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Steps Towards a CSP Yield Calculation Guideline: A First Draft for Discussion in the SolarPACES Working Group *guiSmo*

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Abstract. This paper provides an overview on an important step towards a SolarPACES guideline for CSP yield calculation. With the increasing number of CSP installations, standardization becomes more and more important for further reduction of costs and increase in quality. Yield calculation is a key issue throughout all phases of project development and throughout most of the involved players. Due to the need for more complex process models for CSP compared to other renewables like PV or wind, the yield calculation procedure is more demanding. Uncertainties in the process are covered by additional but partially unnecessary risk surcharges since systematic approaches for avoiding expensive redundancies in risk buffers are not available. It is the main motivation of the mentioned CSP yield calculation guideline to overcome this situation by providing a detailed methodology for yield calculation. A first comprehensive draft version has been compiled and will be subject of discussion in the SolarPACES working group guiSmo. The following sections illustrate the motivation for the guideline, the contents at a glance, as well as expected benefits for selected players.

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THE ROLE OF YIELD ANALYSIS FOR A BROAD IMPLEMENTATION OF SOLAR THERMAL POWER PLANTS

For any financial investment, the return on invest is the most important figure for evaluating the economics of the project. The same holds for concentrating solar thermal power plants (CSP). The return in the case of CSP is dominated by the amount of electricity produced. In market environments with flexible tariffs the annual financial revenue is the figure to be applied. The amount of electricity produced depends on four main factors:

- Installed capacities of solar field, power block, thermal storage, and auxiliary heaters
- Efficiency of these components
- Direct normal irradiance at the site
- Operation strategy applied

Yield analysis is the process of calculating the expected amount of energy to be produced by a power plant project. For photovoltaic or wind turbine installations the performance of the technical components is well known and highly standardized. Yield analysis in this case strongly focuses on the prediction of the solar or wind resource at the site. The impact of solar resource on the annual outcome is more or less linear in terms of CSP technology. However, the challenges in yield analysis are extended by the situation that each project is highly individual in terms of technical setup, environmental boundary conditions, and market conditions for electricity sales. Yield analysis need to consider all these aspects in order to provide reliable figures for financial evaluation of the project. The challenges in the development of standardized methodologies for yield analysis are:

- Need for high flexibility in terms of plant layout
- Compatible approaches for different CSP technologies like trough, linear Fresnel or tower
- Efficiency data of components not provided in a uniform format today
- Effect of transient processes like start-up strongly depends on plant layout and requires experience from similar installations
- Direct validation with performance data from real plants is challenging since
    - available data channels in a commercial plant are not designed for high precision needed for validation,
    - measured values often represent an accumulation of different effects which cannot be separated from each other based on the available sensors.
    - access to plant operational data is strongly restricted by the owners today
- Reliable information on component performance is often not available due to the high degree of innovation.

Despite these challenges the players in the solar business require highly reliable methods to determine the expected yield of their projects. So far, standards on how to carry out a “good” yield analysis are not available so that each company uses its own methodology and tools. Problems arise during interaction between different players in a CSP project, with different roles and objective. For example, when the wording is not consistent, or when the approach used by a partner has to be cross-checked by an independent expert before results are considered as reliable. New players in the market suffer from missing practical experience in setting up yield analysis tool. Commercial tools are rarely available today so it is mainly the role of technical consultants to evaluate yield reports during project development.

The need for yield analysis arises in all phases of a project beginning with early pre-feasibility studies up to the final calculations used for financial performance guarantee evaluation, final acceptance e.g. after 1 year of operation. Most players have activities in all of these phases, thus a consistent methodology is desired, that would provide low-effort calculations with rough assumptions in an early stage as well as high quality yield reports based on detailed technical and resource information. As no other figure of merit, the annual outcome (technical or financial) dominates the CSP project development process. Special care needs to be spent to achieve the high reliability requested by financial partners.

BENEFITS AND IMPACT OF YIELD ANALYSIS STANDARDIZATION

Benefits in the View of the Technical Advisor

The development of a power plant project is a multi-disciplinary tasks, mixing various aspects such as technical, commercial, financial, legal or environmental ones. A large, experienced developer may have certain in-house project management resources and capacities to work through such a task, yet he may need to complement these case by case with additional specialists, for instance, in the solar resource, engineering, financial or legal areas. Typical project development work is an iterative process that works with initial assumptions and estimations to increasingly more granular levels, with more and more detailed data, resulting out of measurement, engineering calculations as well as project contracts and financing terms. In the entire development and financing process of a CSP project, which can regularly take up to three years, a standardization of the yield predictions for CSP technologies would help smoothen interdisciplinary and intersectional communication, reduce cost and significantly increase project development efficiency.

Counting to one of the project initialization steps, the yield assessment is being refined and detailed depending on the stage of the project. In most cases, the update and detailing of the initial yield assessment is being conducted by different technical advisors. This is due to the fact that generally the advisory services are awarded separately by customers for each major development step such as project pre-feasibility, feasibility, concept design, tendering, and possibly due diligence which may be conducted for investment or financing decisions. This leads to the requirement that underlying tools used for yield assessment purposes should "speak the same language", i.e. any advisory or engineering firm should ensure that the model used is based on minimum quality standards for calculation methods, formulas, effects to be considered as well as clarity in the meaning of input and output values. For instance, it may happen that analysis results from advisors active in the initial phase are either misinterpreted or are used for future work without verification of correctness by the successors. It is well known from project management theory that mitigation effort strongly increases with the time passed until such errors are detected. The situation of potential errors in the key energetic figures represents a severe risk for project development due to associated additional costs and time delays. From this background, it becomes obvious, that yield calculation should be based on reliable standards from early stages of project development on.

When looking at the bidding process with potential contractors/IPPs in the tendering of a project, for example, any technical topic related to the basic concept of the plant and resulting from yield assessments, e.g. plant layout and performance values, must be properly elaborated and clearly defined in the tender documents, so that all involved parties have a common understanding of what are the target technical design criteria and performance guarantee values for the bid. Otherwise, technical bids cannot be transparently compared against each other and evaluated in depth. This applies in particular for the contractual performance model which is to be verified by the advisor responsible for the technical bid evaluation. As the performance model will form part of the contract between clients/off-takers and contractors/IPPs and as the results will be the basis for remuneration and financing of the project, it is of foremost importance that the model used for verification of the contractual performance model is appropriate.

Benefits in the View of the Lender and Equity Investor (Sponsor)

Both, investors as well as banks, fundamentally rely on projected cash flows of the project. Both have different key indicators for their interest. Lenders[1] are most concerned about the project's capability to cover the debt service, i.e., payments of interest and principle. For the debt sizing or the assessment of the debt capacity of a project, the main ratio that banks use is the so-called Debt Service Coverage Ratio or DSCR. The DSCR expresses the project's capability in every time sequence observed (typically semi-annually) to generate enough free cash flow to cover debt repayments (*principal*) and interest. On top, banks require a buffer, so that a typical DSCR ranges from 1.2 to 1.4, depending on the lender's risk perception of a project cash flow (under long term Power Sales Agreements with stable offtakers). Now, any uncertainty of projected cash flows – in our case, resulting from energy yield predictions

[1] In this paper, we use the term lenders also synonymous with banks, as these are the main lenders to projects. For reason of completeness, lenders could also be other participants in the financial sector, such as bond holders, insurance or pension funds or others. For all of these, however the described mechanisms and criteria under a project financing scheme would be very similar.

or missing agreements on applied standards for measurement – causes lenders to make discounts to the projected cash flows and, as a consequence, reduces the amount of debt conceded to the project. More expensive equity needs to come up for the balance. In addition, lenders may require higher interest on their loans and/or reduce debt tenors, all of which increase the capital cost of the project.

Any standardization of energy yield predictions and increase of precision of the same would simplify the project evaluation and result in a higher confidence for lenders and hence to better conditions in the terms of debt financing. Standardization would significantly allow reducing long lasting, expensive, and controversial discussions between sponsor's and lender's technical advisors. Usually, much time and effort is spent to find an agreement between sponsors and lenders technical advisors as well as with the EPC on the subject which procedures and results can be considered as trustworthy. These discussions can last months and mostly lead to even higher uncertainty (=risk premiums) for lending parties, not to speak of the cost involved if technical and legal advisors as well as lenders and sponsors need to attend.

Main investors (or s*ponsors)* are usually the ones who initiate and care for implementation of a project, their individual interest is of essential importance. For sponsors, the key figure usually is the return on their investment (mainly equity). To measure economics, a range of figures can be used. For solar projects, however, the two most important ones are the *Project Internal Rate of Return* (Project IRR) and the Equity Internal Rate of Return (Equity IRR). The *Project IRR* indicates the interest the project generates on the overall capital. This figure disregards any financing scheme or the sources of such capital and hence is a measure for the economic strength of the overall project. Now if – as usual - the cost of debt (interest rate) is lower than the Project IRR, and the lenders would be willing to provide a portion of debt to the overall sourcing of the project, there are two principle effects for equity investors: first, equity investors or sponsors only have to provide the balance of the total funding, for example a 30% of total funds. Second, since debt cost are lower than Project IRR, the remaining portion of Project IRR Cash Flow that is not needed to cover principle and interest of Lenders can be used to pay dividends. As a consequence, the Equity IRR is higher than the Project IRR. This is called the Leverage Effect. It is one of the main reasons for the application of project (and other structured-) financing and helps to optimize the capital structure.[2]

Under a given electricity sales scheme such as a Feed-In Tariff, an equity investor would therefore strive to maximize leverage (debt share) in order to minimize his equity investment and maximize Equity IRR. On the other side, in a process where competitiveness of the power price is key, a high leverage and low capital cost can contribute to the competitiveness of the project by lowering the capital cost.

Standardized approaches for yield analysis assure that the input values into financial evaluation are trust-worthy and remaining uncertainties are clearly illustrated. Both, the sponsor and the lenders base their calculation not only on the expected value but need to consider long-term uncertainty as well as inter-annual variation of yield. Therefore, systematic approaches for determining and documenting uncertainties are a key element of every yield analysis.

Benefits in the View of Research and Development

With the CSP technology having just started the descent on the learning curve, significant improvements of components and processes are expected in the near future. The actors in research and development compare their innovations with the state-of-the-art technology to demonstrate advantages of their innovation. A standardized approach for yield calculation assures that such comparison is carried out on an state of the art approach. Furthermore, studies of different authors can be compared more easily if they are based on the same approach and, in an ideal case, even on the same set of parameter values.

[2] To give a very simplified example: a South African project could have a Project IRR of 12%, debt all-in interest cost of 10%, a leverage (debt share of total sources) of 50% and thus achieve an Equity IRR of 14%. (Only for explanatory reasons, since many other effects such as tax shield etc. playing a role!)

A FIRST MILESTONE TOWARDS A GUIDELINE FOR YIELD ANALYSIS

Looking on the CSP business today, it is clear that the aforementioned need for minimum standards for yield assessment models is currently not satisfied. Considering the fact that a lot of experience is available, it is time to initiate the development of guidelines with the aim of creating a standard in performance modeling and yield analysis. Guidelines recognized by the CSP-community would enhance the quality of yield assessments throughout the entire value chain of CSP projects, thereby enabling market players to synchronize and upgrade their models. As a further positive effect, project development costs and risks would be reduced due to an increased transparency and reliability of technical outputs. Moreover, such guidelines are intended to be one step towards standardization of the development process of CSP projects and as such it would lead to an increased confidence of private equity and financing institutions in yield assessments conducted and verified by advisors which in turn could stimulate project participation and improve project financing conditions.

Activities on a guideline for CSP yield calculation date back into the year 2010 when an expert group was founded in the framework of SolarPACES task I, see Fig. 1. By the year 2012, a lot of conceptual work had been carried out by the international team resulting in the definition of an outline of the guideline, a systematic breakdown of typical CSP plants into sub-systems, a list of important terms, and a classification of relevant effects influencing energy yield estimations ([1], [2]). The next logical step of writing handbook chapters could not be realized due to limited resources of all partners. In this situation, a consortium of research institutions and industrial partners obtained national funding from the "German Ministry of Economic Affairs and Energy" and started the project CSPBankability (Improvement of the bankability for CSP plants) in 2014. The aim of the project is to resume work on the yield calculation guideline and to work out a comprehensive draft. It is the understanding of the CSPBankability project to provide a draft version to the SolarPACES community which is considered as basis for discussion. In autumn 2015, the first version of the handbook will be finalized. This version covers general aspects and focuses on parabolic trough systems with oil as heat transfer medium since this is today the most mature CSP technology. Extensions to other CSP technologies are already foreseen and will be added in the near future. The draft version available today is considered as an important milestone on the way to a SolarPACES guideline. At the SolarPACES conference in October, the discussion process on international level will be organized together with all interested partners.

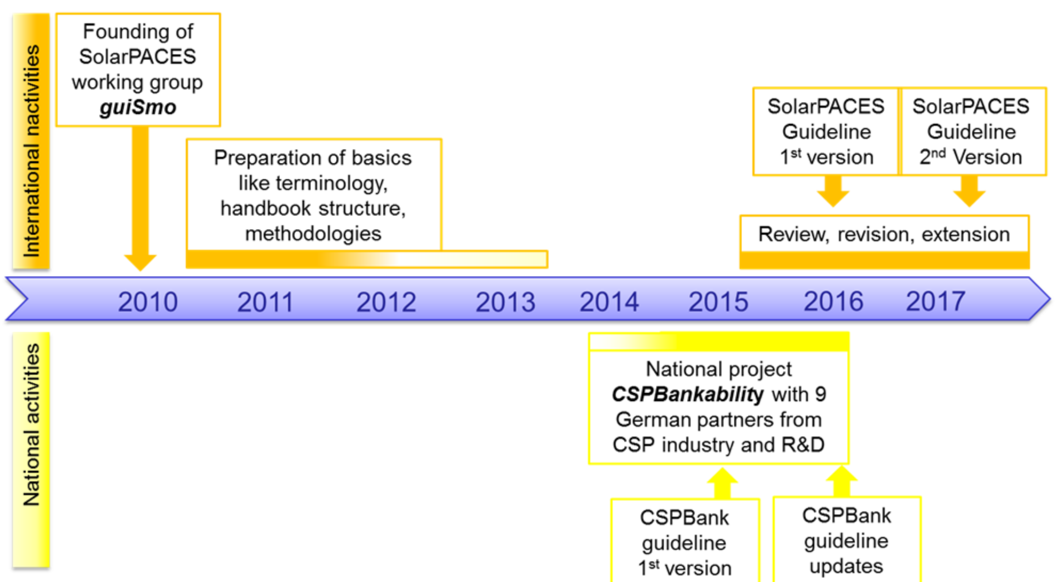

FIGURE 1. Illustration of activities in the guideline development process

CHARACTERISTIC ELEMENTS OF A YIELD ANALYSIS

The proposed approach for yield analysis shall be generally applicable for CSP modeling independent of the specific technology. For this purpose, the whole system is broken down into subsystems which exist in all typical

CSP plants (although individual plants must not necessary show all of these subsystems): solar field, power block, thermal storage systems, auxiliary heater, and electrical system. This break down into subsystems with well-defined interface variables simplifies the implementation of sub-models and enables the modification or exchange of them. On the other hand, an iterative algorithm is required on system level to get the final solution with balanced subsystems.

The models are based on steady state assumptions with 10 minutes temporal resolution. This time step is proposed since high quality meteorological data with this resolution is available today and 10 min time steps allow for a couple of model simplifications which are not possible when using hourly time steps. Furthermore, the calculation speed of conventional computers is high enough for this resolution. The steady state approach is supplemented by additional terms accounting for major start-up effects which typically reduce the net plant output. Interface variables between subsystems are mass flow rates and enthalpies instead of heat fluxes because this approach will allow considering effects in one subsystem caused by deviations from nominal temperatures in another subsystem.

The solar field model will be specific for individual CSP technologies and it consists of a combination of empirical and physical sub-models. The idea of the guideline is not to stipulate each and every equation to be used but rather to identify and nominate those effects with a significant impact on annual yield. Furthermore, models for these effects are proposed which are considered to adequately describe them, in order to reach the "required" accuracy of yield estimates.

The power block model is very similar for all CSP technologies, though the individual power block designs might be different. The model consists of a set of lookup-tables considering the main impact variables like: thermal input, HTF inlet temperature, wet bulb or dry bulb temperature (depending on the cooling type). These lookup tables may be calculated in advance by thermodynamic cycle balance programs and the annual yield model does interpolation in the lookup tables for the conditions at individual time steps.

The thermal storage model is not just summing up input and output heat fluxes but rather uses mass flow rates and enthalpies as the other parts of the plant model do. This is an important feature since deviations from nominal temperatures may cause significant deviations in thermal storage capacity as well as in power block efficiency and output.

Auxiliary heater and electrical system are represented by simpler models. The auxiliary heater is used to provide heat for freeze protection and/or steam production and it uses fossil fuels to heat up a medium to the desired temperature. The electrical system is defined as the electrical transmission, distribution and transformation system, which has mainly the following tasks: Transmission of the produced electric power to the public grid and distribution and transformation of a part of the generated electricity to supply all electrical consumers of the plant.

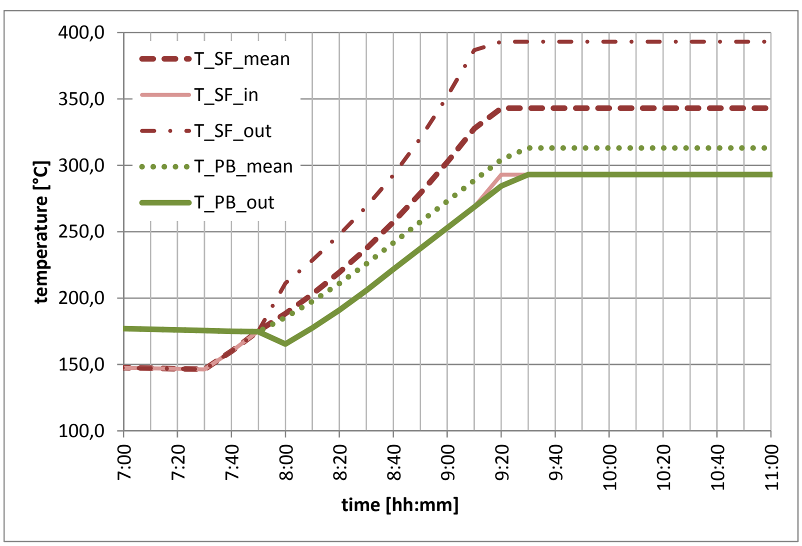

FIGURE 2. Example for a simulated start-up procedure of solar field (SF) and power block (PB). During the first 20 min the solar field is preheated applying a lumped mass temperature. After that power bock and solar field are ramped up in parallel. Inlet and outlet temperatures develop to the final steady-state values.

Daily start-up of solar field and power block is not instantaneous. Since the CSP plant does deliver no or at least reduced net electricity during these time periods start-up needs to be considered for yield analysis. Since detailed process simulations would be too complex to implement, in comparison to the benefit they would offer in terms of accuracy, in annual yield calculation simplified approaches are used to complement the steady state model with proper consideration of transient effects. The startup of both subsystems is based on lumped energy sums and state variables taking a value between zero and one. Zero means the sub system is in a "cold" state and one means nominal temperatures of power block or solar field are reached, respectively. Different operating conditions like startup of solar field with power block already running from storage or start-up of power block without solar field need to be covered for a flexible approach. The model proposed is capable to consider parallel as well as sequential startup of solar field and power block. Figure 2 illustrates an example of a start-up process as calculated by the simplified approach. Cool down of the solar field can be calculated by using the same equations as for the operating state but with zero input from the sun.

The overall model of the CSP plant needs also to consider a certain operating strategy (OS) since the applied OS will have an impact on the annual yield. Although the number of possible OS is manifold, in the guideline a limited number of most representative OS are described: pure solar driven, solar driven with minimum load during night time, load curve defined and price driven. Recommendations are provided that help to document individual operating strategies.

The meteorological data and particularly the DNI time series have a major impact on the results and thus an extended chapter of the guidelines is dealing with this subject. The annual performance model needs meteorological datasets with the same temporal resolution as used in the model as input data. In addition to DNI, the meteorological dataset should contain also ambient temperature, ambient humidity, wind speed, and wind direction. Due to the importance of these input datasets, they should be generated from long term measurements. This means typically at least 10 years of measurement. Since this requirement is often not fulfilled for high quality ground measurements at the planned project site, the combination of high quality ground measurements of about one year or more and satellite measurements for long term data is recommended.

Consideration and calculation of uncertainties is an important part of the guideline. Three sources of uncertainties are distinguished: Uncertainty of the meteorological input data, uncertainty of model parameters and uncertainty of the model itself caused by simplifications and negligence of certain effects. Uncertainty caused by the meteorological data is considered via utilization of datasets with different probability of exceedance known as e.g. P50 or P90 datasets. A probabilistic modelling approach is recommended to calculate the combined uncertainties of the model parameters as well as of the model itself. The major problem with this approach is that individual uncertainties are sometimes not known and modelers have often no method to determine them. In good approximation, the uncertainties of the three different categories are statistically independent. Thus, the combined uncertainty can be obtained by quadratic summation.

The cost structure of a CSP project depends on the kind of project. The main focus of the guideline is on project financing. Thus, expenses are divided into capital expenditures (CAPEX) and operational expenditures (OPEX). Capital expenditures consist of the three main categories EPC costs, Owner's costs, and Financing costs.

The guideline is completed by a detailed spreadsheet based financial model calculating the important figures of merit for the parties which are typically involved into such kind of projects.

Finally examples for a couple of reference systems are shown which can be used as starting point or to check own models.

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REFERENCES

1. M. Eck, H. Barroso, et al., "guiSmo: Guidelines for CSP performance modeling – Present Status of the SolarPACES Task-1 Project," in Proceedings of the 17th SolarPACES Conference, Granada, Spain, 2011.
2. M. Eck, T. Hirsch, J.F. Feldhoff, et al., "Guidelines for CSP yield analysis – optical losses of line focusing systems; definitions, sensitivity analysis and modeling approaches," 19th SolarPACES Conference, Las Vegas, NV, USA, 2013.