ray-tracing, in-house developed software. Moreover, only tools used by the authors during their daily activity were considered, since a good comparison demands a thorough practical knowledge of the tools.

A brief description of each tool and its working principles are presented in the following subsections, including a simple Matlab procedure elaborated to estimate the collected power whose results were also considered in the comparison of simulation results.

2.1. Tonatiuh

Tonatiuh is an open source free-to-use program available at [38]; it is focused on the design and optical simulation of complex solar concentrator systems, and aims to provide the leading-edge of the simulation tools for CSP technologies (Fig. 1). Tonatiuh has been led and improved by CENER for over a decade with the collaboration of the CSP R&D community.

Tonatiuh is based on a Monte Carlo ray tracer method and is written in C++ programming language as multi-platform software with parallelization of CPU. Providing a friendly and easy-to-use Graphics User Interface (GUI) it has become one of the favourite simulation tools for the CSP community, being well-known for the high accuracy results that it provides, having been experimentally validated using real data from different CSP plants [39,44,46].

Tonatiuh's architecture allows one to extend new features in an easy way through plug-ins. The latest and more outstanding features allow the simulation of more complex systems using more realistic materials, the capability to import complex surfaces as a CAD file and a built-in tool for calculating flux distributions.

To begin modeling a CSP system, the user must include several nodes in a tree structure. The properties applied to a node also apply to all the nodes below that node. More than 15 shape nodes to define the geometry of the surface are also available and more than 7 material nodes could be used. The tracker nodes are also included to orientate the subsystems depending of the sun position.

After the CSP system is modeled the Sun must be defined by the position, the azimuth and elevation angles, and the sunshape, Pillbox or Buie sunshape.

The rays are traced, calculating the intersection of the ray with the tree structure, starting with the root node. If a ray intersects the node bounding box, the intersection is verified with that node's children. This action is repeated until leaf nodes are reached. Finally the intersection closest to the ray origin is selected.

2.2. SolTrace

SolTrace [36] is closed-source proprietary software owned and developed by NREL, being freely available at [47]. The software aims to provide a suitable tool to model CSP systems and analyze their optical behavior. It implements a sequential Monte Carlo ray-tracing methodology, through a C++ code with multi-threading capability, presenting an intuitive GUI.

To model a CSP system in SolTrace it must be decomposed in a set of stages, such that once a ray passes through a stage it does not return to it. For each stage a group of elements is defined from a set of predefined geometrical surface elements such as flat, spherical and parabolic surfaces, amongst others, or user defined surfaces based on Zernike series, rotationally symmetric cubic splines and rotationally symmetric polynomials. To each surface element corresponds a user defined optical property set, defining properties such as reflectance, transmittance, refractive indices, slope and specularity errors. The Sun shape can be defined in terms of an angle-intensity distribution such as Gaussian, Pillbox or user defined distributions. The user can define ray tracing options such as the desired number of ray intersections, the seed used to generate random numbers for the Monte Carlo method or the maximum number of CPU cores to utilize. The software has a script functionality, enabling an automatization of the procedures for the definition of the optical system and simulation execution.

SolTrace has comprehensive and intuitive post-processing capabilities, enabling the visualization of both rays and intersection points, the automatic rendering of contour and surface plots for the radiation flux in a chosen surface and the automatic calculation of different values of interest, such as the peak and average flux or corresponding uncertainties, amongst others. Information for each intersection (both intersection point and ray cosines) can be exported as a CSV file for further post-processing.

2.3. TracePro

TracePro by Lambda Research Corporation [3,9], is a lighting simulation software that works in non-sequential mode. It is a general purpose optical CAD, but it is mainly utilized to perform lighting simulations for industrial and architectural applications. TracePro combines Monte Carlo ray tracing, analysis, CAD import/export, and

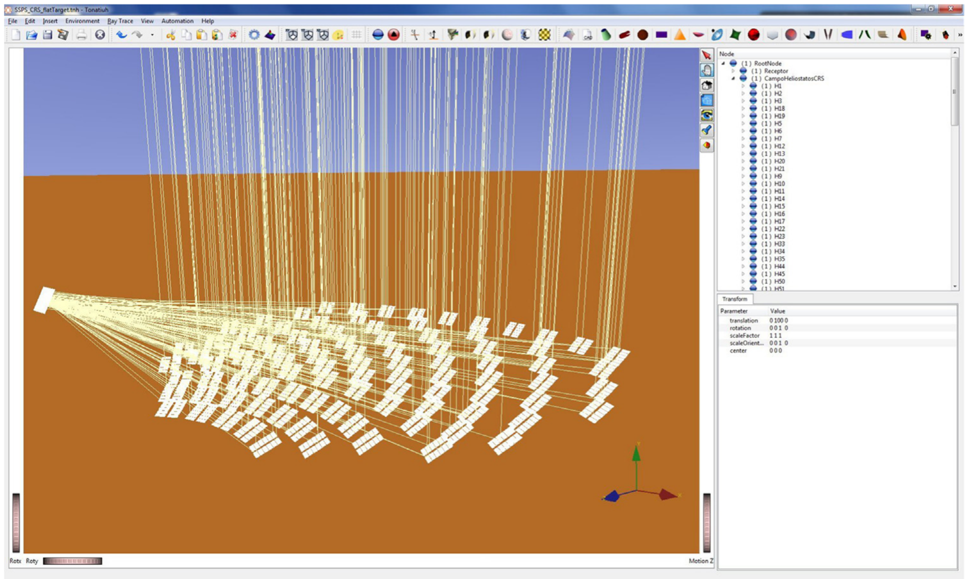

Fig. 1. Tonatiuh main view.

optimization methods with a complete and robust macro language to solve a wide variety of new problems in illumination design. It has no specific utility to work with heliostats, so it is necessary to derive a strategy to simplify data entry and import all the solar plant components. The procedure used by CNR-INO is:

1) Positions and curvatures of each heliostat, position of sun and receiver are listed in an Excel file, deriving a text file.
2) This text file is the input of a MatLab program, whose output is another text file containing positions and curvatures of the individual facets and their direction cosines.
3) The second text file is the input of a TracePro *macro* that inserts into a TracePro file the individual facets of all mirrors, with their reflectance.
4) In the TracePro file the receiver and a virtual source (i.e. a grid where rays start, placed above the mirrors field and completely covering it) are entered manually. This source has irradiation equal to the solar one on the ground, and generates a beam with the solar ray's direction. This beam strikes the heliostats and is partially reflected towards the receiver.
5) The divergence of the virtual source rays is manually set, adding to the real solar divergence all estimated enlargements due to tolerances and implementation errors.
6) The flux on the target represents the beam portion that hits the heliostats, and is reflected towards the target and is collected by the receiver.

Due to the fact that TracePro is a commercial software package, it has some advantages with respect to home-made or freeware software tools: it exploits advanced graphic characteristics and it has a sophisticated model to take into account the interaction between luminous radiation and surfaces. Moreover it guarantees, due to the extensive debug developed both from the producer before the release on the market and from many users along the commercial life of the software, that the results have high reliability and elevated precision.

2.4. CRS4-2

CRS4-2 (an acronym for CRS4 research software for Central Receiver Solar System SimulationS) [17,18] is a numerical code, developed at CRS4, written in Fortran77 and specifically devoted to the study of central receiver systems. The mathematical approach considered to calculate the solar flux collection at the receiver is based on a tessellation of the surface of the heliostats into tesserae. A reference point, an area and a normal vector to the surface at the reference point are associated to each tessera. The sunshape, the curvature and waviness errors of the reflecting heliostats' surface and the tracking errors in the drive mechanism of the heliostats are taken into account. In particular, the solar radiation is described as a conic bundle of rays originating from the center of each tessera and directed towards the sun, with a number of rays (given as input data) composing the bundle, lying on concentric cones, with a semiangle of the cone varying from $\omega_{min} = 0$ (corresponding to the central ray of the bundle) to ω_{max}. The energy carried by the solar beam is distributed amongst the rays of the conic bundle according to a Gaussian density probability function, hereafter recalled for sake of clarity:

$$F(\omega) = (2\pi\sigma^2)^{-1} exp\left[-\frac{\omega^2}{2\sigma^2}\right],\ 0 \le \omega \le \omega_{max} \quad (1)$$

For a given value of σ, a reasonable value of ω_{max} is obtained as $\omega_{max} = 4\sigma$, which ensures that the fraction of DNI (direct normal irradiance) out of the conic bundle is negligible. The use of a Gaussian distribution to describe both the incident and reflected solar radiation is certainly a limitation of the model implemented in the numerical code (more accurate models will be available in the next updated version of the code). Nevertheless, it is worth noticing that the Gaussian distribution, even if not adequate to describe the map of the flux distribution at the receiver, is mostly adequate to calculate the total collected power. In fact, in this case the magnitude of ω_{max}, is responsible for spillage and, as a minor effect, for shading and blocking.

According to the approach implemented into CRS4-2, the goodness of the results mainly depends on the number of tesserae considered to discretize the heliostat surface. Preliminary convergence study allows the choice of an adequate tessellation and minimization of the computational effort without sacrificing the accuracy of the final results.

CRS4-2 is flexible in the choice of the shape of the heliostats (circular, rectangular, etc.): heliostats of different shape (and size) can be considered simultaneously within the same solar field. Also the number, position and height of the towers can be given as input data, making feasible the analysis of multi-tower systems. At present, three different types of receiver are implemented: tilted rectangular aperture, circular receiver and the beam-down system. In this last case, a CPC can also be considered above the receiver. The general form of the implemented algorithm also allows the mixing of different receivers within a multi-tower system.

The lack of a graphical user interface (GUI) and of a parallel version of the algorithm are the two main disadvantages of CRS4-2.

2.5. Estimation with Matlab

CNR-INO elaborated a Matlab program to estimate the collected power. It simulates the heliostat field without the use of ray-tracing techniques, but estimates the irradiance reflected by each mirror on the target for the successive positions of the sun. Knowing the geometry of the heliostats field it is possible to rapidly obtain the value of total power collected by the target on different days of the year and for different hours.

It calculates the solar ephemerides: solar azimuth, solar elevation and solar irradiance (using the "ASHRAE Clear Day Solar Flux Model" [48]). It considers the rotation of the mirrors: azimuth, elevation and cosine (of the incidence angle of sunrays) of each mirror. It estimates the total power concentrated on the receiver for the examined mirrors field.

3. Comparison of the tools

3.1. Main characteristics

The software functionalities are qualitatively compared in the following tables. The comparison focuses on the software features according to four categories: general software characteristics (Table 2); optical model and simulation (Table 3); computation and optimization (Table 4); and analysis of results (Table 5).

The analyzed software have different licensing schemes, with two freeware software, Tonatiuh and SolTrace, a commercial software, TracePro, and an in-house developed software, CRS4-2. Both Tonatiuh and SolTrace are freely available but only Tonatiuh is open-source, allowing the download of the source code and enabling all users to adapt and improve the software to match their specific needs without having to implement a software tool from scratch, benefiting from all previous developments.

Table 2 presents the general characteristics of the studied software tools. It clearly shows that CRS4-2 lacks several of the general characteristics of other codes such as graphical user interface, 3D view of the optical system, and automation utilities such as script editor or macro recording. This is understandable, since it is a home-made code developed for experts with knowledge of the code, placing stronger emphasis on the ability to deliver fast and accurate results and not so much on the usability or the user experience.

The graphic user interface and the optical system 3D view are helpful during early stages of the design process, reducing the software learning curve, simplifying the users understanding of the system and facilitating the identification of design problems. With the exception of the CRS4-2 software all of the tools being analyzed have suitable GUI and 3D view capability.

For expert users and for some applications (such as optimization), a scripting functionality and the ability to execute the applications by console can be more suitable, resulting in faster and more efficient workflow. All four software tools have the possibility to execute as a command in a shell or in other codes, however only Tonatiuh, TracePro and SolTrace have script functionalities. Moreover, TracePro is able to use macros to record the user actions and replicate when needed, giving the ability to automate a task without having to write scripts.

Each software package's main features which are available for the CRS optical modeling and simulation are identified in Table 3. It is interesting to note that, unlike for general characteristics, CRS4-2 is mostly on a par with the other software in terms of features for optical modeling and simulation, confirming the stronger emphasis placed by their creators on the modeling capabilities instead of the usability.

Only two tools (Tonatiuh and CRS4-2) include a functionality to

Table 3
Features for CRS optical modeling and simulation - comparison of codes.

	Tonatiuh	SolTrace	TracePro	CRS4-2
Allows for using Cartesian as well as polar coordinates	No	No	No	No
Heliostats of several facets and different geometries	Yes	Yes	Yes	Yes
CAD import utility	Yes	No[a]	Yes	No
Built-in routine for automated generation of heliostat field layout	Yes	No	No	Yes
Copy, paste and references	Yes	Yes	Yes	No
Slope error definition	Yes	Yes	No	Yes
Other errors: specularity, tracking,…	Yes	Yes	No	Yes
Solar position calculator	Yes	Yes	Yes	Yes
Solar tracking	Yes	No	No	Yes
Built-in solar profiles models	Yes	Yes	Yes	Yes
Built-in atmospheric transmissivity models	Yes	No	No	Yes

[a] Uses a plug-in to connect with Trimble SketchUp.

Table 4
Features for the heliostat field simulation and optimization - comparison of codes.

	Tonatiuh	SolTrace	TracePro	CRS4-2
Parallel computing capability	Yes	Yes	Yes	No
Optimization tool	No	No	Yes	Yes
Built-in Parametric Sweep function	No	No	Yes	No

Table 5
Features for result analysis - comparison of codes.

	Tonatiuh	SolTrace	TracePro	CRS4-2
Built-in data processing utility	Yes	Yes	Yes	Yes
Ability to store direction cosine for light source file generation	No	Yes	Yes	No
Data export	Yes	Yes	Yes	Yes
Flux dependent color display of rays	No	No	Yes	No
Display of user selected rays only	No	Yes	Yes	No

Table 2
General characteristics of the four software tools.

	Tonatiuh	SolTrace	TracePro	CRS4-2
License	Open-source	Freeware	Commercial	Home-made
Graphical user interface	Yes	Yes	Yes	No
Execution as a command	Yes	Yes	Yes	Yes
3D view	Yes	Yes	Yes	No
Increasing program's functionality by plug-ins	Yes	No	No	No
Script editor for automation	Yes	Yes	Yes	No
Macro recording utility	No	No	Yes	No

automatically generate heliostat field layouts without the need to specify each heliostat one by one. Like automation functionalities (scripts and macros) this is very useful, strongly simplifying the modeling process of large heliostat fields, typical of commercial solar tower power plants. Also noticeable is that none of the software have the ability to use polar or cylindrical coordinates, 2D and 3D coordinate systems that are natural of radial systems such as most heliostat fields and are present in many heliostat field design and optimization algorithms. Such features can be replicated through scripting, however it is a functionality of interest that once implemented directly in the software could contribute to simplifying some tasks.

The ability to import geometries through CAD files significantly simplifies the modeling of complex geometries. Tonatiuh and TracePro fully support the import of CAD files. Tonatiuh CAD import utility uses the STL file format, while TracePro can use different file formats such as SAT, IGES, STEP, etc. SolTrace does not have a CAD import utility but has a plug-in enabling the use of Trimble SketchUp for free solid modeling as a geometry source.

A common parameter used by researchers and developers when describing CSP optical objects such as heliostat mirrors is the optical error, usually divided between slope errors and other errors such as specularity errors or tracking errors. The ability to set such parameters are available in all tools except TracePro.

The ability to use solar tracking after defining the geometry of the system enables the user to easily perform several simulations for different sun positions without having to perform any action to adjust the orientation of the heliostats, greatly simplifying tasks requiring several simulations at different Sun positions (such as the computation of heliostat field efficiency matrices). Amongst the four software tools under scrutiny, TracePro and SolTrace lack this feature, forcing the user to redefine the system geometry, namely the heliostats aiming point, either manually or through scripting, for each different Sun position.

Commercial central receiver system power plants typically have solar fields with tens of thousands of heliostats, some located at significant distances from the receiver aperture. In these situations, it is necessary to account for atmospheric attenuation of the reflected beam in order to achieve accurate results. Atmospheric transmissivity models, of particular relevance when performing optical analysis of large CRS plants, are available in all tested software but SolTrace and TracePro, with several models available to describe and account for the attenuation suffered by a radiation beam moving through the plant site's atmosphere. By lacking this feature, SolTrace and TracePro cannot correctly account for this effect and should be avoided or used with great care when modeling large CRS plants. In Tonatiuh an exponential equation or a third degree polynomial can be used to model the atmospheric transmissivity, with the coefficients of that equation defined by the users. In addition, there are different predefined models available from the literature: DELSOL [19], MIRVAL [29], Ballestrin [49], Sengupta-NREL [50] and Pitman & Vant-Hull [51]. CRS4-4 also includes the models presented in [19] and [29].

Finally, all four software allow the definition of heliostats of several facets and different geometries for the same system model, including built-in solar position calculators and solar profile models.

Desirably a tool should not only enable a precise and easy modeling of the heliostat field but also have fast tools for simulation and optimization of the field. All three software using ray-tracing algorithms have parallel computing capability, reducing the time penalty introduced by the computational heavy requirement of casting and tracing thousands and millions of rays to achieve accurate results. CRS4-2 is less computationally intensive and thus lacks parallel computing capabilities. As visible in Table 4, Tonatiuh and SolTrace are not specifically designed for optimization or parametric analysis, lacking specific tools for such tasks; however, users are able to carry out both tasks by using scripting and interconnecting them with other software tools.

Finally, Table 5 shows features related with the processing and visualization of simulation and optimization results. The main results from the heliostat field layout simulation can be obtained with all the software tools without the need for external tools. This is an important feature for the users since it simplifies and accelerates the detection of errors or problems with a given simulation or design, as well as the analysis of the optical system results. Anyhow, post-processing using external tools could be necessary for more complex analysis. The ability to export data resulting from the simulations is present in all four tools under analysis (Tonatiuh, SolTrace, TracePro, CRS4-2). However, the type of data available for export differs. For example, the direction cosine for the rays is only available in SolTrace and TracePro without a post-processing step, despite this being a relevant feature, for example, for further use of the simulation results in other simulations or tools. In the case of CRS4-2, a strict comparison of the available features with the other codes is not easy to accomplish. In fact, CRS4-2 is in-house software continuously under development. For this reason, depending on the specific problem to study, ad hoc features are introduced and the needed imported/exported data are correspondingly made available, and, up to now, no care has been devoted to the format of the exported data, since the code has only an in-house usage. Actually, typical output data, like the flux distribution at the receiver (over a grid with spacing defined as input data) or the solar field efficiency (heliostat by heliostat or overall) are available by default on specific output files.

The analysis of Tables 2–5 highlights some of the differences between the software packages functionalities and usability. Depending on the needs of the task to be carried out, the choice of the most appropriate tool could be different.

3.2. Total power simulation

Lists of features, their qualitative analysis and comparisons are relevant as a first guide within the vast set of tools, helping the practitioner to have a clearer picture of the available tools and their general capabilities. However, in order to have a thorough understanding of their capabilities and suitability to perform a given task, and to understand how they compare with similar tools, it is necessary to perform a quantitative comparison based on the tools' functionalities and the results obtained for such task. However, the strict comparison and understanding of the cause of observed differences of heliostat field optical performances, calculated using different tools, is in general a difficult task since each numerical code is based on a specific physical and mathematical model and a number of approximations.

In this section, results from a series of simulations designed to evaluate the total power incident on a receiver are presented for the four tools described in the previous section and a fast estimation tool developed in Matlab. A real test case is proposed and simulations results are compared under a number of different conditions. The goal is to provide information and insight into the comparative behavior of the total power computation capability of the tools for different sun positions and direct normal irradiance (DNI).

3.2.1. Test-case

Detailed information required to accurately model and simulate the heliostat field performance (e.g. heliostat design, canting and field position) is usually unavailable for commercial plants. Consequently, the solar plant used as a test-case is a well-known experimental facility for which detailed information is available – the Small Solar Power System - Central Receiver System (SSPS-CRS).

The choice to simulate the behavior of this plant is connected to a future possibility to have experimental data in order to validate the simulated results. However, the difficulties to obtain experimental data are well known, and they are mainly due to the extremely high values of irradiance on the entrance window. Consequently, it will be essential to carefully consider the accuracy of a real measurement and to know if it allows us to utilize the experimental data in order to evaluate the performance differences between the various software tools.

Located at Plataforma Solar de Almeria in Spain, its heliostat field is

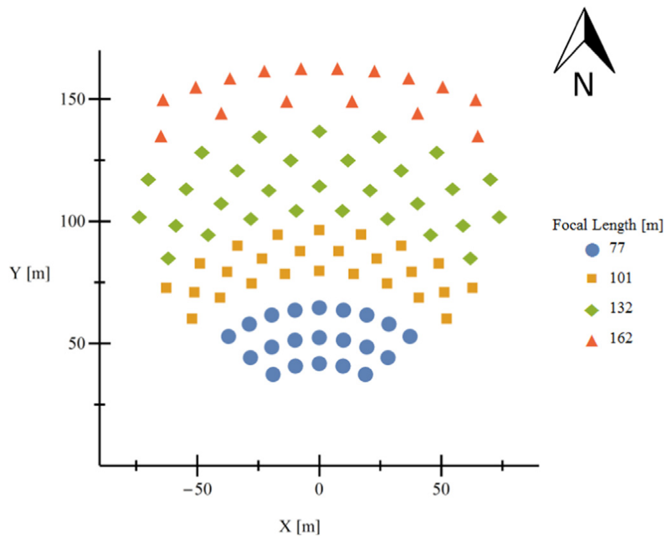

Fig. 2. Field layout and focal length of the heliostats in the SSPS-CRS facility.

formed by 93 heliostats of identical mechanical structure and its tower with a height of 43 m [52,53]. Each heliostat has an aperture area of 39.29 m^2, presenting a rectangular shape sized L_x = 5.766 m and L_z = 6.815 m, being composed of 12 spherical facets. The facets are assembled in such a way as to produce a heliostat with a characteristic focal length. Depending on the distance from the tower, heliostats are grouped according to a specific focal length. The SSPS-CRS field considers four different focal lengths, corresponding to 77, 101, 132 and 162 m, respectively. Fig. 2 illustrates the arrangement of the heliostats with their corresponding focal length [54,55]. Note that the chosen coordinate system considers East to be in the positive x-direction, North in the positive y-direction and the tower coincident with the center of the system of coordinates. It is considered that the heliostats are placed on flat ground with a pedestal height of 3.784 m. Each heliostat is assumed to have an average reflectance of 0.911 and a total optical error of 3.1 mrad at the reflected ray [55].

The receiver aperture is described as a square flat surface (5 m × 5 m – discretized with a uniform grid of 50 by 50 cells), located on top of a tower (which for simplicity is not modeled), with its center corresponding to the Cartesian coordinates (0,0,43.25 m) and tilted 29 degrees with respect to the z-direction.

Table 6 indicates the three different conditions, defined by the solar position and direct normal irradiance value, chosen as scenarios for the SSPS-CRS field performance simulations used to compare the software tools.

The Sun shape model considered in the simulations performed with the different tools is indicated in Table 7. Currently, the CRS4-2 code does not allow the choice of a Sun shape different from a Gaussian distribution, differing from the other analyzed tools, which use a Pillbox model chosen within the available Sun shapes. For this tool, a value of $\sigma = \omega_{max}/4$ has been chosen to ensure that all DNI carried by the solar beam is within the cone used to model the solar radiation.

In this study, taking into consideration that attenuation losses for a small plant like SSPS-CRS are negligible and in order to harmonize as much as possible the assumptions considered in each simulation, it is assumed that the solar radiation does not undergo atmospheric attenuation. This assumption follows the only common option among the analyzed software (since SolTrace and TracePro cannot take into account atmospheric attenuation, as mentioned in Table 3), allowing us to focus the analysis on the differences generated by the tools without having to take into consideration the use of different attenuation models. It must be noticed, however, that SolTrace and TracePro are not the most suitable tools to simulate large CRS plants, unless the atmosphere is noticeably clear, presenting very high atmospheric transmissivity. Otherwise, the attenuation of radiation in the air can significantly affect the intensity of the flux distribution on the receiver without being suitably accounted for by the software.

Table 6
Simulation data for the three scenarios of the tools comparison.

	S1	S2	S3
Azimuth [deg]	180	105	250
Zenith [deg]	14	32	55
DNI [W/m^2]	900	700	400

Table 7
Sun shape model used in the simulations.

	Tonatiuh	SolTrace	TracePro	CRS4-2
Model	PILLBOX	PILLBOX	PILLBOX	GAUSSIAN
θ_{max} [rad]	0,00465	0,00465	0,00465	–
σ [rad]	–	–	–	0.0031

4. Results

Simulations have been performed with Tonatiuh, SolTrace, TracePro and CRS4-2 to compute the total power at the receiver for the SSPS-CRS heliostat field. For each scenario the total power has been calculated and compared for different numbers of casted rays (50,000, 100,000 and 500,000).

The total power corresponding to the three chosen scenarios (S1, S2, S3, defined in Table 6) and calculated with the four software tools is indicated in Table 8. Independently of the scenario and for each software tool, the results obtained present little variation when changing the number of casted rays (variations equal or less than 0,3%), demonstrating result convergence even for small numbers of rays.

Monte Carlo based methods (such as the ones employed by Tonatiuh, SolTrace and TracePro) present inherent statistical fluctuations, thus the total power presented in Table 8 corresponds to the average value obtained from a set of seven runs. The corresponding standard deviations are presented in Table 9. As expected, for the three tools the standard deviation decreases for higher numbers of casted rays. However, it is useful to notice that in all cases the standard deviation is small, so the results are very stable even with low numbers of casted rays. Additionally, it is noticeable that simulation runs performed with the commercial tool TracePro present lower standard deviations than the ones performed with SolTrace and Tonatiuh.

The power collected by the heliostat field can also be estimated using the Matlab code developed by CNR-INO. This calculation is based on statistical considerations of the solar irradiation, so it is not based on ray tracing. Therefore, the results are given once the geometry of the heliostat field is defined. This tool has been applied to the SSPS-CRS field for the verification of its results. The resulting estimations are in good agreement with the results obtained by the other techniques and they are presented in Table 10.

Fig. 3 compares the total incident power on the receiver for each tool. Each subfigure corresponds to the simulations of each scenario as defined in Table 6.

Fig. 3 illustrates the small differences among the results, which are in general good agreement. In particular, the differences between the results of Toniatiuh, SolTrace and CRS4-2 are very small, being almost negligible for practical purposes – the maximum relative difference is less than 1,5%. The TracePro value is similar to the other software results only for the first scenario (S1), while it overestimates the total power for scenarios S2 and S3 by 10–13% relative to the results provided by the other tools. Probably this is due to the fact that TracePro has been utilized outside of its original application domain (industrial

Table 8
Comparison of the total power results for the SSPS field.

Total Power [MW]	Tonatiuh			SolTrace			TracePro			CRS4-2		
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
50×10^3 rays	2,653	1,954	1,103	2,633	1,952	1,091	2,666	2,170	1,228	2,645	1,960	1,107
100×10^3 rays	2,654	1,958	1,104	2,640	1,950	1,093	2,667	2,172	1,228	2,645	1,959	1,107
500×10^3 rays	2,653	1,960	1,104	2,634	1,946	1,092	2,668	2,171	1,228	2,644	1,957	1,104

and architectural applications), with the outcomes depending more significantly on the settings and operation defined by the optical designer.

The Matlab estimation is slightly higher than the values obtained with the other tools (except TracePro for the S2 and S3 cases). Since it is an approximate assessment, it takes into account only the basic features of the solar field, not accounting for all attenuations and losses caused by the numerous components of the SSPS-CRS heliostat field, thus overrating the total power impinging on the target. However, this Matlab code may be useful to rapidly evaluate the total power collected by the target, since the results are close to the values obtained using Tonatiuh, SolTrace or CRS4-2, overestimating them by less than 5%. Such a tool might be very useful for pre-feasibility studies, where there is more room for errors and more demand for speed and ease of use.

The tools under comparison can be applied to the simulation of other CRS optical systems, including large heliostat fields typical of commercial plants. Although the quantitative comparison has been performed for the specific case of the SSPS-CRS facility, its conclusions can be applied to larger fields, since the main physical phenomena remain the same for both small and large heliostat fields, being equally modeled. The main exception is the computation of attenuation losses, which have a larger impact in larger plants, due to the increased distance between the heliostats and the receiver. As seen in Table 3 this is one of the major shortcomings of SolTrace and TracePro, with the other major tools under analysis presenting a set of attenuation loss models.

4.1. Other simulation results

The simulation of the total power incident on the receiver implies the computation of information that can be useful for the analysis of other parameters. In some tools these parameters are automatically computed, being readily available for further characterization and study of the system. This is the case of the receiver's maximum irradiance (directly available in Tonatiuh, SolTrace, TracePro and CRS4-2), its position (Tonatiuh and CRS4-2) and the position of the radiative flux distribution centroid (Tonatiuh, SolTrace and CRS4-2). This section presents and compares these byproducts of the simulation of the total power, which are, themselves, relevant parameters.

The estimation of the maximum irradiance on the target is available in all analyzed tools, with the exception of the Matlab code. Unlike for case for the total power value, relevant differences have been encountered between the tools results. Table 11 and Fig. 4 illustrate these differences. From these results, it is clear that the number of rays needed to achieve convergence for the maximum irradiance value must be higher than in the case of the total power computation, with the exception of the SolTrace results, where it seems that the maximum

Table 10
Estimation of the total power for the heliostat field SSPS.

Total Power [MW]	S1	S2	S3
Matlab estimation code	2,675	1,986	1,136

irradiance value convergence is obtained using fewer rays than in the other tools.

Table 12 and Fig. 5 show the coordinates where the maximum flux is obtained. This information is only readily available for two of the tested software tools, namely Tonatiuh and CRS4-2. It is clear that there are differences in the results obtained, as was already the case for the maximum value. Further work specifically dedicated to this parameter is required to allow for meaningful conclusions.

Table 13 and Fig. 6 report the coordinates of the centroid of the flux distribution map. Considering each tool results individually, it is clear that they present some scattering. This would be expected for Tonatiuh and SolTrace due to the statistical nature of their approach and due to the small differences created between the scenarios, which might lead to flux distribution asymmetries. In fact, the scattering for a given scenario is extremely low in the case of both tools, meaning the main differences of the centroid position are caused by the plotting of results from different scenarios.

The centroid positions obtained with Tonatiuh and SolTrace are very similar, presenting the same pattern with very small variations. However, the same is not true for the results obtained with CRS4-2. This is, of course, a direct consequence of the different representation of the solar radiation, which strongly affects the flux distribution at the receiver. In particular, the use of a Gaussian distribution produces a flux map much more concentrated around its centroid, with a peak value more than double with respect to the pillbox distribution, as shown, for example, in Fig. 7, where a comparison is provided for the case corresponding to scenario S3 with 500k rays.

As indicated in Tables 12 and 13, TracePro directly provides neither centroid coordinates nor maximum flux position; while SolTrace furnishes only the centroid position. It is of course possible to export the photon map information and compute such values, however that is outside of the scope of this work which deals only with results directly generated by the tools.

All the values are very close to the center of the target. This obviously happens because the simulations did not consider tracking errors and hence the spot did not move from the aiming point.

To emphasize the small differences among the tools results, both figures show only a minuscule central portion of the target, which measures 5 m x 5 m.

Table 9
Standard deviation of the total power results for the tools based on statistical ray tracing.

Standard deviation of Total Power results [MW]	Tonatiuh			SolTrace			TracePro		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
50×10^3 rays	0,010	0,004	0,002	0,006	0,006	0,005	0,002	0,003	0,002
100×10^3 rays	0,011	0,005	0,005	0,007	0,005	0,003	0,002	0,002	0,002
500×10^3 rays	0,004	0,004	0,001	0,003	0,002	0,001	0,001	0,001	0,001

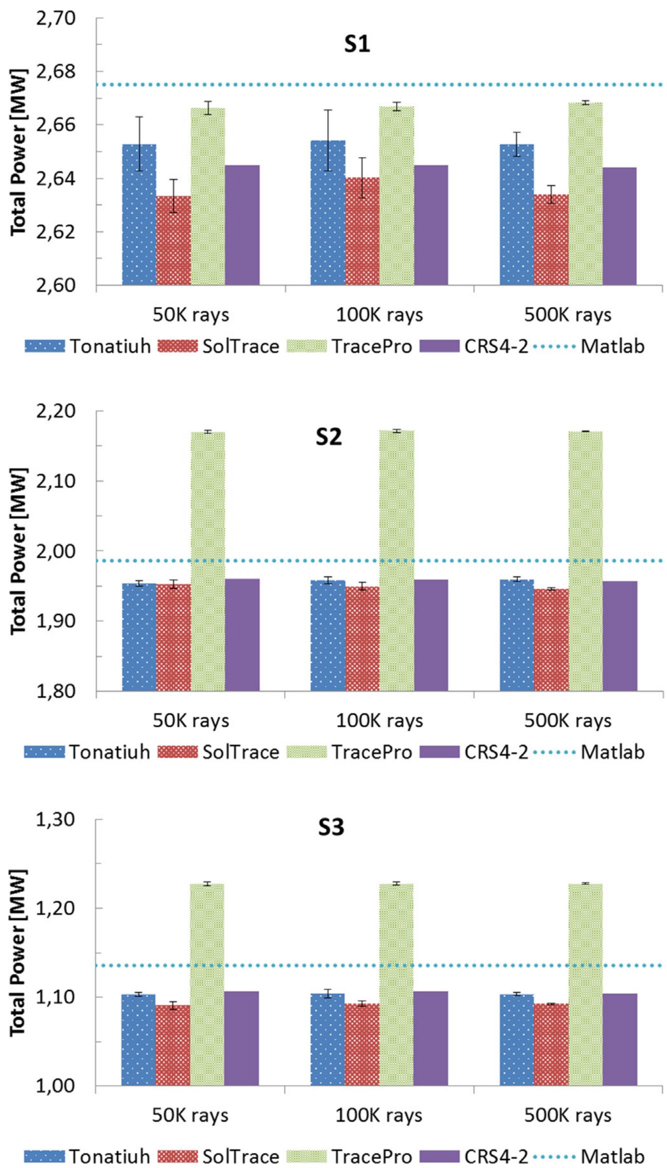

Fig. 3. Total incident power for case S1 (top), case S2 (center) and case S3 (bottom), including standard deviation for the Monte Carlo based tools.

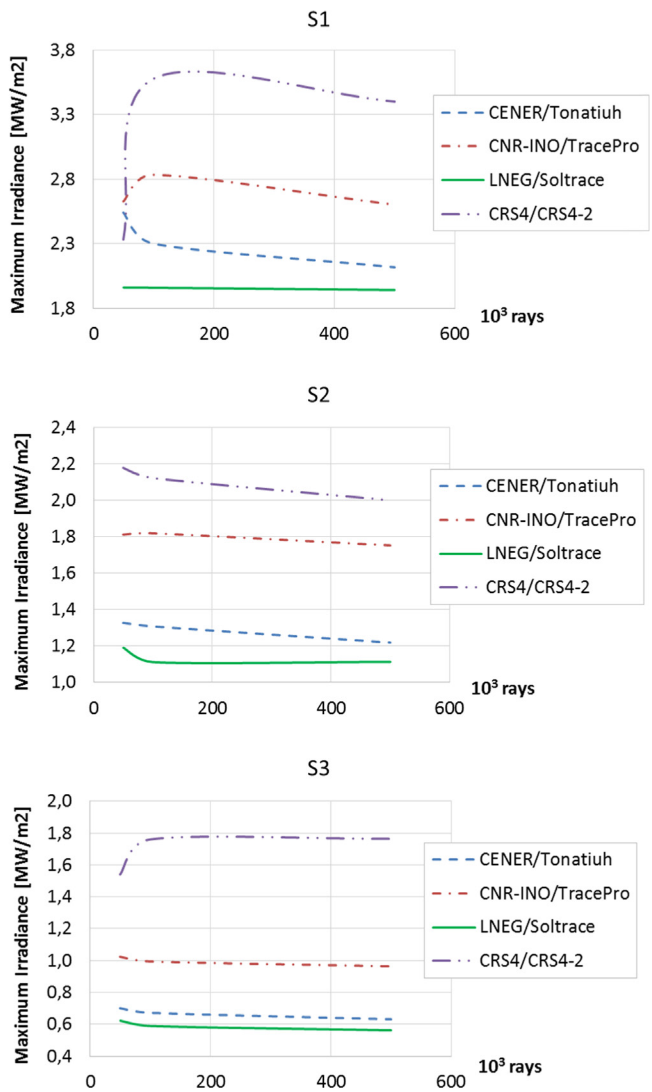

Fig. 4. Maximum irradiance on the target: for case S1 (top), case S2 (center) and case S3 (bottom).

5. Conclusions

The variety of existing software tools able to deal with heliostat fields is large and of various types. This research identified 36 different tools used for optical simulation of CSP (Concentrating Solar Power) systems. A small but representative set of tools was chosen for a comparison based on the authors previous experience and common work developed under the STAGE-STE project ("Scientific and Technological Alliance for Guaranteeing the European Excellence in concentrating Solar Thermal Energy", funded by the European Union Seventh Framework Programme FP7/2007–2013). This comparison considered the application of two freeware software tools developed for CSP applications (Tonatiuh and SolTrace), an in-house developed code (CRS4-2) and a commercial software product (TracePro) for the computation of the total power incident on a CRS plant's receiver. Additionally, the results of a simple Matlab code developed to estimate the total power incident on a target were also included in the comparison.

The four software tools were compared both qualitatively, in terms of their functionalities and usability, and quantitatively, through the comparative analysis of the tools behavior and results for the simulation of the Small Solar Power System - Central Receiver System (SSPS-CRS), located at the Spanish PSA (Plataforma Solar de Almeria).

The qualitative comparison focused on the tools functionalities, comprising general software characteristics, optical model and

Table 11
Comparison of the maximum irradiance for the SSPS-CRS case study.

	Tonatiuh			SolTrace			TracePro			CRS4-2		
Maximum Irradiance [MW/m^2]	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
50×10^3 rays	2,545	1,327	0,700	1,962	1,190	0,623	2,627	1,812	1,022	2,335	2,181	1,538
100×10^3 rays	2,304	1,308	0,672	1,961	1,112	0,5895	2,834	1,819	0,994	3,578	2,124	1,760
500×10^3 rays	2,119	1,220	0,632	1,943	1,113	0,562	2,602	1,753	0,965	3,401	2,000	1,764

Table 12
Comparison of the position of the maximum flux for the SSPS field.

	Tonatiuh			SolTrace			TracePro			CRS4-2		
Maximum flux [m]	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
50 × 10^3 rays												
X	− 0,15	− 0,05	0,05	Not provided			Not provided			0,05	0,05	− 0,15
Y	0,05	0,05	0,15							− 0,05	− 0,15	− 0,15
100 × 10^3 rays												
X	− 0,05	− 0,05	0,05	Not provided			Not provided			− 0,05	− 0,05	− 0,05
Y	0,05	0,05	− 0,05							− 0,05	− 0,05	− 0,05
500 × 10^3 rays												
X	− 0,15	− 0,05	0,05	Not provided			Not provided			− 0,05	− 0,05	− 0,05
Y	0,05	0,05	0,15							− 0,05	− 0,05	− 0,05

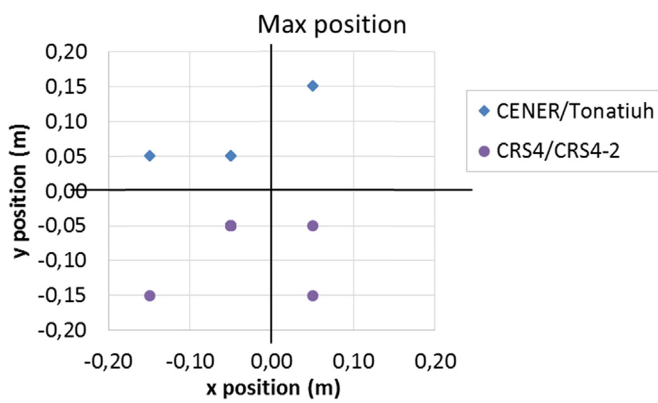

Fig. 5. Coordinates of the maximum flux position.

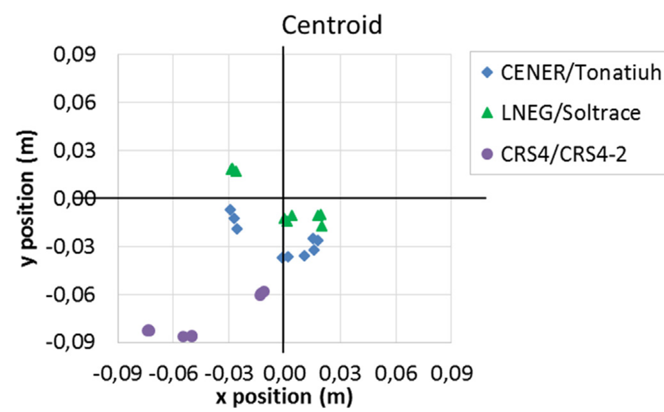

Fig. 6. Coordinates of the centroid point.

simulation, computation and optimization, and analysis of results. All the tools present the basic functionalities required for the simulation of the optical performance of a CRS plant and its heliostat field. However, some differences were identified. These differences are mostly related to the objective and focus behind each tool development.

The results from each tool were quantitatively compared in terms of total power incident on target, but also of maximum irradiance value and position and the flux distribution centroid. The comparison considers three scenarios, defined by the values of Azimuth, Zenith and DNI. For the total power incident on target it is possible to conclude that there is a general agreement among the values achieved with the different tools, with Tonatiuh, SolTrace and CRS4-2 results departing by less than 1,5%. TracePro results are also close to the other software tools for the first scenario under analysis. However, for the other two scenarios, its results exceed by more than 10% the ones obtained with the other three software tools. This is probably due to a usage of the TracePro software outside of its original application domain (lighting simulation for industrial and architectural applications), resulting in a stronger dependence of the results on the settings and operation defined by the user. Another interesting result is the convergence of the total power values for a relatively small number of rays.

Results for the maximum irradiance present the largest differences between the tools and unlike for the total power the simulations seem to require a higher number of casted rays to achieve convergence of the results, except for the SolTrace software.

Some software tools do not directly provide the position of the centroid of the flux distribution map or the coordinates of the maximum flux point. The centroid coordinates are the most fluctuating also inside the results of a single tool, but the points are always located near the center of the receiver, as expected for the given geometry and studied scenarios.

Finally, the preparation and execution time was not considered, because each group utilized their own hardware, running each tool separately, thus introducing variability in the execution time due to the influence of the hardware configuration.

In general, it is not useful to compile a ranking of the examined

Table 13
Comparison of the centroid position for the SSPS field.

	Tonatiuh			SolTrace			TracePro			CRS4-2		
Centroid [m]	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
50 × 10^3 rays												
X	0,01	0,02	− 0,03	0,00	0,02	− 0,03	Not provided			− 0,05	− 0,07	− 0,01
Y	− 0,04	− 0,02	− 0,02	− 0,01	− 0,02	0,02				− 0,09	− 0,08	− 0,06
100 × 10^3 rays												
X	0,00	0,02	− 0,03	0,00	0,02	− 0,03	Not provided			− 0,06	− 0,07	− 0,01
Y	− 0,04	− 0,03	− 0,01	− 0,01	− 0,01	0,02				− 0,09	− 0,08	− 0,06
500 × 10^3 rays												
X	0,00	0,02	− 0,03	0,00	0,02	− 0,03	Not provided			− 0,05	− 0,07	− 0,01
Y	− 0,04	− 0,03	− 0,01	− 0,01	− 0,01	0,02				− 0,09	− 0,08	− 0,06

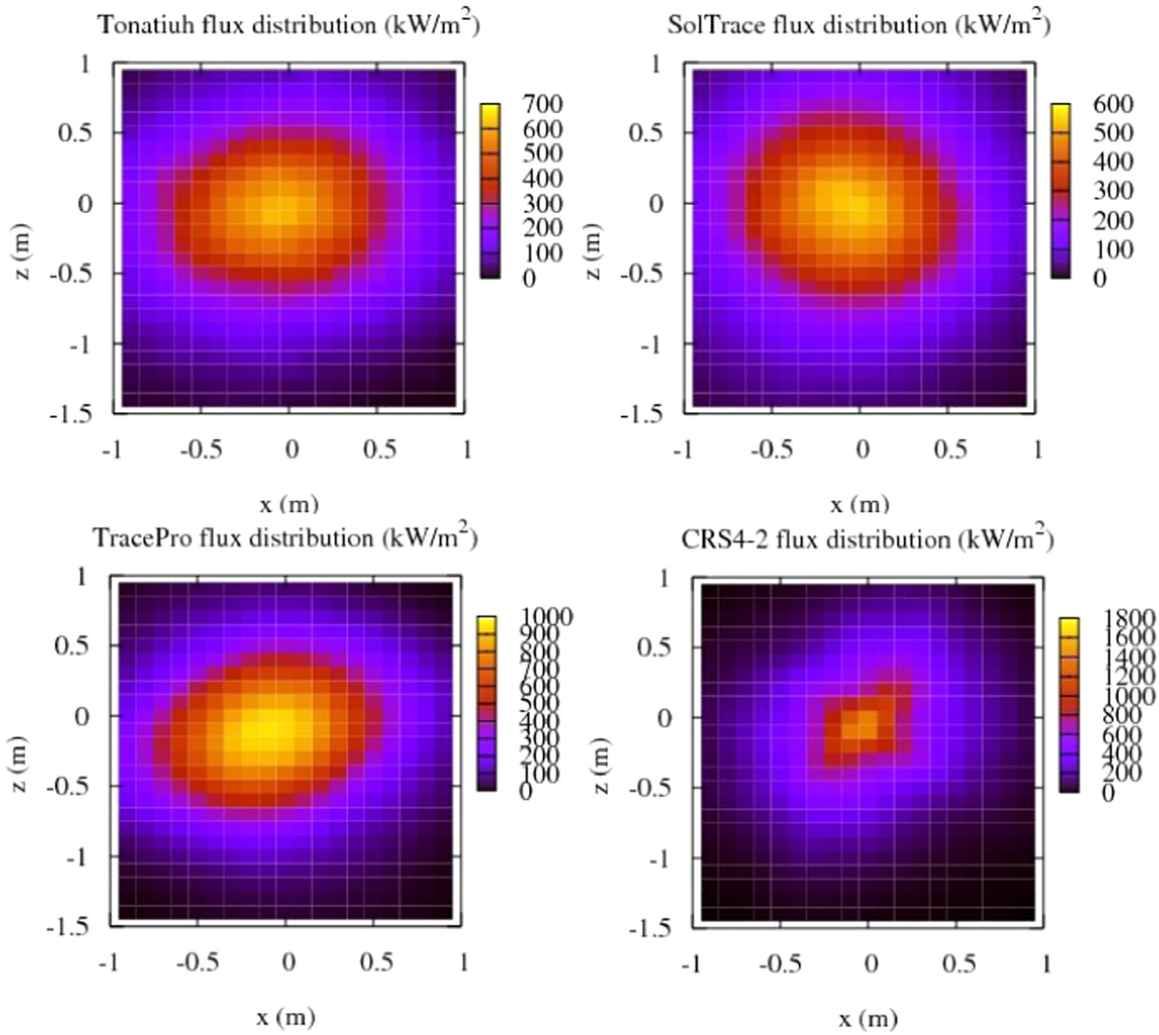

Fig. 7. Comparison of flux distribution at the receiver, corresponding to the scenario S3 with 500k rays, for Tonatiuh (top left), SolTrace (top right), TracePro (bottom left) and CRS4-2 (bottom right).

tools, but it can be stated if some of them provide more features or better results than the other. For every specific application, one tool could be more suitable than others, depending on designer preferences or on the task at hand. For example, SolTrace is a suitable tool for the simulation of small CRS plants, however, less so for large plants due to the lack of atmosphere transmittance models, it being better to use instead tools with such models like Tonatiuh or CRS4-2. Anyhow, the analyzed tools, particularly SolTrace, Tonatiuh, CRS4-2 and the Matlab code all yield similar results, under the analyzed conditions and scenarios, for the total power simulation results. There are entry costs for each tool (in terms of time and effort to move through each software learning curve), thus, before choosing a specific software, users should duly perform a review of the available tools and their characteristics with the help of information akin to that presented in this work.

The present work can be further improved by including real data measured on an actual heliostat field in order to perform a thorough comparison with the results obtained from the analyzed software tools, also enabling their validation. The potential opportunity of having practical data measured on the SSPS-CRS facility at PSA is the main reason for having selected this plant as the test-case for the comparison, which should be the next evolution of this work. Besides, it would be interesting to expand the analysis by including more software tools in the comparison, enlarging the working group and the collaborations.

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