Comparison of steady-state and quasi-dynamic performance-modeling for a parabolic trough plant

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Abstract

A comparison of simulation results from two performance models demonstrates the deviation between a thermodynamic steady-state approach and a quasi-dynamic approach. EBSILON®Professional is applied to simulate the power plant in steady-state and CSPsim, a Suntrace in-house developed software is used as quasi-dynamic tool. The comparison has been based on a theoretical CSP plant, based on parabolic trough technology with gross capacity of 111.5 MW_e and a 2-tank molten salt based thermal energy storage with 3.5 equivalent full load hours capacity. The location shall be in the Northern Cape region of South Africa. Based on the results of this analysis, it is concluded that yield calculations based on steady-state energy balances in hourly time-resolutions usually overestimate the annual yield. In this case an overestimation of roughly 6 % has been found. It is an essential requirement for performance calculations to assess the transient effects during operation implied by the fluctuation of solar irradiation and heat-losses during non-operational periods. This requires consideration of residual data from previous time-steps through qualified algorithms for the simulation of plant status for subsequent time-steps. The thermodynamic accuracy of EBSILON®Professional with its ability to simulate individual power plant designs in combination with quasi-dynamic approaches like CSPsim would lead to a high degree of flexibility with lower uncertainty.

Keywords: CSP, performance simulation, transient effects, EBSILON®Professional, Suntrace CSPsim.

1. Introduction

The development of simulation tools for CSP plants has been a scientific and engineering topic for a few decades already. Efforts are still being done in several companies, universities and research institutes to develop better tools, improve existing ones and create modeling standards. In 2010, the International Energy Agencies' implementing agreement SolarPACES (Solar Power and Chemical Energy Systems) started the guiSmo project (Guidelines for CSP Performance Modeling) with the purpose of promoting the standardization of performance modeling tools [2]. This project makes evident the growing amount of performance modeling tools and techniques and the importance of this topic.

Performance models are essential to evaluate the technical and economical feasibility of any kind of power plant. Solar thermal power plants and other renewable energy systems have to cope with fluctuations in energy input. On the one hand the daily cycle of the sun, but also short-term variations due to clouds have to be considered. Performance simulation of dynamic processes with calculations of at least one complete annual cycle would require substantial effort and computational capacity. Thus, the transient processes have to be simplified for assessments during periods, where the technical concept might frequently be adjusted to reflect boundary conditions resulting from project development.

Commercially available and open domain tools do not fully comply with the range of requirements from different industry players on CSP performance simulation. This paper takes into account the requirements on CSP performance simulation from the project development point of view with main focus on techno-economic optimizations as part of project feasibility analysis during project development [7]. Challenging requirements on performance simulation are, among others:

- Multiple-site analysis: Regional studies may consider several sites for ranking of best options.
- Multiple-technologies analysis: Often several different technologies per site with variation of plant parameters should be evaluated.
- Tailor-made technical concepts: Usually there is no 'standard technical concept', as most projects require tailoring of technology to the project- specific boundary conditions [7]. Especially CSP hybrid concepts require a high flexibility on the performance model.
- Increasing time resolution and consideration of transient effects: According to [5], [6], short-time transients, like broken clouds, start-up or shut down processes have a considerable influence in the plant's energy yield calculation.
- Multiple-year analysis: The risk of volatility of energy yields due to the high inter-annual variation of DNI can be estimated by means of multi-year analysis [4].

These requirements lead to a very large number of scenarios and load cases to be calculated. This can sum up to several hundred or even thousands of simulation runs for one comprehensive study. As the processing time of more complex performance models is approaching one hour for annual simulations with 60 min time-resolution, the computational load is substantial.

The objective of this paper is to analyze the impact of transient effects on performance simulation and on annual yield, especially the difference in annual yield between a steady-state model and a model that takes transient effects into account. EBSILON®Professional software has been applied to calculate the performance of a steady-state approach. CSPsim, a Suntrace in-house development, based on the quasi-dynamic approach has been used to compare the results and illustrate the influence of transient effects on annual performance simulation.

First the two simulation approaches are introduced. Second, the performance simulation results from both tools are compared and analyzed on a case study with a 111.5 MW parabolic trough plant with molten salt storage system in Northern Cape, South Africa. In the outlook an efficient approach for performance modeling of CSP plants is proposed, which takes advantage of both simulation approaches.

2. Methodology and assumptions

2.1. Case study assumptions and technical specifications

The theoretic solar thermal power plant is located in the Northern Cape region in South Africa. The applied Typical Meteorological Year (TMY) in 60 minutes time resolution has a DNI annual sum of 2 637 kWh/m^2/a. The technical concept of the CSP plant considers a parabolic trough system with a two-tank molten salt storage system and a steam turbine generator with 111.5 MW_e gross electric output. The following main technical assumptions have been applied:

- Solar field consisting of parabolic trough collectors, arranged in North-South direction
- 250 solar field loops (each 600 m length) with a row distance of 16.25 m and a total aperture area of 817 500 m^2. The collector performance is considered similar to EuroTrough technology.
- Heat Collecting Elements (HCE) consider Schott PTR70 with a performance according to [1]

- Heat transfer fluid (HTF) system, based on Therminol VP-1 to transport the collected heat from the solar field to the power block and the thermal energy storage system. The HTF maximum temperature is limited at 393°C
- Thermal energy storage facility based on molten salt storage media comprising of 60% $NaNO_3$ and 40% KNO_3 with a capacity of 3.5 hours equivalent full load.
- Water steam cycle with a feed-water pre-heating system and condensing steam turbine generator (STG) with a nominal electric output of 111.5 MW_e. The water-steam cycle efficiency at design conditions is 38.5 % with an air-cooled condenser (ACC)
- Live steam temperature of 377°C at 101.5 bar

The technical specifications have been applied to both simulation tools, the steady-state model EBSILON®Professional as well as CSPsim, to match the technical concept as accurately as possible.

2.2. Steady-state simulation with EBSILON®Professional

EBSILON®Professional is a well-established thermodynamic power plant simulation tool. Its main purpose is the calculation of thermodynamic quantities (enthalpies, pressures) and mass flows in the water/steam cycle and the air/flue gas path. The version of EBSILON®Professional applied for this paper (release 9) is restricted to thermodynamic equilibrium states and usually applies a phenomenological approach to describe plant components. The model includes a component library, which exists of various components, e.g. turbines, heat-exchangers, boiler, pumps, generators, gas-turbines, combustion chambers, tanks, cooling towers, etc.

EBSILON has been designed in the early 90’s to simulate water-steam cycles for fossil fueled power plants. With the release of EbsSolar in 2008, the solar library was added. With this, EBSILON is able to simulate complete solar thermal power plants as well, applying parabolic trough (PT), Linear Fresnel (LF) and Central Receiver (CR) technologies. Together with the existing model library for conventional power plants, the tool allows to simulate the whole plant in design and part-load cases. Furthermore, the simulation tool is able to process time series and hence, yield calculations of whole periods can be modeled.

Suntrace is using EBSILON in two ways. First, the characteristic lines, which describe the power block performance in CSPsim, have been compiled with EBSILON on the basis of manufacturer’s data. Furthermore, Suntrace is using the library EbsSolar to calculate the annual performance of various tailor made CSP technical concepts, especially CSP hybrid plants.

The advantage of EBSILON is its ability to model tailor made technical concepts by using the comprehensive component library as well as EbsScript for individual programming. The conventional power industry is using EBSILON since several decades for simulations in design and part load. However, the heat-balance calculations are only based on stead-state, which means, only the thermodynamic equilibrium of one single time-step is calculated without considering the conditions and results from previous time-steps. Thus, EBSILON is not considering cumulative heat losses during non-operating hours. Furthermore, the annual yield calculation with EBSILON by using the time series dialog (TSD) in 60 minutes time resolution requires a calculation time of about 45 minutes, which is a fairly long, in particular when performing multi annual calculations and sensitivity analyses with many scenarios to be modeled.

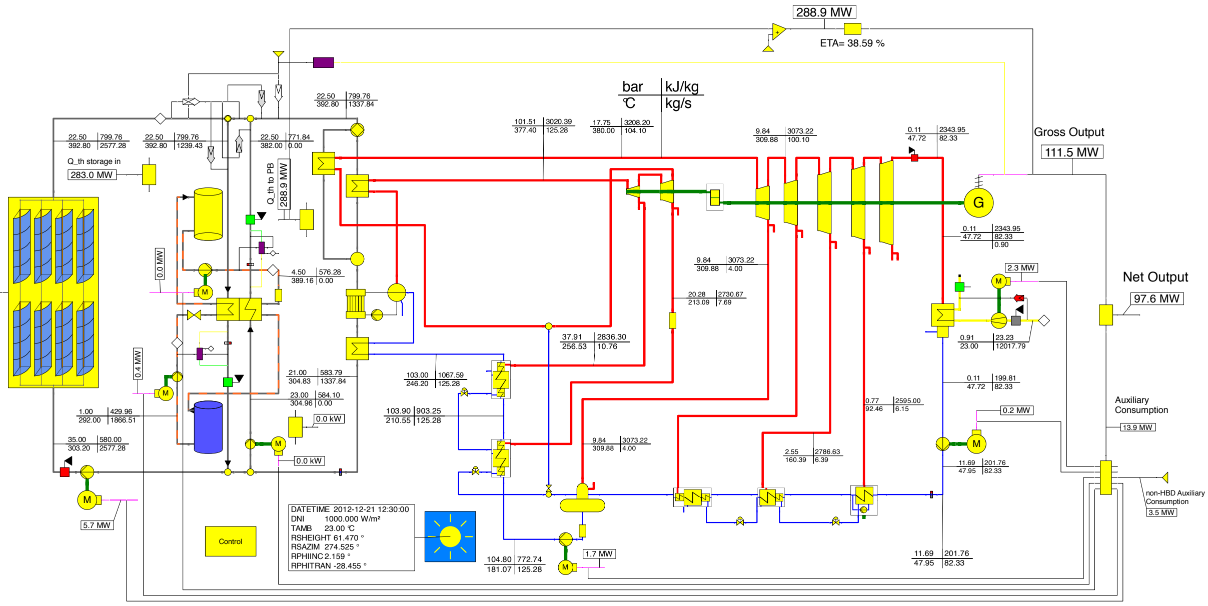

Fig. 1 EBSILON Heat balance diagram with 100% solar mode at design conditions.

2.3. Quasi-dynamic annual performance simulation with CSPsim

Suntrace has developed its own specialized CSP simulation tool named CSPsim, which is a quasi-dynamic model based on MATLAB code. The Parabolic Trough simulation model (PTsim) is calculating the energy yield of parabolic trough solar thermal power plants. Performance data and characteristics are based on vendor offers and do consider part load operation behavior. Depending on solar irradiance and additional weather data the simulation tool calculates the electrical power production of solar thermal power plants in discrete time steps. Transient effects occurring in the solar field due to irradiance changes and in the power block due to load changes are considered by means of empiric formulas. However, detailed analysis was applied to reflect the transient effects resulting from cooling down of solar field during nighttime, changes in storage level and temperature losses from thermal energy storage as well as heat and power consumption during startup processes for solar field and power block. The conventional part of the water-steam cycle is based on manufacturer's data of steam generator and steam turbine. PTsim is using characteristic lines to model the water-steam cycle performance. The characteristic lines are derived from EBSILON and consider part load behavior at design and off-design ambient conditions.

PTsim builds on experience gained from simulation models of DLR and EPURON within the R&D project SESK for standardization of energy yield prognosis for solar thermal power plants. In this project a similar model was developed and inter-compared to a detailed dynamic model of DLR [3]. Moreover, the parabolic trough model of CSPsim has recently been benchmarked by the SolarPACES project guiSmo [2] work package 9.2. 15 performance models participated in this international model comparison. Three models were disregarded after plausibility tests as results revealed obvious problems. From the remaining 12 models the model average has been calculated and taken as the reference case. Among these 12 models it turns out that CSPsim is the closest to the model average: the gross annual yield of CSPsim in this case has a bias of 0.? % to the reference.

Suntrace is using CSPsim for annual yield simulations, such as multiple site analysis for site selection, techno-economic optimizations and sensitivity analyses, and multiple year analyses for high inter-annual variability in solar data. CSPsim is also capable to do annual simulations in smaller time resolution, e.g. 5 minutes. The disadvantage of CSPsim is its high effort in program-code adjustment for non-standard and tailor made technical concepts. Especially CSP hybrid concepts require significant effort in adjusting the code. Furthermore the effort in development work, maintenance and update of CSPsim is quite high as it is an in-house development and not a commercial simulation tool.

3. Comparison and annual yield results

3.1. Annual yield

The annual performance of the parabolic trough plant has been simulated with both performance tools. Assumptions and technical specifications have been synchronized as precisely as possible. As CSPsim is using characteristic lines to simulate the performance of the power block and these lines are generated by EBSILON it can be assumed that the power block has very good compliance at both models at static conditions.

The annual performance of the power plant has been modeled with the following results. The steady-state tool EBSILON computed 412 GWh/a of gross electric output, which is about 6 % above the quasi-dynamic tool CSPsim with 386 GWh/a.

The detailed analysis of selected and representative days and hours showed the reasons for the difference in annual yield. The steady-state model EBSILON calculates the energy equilibrium for each time step without considering the previous time step and their conditions and results. Thus, EBSILON neglected heat losses during non-operating hours, e.g. during night, and consequently overestimates the energy yield.

3.2 Analysis of selected and representative days with clear sky day and cloudy conditions

In a first step a clear sky day has been analyzed. This day illustrates the difference in start up procedure as shown in Fig. 2. As the steady-state model does not consider the cumulative heat losses during night and non-operating hours, the EBSILON model calculates electricity generation one hour before the CSPsim model. Operating rules in both models imply that operation of the plant continues until the storage is completely discharged at the end of the day. Thus, the heat up procedure on the next day is based only on the solar irradiance.

During full load operation the performance of both models show high conformability until end of operation in the evening hours.

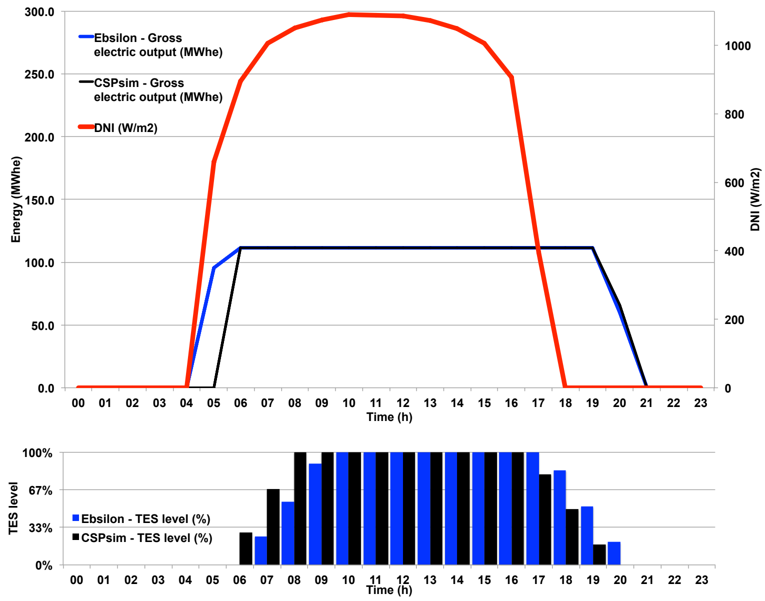

Fig. 2 Comparison of yield at a cloud free summer day with good compliance during the full load operation and deviations at start-up phase.

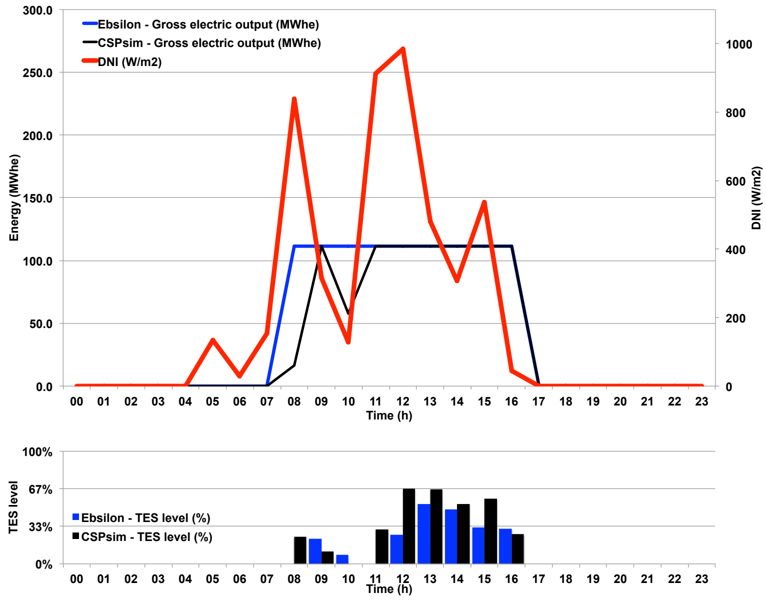

Fig. 3 Comparison of yield at a broken cloud day with deviations at start up and cloudy conditions when storage is not charged due to transient effects.

In a second step the performance on a cloudy day has been analyzed. Beside the differences during start up phase, the steady-state model also does not consider transient losses during time periods with broken cloud conditions. During morning hours between 8-11 am, cloud cover is causing reduction of the solar irradiance. The thermal storage is not sufficiently charged at this moment to provide the balance energy; the plant has to reduce electricity generation. The graph in Fig. 3 is illustrating this difference, as the quasi-dynamic model is considering this reduction in solar input by reduced electric output, whereas the steady-state model is still producing at full load.

4. Conclusion

Based on the results of this analysis, it can be concluded that yield calculations based on steady-state energy balances in hourly time-resolutions will always overestimate the annual yield. The case study in this paper shows an overestimation of about 6 %. It is an essential requirement for performance calculations to assess the transient effects during operation implied by the fluctuation of solar irradiation and heat-losses during non-operational periods. This requires consideration of residual data from previous time-steps through qualified algorithms for the simulation of plant status for subsequent time-steps.

EBSILON has the ability to develop tailor made power plant designs. However, it is based on steady-state calculations with disadvantages in consideration of transient effects and losses. Furthermore, the calculation time required for modeling of a complete annual time series is high, especially becoming a time-constraint when conducting multiple year and multiple site analyses.

On the other hand, the Suntrace in-house tool CSPsim does consider the transient effects in kind of empiric formulas. But CSPsim requires high effort in code adaptation for tailor made concepts, such as CSP hybrid plants. In an international benchmarking of CSP performance models it turns out that results of CSPsim are very close to the model average.

5. Outlook

Steag Energy Services -System Technolgies, the developer of the EBSILON®Professional software, has recently introduced with the latest release (Version 10) a new component, called “indirect storage”. This component is capable to simulate transient effects. However this component could not be considered for this analysis. It is expected, that the application of this component can allow the simulation of transient effects with EBSILON®Professional, but results are not yet obtained. Suntrace is currently developing an update of the CSPSim performance-modeling tool, that uses EBSILON as basic environment and includes the proven transient loss factors from the Matlab based CSPSim version.. However, one major challenge is still the reduction in calculation time.

It is expected, that the thermodynamic accuracy of Ebsilon with its ability for tailor made CSP designs in combination with the validated results from the quasi-dynamic approach of CSPsim will lead to a reliable performance modeling tool with high flexibility on the technical configurations and low uncertainty in simulation results.

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