A NEW METHOD FOR THE BENCHMARKING OF IRRADIANCE PREDICTIONS

Antoine Guérin de Montgareuil [1], Laurent Bellemare [2], Rudy Blonbou [3], Mathieu David [4], Thierry Hedde [1], Philippe Lauret [4], Stéphane Mével [5], Jean-Philippe Morel [5], Philippe Poggi [6], Ted Soubdhan [3], Cyril Voyant [6]

[1] CEA (Atomic Energy and Renewable Energies Agency) - CEATech DPACA - Cadarache, bât. 356 - F-13108 St-Paul-lez-Durance, France - gdm@cea.fr - [2] Martinique Energy Agency - [3] Antilles-Guyane University, Large laboratory - [4] Reunion Island University, Piment laboratory - [5] Meteo France – Carpentras Radiometric Centre - [6] Corsica University

ABSTRACT: In the French overseas departments and in Corsica, insular territories, as well as in Provence, south of France, where the electric grid is weakly interconnected because of the proximity of the Mediterranean Sea and the Alps Mountains, a very high proportion of photovoltaic power will be introduced in the electric grids in the near future. In order to manage the balance between supply and demand of electricity, grid operators ask electricity producers to linearize their production and to announce in advance their energy production plans. The accuracy of these plans depends strongly on the accuracy of the prediction of the solar resource. The article proposes a new method for the benchmarking of irradiance predictions used in this context. It is shown that even for perfect energy predictions, the requirement of energy production plans brings potential costs to energy producers. The new benchmarking method compares the accuracy of the predictions with the accuracy of an ideal prediction made from the linearization of irradiance measurements and with the accuracy of the persistence prediction, which consists in using the irradiance of the current day as predicted irradiance for the next day.

Keywords: Irradiance prediction benchmarking, energy production plans, linearization of irradiance, persistence

1 INTRODUCTION

1.1 Context

The setup of high shares of photovoltaic energy in the French overseas departments and in Corsica is already limited by the ability of the grid operator to take into account the variability of the solar resource and the concomitant variability of electricity production. The problem will be the same in the near future in Provence, south of France, a sunny region where the electric grid is weakly interconnected because of the proximity of the Mediterranean Sea and the Alps Mountains.

1.2 Energy production plans and associated intrinsic financial losses

In order to limit the effects of the variability of the solar resource on the balance of supply and demand of electricity, the grid operator asks for the linearization of the photovoltaic energy production during predefined time intervals and electricity producers have to announce the linearized production for the next day.

When the electric production is lower than the planned production, penalties will be applied. When the available power exceeds the planned power, the power in excess will be lost.

Thus, since the electric power is almost proportional to irradiance and irradiance is not a linear function of time, even the best energy production plan will constantly bring excess or shortage of power and then financial losses. Furthermore, any energy production plan may be characterized by the corresponding wasted and missing energies.

Setting up energy production plans for the next day requires predictions of the solar resource for this day. Depending on the accuracy of irradiance predictions and on the algorithms used for the calculations, the energy production plans will bring more or less losses of income and penalties. Then, depending on the price of electricity, the cost of penalties and on the cost of any alternative solutions such as energy storage (which is not the topic of this article), it will possible to rate the irradiance predictions.

1.3 Present benchmarking of irradiance predictions

How "good" a prediction is depends strongly on the criteria used for the assessment of the prediction. Classical prediction methods [1, 2] forecast the average value of irradiance during predefined time intervals (typically one hour, 30 minutes, 15 minutes…). Each prediction is assigned to the end of the period for which the irradiance is predicted. For example, the prediction of irradiance from 08:00:00 AM (excluded) to 09:00:00 AM (included) is timed to 09:00:00.

The present prediction benchmarks are based on statistical quantities on the difference between the predicted and the measured averages of irradiance during the time intervals. In simple terms, there are 2 criteria for good predictions:

- An average value of the difference between predicted and measured irradiances as low as possible
- A dispersion of the difference around zero as little as possible

These benchmarks look convenient for the power exchange where there is no real interest on the way electricity is produced. This article focuses more on the benchmarking of prediction of irradiance for energy production plans.

1.4 Energy production plans and benchmarking of irradiance predictions

Despite this clear dependence of the rating of predictions on every user's context, this article proposes a simple method for the benchmarking of irradiance predictions for energy production plans, avoiding the use of complex algorithms and based on the following general assumptions:

- The production of electricity is proportional to irradiance
- Thus, t optimization of energy production plans consists in finding the optimal linearized irradiance predictions for the same time intervals
- the optimal linearized irradiance prediction must maximize the energy production, minimize the financial losses and the technical complexity at the electricity production level

1.5 Origin of data

In this article, all irradiance data come from 2 years of measurements of global horizontal irradiance by a horizontal pyranometer at Saint-Pierre, Reunion Island. Predictions have been made by the Piment Laboratory according to [3] and have been provided "as is" to illustrate the benchmarking method.

1.6 Clear sky irradiance as reference

When benchmarking predictions, as irradiance conditions vary a lot between sites and, for a same site, between time of year and seasons, it is interesting to normalize the results with the clear sky irradiance, the irradiance which would be measured with a pure atmosphere.

In this article, the clear sky irradiance has been modelled from the irradiances measured in the morning of a day with no clouds. It has been expressed as a third order polynomial function of the inverse of air-mass [4], calculated for all the days and verified for days with no clouds.

2 LINEARIZATION OF IRRADIANCE

2.1 Definitions

From one day of irradiance measurements, the available irradiation A is defined by Formula 1:

$$A = \sum_i G(t_i)\,.\,\Delta t \quad (1)$$

where $G(t_i)$ is the average irradiance during the i^{th} interval of Δt duration. If Δt is expressed in hours, the irradiation A is expressed in Wh/m².

In Figure 1, the available irradiation is represented by the zone in pink. The considered day is characteristic of the climate of St-Pierre. During the morning of this typical day, there are no clouds. Around 8:00 UT, irradiance increases and becomes higher than the clear sky irradiance because of reflection of sunlight on clouds and probably on walls surrounding the pyranometer [5]. Then, big clouds come, hide the direct irradiance and the diffuse irradiance goes down regularly until sunset.

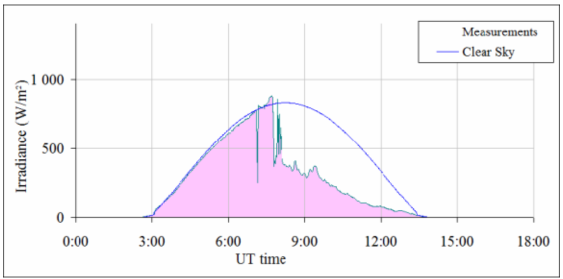

Figure 1: Horizontal irradiance measured at St Pierre, Reunion Island, 6 May 2013.

A linearization of irradiance (or shortly "linearization") is defined by the set of values of irradiance attributed to the middle of the considered time intervals (for example 00:30, 01:30, 02:30… for hourly time intervals). Values for other moments are calculated by linear interpolation of the previous set of values.

The linearized irradiation L is defined by Formula 2:

$$L = \sum_i G_{linearized}(t_i)\,.\,\Delta t \quad (2)$$

The "wasted" irradiation W is defined by Formula 3:

$$W = \sum_i \max\left(G(t_i) - G_{linearized}(t_i), 0\right).\,\Delta t \quad (3)$$

This quantity is calculated from the intervals where the measured irradiance exceeds the linearized irradiance (the excess of irradiance is not used to produce electricity and is "wasted"). In Figure 2 and following, the wasted irradiation is represented by the zones in green (the blue zones are described below).

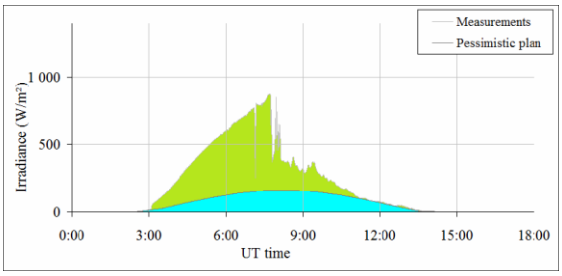

Figure 2: Insufficient use of available irradiance by a low linearization representing a theoretical overcast day

The "missing" irradiation M is defined by Formula 4:

$$M = \sum_i \max\left(G_{linearized}(t_i) - G(t_i), 0\right).\,\Delta t \quad (4)$$

This quantity is calculated from the intervals where the linearized irradiance is greater than the measured irradiance (there is not enough irradiance to produce the announced electricity generation and the difference of irradiance is "missing"). In Figure 3 and following, the missing irradiation is represented by the zones in yellow.

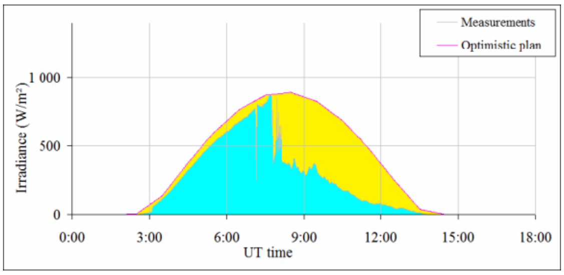

Figure 3: Linearization representing a theoretical clear sky day and constantly exceeding the existing irradiance

The "used" irradiation U is defined by Formula 5:

$$U = \sum_i \min\left(G(t_i), G_{linearized}(t_i)\right).\,\Delta t \quad (5)$$

This quantity is calculated from the available irradiance when it is smaller than the linearized irradiance and from the linearized irradiance in the opposite case. In Figure 2 and following, the used irradiation corresponds to zones in blue.

The "bias" irradiation B is defined by Formula 6:

$$B = L - A \quad (6)$$

The bias irradiation the difference between available and linearized irradiations. It is null if the linearized irradiance brings as much irradiation as the existing irradiance.

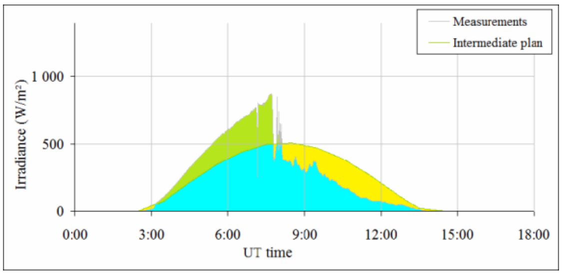

Figure 4: Linearization of irradiance with used, wasted and missing irradiation.

The linearization in Figure 4 has been designed so that the wasted and missing irradiations are equals. The bias irradiation of Figure 4 is null.

The "shifted" irradiation S is defined by Formula 7:

$$S = M + W \tag{7}$$

It represents the total of the irradiations added and subtracted to the available irradiation to get the linearized irradiation. It represents the surface between the measured irradiance and linearized irradiance curves.

Using Figure 4, it is easy to infer Formulae 8 and 9 and to express the relations between the available irradiation A, the linearized irradiation L, the used irradiation U, the wasted irradiation M (positive by definition) and the missing irradiation W (positive by definition).

$$U = A - W \tag{8}$$

The used irradiation is the available irradiation minus the wasted irradiation.

$$U = L - M \tag{9}$$

The used irradiation is also the linearized irradiation minus the missing irradiation

Finally, derived from Formulae 8 and 9, Formula 10 expresses the bias irradiation B as the difference between missing and wasted irradiations.

$$B = M - W \tag{10}$$

The definition of the bias irradiation is coherent with the usual meaning of a bias. When there is more missing irradiation than wasted irradiation, the linearized irradiation is lower than the available irradiation and the bias is negative (see Figure 2). It is positive in the opposite case (see Figure 3).

Then, mathematics (intermediate value theorem) tell us that, for any existing irradiance dataset, it is possible to define at least one linearization of irradiance with a null bias. An example can be seen in Figure 4 where the linearization has been designed so that the total surface of the green and the yellow zones are exactly the same.

All linearizations with a null bias may differ by the value of their missing and wasted irradiations, and then by their shifted irradiation. In Figure 4, the wasted irradiation is limited to the morning and the missing irradiation to the afternoon.

We feel clearly that this intermediate irradiance linearization is not as "satisfactory" as a combination of the linearization in the right part of Figure 2 and the linearization in left part of Figure 3. Such a linearization would minimize *locally* the bias between the measured irradiance and the linearized irradiances.

2.2 Benchmarking of linearizations

Given one measured irradiance dataset and one linearized irradiance dataset, the benchmarking of the linearized irradiance dataset is based on the calculation of 4 quantities:

- The wasted irradiation and the missing irradiation, as defined by Formulae 3 and 4
- the difference between these quantities (the bias irradiation defined by Formula 6)
- the sum of the wasted and missing irradiations (the shifted irradiation defined by Formula 7)

The benchmarking criteria are the following:

- If 2 linearized irradiance datasets have the same bias irradiation, the best one is the linearization with the lowest shifted irradiation
- If 2 linearized irradiance datasets have the same shifted irradiation, the best one is the linearization with the lowest bias.

The following chapter proposes a very simple algorithm to find for any measured irradiance dataset the almost optimal linearized irradiance datasets responding to these criteria.

2.3 Algorithm for the calculation of an optimal linearization

The idea of the algorithm is to keep low the difference between the irradiances and their linearization. The optimal linearization of an irradiance dataset is characterized by the set of the average values of the irradiance for every interval (these values are attributed to the middle of the intervals and the values for other moments are calculated by their linear interpolation).

Figure 5 shows the application of the algorithm to the 6th of May, 2013.

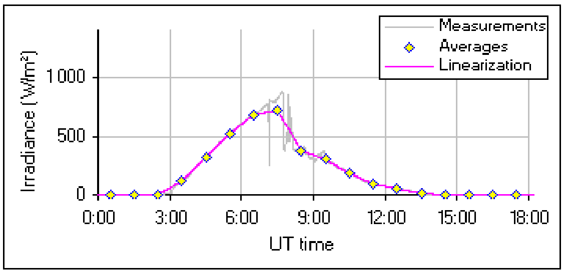

Figure 5: Algorithm for the linearization of the irradiance with null bias and minimum shifted irradiation

It can be easily demonstrated that for that algorithm, wasted irradiation equal strictly missing irradiation at the day level. So, the daily bias is null and remains low at the hourly level. It has been also verified that for most datasets, this linearization minimizes the shifted irradiance.

Used, wasted and missing irradiations are shown in Figure 6. Missing and wasted irradiations are equal and their sum, corresponding to financial losses at the production level, is almost minimum.

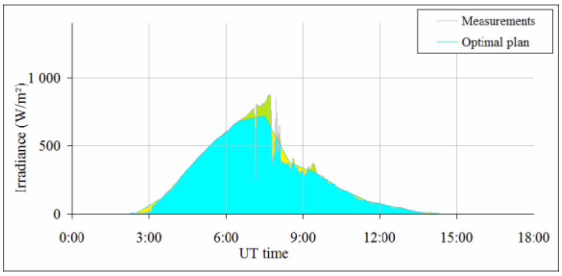

Figure 6: Used irradiation is maximum

3 BENCHMARKING GRAPH

This graph (Figure 7) allows the presentation of the missing irradiation as a function of the wasted irradiation.

It is interesting to draw the lines where the sum of these 2 quantities (the shifted irradiation) is constant (light green lines) and the lines where their difference (the bias irradiation) is constant (light blue lines).

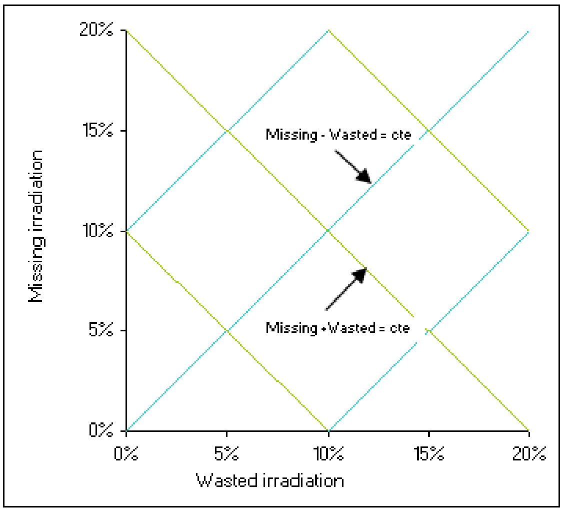

Figure 7: Graph of wasted and missing irradiations between an irradiance and a linearized irradiance

All irradiances during the 2-year period have been linearized with the simple linearization algorithm. Wasted and missing irradiations have been calculated. Figure 8 shows that for all these linearizations with a null bias, the value of the shifted irradiation varies between a maximum, around 2% and a maximum around 30%.

This value depends on the dispersion of irradiance around its linearization.

Days with many passing clouds such as the 2nd of June, 2013, present high shifted irradiations (Figure 9). For this day, the shifted irradiation represents 30 % of the irradiation of a clear sky day and 52 % of the available irradiation.

At the opposite, days without almost no clouds such as the 24th of December, 2012 (Figure 10), present a very limited difference between the irradiance and its linearization.

So, the shifted irradiation depends directly on the intrinsic dispersion of the irradiance around its linearization.

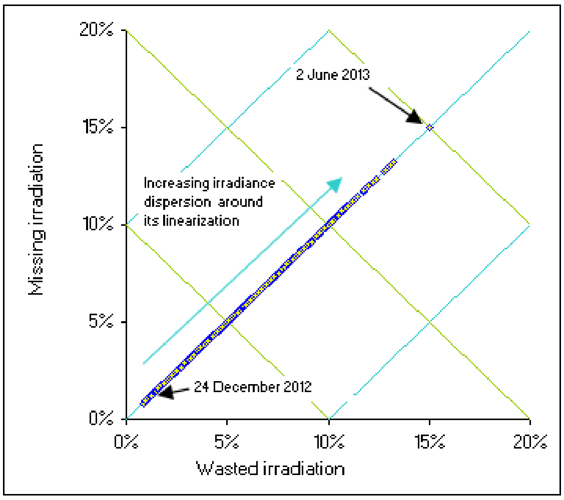

Figure 8: Daily wasted and missing irradiations for the linearization of 2 years of data

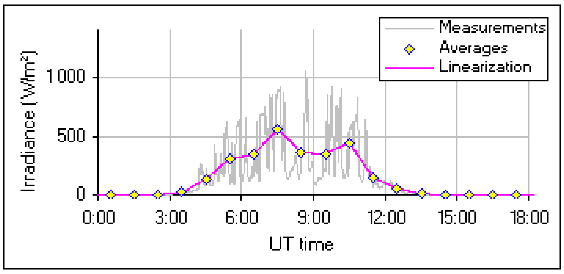

Figure 9: Very high dispersion of irradiance around its linearization, 2nd June 2012

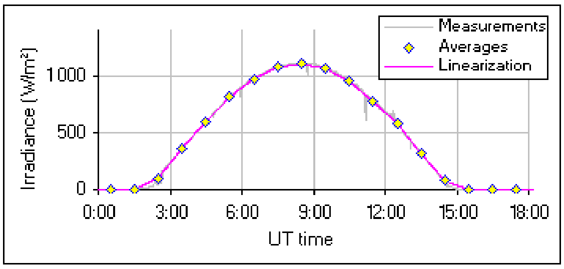

Figure 10: Very low dispersion of irradiance around its linearization, 24th December 2012

The next chapter shows the result of the application of the benchmarking of linearized irradiance to irradiance predictions.

4 BENCHMARKING OF IRRADIANCE PREDICTIONS

4.1 Algorithm for the linearization of irradiance predictions

The values attributed to the middle of the intervals are the values of the prediction of the average irradiance for every time interval.

4.2 Benchmarking of predictions based on persistence

In meteorology, the simplest prediction of weather is the persistence method which consists in saying that the weather remains identical from one day to the next day. It is well known that it is not possible to predict with accuracy the weather more than 10 days ahead with prediction methods such as observation of clouds from earth or satellites, or atmospheric calculations from physical modelling - numerical weather prediction. So, for mid and long term predictions as well as for periods where the type of weather is not changing or changing slowly, persistence predictions are meaningful.

The determination of the predicted irradiance with persistence consists in attributing to every time interval of the next day the average value of irradiance for the same time interval during the current day, corrected by the ratio between the calculated clear sky irradiations for the considered intervals.

Figure 11 shows the irradiance of a very interesting day for the benchmarking of predictions, the 8th of February, 2012, with very big clouds arriving around noon. The irradiance of the previous day (Figure 12) was less variable.

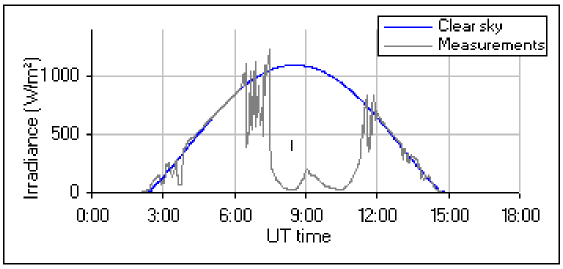

Figure 11: Horizontal irradiance measured at St Pierre, Reunion Island, 8 February 2012

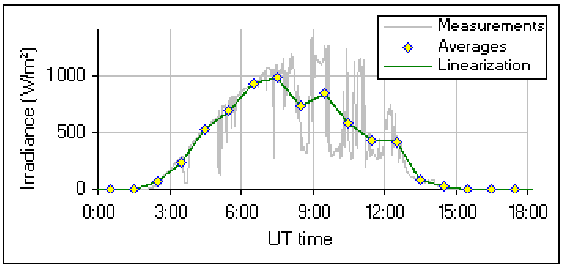

Figure 12: Horizontal irradiance measured at St Pierre, Reunion Island, 7 February 2012

Figure 13 presents in the same graph the measured irradiance, its linearization and the persistence prediction.

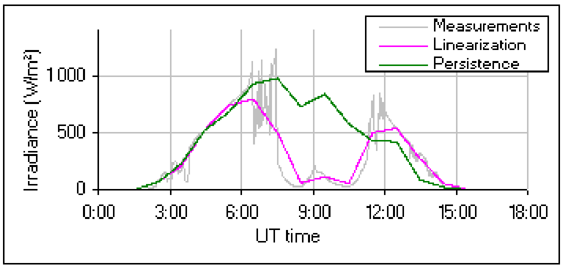

Figure 13: 8 February 2012, measured irradiance and its linearization (pink) considered as the optimal prediction, and linearized irradiance of the previous day corrected by clear sky irradiation, seen as the persistence prediction

The benchmarking of the persistence prediction for the 2 years of data is presented in Figure 14. Results vary strongly, depending simultaneously on the intrinsic dispersion of irradiance around its best possible linearization and on prediction errors.

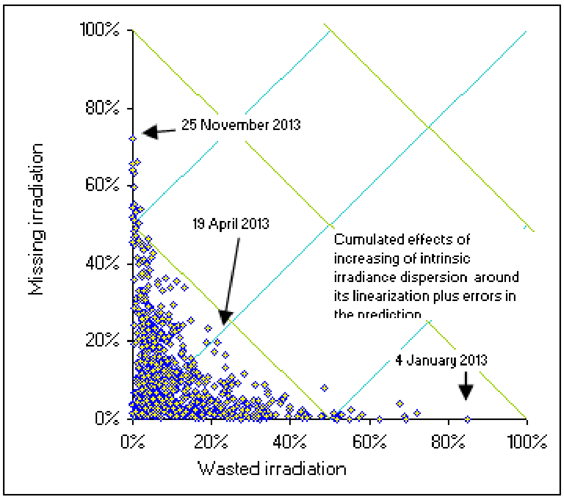

Figure 14: Daily wasted and missing irradiations for the linearization of persistence prediction for 2 years of data

Some days like the 4th of January, 2013, (Figure 15) are a lot sunnier than the previous day and persistence brings wasted irradiation.

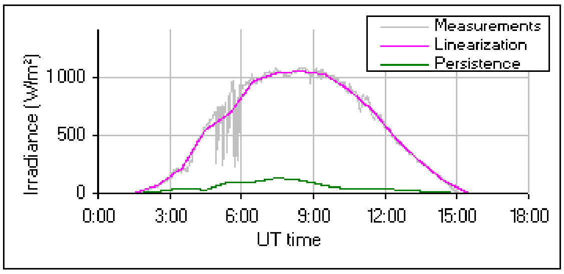

Figure 15: 4 January 2013, stable irradiance but very bad persistence prediction

Other days like the 25th of November, 2013, are in the opposite case (Figure 16). They are a lot less sunny than the previous day and a lot of missing irradiation.

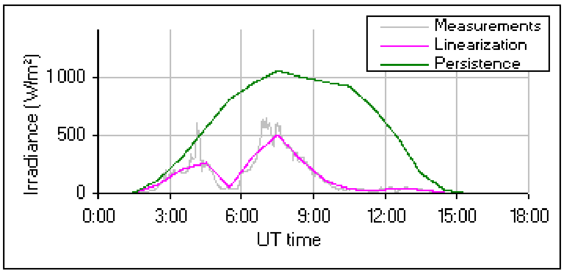

Figure 16: 25 November 2013, stable irradiance but very bad persistence prediction for the opposite reason

The 19th of April, 2013, is a good example of day with almost no difference between wasted and missing irradiations (a small bias irradiation), but with a high shifted irradiation between morning and afternoon (Figure 17).

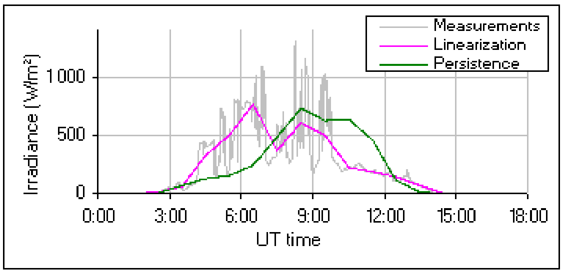

Figure 17: 19 April 2013, persistence prediction characterized by an underestimation of irradiance in the morning and an overestimation in the afternoon

4.3 Benchmarking of other predictions

Predictions are linearized as described above. Figure 18 and Figure 19 present the predictions for the 19th of April, 2013. Clearly, the 6-hour prediction overestimates the irradiance, while the 1-hour prediction is more accurate.

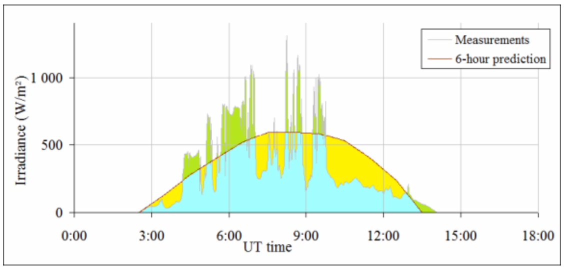

Figure 18: 19 April 2013, linearization of irradiance coming from its prediction 6 hours in advance

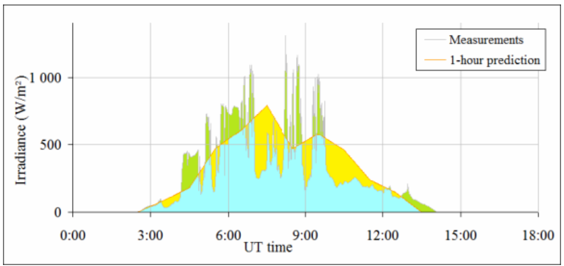

Figure 19: 19 April 2013, linearization of irradiance coming from its prediction 1 hour in advance

Figure 20 presents the results of the benchmarking of persistence and of the 6-hour and 1-hour predictions for the 19th of April, 2013, in the same graph as the benchmarking of the linearization of measured irradiance, which may be considered as the best possible prediction. The figures presented in the graph are the ratio between the wasted and missing irradiations and the clear sky irradiation.

The shifted irradiation for the linearization of the measured irradiance is around 40%, because this irradiance is highly variable. It is around 82% for persistence, because of its inaccuracy and of the intrinsic variability of irradiance. It is 68% for the 6-hour prediction and 60% for the 1-hour prediction.

The bias is null for the linearization and low for the persistence which overestimate by 2% the irradiance. The 6-hour prediction overestimates the irradiation by 8% and the 1-hour prediction is better with an overestimation of 5%. If the main criterion is the total bias of irradiation, persistence is a better prediction than the 6-hour and 1-hour predictions. None of the predictions approaches the performance of the linearization of the measurements considered as the optimal prediction.

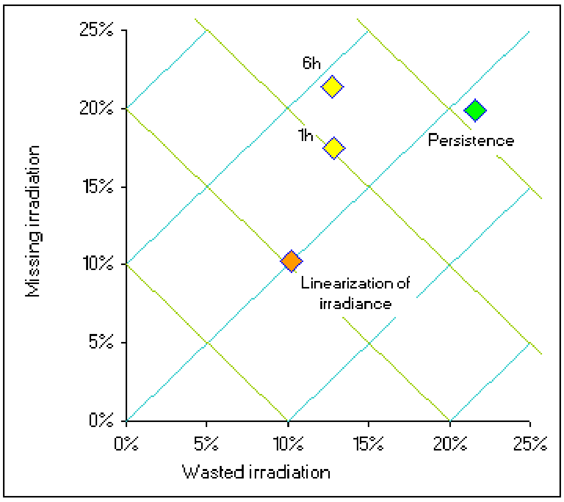

Figure 20: 19 April 2013, benchmarking of predictions and of linearized irradiance as ideal prediction.

4.4 Benchmarking of the irradiance prediction for 2 years of data

Figure 21 presents the result of the benchmarking of all the irradiance prediction for 2 years of data. The presented figures are the ratio between the total wasted and missing irradiations and the 2-year clear sky irradiation.

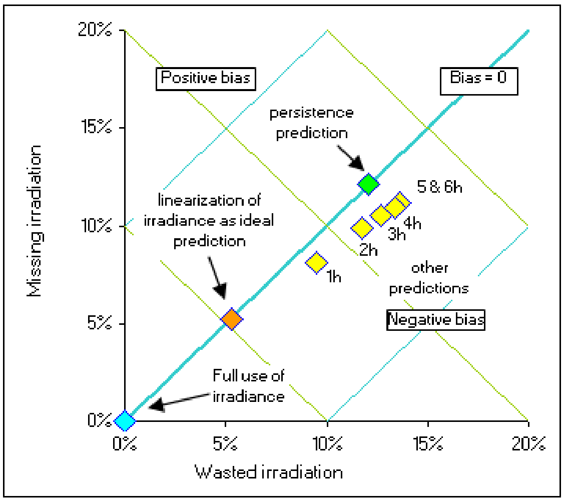

Figure 21: Benchmarking of predictions and of linearized irradiance as ideal prediction for 2 years of irradiance.

Synthetic conclusions may be drawn from this benchmarking:

- Linearization of irradiance, which is very near to the ideal prediction (null bias, minimum shifted irradiation) presents a shifted irradiation around 10.5 %, inherent to the variability of irradiance at this site. It is the intrinsic lower limit for the accuracy of predictions
- The persistence prediction has a remarkably low bias (-7‰) and a limited shifted irradiation around 24 %

- All predictions have a negative bias from -2.5% to -1.4% and underestimate the irradiance.
- The performance of the 6-hour to 3-hour predictions is very close to the performance of the persistence prediction, when considering the whole period. For long term prediction, persistence is better with its null bias
- 2-hour and 1-hour predictions are better. The 1-hour prediction has made half of the way between the persistence prediction and the ideal prediction. Once corrected of its bias error, it could be a real improvement of persistence prediction

5 CONCLUSION

In the French overseas departments and in Corsica, the grid operator asks for the linearization of production and for its announcement, which requires the best possible irradiance predictions.

This article proposes a new method for the benchmarking of the predictions. The idea of the benchmarking is to put in perspective the performance of the predictions by comparing them to an ideal prediction done with the perfect knowledge of the irradiance measurements and to the most simple and conservative prediction, the persistence prediction using the irradiance of the day as prediction for the next day.

Several new quantities have been defined for the benchmarking. They represent the overestimation and underestimation of irradiation between the real irradiance and its linearized predictions.

It can be shown that the linearization of production leads to intrinsic production losses and to potential complexity of electricity management for the electricity producers. The losses and the complexity depend partly on the intrinsic variability of the irradiance at the considered site and partly on the accuracy of the prediction methods.

The simultaneous benchmarking of the predictions with the persistence prediction and with the ideal prediction shows more clearly if improvements are necessary or if the present predictions are enough accurate.

6 REFERENCES

[1] Coimbra C. F. M., Kleissl J., Marquez R., Chapter 8 - Overview of Solar-Forecasting Methods and a Metric for Accuracy Evaluation Solar Energy Forecasting and Resource Assessment. Boston: Academic Press, 2013. p. 171-94.

[2] David M., Diagne H. M., Lauret P., Outputs and error indicators for solar forecasting models, *WREF 2012 - World Renewable Energy Forum*, Denver, United States, 2012.

[3] Lauret P., Lorenz E., David M., Solar Forecasting in a Challenging Insular Context. *Atmosphere* 2016.

[4] Guérin de Montgareuil A., Modelling of a clear sky irradiance with a third order polynomial function of the inverse of air-mass, Personal communication, 2016

[5] David M., Over irradiance explained by reflection of light on walls, Personal communication, 2016