A review of tools dedicated to the modeling and simulation of concentrating solar systems

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Received:11 May 2023; Accepted: 22 July 2023; Published: 03 August 2023

Abstract:

The high growth in the installed capacity of concentrating solar systems requires the use of suitable simulation and modeling tools in order to analyze accurately the various technical and economic parameters that characterize this technology. These parameters are mandatory to help both engineers and policymakers make the right decisions for profitable investments. This article provides a comprehensive review of the tools dedicated to modeling and simulating various concentrating solar systems. The tools are described and arranged into two groups: tools for optical and thermal analysis and tools for complete system analysis. Case studies on the use of each tool to model a concentrating solar power system are presented. Several recommendations and guidelines are provided to assist the engineers and researchers in selecting the appropriate tools to model and simulate a specific concentrating solar system.

Highlights:

- Tools dedicated to investigating concentrating solar power systems are reviewed.
- A case study on the use of each tool is presented.
- Recommendations to select the most suitable tools are provided.

Keywords: concentrating solar power; CSP modelling; CSP simulation; CSP software.

DOI Number: 10.48047/nq.2023.21.6.nq23164 NeuroQuantology2023;21(6): 1630-1651

Word Count: 7136

1. Introduction

Solar energy is a vast, inexhaustible, and clean resource. It can be used for heating and cooling, for power generation, and for a variety of other commercial and industrial uses. Solar energy represents a clean alternative to fossil fuels, with no air and water pollution, no global warming, no risks of electricity price spikes, and no threats to our public health. Thus, the use of concentrating solar power (CSP) to produce electricity, heat, water desalination, and so on is attracting a lot of attention day-to-day.

Because of the high capital expenditure (CAPEX) and the complexity of the mathematical models required in both optical and thermal analyses of CSP systems **[1,2],** scientists and engineers have thought to use simulation tools to investigate and advance their performance. To facilitate the thermal and optical analysis of CSP systems, numerous codes and software have been developed, including ASAP, Biomimetic, Campo, CRS4-2, (Win) DELSOL, HELIOS, HFLCAL, HFLD, HOpS, NSPOC, SoFIA, SAM, SOLFAST, SolTrace, SPRAY (MIRVAL), STRAL, and Tonatiuh. **Cruz et al. [3]** presented a review of software that can be used to analyze the optical performance of the heliostat field of the central receiver system. The authors highlighted the lack of open tools for the optical performance of the central receiver systems. **Yellowhair et al. [4]** evaluated the performance of four optical codes for modeling and analyzing complex solar receiver geometries, namely DELSOL, HELIOS, SolTrace, and Tonatiuh. The authors concluded that SolTrace and Tonatiuh are more flexible for modeling complex receiver geometries, whereas DELSOL and HELIOS are limited to standard receiver geometries. **Clifford K. Ho [5]** reviewed the software and codes for the analysis of CSP systems. The author provided a summary of the codes with recommendations regarding the use and retention of the codes. **Collado et al. [6]** reviewed the heliostat field layouts yielded by Campo. The authors considered Gemasolar as a case study and presented a comparison between the real data of Gemasolar and the estimated data by Campo. Wagner and Wendelin [7] presented a detailed description of SolarPILOT including its algorithms and its advantages over DELSOL. The author also gave a summary of power tower modeling software, including generation of heliostat layouts, characterization of the optical performance, prediction of the annual plant electricity production, and maintenance status of the code. A comparative review of the most popular tools for the analysis and design of heliostat fields was presented by D. **Jafrancesco et** al **[8]**. The author chose three representative software, including Tonatiuh, SolTrace and CRS4-2 and tested their performance against the data of the test facilities located in Almeria, Spain. They reported that the results of the targeted tools were much closer and that the final selection of the appropriate software depends on the application and the specific needs of the users. **Noone et al. [9]** introduced a new code to design the heliostat field of the central receiver system. The code is used to optimize the PS10 heliostat field. Regue et al. [10] used Soltrace and Ansys-CFX software to carry out a numerical simulation of fluid flow and conjugate heat transfer in a solar thermal parabolic trough collector. D. Jafrancescoet al. [11] compared Tonatiuh, SolTrace, TracePro and CRS4-2 by focusing on functionality and usability. A quantitative comparison is carried out providing simulation results for a test-case. The authors found that the estimated total power is in good agreement across most tools. The total power values are very close for Tonatiuh, SolTrace and CRS4-2. M. Sheikholeslami and Z. Ebrahimpour [12] have used Soltrace and Ansys-Fluent to investigate the performance of linear Fresnel collector. The authors compared the local concentration ratio estimated by the two software and found good agrement.

The review of the previously published studies showed that few papers have reviewed the code and software for the modeling and simulation of CSP systems. Some published papers have just presented the capabilities of a few codes. Indeed, there is norecent published paper that presented a review of the tools dedicated to CSP systems. To the knowledge of the authors, the code and software used to model and simulate parabolic trough, linear Fresnel, and dish have not been reviewed since 2008. The rapid growth in the installed capacity of CSP systems requires simulation and modeling tools to calculate accurately their technical and economic data, which are mandatory to help engineers and policymakers make the right decisions for profitable investments. This paper aims to fill the gap with a comprehensive review of the tools and codes dedicated to modeling and simulating various CSP systems. The paper thoroughly reviews the CSP tools by providing a case study on the application of each tool. The next section describes the tools dedicated to the optical and thermal modeling of CSP systems. Section 3 presents the tools dedicated to modeling the complete solar thermal power systems. Section 4 provides a case study on the use of each reviewed software to give the researcher a good idea of the capabilities of each software in the field of CSP modeling and simulation. Section 5 provides guidelines and recommendations to help the researchers select suitable simulation tools for their applications. The last section presents the main conclusions.

2. Tools for optical and thermal analysis

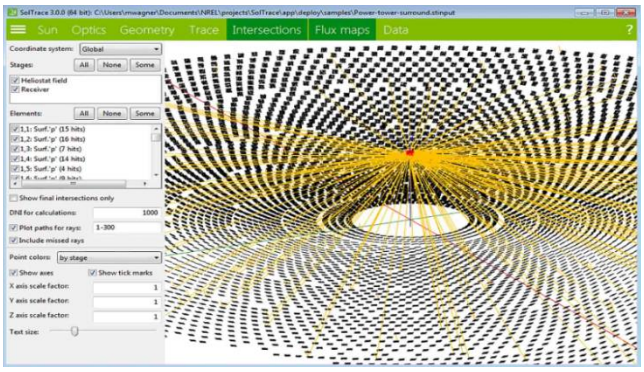
This section gives an overview of the tools dedicated to the optical and thermal modeling of different types of CSP collectors.

2.1. Soltrace

Soltrace is an available open-source software developed by the National Renewable Energy Laboratory (NREL) in 2003. It has been written based on the Monte Carlo Ray Tracing (MCRT) algorithm to model CSP systems and analyze their optical performance. The code was developed at the beginning with Pascal-based software and then moved to C++ **[13]**. The need for more complex CSP system modeling than could be modeled with existing tools led to the design of this efficient software **[14-17]**.

The software simulates the path of a predefined number of rays between the sun and a defined system while respecting the energy distribution corresponding to the shape of the sun. It takes into account various optical interactions. Soltrace was designed to simulate parabolic trough collectors, linear Fresnel systems, dishes, and power tower systems. It displays data as scatter plots and flux maps and can save data for processing with other software. The system can be modeled through a series of stages. The first stage is the only one to interact with the sun. The sun is defined by the shape of its profile and its position. The shape of the sun can have three types of profiles. A Gaussian profile, a pillbox profile, or a profile to be defined by the user. Once the system is defined, we can select any number of rays (accuracy increases with this value) to be simulated through the system **[13]**.

The simulation under Soltrace gives data results as scatter plots and flux maps and can save data for processing with other software. The visual rendering allows checking the orientation of the elements, the angle of incidence of solar rays, and the convergence of reflected rays. The modeling of the power tower system is shown as an example in **Figure 1**.



Coordinate system: Global

Stages:
☑ Heliostat field
☑ Receiver

Elements:
☑ 1,1: Surf.'p' (15 hits)
☑ 1,2: Surf.'p' (16 hits)
☑ 1,3: Surf.'p' (7 hits)
☑ 1,4: Surf.'p' (14 hits)
☑ 1,5: Surf.'p' (4 hits)

☐ Show final intersections only
DNI for calculations: 1000
☑ Plot paths for rays: 1-300
☑ Include missed rays
Point colors: by stage
☑ Show axes ☑ Show tick marks
X axis scale factor: 1
Y axis scale factor: 1
Z axis scale factor: 1
Text size:

Fig. 1. SolTrace user interface (version 3.0) **[13]**.

2.2. Tonatiuh

Tonatiuh is free and open source software for optical design, simulation, and analysis of all CSP systems, including both reflection and refraction applications. It has been developed by the National Renewable Energy Centre in Spain and the University of Texas at Brownsville in collaboration with the NREL. Tonatiuh is an object-oriented program developed in the C++ language based on the MCRT algorithm and has the capability of parallel CPU processing. It has been provided with an informative and easy-to-use interface (see **Figure 2),** making the package one of the most preferred simulation tools by the researchers and developers of CSP systems **[1–4]**.

The program accuracy was validated using experimental data obtained from CIEMAT’s Plataforma Solar de Almería (PSA) in Spain and the Mini-Pegase CNRS-PROMES central receiver test facility in France. The flux distribution results of Tonatiuh showed very good agreement with the experimental data of CNRS-PROMES. However, the lack of some optical experimental data, such as sunshape's circumsolar ration and atmospheric transmissivity, resulted in a lack of clarity in the flux distribution results when compared to CIEMAT measured data [5, 6]. Also, a comparison between Tonatiouh and the well-known software SolTrace was conducted by Blanco et al. **[24]**. Three technologies were used, including parabolic dishes, parabolic troughs, and solar furnace systems. The maximum deviation between the two software was found to be no more than 3% in the three different technologies **[24]**.

The software structure has a plug-in tool to allow the developers to easily extend the program features. There are more than 15 shapes in the internal library of the software in order to define the system geometry, and more than 7 materials can be used to make the optical simulation more realistic. In addition, it has the capability to import CAD files for more complex geometries and has an option to simulate the systems statically or follow the sun's position by adding a tracking system to the model. Flux mapping and distribution can be visualized using the built-in visualizer of the program and can be generated by external tools such as Python or Mathematica **[8]**.

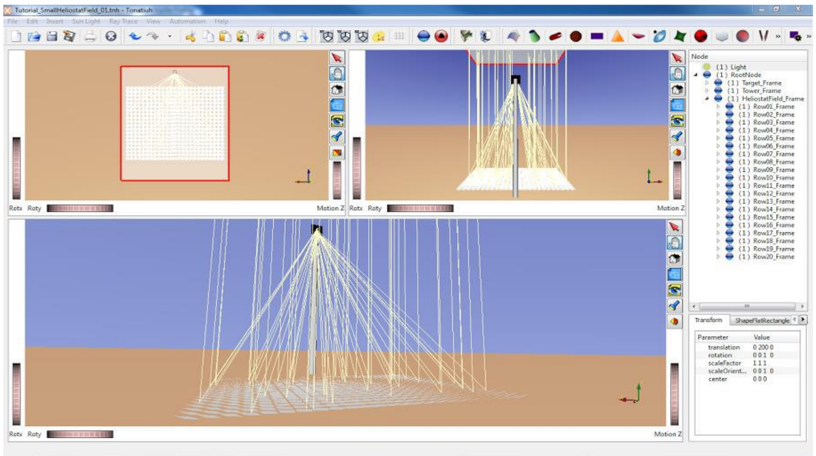


Fig 2. Tonatiuh user interface.

2.3. Solar PILOT

Solar PILOT software is dedicated to the design and estimation of central receiver system performance. It was developed as an extension to DELSOL3 **[7]** with several improvements in the heliostat field layout, characterization, parametric simulation, plotting, and optimization of the central receiver system **[7]**. It applies the analytical model to individual heliostat images using the analytical flux image Hermite series approximation [7]. In addition, it uses an MCRT technique for the optical modeling of the solar receiver **[25]**. **Figure 3** shows the user-interface of SolarPILOT. Among the applications of SolarPILOT are [25]:

- Heliostat field layouts, receiver geometry, and tower height,
- Simulate receiver flux profiles
- Execute parametric simulations
- Optimize the heliostat field layout and receiver dimensions
- Calculate heliostat field cost.

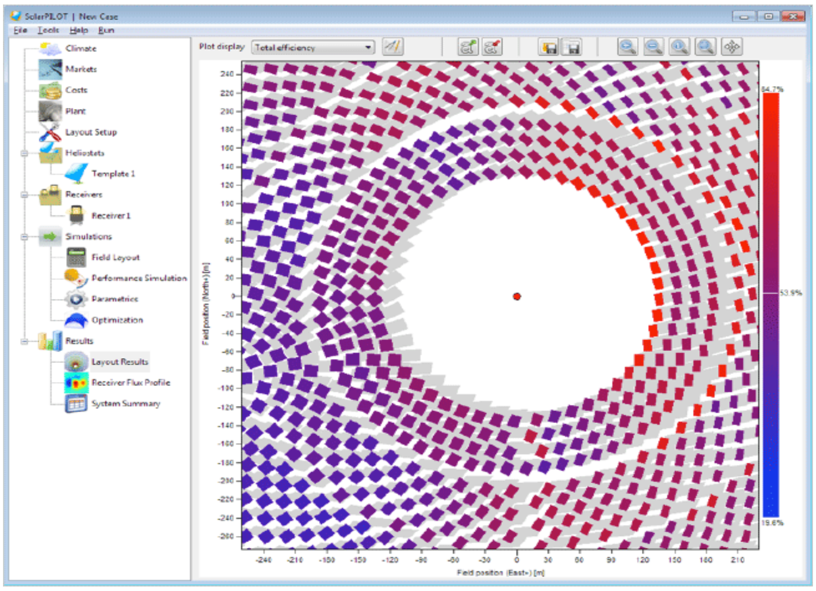


Fig.3. Solar PILOT user interface.

2.4. Ansys Fluent

ANSYS is a technology-leading software for numerical simulation in product development. It covers all the steps necessary for a simulation: geometric processing, meshing, resolution, result processing, and optimization. It offers a multi-physics computing platform integrating fluid and structural mechanics, electromagnetism, thermal processes, as well as the simulation of systems and circuits. Workbench is the central simulation environment with a uniform user interface of ANSYS and it simplifies the input of calculation problems **[26]**.

Regarding CSP applications, all numerical simulations of CSP systems can be carried out using Ansys Fluent CFD software. Ansys Fluent’s physical modeling allows researchers to study the effects of advanced turbulence models, multiphase flows, mass and heat transfer, and much more, which helps researchers to improve both shape and performance. The modeling of the parabolic trough system is shown as an example in **Figure 4** **[27]**.

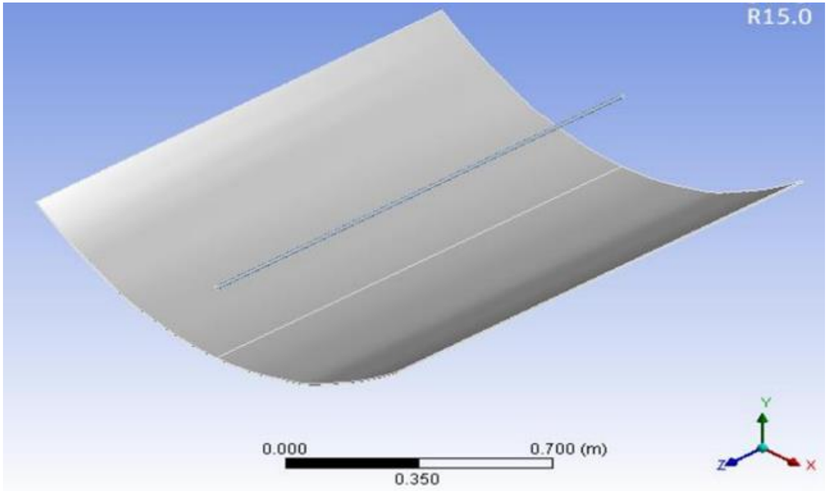


Fig. 4. Parabolic trough simulated in ANSYS software (version 15.0) **[2]**.

Fluent or comparable CFD software (CFX, Star-CCM+, OF, etc.) is better suited for turbulence, heat and mass transport, chemical processes, combustion, multiphase flows, and so on. However, it should be noted that Ansys Fluent contains a much broader set of turbulence models, multiphase flows, reactive flows, and integration capabilities with other numerical simulation software packages. Whereas, Polyflow is appropriate for viscous and viscoelastic flows and fluids with complicated rheology. This is suitable for a wide range of applications, including polymers, glass, plastics, rubber, and paints.

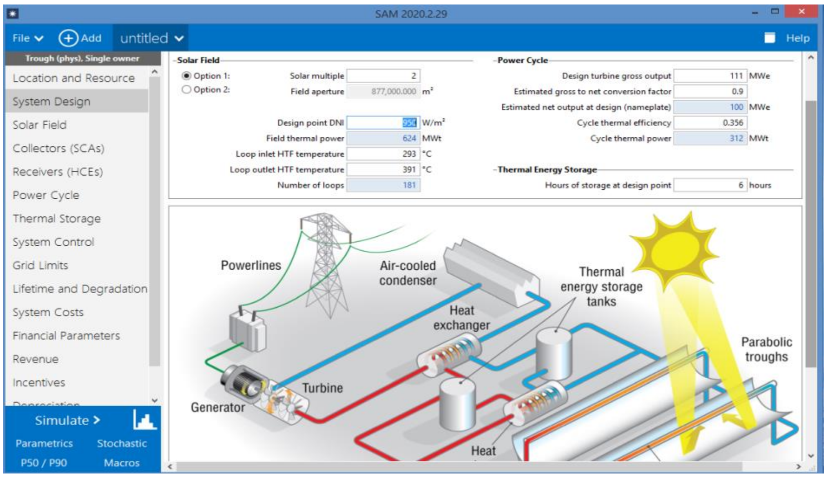
3. Tools for system analysis

In this section, a description of the software dedicated to analyzing the whole system of the CSP plants, from the solar field to the generated energy.

3.1. System advisor model (SAM)

SAM is a technical, economic, and financial simulation tool for renewable energy systems, including CSP systems. It is free open-source software developed by the NREL for researchers, designers, and investors in the renewable energy sector. SAM predicts the hourly, monthly, and annual performance of parabolic trough, central tower, linear Fresnel, and parabolic dish technologies with and without thermal energy storage. The graphic user interface of the software is well designed, making it a friendly and easy-to-use simulation tool **[28,29]**.

SAM model of a CSP project starts by specifying the weather file of the site, whether it is from the SAM database or from an external source. The design parameters of CSP components are assigned, including solar field, power block, and system storage. SAM provides an economic model of Power Purchase Agreement (PPA) and retail electricity sell. SAM can simulate and predict the detailed technical performance of the systems, including electricity injected into the grid and energy losses of optical, thermal, and electrical components. Then, the economic outputs such as LCOE and payback period are predicted based on the installation, operation, and maintenance costs that are specified as input variables in the software **[28]**. The typical interface of SAM is shown in **Figure 5**.



Solar Field
● Option 1: Solar multiple 2
○ Option 2: Field aperture 877,000.000 m²
Design point DNI 950 W/m²
Field thermal power 624 MWt
Loop inlet HTF temperature 293 °C
Loop outlet HTF temperature 391 °C
Number of loops 181

Power Cycle
Design turbine gross output 111 MWe
Estimated gross to net conversion factor 0.9
Estimated net output at design (nameplate) 100 MWe
Cycle thermal efficiency 0.356
Cycle thermal power 312 MWt

Thermal Energy Storage
Hours of storage at design point 6 hours

Fig. 5. SAM user interface (version 2020.2.29)

3.2. Trnsys

Trnsys is a simulation tool for time-dependent energy systems such as solar energy applications, cooling systems, and energy building analysis. It was developed by the Solar Energy Laboratory, the University of Wisconsin, in collaboration with the University of Colorado. Trnsys was originally designed for solar thermal applications and then developed to include a wide range of transient energy systems.

The software consists of two main parts: the first one is the system solver, also called the engine of the software. This part is responsible for connecting different components of the system; reading input files; solving the mathematical model using an iterative technique; finding conversion solutions; and visualizing the results. The second part is an add-on library of components called "type." Each type is an independent mathematical subroutine that represents the physical phenomena of the subsystems of any energy application **[30]**.

Regarding the CSP application, Trnsys has a solar library, which includes some solar concentrating collectors such as parabolic trough and linear Fresnel. These components can be integrated with other components in different Trnsys libraries in order to build a whole CSP plant. In addition, the German Aerospace Centre (DLR) developed the Solar Thermal Electricity Components (STEC), a Trnsys library dedicated to CSP applications. The STEC library includes Rankin and Bryton cycle components in addition to the CSP solar field system (central receiver, heliostats, parabolic trough, and linear Fresnel) **[31]**. **Figure 6** shows the simulation studio of Trnsys (case: modeling of a hybrid solar gas turbine).

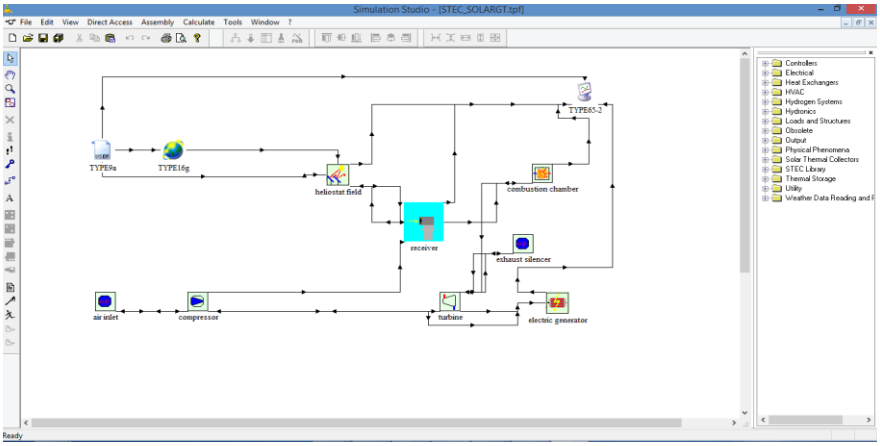


Fig. 6. Trnsys user interface (version 17).

3.3. RET Screen

RET Screen is a study tool and software developed by the Canadian Ministry of Natural Resources. **[32]** This simulation tool makes it possible to manage clean energy for the feasibility analysis of energy efficiency and renewable energy projects. RETScreen Expert is an advanced premium version of the software and is available in Viewer mode completely free of charge. Simulation through RET Screen provides an assessment and optimization of the technical and financial viability of potential renewable energy projects, in addition to measurements of the actual performance of their installations **[33, 34]**. It was conducted with an easy-to-use interface (see **Figure 7**).

Fig 7. Retscreen user interface **[35]**

Retscreen provides a standard five-step analysis as follows [36]:

1.a) Energy analysis, b) cost analysis, c) emissions analysis, d) financial analysis, e) decision-maker sensitivity/risk analysis

RETScreen software provides users with access to climate data from ground monitoring stations and NASA satellite data. The NASA Forecast Project [37] provides NASA satellite climate data for any location on the planet for use with RETScreen.

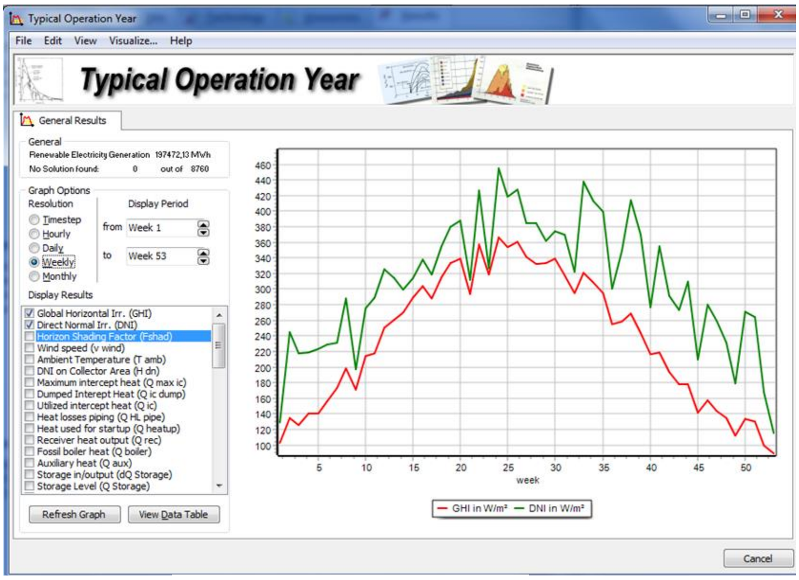
In Retscreen software, the Benchmark Database collects indicative minimum and maximum power generation costs (LCOE) of different types of power generation systems; these costs arise from the installation technology, location, and operation and maintenance (O&M) costs of typical power plants **[38]**.

With the Retscreen simulation tool, the economic feasibility and assessment of the CSP plant were realized for four sites in the Sultanate of Oman. For example, among the capabilities of this software is, for example, an analysis of a given CSP project in terms of energy and economic impact assessment **[39]**. In addition, with this simulation tool: the models of CSP installations of different capacities (5, 10, 25, 75, and 100 MW) were simulated and evaluated in Namibia **[40]**.

3.4. Greenius

Greenius simulation tool is free, open-source software for performing multiple calculations. For accuracy, the user should specify detailed performance and cost data for all subsystems, like CSP technologies. The Solar Research Institute of DLR, located in Köln, Germany, has developed Greenius **[41-43]**.

The technical-economic evaluation of hybrid CSP plants is one of the strengths and capabilities of this software. The user-friendly interface and calculation performance were the primary axes for this software's development [42], [43]. The interface of Greenius is presented in **Figure 8**.



General
Renewable Electricity Generation 197472,13 MWh
No Solution found: 0 out of 8760

Graph Options
Resolution
○ Timestep
○ Hourly
○ Daily
● Weekly
○ Monthly

Display Period
from Week 1
to Week 53

Display Results
☑ Global Horizontal Irr. (GHI)
☑ Direct Normal Irr. (DNI)
☐ Horizon Shading Factor (Fshad)
☐ Wind speed (v wind)
☐ Ambient Temperature (T amb)
☐ DNI on Collector Area (H dn)
☐ Maximum intercept heat (Q max ic)
☐ Dumped Interept Heat (Q ic dump)
☐ Utilized intercept heat (Q ic)
☐ Heat losses piping (Q HL pipe)
☐ Heat used for startup (Q heatup)
☐ Receiver heat output (Q rec)
☐ Fossil boiler heat (Q boiler)
☐ Auxiliary heat (Q aux)
☐ Storage in/output (dQ Storage)
☐ Storage Level (Q Storage)

Fig 8. Greenius user interface.

New technologies and features are continuously updated and enriched in this simulation tool. **[44]**. Solar thermal power plants can be studied by Greenius. In recent years, models for detailed simulations of several other renewable energy technologies have been added to the Greenius, including non-concentrated solar collectors, photovoltaics, and wind farms **[44, 45]**.

CSP systems are the main axes of simulation by Greenius software. Greenius provides an economic assessment of the CSP plants, taking into consideration the investment costs as well as the operation and maintenance costs. The key economic feasibility parameters of each CSP system, such as the LCOE and internal rates of return (IRR) can be calculated by Greenius **[46]**. In addition, the user can select the operational strategies such as power supply load limits as well as the state of the thermal energy storage of CSP systems **47]**.

4. Case studies

This section shows the application of the above-cited software to model and simulate various CSP systems. To provide useful information, each software has been used to model a real case of operational CSP systems.

4.1. Modeling of the Luz LS-3 parabolic trough solar collector using Tonatiuh software

In the case of Tonatiuh software, the Luz LS-3 parabolic trough solar collector is used as a case study. The input parameters used in the simulation are presented in Table 1. Tonatiuh needs to define the sun shape, including Pillbox or Buie, and the geometry of the reflector and receiver, including their optical properties.

Table 1. Input parameters of the Luz LS-3 parabolic trough collector.

Parameter	**alue**	**nit**
Receiver length	12	m
Collector width aperture	5.75	m
Focal distance	1.71	m
Receiver internal diameter	0.066	m
Receiver external diameter	0.07	m
Glass cover internal diameter	0.109	m
Glass cover external diameter	0.115	m

Reflected surface reflectivity	0.93	-
Glass cover transmittance	0.956	-
Receiver absorptance	0.906	-
Glass cover absorptivity	0.0225	-

Tonatiuh provides a simulation of rays tracing from the sun, as illustrated in **Figure 9**. Flux distribution and intensity can also be provided by Tonatiuh, including some useful statistics such as average flux on the receiver surface and maximum flux point (see **Figure 10**).

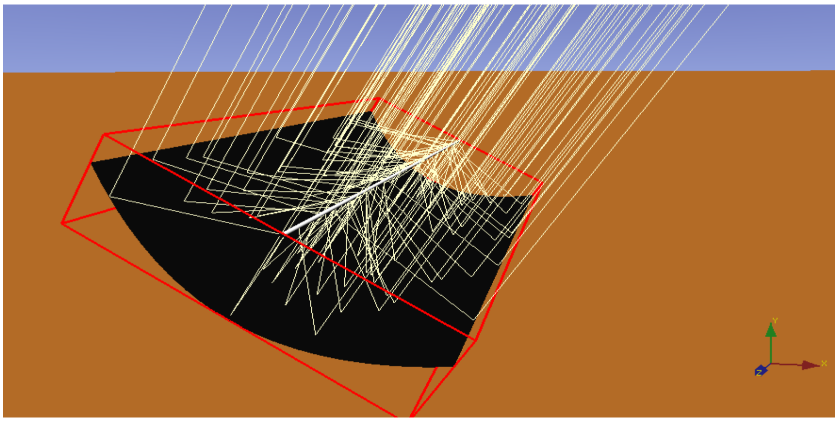


Fig. 9. Ray tracing simulation of Luz Ls-3 using Tonatiuh.

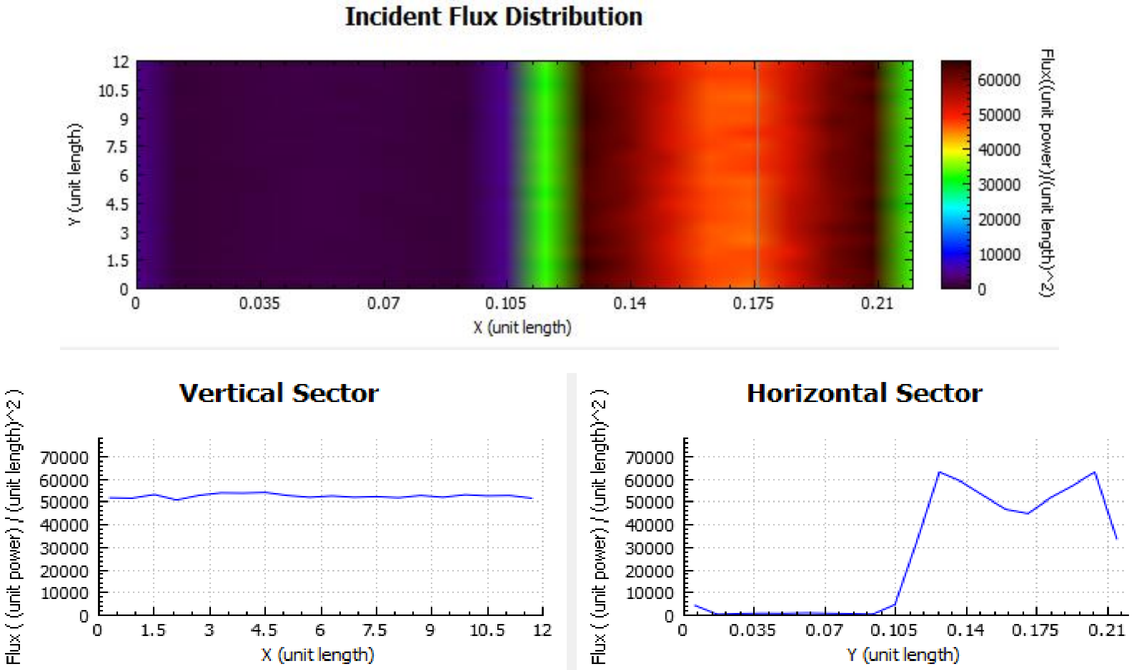


Fig. 10. Flux distribution and intensity on the receiver.

4.2. Modeling of Luz LS-2 parabolic trough solar collector using Soltrace software

Soltrace is used to model the heat flux distribution on the absorber tube of LS2. The technical data of LS-2 is given in **Table 2**. **Figure 11** provides the distribution of the heat flux on the circumference of the absorber tube for various incidence angles. As can be seen, the heat flux is not uniform on the absorber surface. Besides, the lower the incidence angle, the higher the heat flux.

Table 2. Technical data of LS-2 collector.

Parameter	**Value**	**Unit**
Receiver length	7.8	m
Collector width aperture	5	m
Focal distance	1.84	m
Receiver internal diameter	0.066	m
Receiver external diameter	0.070	m
Receiver tube thermal conductivity	54	W/m. K
Glass cover internal diameter	0.109	m
Glass cover external diameter	0.115	m
Concentration ratio	22.42	-
Reflected surface reflectivity	0.93	-
Glass cover transmittance	0.956	-
Receiver absorptance	0.906	-
Shape factor	0.92	-
Receiver emittance	0.14 at 350°C	-
Glass cover absorptivity	0.0225	

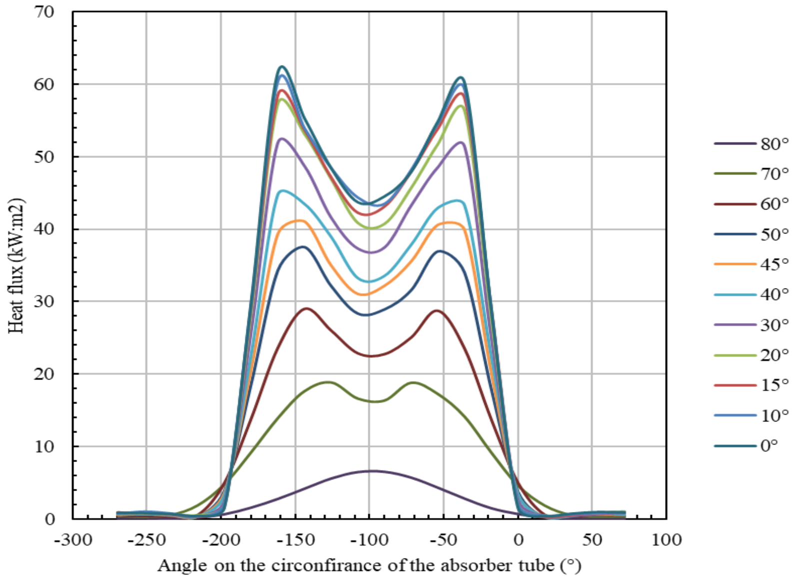
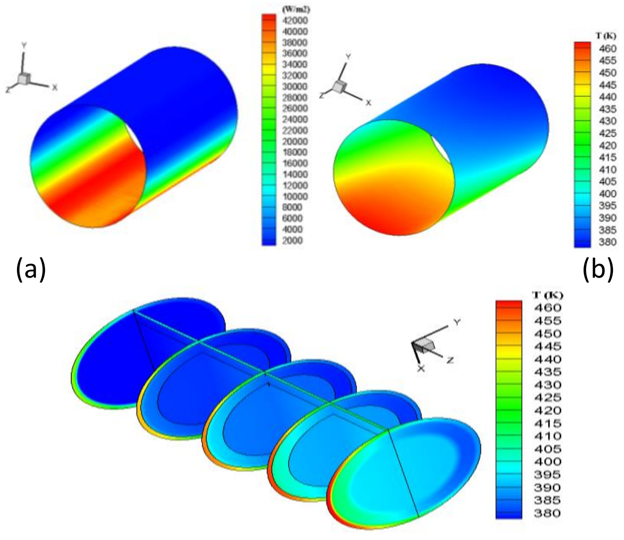


Fig. 11. Heat flux distribution on the absorber tube for various incidence angles.

4.3. Modeling of the heat flux on the absorber tube using ANSYS

In order to study the thermal performance of the absorber tube using ANSYS, we have chosen the solar parabolic trough collector with air in the annulus space, which has been tested in SNL by **Dudley et al. [48]**. **Figure 12** shows the temperature distribution on five cross-sections for every two meters of the receiver. It can be seen that the temperatures of both the absorber and fluid increase along the axial direction lines. Whereas **Figure 12.a** shows the heat flux distribution on the outer surface of the tube absorber in the ideal case (incidence angle of 0°), Figure **12.(b and c**) show the temperature distribution of the absorber tube and the HTF on the same five cross-sections, respectively. It can be seen that the temperatures of both the absorber and fluid increase along the axial direction lines.



(a) (b)

(c)

Fig. 12. Heat flux and temperature distribution on the absorber tube for an incidence angle of zero.

Modeling of ANDASOL 1 using Greenius Software

Andasol 1 is 50 WMe parabolic trough solar thermal power plant located in Aldeire, Spain. The solar field consists of EuroTrough 2008 collectors with Schott PTR70 absorber tubes. The thermal energy storage system is composed of two molten salt tanks. The power block is a Siemens SST-700 steam turbine **[45]**.

As shown in **Figure 13**, the three main components of the Andasol power plant are the solar field, the thermal storage system, and the power block, which are connected by several heat exchangers. The technical data of the power plant is presented in **Table 3** **[45]**.

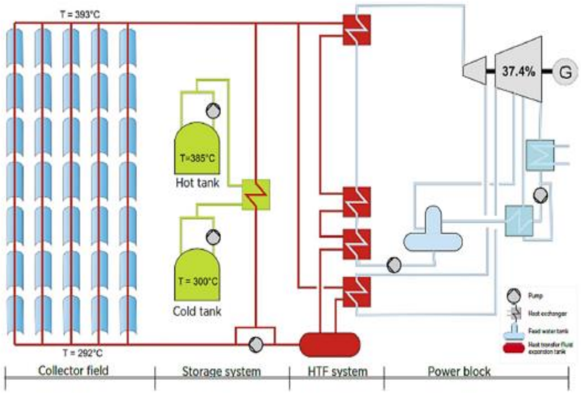


Fig. 13. Configuration of the Andasol-1 power plant **[45]**.

Table 3. Andasol power plant technical data **[45]**.

Parameter	**Value**

Nominal capacity	50 MW
Aperture area of the solar field	510.120 m²
A single collector length	148.50 m²
Aperture width	5.76 m
Focal length	1.71 m
Optical efficiency	75%
Row spacing	17.30m
Mirror cleanliness	97%
Temperature for nominal field entrance	292° C
Temperature for nominal field exit	385° C
Nominal net-capacity of thermal storage	970.000 kWh_{th}

Table 4 presents the results of the simulation using Greenius software.

Table 4. Technical results of ANDASOL 1

Parameter	**Value**	**Unit**
Annual thermal field output	471 508	MWhth
Solar annual net electr. Output	138 066	MWhel
Total annual gross electr. Output	154 959	MWhel
Mean annual field efficiency	43.79	%
Mean system efficiency	12.82	%

Figure 14 shows both the average daily efficiency of the solar field and the total system during the 2018 reference year.

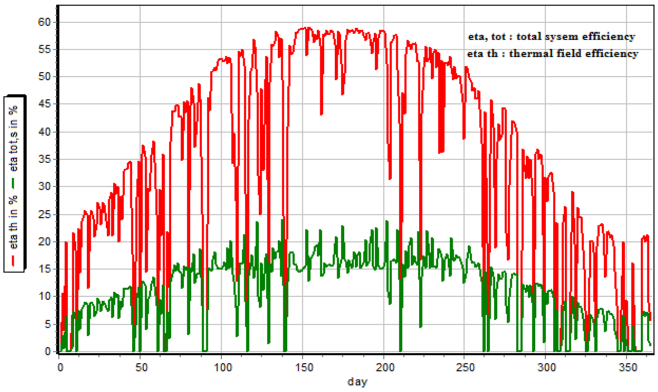


Fig. 14. The mean daily efficiency of the solar field and the total system over the year (2018 reference year).

In **Figure 15**, the monthly average level of the storage in MWh is given. From April to June 2018, the storage system can be fully charged. On the other hand, during the other months, there is insufficient excess heat supplied by the solar field to recharge the storage system.

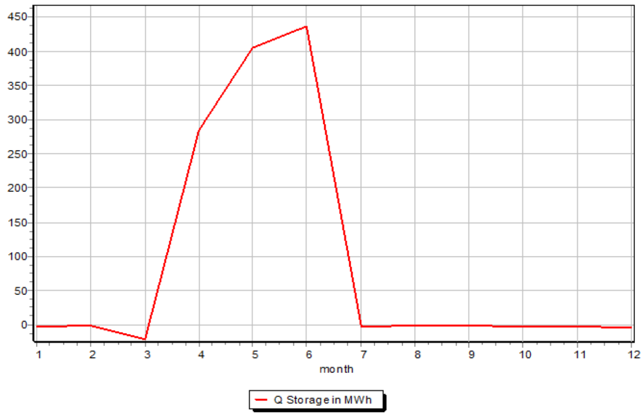


Fig. 15. Annual storage level (2018 reference year)

Table 5. Main input data to simulate the heliostat field system of Cerror Dominador using SolarPILOT.

Parameter	**Value**	**Unit**
Solar field design power	670	MWth
Design point DNI value	1000	W/m²
Tower optical height	220	M
Layout method	Radial stagger	
Heliostat geometry	12.2 x 12.2	m x m
Mirror reflectivity	0.95	
Mirror soiling	0.95	
Receiver type	Cylindrical	
Receiver height	21.6	M
Receiver diameter	17.65	M
Receiver thermal absorptance	0.94	
Allowable peak flux	1000	kW/**m²**

4.4. Modeling of the heliostat field of the Cerro Dominador using SolarPILOT

The Cerro Dominador consists of two parts 100 MW PV plant and a 110 MW tower power plant https://en.wikipedia.org/wiki/Concentrated_solar_powerwith 17.5 h storage **[49]**. It is located in Antofagasta, in the north of Chile.

Table 5 shows the main input data, which is used to simulate the heliostat field of the Cerro Dominador. Overall, SolarPILOT needs the geographical parameters of the site, the geometric design parameters of the solar receiver, and the tower height to calculate the optical performance of the heliostat field.

Figure 16 shows the layout and the annual efficiency for the heliostat field of Cerro Dominador.

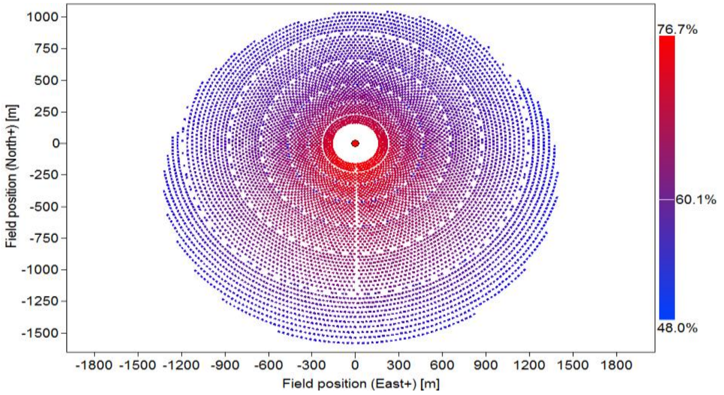


Fig. 16. Layout and annual optical efficiency of the Cerro Dominador's heliostat field generated using SolarPILOT.

SolarPILOT provides the costs of the central receiver system and the heliostat field area. It has the potential to simulate the performance of the central receiver system at any time. Table 6 illustrates the predicted performance on December 20th at noon.

Table 6. Summary of the costs of the central receiver system and performance on December 20 at noon

Parameter	Units	Value	Minimum	Maximum	Std. dev
Total plant cost	$	338721433.02			
Simulated heliostat area	m2	1149368			
Absorption efficiency	%	94.00			
Solar field optical efficiency	%	64.89	47.34	84.89	7.6057
Optical efficiency incl. receiver	%	61.00	44.50	79.80	7.1493
Annualized heliostat efficiency	%		47.98	76.68	6.3634
Incident flux	kW/m2	622.72	86.24	953.07	242.2492

4.5. Modeling of Dunhuang linear Fresnel power plan using SAM

Dacheng, Dunhuang linear Fresnel power plant is the world's largest solar thermal power plant based on this type of collector and is located in Dunhuang, China. The installed capacity is 50 MW using molten salt as heat transfer fluid and in the thermal storage system. It is expected to generate 214 million kWh per year and to operate for 4283 hours per year. The storage capacity is 13 hr of 2-tank type. The plant is modeled and simulated using SAM. In addition to the weather data, SAM needs all the design, economic, and financial parameters for all parts of the plant. **Table 7** demonstrates a sample of the economic and performance results provided by SAM for the Dunhuang 50 MW linear Fresnel power plant.

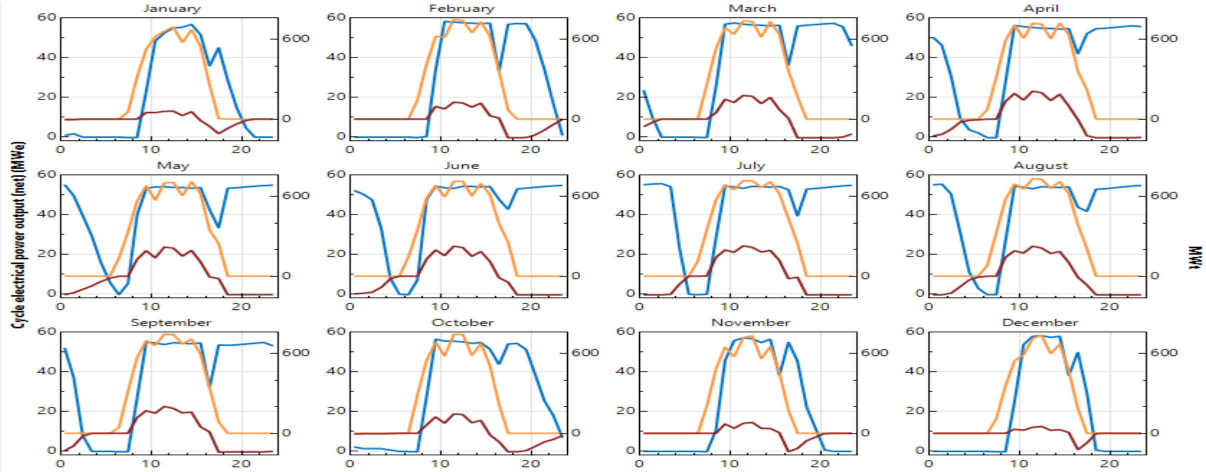
Table 7. Summary of SAM results

Metric	Value
Annual energy (year 1)	202,513,152 kWh
Capacity factor (year 1)	46.20%
Annual Water Usage	24,773 m^3

PPA price (year 1)	14.76 ¢/kWh
PPA price escalation	1.00 %/year
Levelized PPA price (nominal)	20.73 ¢/kWh
Levelized PPA price (real)	16.46 ¢/kWh
Levelized COE (nominal)	19.16 ¢/kWh
Levelized COE (real)	15.21 ¢/kWh
Net present value	$31,116,198
Internal rate of return (IRR)	11.00%
Year IRR is achieved	20
IRR at end of project	12.76%
Net capital cost	$491,022,720
Equity	$228,218,320
Size of debt	$262,804,400

SAM can also provide detailed annual, monthly, and hourly technical results for each component of the plant as can be seen in **Figure 17**.

Fig 17. Hourly data of net energy generated, field thermal power, and the thermal energy into storage.



4.6. Modeling of the hybrid solar gas turbine using TRANSYS

A hybrid solar gas turbine power plant is simulated using TRNSYS. The solar system of the plant is a heliostat solar field that concentrates the solar arrays into a central pressurized air receiver. The solar system is attached to a conventional gas turbine unit that includes a compressor, burner, turbine, and generator. The input data of the solar unit are shown in Table 8. It has to be mentioned that the optical efficiency of the heliostat field needs to be defined in an external file as a function of zenith and azimuth angles. This file is attached to the TRNSYS model during the simulation of the plant. The results of the simulation are demonstrated in **Figure 18,** which includes power generated, fuel consumption, and temperatures of the units.

Table 8. The input data of the solar system in TRNSYS.

Component	**Values**
Receiver optical efficiency	0.9
Receiver emissivity	1.0
Receiver aperture area	25 m^2
Receiver design inlet temperature	500 °C
Receiver design inlet mass flow	75000 kg/hr
Number of heliostats	150
Mirror surface area	100
Mirror reflectivity	0.9

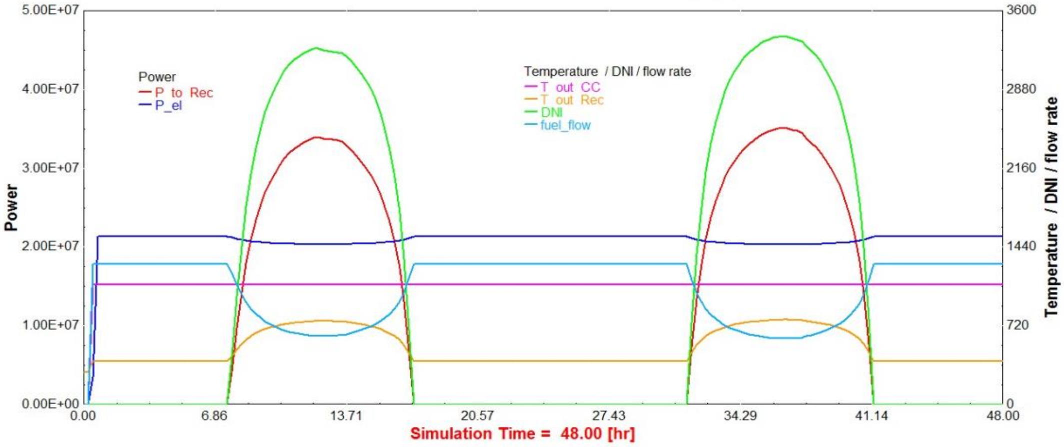


Fig 18. Sample of TRNSYS results of a hybrid solar gas turbine power plant.

4.7. Sample of comparisons of system tools outputs

The comparison between the results of the simulation tools is out of the objective of this review. The idea of this contribution is to show the capability and features of each tool to enable the users to select the appropriate simulation tool for their applications. However, a simple comparison between the results of two systems simulation tools namely SAM and Grrenuis is presented in this section. The reference plant that has been used in the comparison is the Andasol-1 parabolic trough power plant. The technical and economic input data of the reference plant are described previously in Table 3. In order to compare the CSP capabilities only, the backup fossil fuel boiler of Andasol-1 was not included in the simulation. A summary of the key results of the two software, SAM and Greenuis, is demonstrated in Table 9. The comparison included the annual electricity output, annual overall efficiency, capacity factor, and the Levelized cost of electricity. It can be noticed that the results are very close and the difference is very small. The biggest difference is reported in the LCOE results with about 3.2% and that is due to the difference in the economic models adopted by the two tools.

Parameter	**SAM**	**Greenius**	**Difference**
Solar annual electric output (GWh/year)	163.72	165.26	0.94%

Annual solar to electric efficiency (%)	16	16.3	1.8%
Annual capacity factor (%)	41.2	42.7	2.4%
Levelized cost of electricity ($/kWh)	0.297	0.307	3.2%

Table 9. Simple results comparison between SAM and Greenuis.

Tool name	**Developer**	**Availability/ open source**	**Concentrating technology**	**TES**	**Different HTF**	**Conventional backup**	**Optical simulation**	**Thermal simulation**	**O sy si**
SAM	NREL	Free/open source	All technologies (PT-CT-LF-PD)	Yes	Yes	Yes	Yes	Yes	Y
Trnsys	University of Wisconsin/university of Colorado	License/open source	All technologies (PT-CT-LF-PD) External library is required	Yes	Yes	Yes	No	Yes	Y
Tonatiuh	NRECS/university of Texas/NREL	Free/open source	All technologies (PT-CT-LF-PD)	No	No	No	Yes	No	N
Greenius	DLR Solar Research Institute, Köln, Germany	Free	All technologies (PT-CT-LF-PD)	Yes	Yes	Yes	Yes	Yes	Y
Soltrace	National Renewable Energy Laboratory,NREL, Colorado, USA	Free/open source	All technologies (PT-CT-LF-PD	No	No	No	Yes	No	N
Ansys	Ansys, Inc, Canonsburg, Pennsylvania, USA	License	All technologies (PT-CT-LF-PD	Yes	Yes	No	Yes	Yes	Y
Solarpilot	National Renewable Energy Laboratory,NREL, Colorado, USA	Free/open source	All technologies (PT-CT-LF-PD	No	No	No	Yes	Yes	N

Table 9. Comparisons CSP modeling and simulation tools.

The information given in Table 9 should help the reader to save time and select the most suitable software for her/his study.

5. Software selection

Finding the most suitable software is always a hard task for researchers and engineers to fulfill their requirements. It is required to analyze the project objectives and decide the features needed for the tools. This section aims to give some general guidelines to help make selecting the simulation tool much easier and more straightforward. In this regard, **Table 9** reports a comparison between the reviewed tools in terms of the capabilities that can be applied in the CSP systems. **Table 9** presents detailed information about the availability of the software, the CSP technologies that can be simulated by each software, the optical simulation, thermal simulation, and the complete CSP system simulation. It also gives the link to each software.

6. Conclusions

This review article has presented an overview of different software that are used for modeling, simulation, and optimization of concentrating solar power systems. The reviewed software were grouped into two categories: tools used for optical and thermal analysis at the level of a single or field of collectors, and tools used at the system level as a CSP plant. In addition, case studies using the software from both categories have been carried out. The purpose of this section was to demonstrate the capabilities of the most common software in the field so that it will help researchers and users choose their simulation tools easily.

During the last decade, the CSP field has been growing exponentially towards the commercialization of this technology on a utility scale. Accordingly, a noticeable advance in the CSP simulation tools has been reported. It has been driven by researchers, developers, investors, and decision makers who need simple tools to investigate the implementation of these technologies in different locations. The intention of this contribution is to provide the stakeholders with the guidelines, limitations, and main features of these tools that can help them choose the appropriate simulation tool for their applications.

Acknowledgments:
The authors gratefully acknowledge La Agencia Nacional de Investigación y Desarrollo de Chile (ANID), project number ANID / FONDAP / 15110019, Solar Energy Research Center (SERC-Chile).

Nomenlature

$W_{el,\ s}$: Solar annual electric output (GWh/year)
$Eta_{tot,s}$ Annual solar to electric efficiency (%)
Eta_{th} Thermal field efficiency (%)
CF : Capacity factor (%)
LCOE : Levelized cost of electricity ($/kWh)
Q_{field} : field thermal power (MWh)
E_{net} : net energy generated (kW)
$Q_{storage}$: Annual storage level (MWh)
W_{gross} : Total annual gross electr. Output (MWh_{el})
$W_{el\ (HV)}$: Solar annual net electr. Output (MWh_{el})
Φ Heat flux distribution (kW/m²)

Abbreviation

CPU : Central Processing Unit
NPV : Net present value
CSP : Concentrated Solar Power
SAM : System Advisor Model
PPA : Power purchase agreement
IRR : Internal rate of return

CAD : Computer-Aided Design
MCRT : Monte Carlo radiative transfer

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