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Road Map for Creation of Advanced Meteorological Data Sets for CSP Performance Simulations

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Preface

The best way to determine the production from a solar facility is to take the 10 – 20 – 30 years of data that are available and run a simulation with that data. If time of day or capacity matter, those parameters can be factored in at this time. Now the variation in generation over the time span under consideration can be seen and it is possible to select the typical year's production and get a feeling for the variation from year to year and month to month. If available, use of one year of high quality measured data can be used as input and a more detailed analysis of the plant generation can be performed. Adjustments can be made if the more detailed analysis shows that it is necessary.

Trying to select one year that is typical before running the data might be fine for an initial survey, but a universal typical year dataset that is applicable for all types of generation probably is not be the best solution because different facilities can react differently to the same input irradiance. Storage and the ability to adapt to rapidly changing irradiance are likely factors that can influence the selection of the most typical solar year.

The annual DNI is likely to vary less than 10% from year to year, so the characteristics of the incident solar radiation and how the plant handles variations in the resource are likely to play as important a role in the annual production of the solar facility as the annual DNI.

In addition, I have never been a fan of breaking the production down into monthly blocks and selecting the most typical monthly production. Weather comes in waves and patterns and cutting and splicing break up these patterns. This is how some TMY files can create annual irradiance estimates that are above or below any experienced at the site.

A moving average approach can yield a full range of generation estimates although the beginning and ending year are underrepresented.

Frank Vignola
Director of the Solar Radiation Monitoring Laboratory
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Executive summary

The demands on the quality and contents of solar and meteorological data sets increase rapidly with the growth in Concentrating Solar Power (CSP) and other solar energy systems. This document is a deliverable of the SolarPACES Project: "Beyond TMY," and it is produced as recommendations for what to do next and a road map of future improvements in extension of our elaborate report: *Discussion of currently used practices for: "Creation of Meteorological Data Sets for CSP/STE Performance Simulations"*.

High quality ground-based measurements of global, direct and diffuse solar radiation are of fundamental importance. This includes the use of appropriate instruments, proper data quality control and gap-filling procedures, and improvements in satellite-derived data site-adapted with the ground-based measurements. Uncertainty assessments of both these data sources are essential. Furthermore, long-term solar resource scenarios and auxiliary meteorological data are important. These include the sunbeam shape, low level extinction and soiling. Reanalysis data from weather models and the prospects of realistic multi-year generation are all main topics that we summarize in this road map.

At the end of this document, a summary of recommendations for future works it is proposed.

This roadmap aims to help non-experts in solar radiation or meteorological information in the understanding of the current state of the art and the needed steps for the Creation of Advanced Meteorological Data Sets for CSP Performance Simulations.

1. Introduction

A Concentrating Solar Power (CSP)/Solar Thermal Electric (STE) power plant is a substantial long-term investment. To evaluate the opportunities and risks associated with such a long-term investment requires careful technical and economic analysis. Usually, the results of such analysis are presented in what are known as feasibility studies.

Traditional CSP/STE feasibility studies start by defining an economic model to estimate the economic metrics that characterize the quality and attractiveness of the investment project associated with the construction and operation of the CSP/STE power plant. Typical economic metrics are the Levelized Cost of Energy (LCOE), the Internal Rate of Return (IRR), the Net Present Value (NPV), and the Debt Coverage Ratio (DCR). A technical model has to be defined as well, and the parameters covering the properties of the plant components have to be stated.

Once the economic model is defined, the next task is to accurately estimate the variables and parameters that are inserted into the model, such as the project's total investment, the annual O&M costs, the discount rates, the equity-to-debt ratio, and of course, the amount and characteristics of the electricity generated during the plant lifetime.

The electricity generated is an important intermediate result that is characterized by the solar resource at the CSP/STE plant site and the technical performance of the CSP/STE technology selected for the solar power plant. To estimate it, one should first develop or acquire a time series of relevant solar radiation and other meteorological data that is as long as possible and representative of the long-term meteorology at the solar plant site. When the solar resource is combined with the technical parameters that define the plan technology, configuration and operation strategy, a technical model of the plant is created and an estimate the electricity generation is produced.

Often, only one yearly data set is used that is representative of the average meteorological year to be expected at the site in the long-term. Sometimes this is supplemented by estimates of the production in a bad year that will be exceeded with a certain probability.

Although the above approach, combined with a sensitivity analysis of the variables and parameters of the model is already useful to banks and other potential investors in the decision making process related to the decision of carrying out the investment, there are other more sophisticated approaches that can be pursued.

The one we think is worth exploring is a full stochastic approach, in which the following aspects are explicitly modeled and taking into account:

- The inter-annual variability of the solar resources and other meteorological variables.
- The uncertainty of these meteorological variables – mainly the DNI.
- The uncertainty of the technical input parameters.
- The uncertainty of the technical model used to determine the annual electricity yield.
- The uncertainty associated with all the different component costs, including commodity-like cost components, such as molten salt and other costs that determine the aggregate values of the plan investment and the annual O&M cost.

In such a model, all the input variables and parameters are considered probability distributions. The challenge is to determine these distributions. How to determine the probability distribution of the electricity yield of the CSP/STE plant better is the overarching theme of this document. Obviously, it starts with how to model the probability distribution of the solar radiation and other relevant meteorological variables.

In this report, we discuss the main points affecting the creation of meteorological data sets for CSP performance simulations, and thus affecting its probability distribution.

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2. Ground-based measurements

Background

A typical-sized Concentrating Solar Power (CSP)/Solar Thermal Electric (STE) power plant with a size in the order of 100 MW may require an investment volume of about 400 million USD. An in-situ measurement campaign at the site is required to achieve financial closure. Nowadays satellite-derived direct normal irradiance data are available for all potential sites although these data have pertinent uncertainties. Therefore, a local measurement campaign of at least one year of duration has several relevant advantages for the following reasons:

- The information is directly related to the location that has to be characterized. No consideration on spatial relation has to be made.
- It is not possible to derive meteorological information in very high frequency (minutes or seconds) directly from satellite images or numerical weather prediction (NWP) models. Such high frequency can be essential for the plant simulation.
- A measurement campaign of solar radiation during a year serves to check or to adjust locally the results and estimations from longer periods like those coming from satellite images or reanalysis with NWP models.
- The meteorological information like temperature, humidity and wind speed can be assessed and compared with the output from NWP model.
- The investment in the instrumentation could be used latter in the power plant operation if it is built in the selected location or at a future location for new characterization.

On the other hand, some important points have to be considered in relation with a solar radiation measurement campaign:

- Solar radiation instruments have to be properly maintained. The instruments have to be cleaned and the data quality has to be monitored on a week-daily basis to ensure proper operation. Otherwise problems can occur that typically result in a negative bias in the estimated solar resource.
- Some instruments are more robust for isolated locations as it is the case of rotating shadow band irradiometers (RSI). However, this device has its own limitations vs. a standard pyrheliometer that result from the spectral response characteristics of the solar cell based pyranometer used or uncertainties in the correction algorithms used to remove systematic deviations. The decision of whether to use one type of solar radiation instrument or another has to be assessed for each site and project and could be different at different stages of the project.

In addition to the measurement campaign previous to the power plant erection, local measures are also needed for the solar field characterization and the assessment of the real plant performance.

Future steps:

1. Recommendations on meteorological stations including devices selection for each stage of the project and depending on the site should be formulated. Each stage and site has different characteristics and might need different instrumentation, time frequency and accuracy.
2. Networks of meteorological stations as the ones from the WMO (World Meteorological Organization) should be continued and upgraded to accommodate the need of the solar energy industry by including instruments for monitoring of direct and diffuse irradiances.
3. Recommendations should be made on the number of stations needed to ensure proper characterization of the solar resource distribution on the solar field for performance estimations. Especially for the commissioning of large CSP plants it can be useful to use several pyrheliometers and other sensors such as all-sky imagers or RSIs to determine the variability of the DNI in the solar field. The optimal solution cost-wise should be found.
4. Instrument specific recommendations for adequate maintenance of ground-based solar radiation measurements in the WMO framework should be improved, like the recommendation to use systems or methodologies to avoid soiling.
5. Further improvement of solar radiometers to avoid soiling of instruments with clear entrance windows (especially pyrheliometers) and to further reduce the systematic errors of rotating shadowband irradiometers should be made.
6. Determine a specific standard calibration method for sensors like RSIs or SPN1.

3. Quality control and gap-filling

Background

Quality control is an important point in the solar radiation data treatment. One common goal of most solar radiation assessment is to calculate the sum of the solar radiation during a period. This can be expressed as daily, monthly or annually irradiation.

In the case of solar radiation the characterization of the distribution function has not been established as for the wind energy case, and long time series are needed for the long-term characterization of the local solar resource. When serially complete energy values have to be addressed quality control and gap filling methodologies become essential. A compromise of the quality control filters' level of restrictiveness minimizing the gaps has to be achieved, because of gaps have to be filled to determine any daily, monthly or annual energy calculation. Filters have to be carefully applied to identify if the data are suspicious, e.g. as a result of insufficient maintenance. Methods to detect high soiling levels and to partly correct the soiling's effect on the data can be applied. A station logbook or other ways of documentation should be kept, so that cleaning events can be identified and corrections applied.

When there are measurements for the three solar radiation variables (global, diffuse and direct normal) filters can be applied following well established methodologies including relationships between the variables. But when any of the three variables are not recorded, the closing equation cannot be performed, a very powerful way for identifying errors. Issues with too high irradiance values can be detected relatively well, while too low values may remain undetected. Thus, both phenomena: removal of the highest values and missed detection of wrong low values could contribute to a systematic underestimation of the expected direct normal irradiance. Even when all three variables are recorded, tracker or rotation failures have to be specifically detected.

Future steps:

1. Determine a standard method for adequate direct normal irradiance quality control filters, including failure detection of tracker systems or rotation errors of RSIs.
2. Determine a standard method for adequate and harmonized gap filling methodology. Options based on different interpolation models or on historical patterns have to be compared and accepted.
3. Determine a standard method for the detection of soiling and its correction.
4. A recommendation on the appropriate minimum temporal resolution (probably of 5 minutes or preferable 1 minute) would be very helpful when applying quality control and gap-filling treatments.

4. Satellite-derived data

Background

The main advantage of using satellite-derived solar radiation is the provision of long-term solar radiation and meteorological data in places without ground-based measurements. Setting up new ground stations is necessary for CSP project planning, but it is impossible to wait for many years until enough data for a reliable yield analysis are available. Due to the inter-annual variability of DNI, at least 20 years of data are recommended for CSP resource assessments. The minimum of 10 years as mentioned in some publications and even by the SolarPACES guiSmo Report (2017) is questioned by some as the past 10 to 15 years have been extraordinary stable and sunny in many regions compared to earlier years. On the other hand, if the recent brightening in Europe and Northern America is due to less aerosol pollution, as many have suggested, this is not a statistical sampling issue that requires longer historical data sets. In that case, the question is how future aerosol climate scenarios can be accounted for.

The uncertainty of satellite-derived data is generally greater than that of well-maintained and appropriate ground-based measurements. Depending on the local conditions, systematic errors may remain and an adaptation to take account of local effects on the satellite-derived data should be performed. Where local measurements are available and after utilizing such adaptations, the accuracy of the long-term data sets is suitable for CSP resource assessment.

Satellite-derived solar radiation data sets are based mainly on the monitoring of clouds by geostationary satellites and need to be combined with water vapor, aerosol, and ozone from meteorological reanalysis data sets.

Satellite-derived solar radiation databases are often available as commercial products; some of them provide useful meta-data and regular validation reports. Few satellite-derived solar radiation data sets are free and available to public access. For the local adaptation and validation of all satellite-derived data bases there are only a limited number of solar radiation measurements stations available around the world. Satellite-derived data have to be carefully tested especially in regions without measurement stations. Often satellite-derived data bases are bias-corrected with the help of the existing public solar radiation measurements. Unfortunately, several validation studies use the same stations to compare against. Therefore, results at other locations even in the same regions may result in higher errors.

The gridded satellite data have a limited spatial resolution and consists of image-like data taken at discrete time steps. Currently, the highest spatial resolution of the relevant geostationary weather satellites is in the range of one to several kilometers (depending on the region) and the temporal frequency is down to five minutes, but typically rather one snapshot every 15 to 30 minutes.

Future steps:

1. Improvements in the temporal and spatial resolutions should be made. One option to improve DNI from satellite images is to solve the parallax problem by considering 3-dimensional radiative transfer. This would require the use of improved cloud bottom and cloud top height data. Temporal and spatial variability of the satellite derived cloud parameters also need to be considered.
2. Determine a standard method for adequate, harmonized blind testing to assess the differences of the satellite-derived solar radiation from ground-based measurements. As most satellite solar radiation retrievals are tuned by ground-based measurements it is very difficult to derive their actual uncertainty not influenced by data dependency issues. Therefore, uncertainty for new sites tends to be underestimated.
3. Determine a set of metrics that permit the qualification of a satellite dataset. For instance, for quantifying the expected difference when comparing point-measurements from the ground versus spatially-averaging satellite observations; or a reliability index as a weight or warning to use specific dataset.

5. Uncertainty

Background:

All measurements have **uncertainties**[1]. These uncertainties can be random or vary depending on other variables such as temperature or the intensity of incident radiation. To a certain degree, **random effects** average out as longer time averages or intervals are considered. **Systematic effects,** that depends upon the environment or configuration under which the measurements are conducted, average to specific values with finite differences from the true value. Different systematic effects can cancel out with other systematic effects, but they can also be additive. With careful studies, the systematic effects can be measured and modeled. With a sufficient knowledge of these systematic effects and measurement of the environmental conditions that produce these systematic effects, the systematic uncertainties can be reduced significantly.

When financing a solar electric system, the probability that the system will exceed a certain level of electricity generation (**probability of exceedance**) – the PoE-value – is important for risk evaluation in the financial model. Due to the match between percentile 50 (P50) and PoE50, percentile and probability of exceedance sometimes are confused. Usually the central value P50 (or PoE50), is taken as the base case. To approach the distribution of the expected CSP yield most financial models also assume a normal distribution. Under this assumption for quantifying this distribution curve only one additional point is required. Many banks simply take the PoE90-value, which should be exceeded in 90% of the cases and match with the Percentile 10.

Two different points have to be discussed regarding the uncertainty of the PoE90. One is related to the relationship of a PoE90-value of annual values of DNI and a PoE90-value of annual values of energy output. This relationship is not well characterized and its uncertainty is sometimes unknown. The second is related with that there is a wide range of annual electricity yield values coming from different DNI PoE90-series with the same DNI PoE90-value and thus, this could be a big source of uncertainty. Also the uncertainties in the underlying measurements and model data, the relatively low number of years with DNI data, and the above mentioned other sources of uncertainty contribute to this.

Financers often take a conservative approach and subtract some of the uncertainty in the probability of exceedance (give it a 'haircut') from the system production estimates. For example, if the PoE90-value of annual DNIs has a 3% uncertainty, then a financial analysis may give the yield gained from a PoE90-serie an additional 3% reduction in order to derive the PoE90-value of energy output.

Current practice used the determine uncertainty estimates are difficult to defend with a high degree of confidence. The values often assume that many random effects cancel for long time periods and that extremes caused by systematic effects don't contribute significantly to the overall uncertainty. For example, the DNI measurements have larger relative uncertainties when the sun is very low in the sky, but the uncertainty in the DNI measurement more towards the median solar elevation is used in the analysis.

The **G.U.M.** methodology of uncertainty analysis is the standard for quantifying uncertainties in measurements. For relatively complex outdoor measurands such as solar radiation measurements it is still a major effort to follow the GUM approach. The long-term goal should be to identify individual uncertainty levels for each and every measurement that depending on instrumentation, maintenance, calibration date and time of day may be different for each time-step. The GUM methodology can also be applied to the analysis of solar plant yield and this will help provide a solid basis for determining the uncertainty of the yield levels.

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[1] Words printed in bold type are defined in the glossary for the uncertainty discussion.

The future goal of uncertainty analysis is to more reliably determine the uncertainty in the measurements and its sources. It should be determined if it is possible to reduce these uncertainties with adjustments that account for systematic effects that increase uncertainty and such corrections should be developed or improved whenever possible. Additionally, the uncertainty of the adjustments needs to be given.

Future steps:

1. Determine a standard method to measure the uncertainties of all relevant measurements that are used in STE system performance estimates. It is recommended that these uncertainties are determined in the field under settings in which the instrument is used and not under laboratory conditions where some systematic uncertainty effects can be masked.
2. Characterize and model systematic effects and determine the degree to which these models reduce the uncertainty in the data values and electricity yield estimates. Adjustments for systematic effects should be developed where an overall uncertainty reduction can be achieved.
3. Develop a check list with the uncertainties associated with different sources of input data and the likely effect of these uncertainties on plant yield estimates. Create a document that illustrates how to use these uncertainties to determine the overall uncertainty in plant yield.
4. Evaluate and characterize uncertainties used in modeling and/or modifying irradiance data used in plant yield analysis.
    a. For example, methods that modify satellite-derived irradiance values using ground-based measurements.
    b. Models that simulate short interval irradiance from hourly data.
5. Characterize uncertainties into random effects that will be reduced with a long-term analysis and uncertainties introduced by systematic effects that can be accounted for by modeling.

Glossary of uncertainty terminology

G.U.M.: The Guide to the Expression of Uncertainty in Measurement (GUM) is a product of the Joint Committee for Guides in Metrology (JCGM). JCGM is producing a series of documents to establish general rules for evaluating and expressing uncertainty in measurement. The GUM methodology is becoming a standard in the analysis of irradiance and other meteorological measurements.

http://www.bipm.org/en/publications/guides/gum.html
http://www.iso.org/sites/JCGM/GUM-introduction.htm

Uncertainty: Uncertainty is an expression of doubt about how well the result of the measurement represents the value of the quantity being measured. The uncertainty of a measurement is a parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand (G.U.M.)

Error: Error is the difference between the measured or modeled value and the true value. Error and uncertainty are distinct concepts describing the same measurements.

> **Random effect – Random error**: Random error is presumed to arise from stochastic, temporal, and spatial variations in the measurements. Random error usually can be reduced by increasing the number of measurements. When the GUM methodology is used, these are characterized as random effects.
>
> **Systematic effect – Systematic error**: A systematic error arises from a recognized quantity on the measurement. This is now called a systematic effect. This effect can be quantified and a correction factor can be applied to compensate for the effect. As with the random effect, the uncertainty caused by a systematic effect can be reduced but it cannot be eliminated.

Probability of exceedance: In this document, the probability of exceedance is determined from an analysis of the plant yield under meteorological situations that the system is likely to experience. For example, “PoE50-value of energy yield” is the estimated annual electricity generation that will be exceeded by 50 percent of the years. “PoE90-value of energy yield” is the yield that will be exceeded in 90 percent of the years. The input parameters can be measured or modeled irradiance and other relevant meteorological parameters along with system performance characteristics.

6. Long-term data variability

Background

The use of a TMY dataset with a CSP simulator allows analysis of the average or median profitability of a CSP project. However, TMY does not contribute, by its own, to the financial risk analysis to account for potential hazards associated with the long term inter-annual variability of the solar resource in conjunction with other relevant meteorological parameters (e.g. air temperature, wind speed).

The creation of solar resource scenarios and related meteorological parameters is the key to contribute, with other sources of variability at the power plant system level (system piloting and defocusing, system failures, soiling, maintenance efficiency, etc.) to the development of energy production scenarios according to different levels of probabilities of exceedance (e.g. PoE75, PoE90, etc.).

The current state of the art method is to analyze historical time series of radiometric and meteorological data over 10 to 20 years or more at the site of interest of the CSP project. These data and their associated uncertainties enable modeling the inter-annual variability of the annual sums of relevant solar irradiations constituting the solar resource for the project under study. To determine the annual irradiation values for a given probability of exceedance, non-parametric or parametric distribution function techniques are used by optimizing and testing families of density of parametric probabilities (normal, log-normal, Weibull, Gumbel, etc.).

However, these approaches are limited for several reasons. First, they are based on the assumption that the time series of annual irradiations from the historical data series are independent and identically distributed (i.i.d.) stochastic processes. Observed long-term trends –for example due to increasing or decreasing levels of aerosol pollution– and correlations (memory effects) in solar radiation time series raised the question of the validity and applicability of this assumption. Its use is likely to introduce biases in the determination of the scenarios.

In addition, in practice, the number of years of the series of historical data is between 10 and 20 years: with “so few” annual irradiations, even neglecting the errors caused by the hypothesis that the years are independent and identically distributed errors occur. The parametric or nonparametric determination of the distribution function is very sensitive and the confidence intervals of the irradiation levels for a given probability of exceedance can be very large.

Finally, these approaches are based only on the statistical analysis of the past years, on the site of interest. But the need is to qualify the site for the future multi-decennial lifetime: any long-term change whose time scales are beyond the duration of the historical data cannot be correctly modeled.

Future steps:

1. In the case of yearly direct normal irradiation, further investigation is needed to be able to test if the time series has indeed no trends or inter-annual correlation and whether the distribution is Gaussian, Weibull, log-normal, Gumbel, etc. Also these methods should be standardized.

2. Proposal of a standard methodology for the detection and treatment of data from years with the impact of volcanic eruptions that are Plinian or ultra-Plinian eruptions.
3. Methods to estimate the uncertainties of PoE90-values of annual DNI e.g. with Monte-Carlo simulations of given statistical distributions should be developed further, tested and standardized.
4. Methods to include long term changes and climate scenarios in future profitability studies, must be developed further and standardized. In particular, aerosol pollution scenarios could be important.

7. Auxiliary meteorological data

Background

Besides DNI also other measurands are needed for CSP yield analysis. These data include wind speed, wind direction, wind gusts, temperature, ambient pressure and humidity. Additional meteorological data needed for CSP/STE plant simulations include all-sky cameras, low level radiation extinction, circumsolar radiation, soiling of plant components, and upper air winds for solar power tower plants.

The use of all-sky cameras to observe clouds and aerosols for cloud cover characterization has trended strongly in recent years. For cloud cover characterization these data resolves features that the satellite-images cannot resolve. These cloud cover features are very important for high-frequency solar radiation variability characterization.

For Central Receiver plants the sunlight reflected at the heliostats has to cross substantial distances through the atmosphere near the ground. As the optical losses caused by extinction along this path can be sufficient it is required to quantify these losses. Recently, methods have been suggested for measuring and estimating this extinction. They include aerosol optical depth (AOD), DNI or visibility measurements but the methods have to be harmonized and standardized.

Methods and models to determine the sun beam shape and the distribution of the circumsolar radiation are needed for CSP/STE plant simulations. Measurement accuracy can still be improved and models are in prototype status and should be improved. The uncertainties of measurements or models have not been investigated in detail and there are no standards for its determination.

The soiling rate for mirrors is the reduction of reflectance with time due to the accumulation of dust on the mirrors. Similarly soiling rates are also defined for the transmittance of entrance windows (envelope tubes of line focusing collectors). The soiling rate can be measured with different methods, which are not standardized so far.

With advent of the 'internet of things' large quantities of 'Big Data' of low quality are becoming available. A major issue is, if and how these can be quality assured. The quality of the many different types of Big Data for meteorology could be assessed. This is an overall issue in the field of meteorological science. In particular, regular and surveillance camera data can potentially be used to provide high coverage cloud cover and visibility data that can complement high quality ground-based data and satellite-derived data.

Future steps:

1. The use of all-sky camera data for cloud and aerosol observations should be further established and standardized.
2. Methods for estimating extinction near the surface should be applied, and thus previously tested further and standardized. More work is needed to standardize these methods and to estimate their uncertainties better.

3. The usefulness of conventional camera images and surveillance camera data (Big Data) for cloud and visibility observations should be investigated.
4. Methods to measure and model circumsolar radiation should be applied, and thus previously tested at more sites, standardized and developed further.
5. Weather models that include uptake and deposition of dust that can cause soiling exist. These, however, need improvement, in particular when it comes to the dust uptake into the atmosphere and the transfer of particle deposition rates to mirror and entrance window soiling.

8. Reanalysis data

Background

Numerical weather prediction models are developed for weather forecasting purposes. In the re-analysis mode the NWP models are run using all available initialization input data. Available reanalysis products cover different periods in different temporal and spatial resolutions. Re-analysis products are operated by institutional bodies, but sometimes their results are not free.

Re-analysis datasets are made with respect to climatological purposes and therefore cover more than 30 years. For long-term purposes they need to be harmonized as the underlying observations have been made with a series of instruments, while the reanalysis is per definition use a single NWP physics and data assimilation scheme.

Recent comparisons of solar radiation data from reanalysis products have demonstrated that in general, its results are still far less accurate then satellite-derived solar radiation data. Even so, there are specific developments that show a relevant improvement when using post-processing treatments. These types of post-processing treatments are also commonly applied in the case of satellite-derived models.

While satellite-derived models have been developed focused on solar radiation variables, NWP models were focused on meteorological variables such as temperature, precipitation and humidity, while the irradiance at the ground has not been a main focus. Assimilating cloud data with the methods of the satellite-irradiance models have prospects for significantly improving reanalysis data sets. As in the case of satellite-derived data, NWP model data are gridded area averages with a limited spatial resolution with accumulated irradiation as output. For the upcoming ERA 5 global reanalysis data the spatial resolution will be 31 km and the output frequency 1 hour. Regional reanalysis data sets can have spatial resolutions down to the kilometer scale.

Reanalysis data sets are typically the only option to obtain reliable long-term information about some meteorological parameters needed for CSP simulations such as wind, temperature, humidity and pressure, when ground-based measurement are not available.

Future steps:

1. The cloud assimilation methods of reanalysis models need to be improved.
2. Improvements in the temporal and spatial resolution are needed.
3. Dedicated kilometer scale regional reanalysis models should be run for regions with high solar resources.
4. The methods for adequate, harmonized blind testing to assess the differences of the NWP modeled solar radiation and ground-based measurements should be improved with a focus on solar resource assessment.

9. Realistic multi-year generation

Background

In carrying out feasibility or other types of economic assessment studies of CSP/STE systems, it is of great interest to model the uncertainty and variability associated to different inputs of the economic model used in the study. A sound and elegant approach to carry out this modeling is to associate each input variable with a probability distribution. A key input in any techno-economic model of a CST system is the annual energy yield of the system. The traditional approach to generate an estimate of the annual yield is to feed the Typical Meteorological Year (TMY) at the location of the CST system to an energy model of the system. But this approach does not produce a probability distribution of the energy yield. To produce a probability distribution the energy model of the CST system has to be fed with a large series of realistic meteorological years which are consistent with the TMY and with the long term expectations of the different meteorological variables within the meteorological year (DNI, ambient temperatures, relative humidity, wind speed and direction, etc.)

An approach to generate these large series of realistic meteorological years it is to automatize the treatment of available meteorological measurements in a given site and use them to generate full annual series of realistic meteorological years with high resolution solar radiation data. The most common procedure assumes a distribution function for the annual and monthly values that is sampled to generate realistic long term monthly and yearly sequences.

Future steps

1. Determine a standard methodology for adequate and harmonized assessment of realistic multi-year generation.
2. Include the new methodology in the most common feasibility assessment tools.

10. Summary of recommendations for future works

Ground-based measurements

1. Recommendations on meteorological stations including the selection of measurement devices depending on the site, the development stages of the solar projects and its size in terms of MW.
2. Networks of meteorological stations should be continued and upgraded to accommodate the need of the solar energy industry by including instruments for monitoring of direct and diffuse irradiances.
3. Recommendations should be made on the number of stations for the solar resource distribution characterization on the solar field and on the use of other sensors such as all-sky imagers.
4. Instrument specific recommendations for adequate maintenance of ground-based solar radiation measurements in the WMO framework should be improved, like the recommendation to use systems or methodologies to avoid soiling.
5. Further improvement of solar radiometers to avoid soiling of instruments with clear entrance windows (especially pyrheliometers) and to further reduce the systematic errors of rotating shadowband irradiometers should be made.
6. Determine a specific standard calibration method for sensors like RSIs or SPN1.

Quality control and gap-filling

7. Determine a standard method for adequate direct normal irradiance control filters.
8. Determine a standard method for adequate and harmonized gap filling of missing data.
9. Determine a standard method for the detection of soiling and its correction.
10. Recommendation on a minimum temporal resolution (probably of 5 minutes and suggest that one-minute) could be very helpful when applying quality control and gap-filling treatments.

Satellite-derived data

11. Improvements in the temporal and spatial resolutions should be made.
12. Determine a standard method for adequate, harmonized blind testing to assess the differences of the satellite-derived solar radiation vs. the ground-based measurements.
13. Determine a set of metrics that permits the qualification of a satellite dataset.

Uncertainty

14. Determine a standard method to measure the uncertainties of all relevant measurements that are used in STE system performance estimates.
15. Characterize and model systematic effects and determine the degree to which these models reduce the uncertainty in the data values and electricity yield estimates.
16. Develop a check-list with the uncertainties associated with different sources of input data and the likely effect of these uncertainties on system performance estimates. Corrections for effects should be developed or improved where an overall uncertainty reduction can be achieved.
17. Evaluate and characterize uncertainties used in modeling and/or modifying irradiance data used in plant yield analysis.
18. Characterize uncertainties into random effects that will be reduced with a long-term analysis and uncertainties introduced by systematic effects that can be accounted for by modeling.

Long-term data variability

19. In the case of yearly direct normal irradiation, further investigation is needed to be able to test if the time series has indeed no trends or inter-annual correlation and the most probable distribution shape.
20. Standardize the identification and treatment of years with impact of volcanic eruptions that are Plinian or ultra-Plinian eruptions.

21. Methods to estimate the uncertainties of PoE90-values of annual DNI e.g. with Monte-Carlo simulations of given statistical distributions should be developed further, tested and standardized.
22. Methods to include long term changes and climate scenarios in future profitability studies, must be developed further and standardized. In particular, aerosol pollution scenarios.

Auxiliary meteorological data

23. The use of (all-sky) camera data for cloud and aerosol observations should be further established and standardized.
24. Methods for estimating extinction near the surface should be tested further and standardized.
25. Methods to measure and model circumsolar radiation should be tested at more sites, standardized and developed further.
26. Weather models that include uptake and deposition of dust that can cause soiling exist. These, however, need improvement, in particular when it comes to the dust uptake into the atmosphere and the transfer of particle deposition rates to mirror and entrance window soiling.

Reanalysis data

27. The cloud assimilation methods of reanalysis models need to be improved.
28. Improvements in the temporal and spatial resolution are needed.
29. Dedicated kilometer scale regional reanalysis models should be run for regions with high solar resources.
30. The methods for adequate, harmonized blind testing to assess the differences of the NWP modeled solar radiation and ground-based measurements should be improved with a focus on solar resource assessment.

Realistic multi-year generation

31. Determine a standard methodology for adequate and harmonized assessment of realistic multi-year generation.
32. Include the new methodology in the most common feasibility assessment tools.