TOWARDS STANDARDIZATION OF CSP YIELD ASSESSMENTS

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Abstract

The paper gives recommendations to reach high quality, traceable and reproducible yield prognosis for solar thermal power plants. The whole process chain from solar resources to simulation is evaluated to identify main error sources. Three main fields are identified, which have significant impact on accuracy of potential electricity yields: Firstly, much care must be taken to create realistic site-specific meteorological time-series in high temporal resolution, which well match the long-term average solar radiation conditions. A set of rules is given, which allow estimation of the uncertainty of solar resource data. Secondly, ambiguity of the technical performance of the plant can have severe impact on yield prognosis. This must be overcome by realistic parameterization of major components of the plant in yield simulations and appropriate performance guarantees from suppliers. Thirdly, the model applied to calculate potential energy yields must be capable to simulate the processes in a plant under evaluation fine enough in respect to spatial and temporal discretization. The model must be capable of reproducing realistically the major processes which are relevant for energy yields. This includes the definition of appropriate rules for plant operation. A quasi-static model approach can be sufficient, if corrections terms are introduced, which are derived from case studies with a dynamic model capable of simulating the relevant transient processes. The focus of this paper is on parabolic trough plants, but most findings also help for yield prognosis of other concentration solar technologies.

Keywords: Parabolic trough, solar thermal power plants, direct normal irradiation, simulation of energy yields, certification, validation.

1. Introduction

While lenders today can appreciate reliable tariff schemes for renewable power plants in several countries, the reliable prognosis of electricity yields – in contrast to the fossil power sector – still is challenging. For the more established renewable technologies such as photovoltaics or wind the introduction of industry-wide accepted best practices for determination of yields has created the required comfort for financing of projects. In the field of concentrating solar power (CSP) standardized procedures for the assessment of energy yields are still missing. High overall quality of yield prognosis and their reproducibility, together with derivation of uncertainties in the involved processes are preconditions to get access to debt and equity funding for CSP.

Other technologies such as wind energy or photovoltaics have already implemented many more projects than CSP so far. So there is much more experience in these technologies, while the general procedure is similar. The German guideline for yield assessment of photovoltaic parks [1] and the recommendations for wind energy prognosis [2] may therefore serve as a starting point for CSP industry. Meteorological input data in both cases are of high priority for yields as the solar resource replaces the fossil fuel for a thermal power plant. Therefore the project SESK (Standardisierung der Ertragsprognose für Solarthermische Kraftwerke), which aims for standardization of yield prognosis for solar thermal power plants, puts high emphasis on this part of yield assessments.

Important for reproducible results are definition of clear rules for data generation and quality control procedures, which in the future shall be fixed in standards. The goal is to estimate uncertainties of all relevant processes. Based on sensitivity studies with simulation models, recommendations on allowed ranges of uncertainty shall be given. This includes also technical parameters defining the plant layout and performance.

In project development the following phases are common: During pre-feasibility phase a site is roughly evaluated whether it makes sense to study it more deeply. Important part of this is the analysis of potential energy yields. During the feasibility phase, which typically takes few weeks or months time, the remaining sites receive more detailed attention. Succeeding sites then enter project phase, where much emphasis is taken also to finally qualify the energy yield analysis for due diligence (DD), which is required to get the project financed. For all these project development phases certain quality grades with increasing quality should be reached. In the following recommendations are given, what kind of measures are suitable in which project phase.

For this purpose the whole process chain from solar irradiance to the simulation of electricity generation needs to be defined and evaluated. For each major step “satellite-derived solar irradiance data”, “ground-based meteorological measurements”, “combination of satellite and ground-based measurements”, and “CSP yield simulation” criteria must be fixed.

2. Measures for reliable and representative site-specific meteorological data products

For proper CSP yield simulation much emphasis has to be laid on generation of valid meteorological input data. The requirements on the irradiance information for CSP are increased compared to those for photovoltaic power plants. CSP mainly depends on direct normal irradiance (DNI) which, compared to global horizontal irradiance (GHI), shows stronger spatial and temporal variability. In addition, CSP reacts in a non-linear way to this input. Thus, detailed information on the statistical distribution of direct irradiance is required. For standardization of CSP energy yield assessments the meteorological input requires in depth analysis and well-defined procedures to produce reliable results of defined quality.

To reach site-specific meteorological data in high quality it is common sense within the CSP industry to set up measurements at the site. For connecting these short-term measurements to the climatological mean the application of long-term satellite-derived DNI time-series is the method of choice.

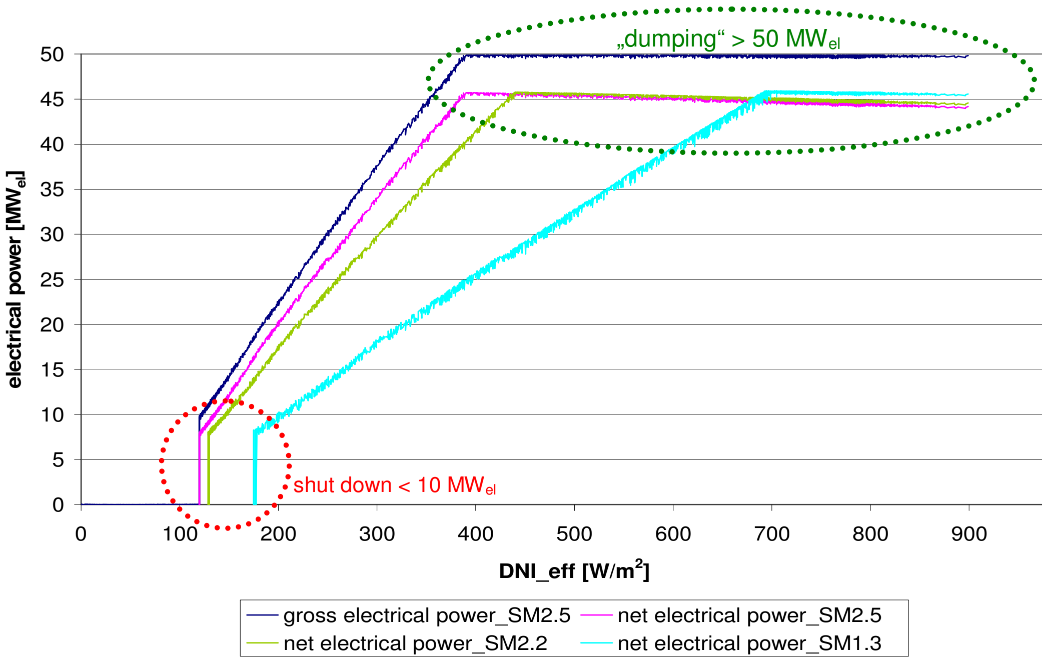

Fig. 1. Transfer function of effective DNI into electric power for various solar multiples (SM) derived from simulations over a full year.

2.1. Recommendations for application of satellite-derived irradiances

Satellite-derived DNI data are state of the art for feasibility studies. The DNI-products shall be qualified by benchmarking against high quality ground-based solar irradiance measurements. An example is the satellite data inter-comparison carried out in the MESoR-project [3]. To reach reliable statistics for such benchmarking as many stations as possible shall be considered. However, only measurements with proven quality shall be applied. The quality of these stations should clearly exceed the expected quality of the satellite data. Compared to global horizontal irradiance, it is harder to derive DNI from measurements and satellites. Only few meteorological stations provide DNI at all and some of those do not fulfill the required quality criteria.

For CSP, however, it is recommended to do a modified benchmarking. First of all, the effective direct normal irradiance DNI_{eff} should be used instead of DNI as recommended earlier by [4]. For typical North-South aligned parabolic troughs it is calculated by

$$DNI_{eff} = \left(\sqrt{1-\cos^2(sunhgt)\cdot\cos^2(sunazt)}\right)\cdot DNI$$

where *sunhgt* is the angular height of the sun above the horizon and *sunazt* is the sun azimuth angle, where 0° refers to North. DNI_{eff} is the irradiance, which actually can be converted by parabolic troughs into heat. The DNI_{eff} has the advantage it is, as a first approximation, proportional to the energy yields (see also figure 1).

At higher latitudes lower sun elevations lead to a lower ratio of DNI_{eff} / DNI – the usable fraction for parabolic trough plants. Also more shading decreases energy yields for all CSP technologies with increasing latitude. Therefore, most of the commercial CSP plants will be built at latitudes below 45°. A CSP-specific benchmarking of satellite data shall consider this. Unfortunately, only few measurement stations offering DNI are situated below 45° latitude today.

As a further step, it is recommended to cut-off all irradiance values taken when the sun height is below 5°. Due to strong shading effects the solar fields of CSP plants are usually not operated at such low sun heights. Another criterion for identifying usable irradiance is that low values of DNI_{eff} are of limited value for power generation. Depending on plant layout, mainly of the solar field, it is assumed that thermal losses and parasitic consumption exceed the collected energy when DNI_{eff} drops below 200 W/m². Thus, this criterion should be used for filtering DNI when benchmarking satellite data.

Errors of satellite data and also of measurements usually occur predominantly at low sun height. Especially satellite-derived irradiance data show higher frequency of errors at other times with low DNI. E.g. broken cloud situations lead to geometrical mismatches of satellite-derived DNI against measurements. Thin cirrus clouds or situations with enhanced atmospheric aerosol load have already strong impact on DNI, but often are not correctly detected by today's satellite algorithms. Therefore, it is assumed that the proposed cut-off rules for a CSP-specific benchmarking lead to significantly lower deviations between satellite and measured data than those given in [3].

Satellite data shall be as specific as possible for the site under consideration. Therefore, a minimum spatial resolution of 0.1° (approx. 10 km) is recommended. As variability of DNI is relatively high, satellite products with lower spatial resolution are of limited value for siting of CSP plants. Higher spatial resolution in the range of 1 km would be of advantage for micro-siting of the plant. Today, 1 km data sets are not highly reliable as actual horizontal resolution of geostationary satellites is lower than indicated and parallax effects in the viewing conditions usually are not considered.

Long-term annual averages of DNI are sufficient for pre-feasibility studies but at least the effect of latitude on energy yields should be taken into account. For feasibility studies it is recommended to model the power plant performance at least based on 60 min time resolution. This is in line with data sets being offered by most providers of satellite-derived DNI products such as SOLEMI [5]. However, hourly time resolution is not sufficient to simulate transient processes in the power plant, which may have some influence on energy yields. Therefore, higher time resolution is recommended to prepare for due diligence. Since 2004, the new Meteosat Second Generation (MSG) delivers data in 15 min time resolution. [6] adapt the Heliosat-scheme to derive DNI from MSG data.

To average out inter-annual variability of DNI it is recommended to use as many years as possible to derive the long-term average of DNI. Assuming that each single year represents an independent measurement the uncertainty $\Delta DNI_{longterm}$ due to interannual variability is reduced. It is important that only regular years without severe influence of stratospheric aerosols due to high-reaching volcanic eruptions are considered in the analysis. According to [7] such atypical years must be excluded, which has the effect that the frequency distribution across the years approaches a normal distribution. $\Delta DNI_{longterm}$ shall express the uncertainty of the longterm average, due to taking only *n* complete years into account. Neglecting that there is some connection between consecutive years $\Delta DNI_{longterm}$ can be calculated from

$$\Delta DNI_{longterm}(n) \approx \frac{\sigma_{annual}}{\sqrt{n}}$$

According to [8] the average of the standard deviation of annual averages σ_{annual} for regions below 45° latitude without the effect of high-reaching volcanic eruptions is 7.6 % for DNI, but only 2.1 % for GHI. Consequently, it is expected that the long-term uncertainty of an ideal solar resource data set (without methodological uncertainties) is 3.4%, when accounting for only 5 years, 2.4 % for 10 years and can be reduced to 1.7 %, when 20 years are taken into account.

It is recommended to use two independent satellite data sets for DD. It is assumed that a combination of independent overlapping time-series further reduces the uncertainty of average DNI at the site. To be truly independent the satellite-derived irradiances should be based on separate satellite instruments, on individual satellite platforms with differing viewing angles, independent auxiliary data like water vapor, aerosol, or ozone and best also be retrieved from independent algorithms.

For our analysis we apply two independent satellite data sets. The SOLEMI DNI products from DLR use Meteosat First Generation (MFG) data and currently cover the period from 1991 to 2005 and the Heliosat products provided by University of Oldenburg, which rely on data from the Meteosat Second Generation, which provides data since 2004.

2.2 Recommendations for ground based meteorological measurements

To achieve due diligence for project finance of CSP plants today it is required to execute measurements at the site of the power plant under consideration. A suitable measurement station shall be placed as close as possible to the lot of the plant and not exceed 5 km distance. As suitable stations almost never are available in such a close distance, usually dedicated meteorological stations should be set up for qualification of each CSP project.

The single most important meteorological parameter for CSP yields is DNI. Therefore, much care has to be taken to derive this value with high quality from reliable radiometers. The instruments, which are best suited for precision measurements of DNI are pyrheliometers. Unfortunately, pyrheliometers must be cleaned daily [9]. Otherwise degradation due to soiling and dew can lead to severe underestimations of DNI measurements [10]. Rotating shadowband radiometers (RSR) show much less soiling and [11] developed a procedure to detect and correct such systematic deviations.

Much care has to be taken with individual calibration and correction of instruments to reach reliable values. From a long-term calibration experiment with 3 RSR sensors, which have been operated for up to 18 months at PSA (see figure 3), it is concluded that the calibration time period should be at least 4 weeks to reach accuracy requirements for sound DD. From the long-term calibration (figure 2) it also can be concluded that the DNI calibration coefficient of RSR2 instruments is highly stable. DNI can be derived by RSR2 more reliable than global or diffuse radiation components.

RSR sensors show low influence of soiling. Nevertheless, it is recommended to clean at least once every 4 weeks, and potentially more frequent at sites with fast contamination. Weekly cleaning is recommended for sound DD. All cleaning, changes and relevant observations at the station must be documented in a station logbook.

Regular quality control (QC) of measured data should be executed to detect errors or station outages as soon as possible. QC procedures such as SERI-QC [12] or the MESOR-routines [3] must be applied to detect outliers. These need to be flagged as erroneous. The total amount of missing or erroneous data shall not exceed 7% for DD, and should stay below 5% for sound DD.

Further, it is recommended for sound project qualification to do an in situ cross-check against a traveling standard station. This traveling standard (see fig. 2) should be equipped at least with a precision pyrheliometer and another RSR. For redundancy, further additional sensors like precision thermal pyranometers are recommended. The cross-check in the field should be done at least directly after setting up the station and before removal. Additional cross-checks are recommended at least every 18 months. The duration of each cross-check should cover at least a full day and reach an irradiation sum of at least 5 kWh/m² and must include DNI values of at least 700 W/m².

If all recommended procedures are applied properly the root mean square deviation (RMSD) against a reference pyrheliometer should be 2 % for monthly averages derived from RSRs. For daily mean values an RMSD of 3 % and 5 % for hourly is expected.

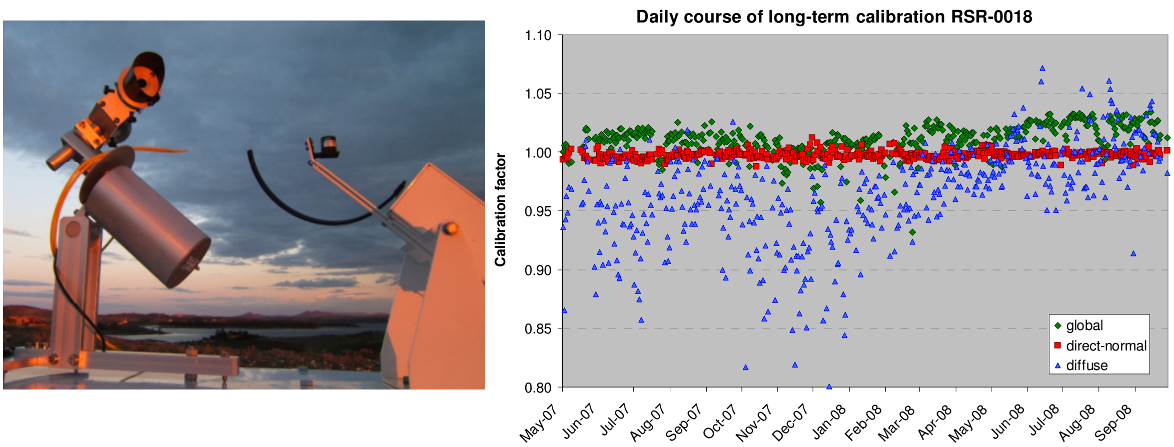

Fig. 2. Cross-check of a meteorological station at a site in Spain (left). The operational solar radiation sensor at the right (rotating shadowband radiometer RSR2 from Irradiance Inc.) is checked by a precision pyrheliometer (CHP1 from Kipp&Zonen).
Right: Day to day variability of calibration constants for the RSR2 instrument.

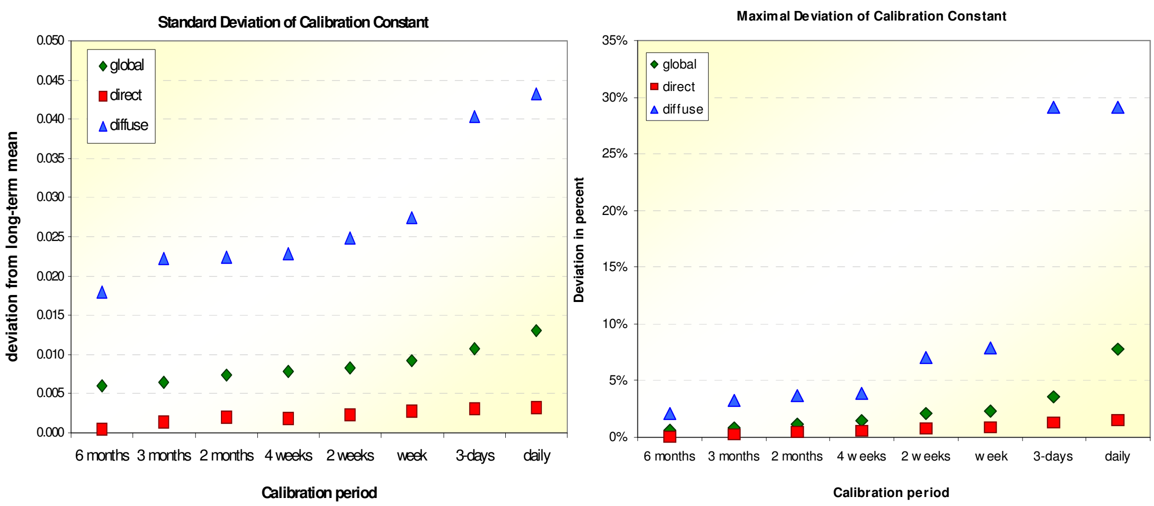

Fig.3. Effect of calibration period on the accuracy of the derived calibration parameters.

Some other meteorological parameters have influence on plant design and yields. Therefore, for sound CSP project qualification it is recommended to add instruments, which allow to measure also ambient air temperature, humidity, wind velocity and direction. To get meaningful values wind measurements shall be taken at the WMO standard height of 10 m and air temperature and humidity shall also follow the WMO standard of 2 m height above ground. These auxiliary meteorological data shall be logged at least with 10 min time resolution, but 1 min (equivalent to DNI data logging) is recommended for high quality assessments.

2.3. Recommendations for combination of ground-based and satellite based data

For combination of the satellite data sets with on site measurements the method of [13] is taken to derive the best estimate of the long-term average. [13] also provides an overall methodological accuracy ΔDNI_{method} of the combined data. This depends on the individual uncertainty of the underlying data sets used to generate the best estimate. Additionally, the aspect of inter-annual variability (see 2.1) needs to be considered. This independent error source has also to be taken into account to calculate the final uncertainty of DNI. Again, it can be assumed that the uncertainty of the method is independent from the uncertainty introduced from taking a limited number of years. Thus, the Gaussian error propagation law may be applied, which leads to an overall uncertainty of

$$\Delta DNI \approx \sqrt{\Delta DNI_{longterm}{}^2 + \Delta DNI_{method}{}^2}\,.$$

E.g. a long-term average derived from 10 years of data, which show a methodological uncertainty of 3 %, has an overall accuracy of 3.8 %, while a 5 year covering data set with 6 % methodological uncertainty leads to an overall accuracy of 6.9 %.

So far, only the long-term average irradiance or average annual irradiation sums are considered. However, for the actual output of a CSP plant the actual weather conditions play an important role. The site-specific distribution function shall be met as close as possible, to account properly for high-resolution temporal variability of the data. [14] describe methods how to get characteristic meteorological data sets, which match the derived long-term average. Quality parameters like those of [15] help to classify the quality of specific solar resource data.

3. Qualified simulation of CSP yields

Proper prognosis of energy yields of planned solar thermal power plants requires simulation models, which are capable of calculating the relevant processes in appropriate time-steps. To reach high reliability of the prognosis, simulation runs should cover also long time-periods. For analysis of the plants' response to climatological variability it is recommended to analyze not only a single representative annual data set, but to apply multi-year data sets. For analysis of weather related risks at least 10 years of high resolution data are recommended.

In the course of project development simulation runs often have to be executed for several different plant layouts with a multitude of technical parameters to assess technical risks and optimize plant layout. The multitude of requirements results in significant computational effort, which makes fast processing tools necessary. Therefore, a quasi-static model approach is preferred. However, a parabolic trough plant shows some non-linear behavior and has relevant thermal inertia. Therefore, transient weather conditions can have significant effects on the resulting electricity production. To account for such effects inter-comparisons with a transient dynamic simulation model are performed. These shall lead to correction terms in the quasi-static model.

Today depending on the care taken to derive the characteristic meteorological data sets [14], it must be assumed that the deviations from deriving characteristic meteorological data can lead to uncertainties in the electricity output in the range of 1% to 10%.

From sensitivity studies for the meteorological input data with the quasi-static model it is derived that DNI is by far the most dominate parameter. The dependency of the electricity yield E_{el} is roughly $\Delta E_{el} \propto 0.7\ \Delta DNI$. This dependency is derived for a plant with a relatively high solar multiple of 2.5 and 7.3 equivalent full load hours of thermal storage. The deviation from a straight linear dependency is mainly caused by irradiance conditions, when solar radiation is plenty and more solar input does not lead to higher engine output and also can not be stored, because the buffer is already full. For smaller storage sizes or larger solar fields we expect that situations, where energy needs to be 'dumped' occur even more frequent. This would lead to smaller sensitivity than 0.7 and vice versa.

Fig. 1, which is derived from a full year of measured meteorological data, shows that the electrical power generation is fairly close related to DNI_{eff}. Only some overlaying 'noise' shows that other meteorological parameters have slight influence on yields. From this experience, a list of recommendations for meteorological data is derived. Table 2 gives weighting factors for driving meteorological auxiliary data. Compared to other weighting rules such as [7] the recommendations for CSP clearly focus on DNI, which is by far the most important parameter.

Parameter	Sandia Method	NSRDB TMY	SESK recommendation for CSP
DNI	not used	5/20 = 25 %	85 %
GHI	12/24 = 50 %	5/20 = 25 %	not used
max. wind velocity	2/24 ≈ 8 %	1/20= 5 %	4 %
mean wind velocity	2/24 ≈ 8 %	1/20 = 5 %	2 %
wind direction	not used	not used	1 %
max. air temperature	1/24 ≈ 4 %	1/20 = 5 %	1 %
min. air temperature	1/24 ≈ 4 %	1/20 = 5 %	2 %
mean air temperature	2/24 ≈ 8 %	2/20 = 10 %	1 %
max. dew point temp.	1/24 ≈ 4 %	1/20 = 5 %	2 %
min. dew point temp.	1/24 ≈ 4 %	1/20 = 5 %	0 %
mean dew point temp.	2/24 ≈ 8 %	2/20 = 10 %	1 %
air pressure	not used	not used	1 %

Tabe 1. Recommendations from SESK (right hand side) for weighting of various meteorological parameters when constructing characteristic meteorological years for CSP assessments and intercomparison to weighting for TMY2 (left) and TMY3 (middle) acc. [7].

4. Conclusions and Outlook

The paper proposes an initial set of procedures for best practices for CSP yield prognosis. The newly developed methodology for parabolic trough plants follows existing standards for yield prognosis in other renewable energy industries such as photovoltaics and wind energy. It is based on existing satellite solar resource products and practical instrumentation for the ground-based measurements. Uncertainties of the recommended data and methods are derived from reference stations and models. Besides best estimates for the long-term average advices for risk analysis are given.

The methodology is focused on parabolic trough plants, but it is kept open for extension to other CSP technologies. Several points for further improvement of the proposed methodology are identified. Satellite data shall be improved mainly by enhanced aerosol data. Concerning use of meteorological stations measures to reduce the current effort shall be evaluated guided by the resulting overall uncertainty. These improvements shall be developed and tested in the course of the project. Based on evaluation of results a revision of the recommendation for best practices is planned. Finally, the whole process chain shall be certified to guarantee high and reproducible quality.

Based on the results and the experience gained in the project SESK important steps for proper CSP yield prognosis shall be documented in best practice handbooks to be agreed with the CSP community and coordinated through IEA SolarPACES. Such best practices shall be the base for the long-term activity of inventing appropriate international standards.

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