5th Cologne Solar Symposium · Cologne · 21 June 2001 · pp. 46-50

Simulation of Parabolic Trough Power Plants

Volker Quaschning, Rainer Kistner, Winfried Ortmanns

Deutsches Zentrum für Luft und Raumfahrt e.V.
Plataforma Solar de Almería
Apartado 39 - E-04200 Tabernas - Spain
Tel.: ++34 950 38 7906, Fax: ++34 950 36 5313
e-mail: volker.quaschning@psa.es

Abstract

New fed-in laws in Spain and World Bank funding promise good opportunities for the construction of new solar thermal power plants. Here, one of the most challenging tasks represent the determination of an economically optimised project site and plant design. Such multidimensional problems can only be solved by means of specific simulation software tools, like the new simulation environment “greenius”. In the following, the modelling approach for a parabolic trough plant applied within the greenius software will be explained. It will become obvious on the sample simulation runs that the variation of the solar irradiance given by different sources for a specific site has a high influence on the expected operation results of new power plants.

Trough Collector

The thermal output of a parabolic trough collector depends on the absorbed solar radiation incident on the collector reduced by the heat losses of the collector.

$$\dot{Q}_{\mathrm{col}} = \dot{Q}_{\mathrm{abs}} - \dot{Q}_{\mathrm{heatloss}} \tag{1}$$

The absorbed heat varies with the solar irradiance E_{col}, the effective mirror area A_{col}, the optical efficiency η_0, the mirror cleanliness factor f_{C} and the incidence angle modifier K.

$$\dot{Q}_{\mathrm{abs}} = E_{\mathrm{col}} \cdot A_{\mathrm{col}} \cdot \eta_0 \cdot K \cdot f_{\mathrm{C}} \tag{2}$$

The solar irradiance E_{col} is the direct normal irradiance (DNI) projected on the collector area considering mutual collector shading as well as collector end losses and gains. The incidence angle modifier K can be calculated with the angle of incidence θ in degrees and two empirical constants a_1 and a_2.

$$K = \max\left(1 - a_1 \cdot \frac{\theta}{\cos\theta} - a_2 \cdot \frac{\theta^2}{\cos\theta}, 0\right) \tag{3}$$

The computation of the heat losses is based on an empirical model. The parameters b_1 to b_3 have been determined during several collector tests[1], so that this formula can be applied to common collectors depending on the temperature difference ΔT of the mean collector fluid temperature and ambient temperature.

$$\dot{Q}_{\text{heatloss}} = (b_1 \cdot K \cdot E_{\text{col}} + b_2 + b_3 \cdot \Delta T) \cdot A_{\text{col}} \cdot \Delta T \tag{4}$$

Trough Field

An analytical description of the heat losses in the trough field is not easy to find, since all losses such as heat transfer through the pipes isolations, losses in connections, fixings and other circuit components have to be considered. Empirical equations deliver a sufficient description of the heat losses in the pipes

$$\dot{Q}_{\text{pipe}} = c_1 \cdot A_{\text{field}} \cdot \Delta T_{\text{f}} \tag{5}$$

and the expansion vessel

$$\dot{Q}_{\text{vessel}} = d_1 \cdot \Delta T_{\text{f}} \tag{6}$$

depending on the total solar field size A_{field} and the mean solar field temperature ΔT_{f} above the ambient. The parameters c_1 = 0,0583 $\text{Wm}^{-2}\text{K}^{-1}$ and d_1 = 9345 WK^{-1} are given by Lippke (1995) for the SEGS power plants. For most sites only hourly meteorological data are available. When simulating the system performance with hourly data it is recommended to pass over to minute time steps during heating-up and cooling-down of the solar field. If the heat capacity of the heat transfer fluid, the absorber tubes and the connecting pipes is considered, a good description of the behaviour during heat-changes can be obtained.

Power Block and Operation

Power blocks and their operation are calculated with heat cycles. A group of equations, that describe the form of property changes of the affected working fluid (i.e. steam, gas, flue gas, air, water), represent the cycle components such as turbines, heaters and pumps.

The total number of equations can easily reach thousands depending on the number of used components, the complexity of their description and their number of recursive dependencies. The solution of such complex equation systems was done by external professional applications such as ISPEpro and GATE Cycle.

A calculation with the above mentioned tools takes approximately three to four seconds, hence a typical operation year with 8760 calculation points (hours) needs between seven and nine hours. To reduce this calculation time and to find a common interface between a global calculation tool and the different heat cycle programs, the resulting data is stored in a n-dimensional matrix. n is the number of conditions influencing the power block operation, i.e. the solar thermal heat input, ambient conditions and electric demand. Each result (e.g. generated power, parasitic, emissions, backup heat) has its own matrix or

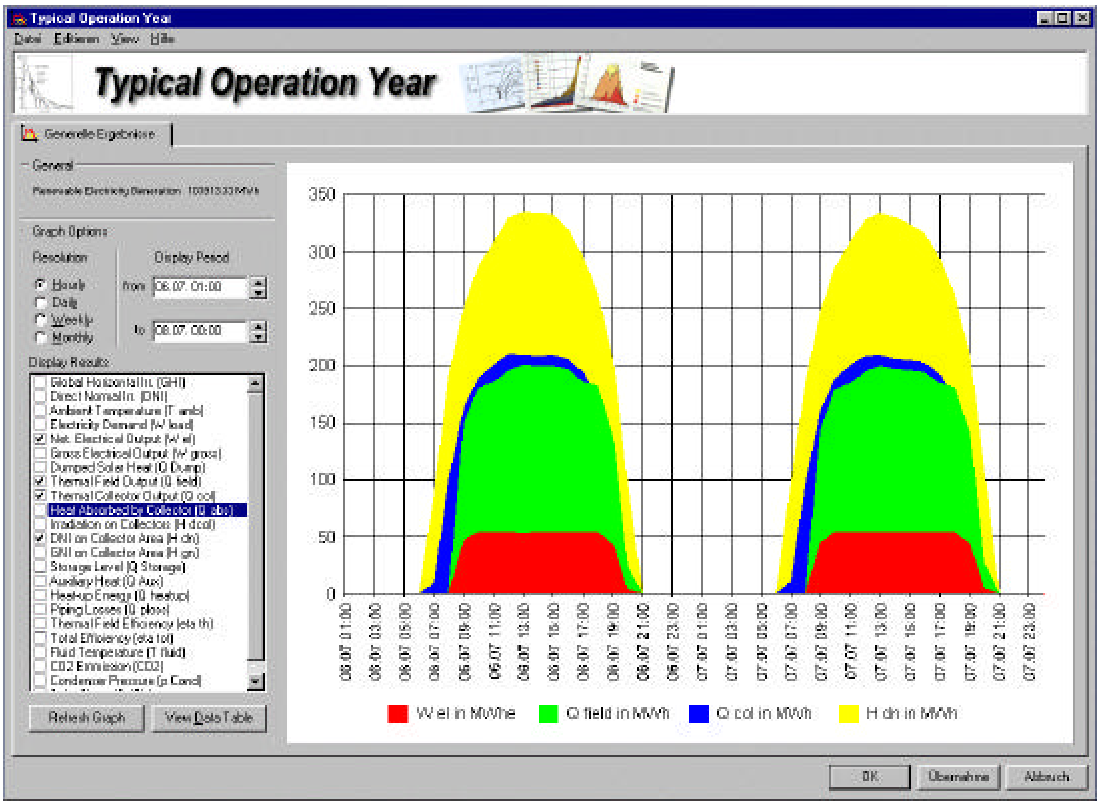
---

[1] For the LS-2 collector the constants $\eta_0 = 0.733$, $a_1 = -0.000884/1°$, $a_2 = 0.00005369/(1°)^2$, $b_1 = 0.00007276\,\text{K}^{-1}$, $b_2 = 0.00496\,\text{W}\,\text{m}^{-2}\text{K}^{-1}$ and $b_3 = 0.000691\,\text{W}\,\text{m}^{-2}\,\text{K}^{-2}$ are given by Dudley et al. (1994).

look-up table. These matrixes or tables then only need to be calculated only once. Real operational data will be available with an *n*-dimensional interpolation, which take much less time than a full cycle calculation. The precision of the results then only depends on the resolution of the matrixes.

Implementation

The described models were implemented in the simulation environment greenius (Quaschning et al., 2001). The software computes efficient simulations for technical and economical key-parameters based upon hourly meteorological data. A validation of the simulation results with real measured data from the SEGS power plants has proven an acceptable correspondence. The screenshot in Figure 1 shows the simulation results for two days of a 50 MW_e plant using meteo data with a DNI of 2,200 kWh/(m^2a).



Renewable Electricity Generation: 100813.33 MWh

● Hourly
○ Daily
○ Weekly
○ Monthly

from 06.07. 01:00
to 08.07. 00:00

☐ Global Horizontal Irr. (GHI)
☐ Direct Normal Irr. (DNI)
☐ Ambient Temperature (T amb)
☐ Electricity Demand (W load)
☑ Net. Electrical Output (W el)
☐ Gross Electrical Output (W gross)
☐ Dumped Solar Heat (Q Dump)
☑ Thermal Field Output (Q field)
☑ Thermal Collector Output (Q col)
☐ Heat Absorbed by Collector (Q abs)
☐ Irradiation on Collector (H dcol)
☑ DNI on Collector Area (H dn)
☐ GNI on Collector Area (H gn)
☐ Storage Level (Q Storage)
☐ Auxiliary Heat (Q Aux)
☐ Heat-up Energy (Q heatup)
☐ Piping Losses (Q ploss)
☐ Thermal Field Efficiency (eta th)
☐ Total Efficiency (eta tot)
☐ Fluid Temperature (T fluid)
☐ CO2 Emission (CO2)
☐ Condenser Pressure (p Cond)

Figure 1. Screenshot of the greenius simulation software

Simulation Results

A fast and powerful computer tool is suitable when choosing a site, planning and engineering a solar thermal power plant. Figure 2 shows the impact of the annual direct solar irradiation (DNI) on the annual power generation and the levelized electricity costs (LEC) of a 50 MW_e SEGS type power plant with a 375.000 m^2 solar field. The economical parameters (e.g. discount rate of 6.5 %, solar field costs of 200 Euro/m^2, power block costs of 1,000 Euro/kW and O&M costs of 3.7 million Euro p.a.) have been kept constant. The annual electricity generation is approximately proportional to the DNI. However, there are high variations of the results for then same DNI range caused by different meteo files and latitudes. Unfortunately, reality is much more complex, thus the determination of an economically optimised project site not only depends on the solar irradiation but on many other influencing parameters.

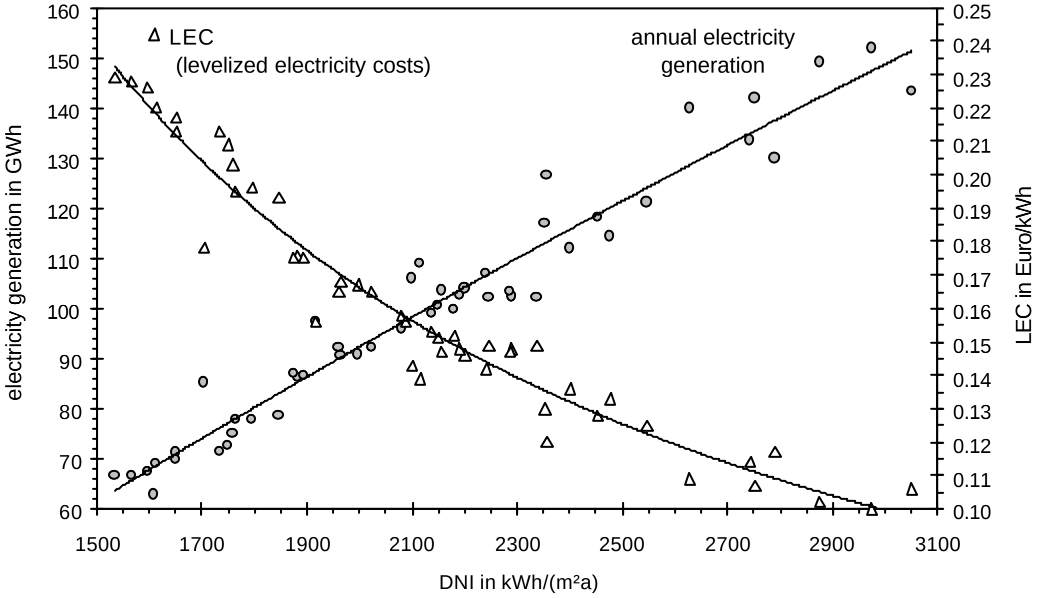


Figure 2. Annual electricity generation, efficiency and LEC for a 50 MW$_e$ trough plant with a 375,000 m^2 solar field size in dependence on the DNI (direct normal irradiation) for 50 random chosen sites

As soon as the project site has been selected a detailed plant design has to be developed. Choosing representative meteorological data is the first hurdle to be taken in the planning an engineering phase. For the following simulations three different hourly meteo data files have been used for the same site in southern Spain. The first data file with a DNI of 1,800 kWh/(m^{2}a) was obtained from the METEONORM software database. The other two files with 2,000 and 2,200 kWh/(m^{2}a) are specific measured years. One file is based on ground-measurements at the ground the other on satellite data. Figure 3 shows the annual electricity generation, efficiency and LEC for all three meteo data files for a 50 MW$_e$ solar trough power plant with a variation of the solar field size. With decreasing irradiance the economical optimum of the solar field size drifts to higher values. The simulation results of both measured meteo files show the same characteristics. The METONORM data file, however, produces different results. The reason is not only the lower DNI but also the different irradiance distribution within the file.

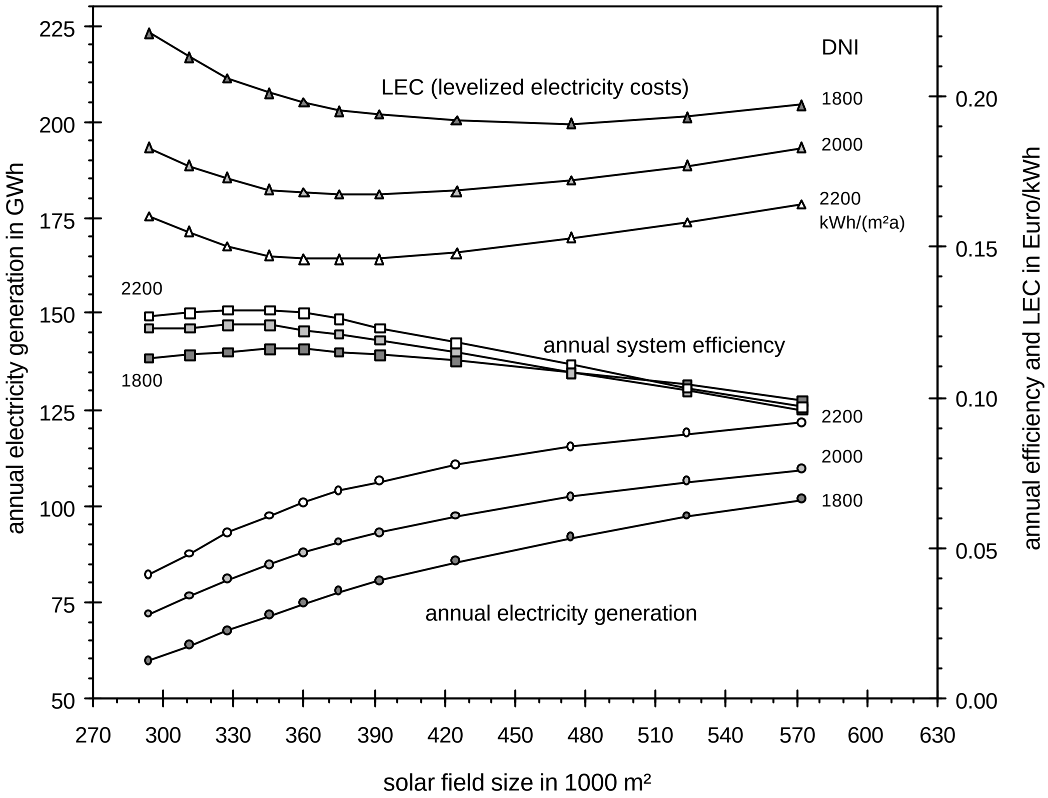


Figure 3. Annual electricity generation, efficiency and LEC in dependence on the solar field size of a 50 MW$_e$ trough plant for different irradiation

These examples show clearly, that comfortable simulation tools are essential for an efficient project development of any solar power plant. Accurate and well-validated algorithms have a high influence on the quality of the results. But if there is a high uncertainty of the used input parameters, especially the meteo data, the simulation tools can only deliver qualitative statements. The expressiveness of the quantitative results corresponds to that of the input parameters.

References

Dudley, Vernon E.; Kolb, Gregory J.; Sloan, Michael; Kearney, David (1994) Test Results SEGS LS-2 Solar Collector. SAND94-1884, Sandia National Laboratories, Albuquerque, 1994

Lippke, Frank (1995) Simulation of the Part-Load Behavior of a 30 MWe SEGS Plant. SAND95-1293, Sandia National Laboratories, Albuquerque, 1995

Quaschning, Volker; Kistner, Rainer; Ortmanns, Winfried; Geyer, Michael (2001) greenius – A new Simulation Environment for Technical and Economical Analysis of Renewable Independent Power Projects. In: Proceedings of ASME International Solar Energy Conference Solar Forum 2001. Washington DC, 22.-25. April 2001, p. 413-417.