Performance Analysis of 10,000 Residential PV Systems in France and Belgium

Jonathan Leloux[1,*], Luis Narvarte[1], David Trebosc[2]
[1]Instituto de Energía Solar, ETSI Telecomunicación, Ciudad Universitaria, s/n, 28040, Madrid, Spain
[2]BDPV, Rue du Capitaine Fracasse, 1, 31320, Castanet Tolosan, France
[*]Corresponding author: Jonathan Leloux (jonathan.leloux@ies-def.upm.es)

ABSTRACT: The main objective of this paper is to review the state of the art of residential PV systems in France and Belgium. This is done analyzing the operational data of 10650 PV systems (9657 located in France and 993 in Belgium). Three main questions are posed. How much energy do they produce? What level of performance is associated to their production? Which are the key parameters that most influence their quality? During the year 2010, the PV systems in France have produced a mean annual energy of 1163 kWh/kW$_p$ in France and 852 kWh/kW$_p$ in Belgium. As a whole, the orientation of PV generators causes energy productions to be some 7% inferior to optimally oriented PV systems. The mean Performance Ratio is 76% in France and 78% in Belgium, and the mean Performance Index is 85% in both countries. On average, the real power of the PV modules falls 4.9% below its corresponding nominal power announced on the manufacturer's datasheet. A brief analysis by PV modules technology has lead to relevant observations about two technologies in particular. On the one hand, the PV systems equipped with Heterojunction with Intrinsic Thin layer (HIT) modules show performances higher than average. On the other hand, the systems equipped with Copper Indium (di)Selenide (CIS) modules show a real power that is 16 % lower than their nominal value.
Keywords: Residential PV, Performance Ratio, Performance Index, PR, PI, CIS, HIT, France, Belgium

1 INTRODUCTION

The main objective of this paper is to review the state of the art of residential PV systems in France and Belgium. This is done analyzing the operational data of a representative sample of 10650 installations (9657 located in France and 993 in Belgium), totalizing a peak power of approximately 33 MW (29 MW in France and 4 MW in Belgium), and installed between 2007 and 2010. At the end of March 2011, 1146 MW were installed in Metropolitan France[1,2]. About half of the total power is installed in residential PV systems of less than 10 kW$_p$. The database here considered represents approximately 3.5% of the residential PV in Metropolitan France and 5% of the French-speaking part of Belgium.

This work articulates around three main questions:

1) How much electricity do PV systems produce? (in terms of kWh per kWp)
2) What is their performance for producing electricity? The PV systems quality is analyzed using different performance indicators such as the Performance Ratio (PR), the Performance Ratio at Standard Test Conditions (STC), (PR$_{STC}$) and the Performance Index (PI).
3) Which are the key aspects that influence the quality of PV systems? Statistical tools are applied to find them out.

For the first question, related to energy production, a survey is realized over the monthly energy production data supplied by the PV systems' owners through 2 Websites[3,4].

For the second question, related to the performance of PV installations, the assessment is based on the aforementioned performance indicators, all of them consisting on comparing the real energy production of each of the systems with the production simulated for a corresponding hypothetical system used as a reference.

For the third question, an Analysis-of-Variance (ANOVA) applied on the *PI* uncovers the key aspects that influence the quality of PV systems. A general multidimensional ANOVA is realized by grouping the PV systems according to four characteristics: PV modules manufacturer, inverters manufacturer, installer, and PV generator power. The goal is to isolate the causes explaining the PI differences.

The results presented in this work allow extracting conclusions about the expected energy production of residential PV systems. They define the state of the art, and they quantify the energy production losses due the orientation and inclination of the PV generators. The important quantity of PV systems analyzed makes it possible to extend the results not only to the French and Belgian markets, but also to the European one and, hence, they are of general interest. In fact, the conclusions of this work are congruent with previous analyses of the operational performance of residential PV systems installed during the last two decades in Germany, Switzerland, Italy, Spain, Netherlands, Japan and USA[5-8], and can be useful to important works that are presently ongoing[9] and whose main purpose is the assessment of the performance and reliability of PV systems.

2 RESIDENTIAL PV IN FRANCE AND BELGIUM

The data analyzed in the present study concerns Metropolitan France (i.e excluding Overseas France), and the French-speaking part of Belgium. Although Belgium is composed of three regions, the data come from Wallonia and Brussels and not from Flanders, due to availability reasons. Nevertheless, the data is still representative of the state of the art, since typologies are very similar. PV experienced an important growth in France since the year 2004, with the establishment of a tax credit of 40% of the PV system cost. The growth was accelerated in 2005 with the rise of that tax credit up to 50%. But the decisive moment was the vote in 2006 of a new feed-in tariff specific to PV of at least 0.30 €/kWh, and up to 0.46 €/kWh for Building Integrated Photovoltaics (BIPV). As a direct consequence, from the year 2007, the number of residential PV systems started to take off, reaching 20 MW at the end of that year. At the end of March 2011, residential PV systems represented more than 550 MW. That power was distributed over more than 160,000 installations. Since the end of 2007, Wallonia and Brussels established a supporting scheme (consisting of a mix of subventions and production based support, called *"green certificates"*) to promote residential PV. The PV power connected to the grid consequently jumped from 200 kW in 2007 to 50 MW at the end of 2009. That power is distributed among more than 10,000 PV installations.

The database reveals that 98% of the residential PV systems installed in France have a peak power of 3 kW_p or less, and more than half of the installations have a peak power very close to 3 kW_p. This situation arose as a direct consequence of a legal frame that strongly discourages installations of more than 3 kWp, mainly for two reasons. First, the tax credits are denied for the PV systems of more than 3 kW_p. Second, a VAT of 5.5% is applied to systems of less than 3 kW_p, while it jumps to 19.6% for systems of more than 3 kW_p. The power distribution among residential PV systems in France is thus mainly explained by legal considerations, rather that technical ones. In Belgium, residential PV systems of less than 10 kW_p account for 98% of the total installed PV power. The power of nearly three fourths of the PV systems in our database is comprised between 3 and 5 kW_p. That range arises as a consequence of limiting the most interesting public financial support to systems of several kW, and from the surface typically available on the roofs. The *"green certificates"* are also limited in relation to the electricity consumption of the household, which in Belgium typically lies between 3000 and 4000 kWh/year. The market therefore developed towards residential PV systems of small power.

PV modules based on classical crystalline Silicon (xSi) technology represent more than 90% of the market in Belgium, and almost 80% in France. In France, the rest of the market is almost under control of Heterojunction with Intrinsic Thin layer (HIT) (17%). The rest of the technologies only achieve some percents, in France as well as in Belgium. They mainly comprise amorphous Silicon (aSi), Copper Indium (di)Selenide (CIS), and Cadmium Telluride (CdTe).

The database contains 121 PV modules manufacturers, 23 inverters manufacturers and 652 PV systems installers. The relative market penetration within PV modules and inverters manufacturers is satisfactorily modeled by a power-law, indicating that the market is dominated by a reduced number of actors. The most extreme case of market domination is the control of more than 50% of the market by one single inverter manufacturer. The leading PV modules manufacturer in France distributes a HIT technology and has a market share of 17%. In Belgium, it is a xSi PV module, with a market share of 16%. The installers market also follow a power-law in Belgium, but it does not in France, mainly because many installers are small familiar enterprises that only work at local scales, much smaller than the country.

3 METHODOLOGY

3.1 Energy production

As mentioned earlier in the text, the data concerning the PV systems were supplied by their owners. Each PV system is localized by its latitude and longitude, completed with the corresponding altitude. The PV generator is characterized by its orientation and tilt angles, its total surface, and its total peak power. The data also provides information about the manufacturers of the PV modules and inverters that equip the system, and the installer. The net energy production is reported on a monthly basis, and is read at the inverter (95% of the database), or at the meter (20%), or at both sources (15%). The PV owners also communicated the annual energy that they expected to produce, and that was generally estimated by the installer before the commissioning of the installation. Not all the PV owners reported the energy production corresponding to each month, and only 25% of them reported it systematically and correctly.

Thanks to the PV owners that simultaneously provided the energy production data coming from both the inverter and the meter, it was possible to compare both sources of information. Figure 1 shows the results of these comparisons. The ratio $E_{inverter}/E_{meter}$ shows a value ranging from 0.93 to 1.09. A ratio superior/inferior to 1 indicates that the inverter systematically overestimates/underestimates the energy produced. When the inverters are grouped by manufacturer and model, these ratios show a much lower dispersion, which shows that some models of inverters systematically overestimate/underestimate the energy that is really produced. Therefore, in the present study, the data provided by the inverters are adjusted by comparison with the data provided by the energy meters.

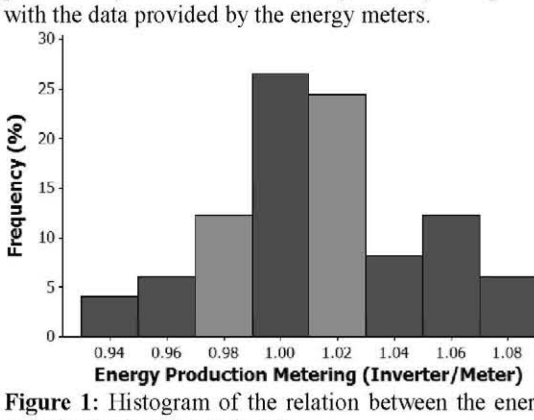

Figure 1: Histogram of the relation between the energy metering by inverter and meter

3.2 PV systems performance

The simulations require the input of the horizontal solar radiation and the ambient temperature data, both on a monthly basis, which have been obtained from SoDa[10] and PVGIS[11] respectively. The solar radiation received on the surface of each of the PV generators is estimated using widely accepted solar radiation models[12-14]. The performance of PV systems is realized by comparison with a corresponding reference system. The estimation of the energy production of the reference system is simulated with a tool developed at *Instituto de Energía Solar – Universidad Politécnica de Madrid* (IES-UPM) and based on widely accepted models, whose details have been described elsewhere[15-22].

The energy performance indicators that are used to assess the technical quality of a particular PV system are obtained by comparing its actual production along a certain period of time with the production of a hypothetical reference system (of the same nominal power, installed at the same location, and oriented the same way) somewhat free of certain kinds of losses. Different performance indicators are used to assess the quality of a PV system. Three possibilities are presented in the text here below. All three compare the real energy production of the PV system during a certain period of time to the corresponding reference system. The variation between them comes from the different reference system that is chosen in each case.

The PR is, by far, the most widely used performance indicator today, because the unitary energy production, which is of paramount importance for economic analyses, is simply given by the product of the irradiance, (or the number of "sun-hours") by the PR. It is defined mathematically as

$$PR = \frac{E_{produced}}{\frac{P^{STC}}{G^{STC}} \int G dt}$$

where $E_{produced}$ is the net electrical energy produced by the PV system during a period of time T, P^* is the rated power of the PV generator under STC, G^* is the global solar irradiance under STC (i.e. 1000 W/m^2), and G is the global solar irradiance received by the PV generator. The difference between 1 and PR lumps together all imaginable energy losses (real power of the PV modules power below nominal rating, mismatch, wiring, shades, dust, thermal, DC/AC, failures, etc.). Because thermal losses are site-dependent (they depend on climate), the PR of a given, unchanged PV system fluctuates from one place to another, and along the course of a year or a day, which represents an obvious inconvenient for strictly qualifying its technical quality. The PR_{STC} takes away such thermal losses, which requires to consider (measure or estimate) the temperature of operation of the solar cells.

It is mathematically defined as

$$PR_{STC} = \frac{E_{produced}}{\frac{P^{STC}}{G^{STC}} \int G(1 - \Delta P_{STC}) dt}$$

where ΔP_{STC} represents the thermal power losses in the PV cells due to their operational temperature which is different than STC. Because of that, it is of more complex calculation than the PR, but it becomes practically independent from time and site, thus being more appropriate for strictly qualifying technical quality. However, the PR_{STC} value corresponding to an excellent quality and properly maintained PV system is lower than 1, mainly because real inverters always associate some energy losses to the DC/AC conversion. Hence, one further step can still be taken subtracting the DC/AC conversion losses corresponding to a top class inverter, let us say, one whose European efficiency is 96%. That leads to the so called PI[23]. It is defined mathematically as

$$PI = \frac{E_{produced}}{\frac{P^{STC}}{G^{STC}} \int G(1 - \Delta P_{STC})(1 - \Delta P_{DC/AC}) dt}$$

where $\Delta P_{DC/AC}$ represents the conversion losses due to the inverter that equips the reference system.

It should be noted that a PI =1 corresponds to a PV system composed by an inverter and a PV generator whose real power and characteristics coincide with their rated nominal value, free of shading, dust and wiring losses and also free of failures. Consequently, the difference between 1 and PI can be understood as a measure of the somewhat avoidable energy losses. The PI thus allows comparing directly the quality of PV systems under different climatic and installation conditions. Because of that, this paper pays particular attention to the analysis of PI values. Figure 2 shows the evolution during the year 2010 of both PI and PR for a typical PV system of the sample, free of shading, not experiencing any lack of availability or other second order problems, whose PI is 84%, whose PR_{STC} is 80.5% and whose PR is 76.5% (mean values for the year). The PI is relatively constant along the year, while the PR varies of some 10% between winter and summer, mainly due to the evolution of cell's temperature. This lesser fluctuation of PI respect to PR suggests that PI is a better quality indicator of the intrinsic quality of a PV system than PR.

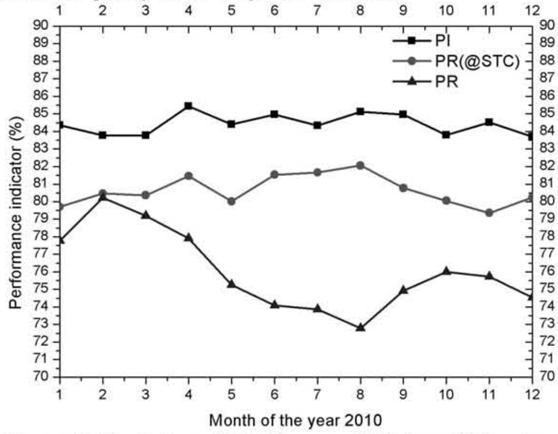

Figure 2: Evolution of PI, PR_{STC} and PR for a PV system in France during the year 2010.

3.3 Statistical analysis on the parameters affecting PV systems performance

To investigate furthermore the main causes of the quality differences observed among the PV systems, they have been grouped by common properties. The statistical method Analysis-of-Variance (ANOVA) has been used to study the causes of the dispersion of PI. ANOVA procedures rely on a distribution called the F-distribution. The key statistic is F = MSTR/MSE, where MSTR (Mean Square Treatment) represents the variation among the means of the different groups, and MSE (Mean Square Error) represents the variation within the groups. Large values of F indicate that the variation among the groups is large relative to the variation within the groups, and hence that the groups are significantly different. A general multidimensional ANOVA was realized according to four criteria: PV modules manufacturer, inverters manufacturer, installer, and PV system peak-power.

4 RESULTS

4.1 Energy production

The energy production analysis is carried out for the year 2010 and for the 1635 PV systems in France and 352 in Belgium, from which the monthly production was correctly reported for the 12 months of the year. The figure 3 shows a histogram of those energy productions in France. On average, the PV systems produced in 2010 a net annual energy of 1163 kWh/kW$_p$ in France and 852 kWh/kW$_p$ in Belgium. The dispersion is mainly due to three factors: geography (and therefore solar radiation and temperature), orientation and performance. The solar radiation during the year 2010 in France and in Belgium was globally comparable to the mean radiation during the last decade. The energy productions reported are thus sufficiently representative to be compared with other previous studies in the literature. As a comparison, annual productions around 800 kWh/kW_p were reported for PV systems installed 5-10 years ago in the North and East of Germany[5], which are similar to the productions observed for Belgium, with similar climatic conditions. Two main causes explain the lower productions reported for the PV systems in Germany respect to France. First, the solar radiation is globally higher in France. Second, the energy productions reported in Germany correspond to PV systems installed about 10 years ago, whose quality was lower, and whose power has decreased with time, mainly due to the light soaking.

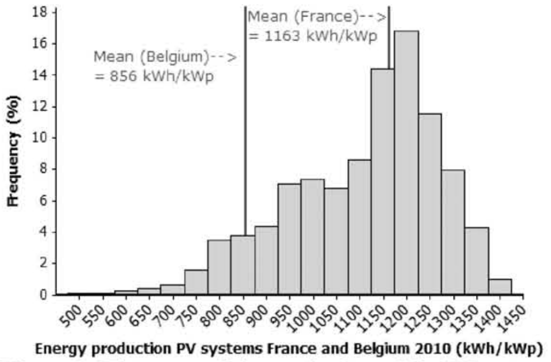

Figure 3: Histogram of the production of the PV systems in France and Belgium in 2010.

4.2 Energy losses related to tilt and orientation

The vast majority of PV generators have a tilt angle between 20 and 50 degrees, which generally corresponds to the configuration of the roofs on which they are mounted. At the latitudes of France and Belgium, from 43º to 51º North, a PV generator maximizes its annual energy produced when it faces South and benefits from a tilt angle around 40º. When the orientation is different, which is usual in residential PV, the energy produced diminishes by an amount that is shown in figure 4. That same figure also shows the relative distribution, in percent, of the number of residential PV systems installed, in function of the orientation and tilt. It is worth underlying that low tilt values favor dust accumulation (tilt angles of less than 10º have been reported to keep hold of important quantities of dust[24]), but figure 4 shows that it is not frequent to find those low tilt values.

(<-- East) Deviation from South (º) (West -->)

Tilt angle (º)	-90	-80	-70	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	90
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0.1	0.1	0	0.1	0	0.2	0	0	0	0.1	0	0	0	0	0.1
20	1	0.4	0.8	0.5	1	2	2	3	3	9	3	3	2	2	2	0.7	0.8	0.5	0.9
30	0.2	0.3	0.5	0.4	0	1	2	2	2	7	2	2	1	1	1	0.5	0.3	0.4	0.7
40	0.2	0.3	0.4	0.4	0	2	2	2	2	6	1	1	1	1	1	0.6	0.6	0.3	0.7
50	0.2	0.1	0.2	0.5	0.3	1	0.8	1	1	3	1	2	0.8	0.6	1	0.5	0.1	0.1	0.3
60	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0	0	0.1	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Numbers: Proportion of PV systems installed (%)

Colors: Annual energy production (E in %) relative to MAX = 100%

E = 100 | 100 > E ≥ 95 | 95 > E ≥ 90 | 90 > E ≥ 80 | 80 > E ≥ 60 | E < 60

Figure 4: Distribution of the number of PV systems installed in France and Belgium (out of a total of 10,650) in function of orientation and tilt, together with the corresponding net annual energy produced by a PV system respect to the optimal inclination, in percent.

Figure 5 shows the relation between the energy losses due to orientation and the proportion of PV systems installed in France and Belgium. It is satisfactorily described by a power-law (R^2 = 99.4%). Almost 65% of the PV systems lose less than 5% of their annual energy due to orientation, and less than 10% lose more than 15%. As a whole, the orientation of residential PV causes energy productions to be 7% inferior to optimally oriented PV systems, what can be interpreted as the price to pay, in terms of energy losses, for installing PV systems on roofs instead of installing PV farms.

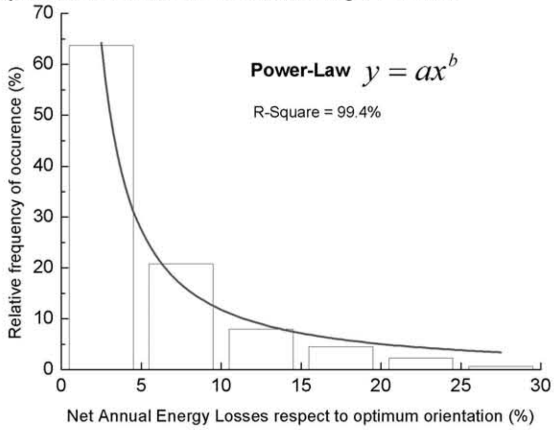

Figure 5: Proportion of PV systems (in %) oriented so that they lose less than a given percentage of net annual energy respect to the optimum orientation. Almost 65% of the PV systems lose less than 5% of annual energy due to their orientation, and less than 10% lose more than 15%.

4.3 Performance of PV systems

Figure 6 presents the histogram of PR and PI of 1987 PV systems in France and Belgium that correctly provided the monthly produced energy for the year 2010. The mean value of PI is very close to 85%, which indicates that, on average, the PV systems are producing an annual energy that is 15% inferior to the reference system. The PI observed in 2010 tends to be slightly higher for newer installations. The mean PI measured in 2010 for PV systems installed in 2007, 2008 and 2009 yielded respectively 82.9%, 83.5% and 85.5%. Two main causes probably explain that trend. First, the power of PV modules is known to decrease with time due to the light soaking. Second, quality controls have been given a growing importance during these last years. It was not possible to track PI values from previous works to compare them with the ones obtained in the present study. To make possible a direct comparison using the more widely spread concept of PR, figure 6 shows its corresponding histogram. The mean value of PR is 76%. As a comparison, values of PR between 48% and 93% have been reported in other works[25,26].

The distribution of *PI* is nearly normal between values from 70% to 100%. It is left skewed, which physically arises from the existence of PV systems suffering from major issues and thus showing PI values abnormally low, while even a very good PV system can hardly have a PI much higher than 100%. The skewness can be approximated through a Weibull distribution (at a confidence level of 95%, Anderson-Darling goodness of fit = 1.452). The distribution of *PR* is more symmetrical, mainly because the influence of cell's temperature on the

PR introduces wider variation among the PV systems installed in different climatic conditions.

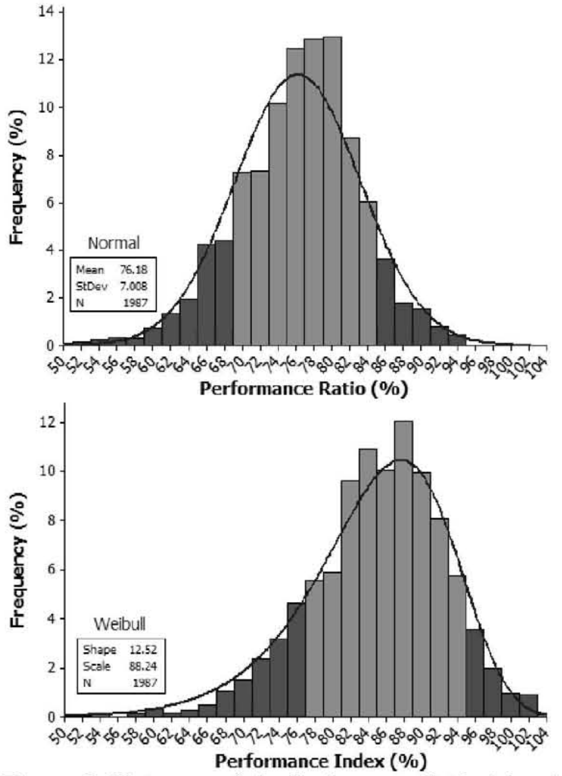

Figure 6: Histogram of the Performance Ratio (above) and Performance Index (below) of the PV systems analyzed in France and in Belgium.

In order to look for the causes that explain the PI differences among the different PV residential systems, an ANOVA was applied to the whole database. It did not allow associating significant variations of PI to the nominal power of the installations, the inverter manufacturers or the installers. This failure to identify significant trends does not imply the absence of differences. It simply means that the PI differences cannot be statistically attributed to any of these parameters with a sufficient confidence level.

Table 1: ANOVA on PV Modules present at least on 25 PV installations. N indicates the number of installations.

PV Module	N	Mean PI (%)	StDev PI (%)
bcSi1	63	83.7	6.2
CIS1	41	72.7	6.5
HIT1	304	88.7	6.1
xSi1	51	86.0	4.3
xSi2	32	83.6	8.8
xSi3	65	85.4	7.0
xSi4	54	79.3	8.1
xSi5	187	83.9	7.2
xSi6	145	87.2	6.5
xSi7	46	87.5	5.5
xSi8	34	87.9	6.8
xSi9	41	85.8	6.9

The ANOVA did however allow to establish strong evidence that the PV modules explain the majority of the dispersion of PI ($F=23.21$ and P-Value <0.001). The results of this ANOVA for PV modules that are present on at least 25 installations are detailed in table 1. Manufacturers' names have been hidden under symbols for confidentiality reasons. xSi stands for crystalline silicon; bcSi stands for back-contact silicon; HIT stands for Heterojunction with Intrinsic Thin layer; CIS stands for CuInSe2 based solar cell (thin film). Among the results, it is possible to draw important observations about two PV modules technologies. On the one hand, the PV systems equipped with the module tagged as "HIT1" show *PI* values higher than average. This module is also the most represented on the PV systems of the database. On the other hand, the systems equipped with the PV module tagged as "CIS" clearly show a *PI* pretty low respect to all the other groups.

Figure 7 shows a boxplot that allows visualizing the PI variations among and within the groups of PV modules.

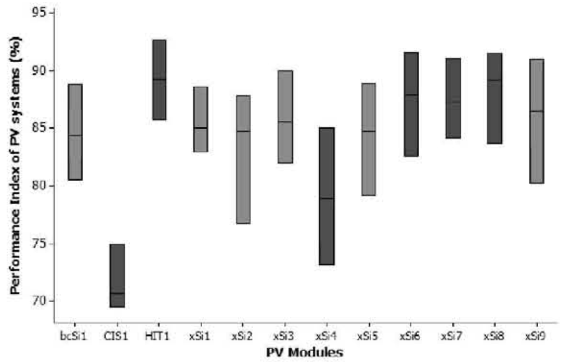

Figure 7: Boxplot of Performance Index for PV modules present at least on 25 PV installations. The boxes show the first, second and third quartiles, represented respectively by the lower, medium and upper horizontal lines. The second quartile is also the median.

In order to estimate the real power of the PV modules, we assume that the losses due to the Balance of System (BOS) are 10% higher than in the reference system. This assumption is supported by previous works that describe the losses typically present at a PV system. The soiling losses typically account for 3%[21,22]. The average inverter has a yield 2% lower than the high quality inverter that equips the reference system[27]. PV generator mismatch and wiring losses can typically be 2%[28]. Shading can lead to important energy losses in some cases. The evaluation of shading losses is particular to each project and often implies complex models. The shading losses were not simulated for each PV system, but were instead estimated to 2% on average, which seems a reasonable hypothesis for the typical residential PV systems in France[29]. Other losses, such as the ones due to the availability of the system, can account for 1%[30]. Those losses can thus be estimated conservatively to account for 10% of annual energy losses. As the mean value of PI is 85%, there is a 5% left that is probably due to a power default in the PV modules.

Under those assumptions, it is possible to group the PV modules by manufacturer and to estimate the deviation of their real power respect to their corresponding nominal power announced by the manufacturer. The figure 8 shows the result of this exercise for 51 different manufacturers of PV modules. It is worth mentioning that the PV modules analyzed here have a mean exposure time of 2 years.

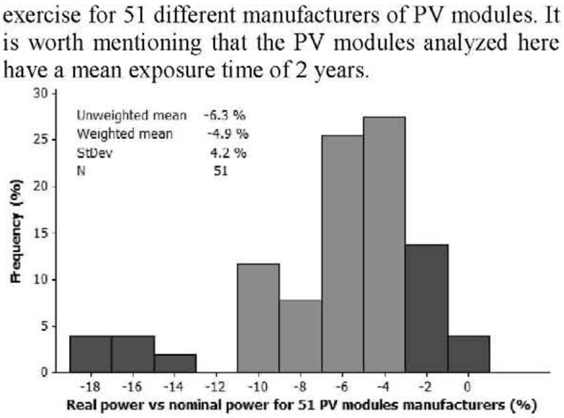

Figure 8: Histogram of the deviation of the real power of the PV modules respect to their nominal power. On average, the PV modules real power falls 4.9% below their corresponding nominal power.

The majority of the PV modules have a real power between 2% and 8% lower than their nominal power. The presence of PV modules showing a real power higher than their nominal power correspond to PV modules delivered with positive power tolerances, or to a BOS better than the one considered in this analysis, or a combination of both factors. Two kinds of averages can be used to characterize the distribution as a whole. The first possibility is to give the same weight to the power deviations of each PV module manufacturer (unweighted average). The second possibility, more representative of the state of the art, is to weight the power deviations of each PV module manufacturer by the total power of its modules present in the sample (weighted average). The unweighted average yields 6.3%, and the weighted average yields 4.9%. The PV module that yields the best results is also the one that sold the best in 2010 in France. It is a module based on HIT technology. Some models of PV modules show poor quality. A relevant observation concerns a PV module based on CIS technology, showing with a mean real power up to 16% below the nominal power. To investigate the reasons for such a low power, the PV systems equipped with this module have been grouped by year of installation. On average, a loss of power of 5% per year has been observed on the modules from 2007 to 2010. The low power is thus very probably due partly to an initial low power, and partly to a light soaking effect higher than for the other technologies. The multidimensional ANOVA allowed verifying that those conclusions about the real power of PV modules are not affected by other parameters of the installations, such as the inverters or installers.

The comments received from the users of BDPV indicate that the geographical origin of the PV modules and inverters is often taken as an indicator of quality. In particular, they tend to consider as high quality the PV components manufactured in their country or in Europe, while they often turn down PV modules manufactured in China on the sole basis of their origin. Nevertheless, the analysis of the data of BDPV has demonstrated that no clear correlation exist between the performance of PV modules and the country where they were made. For example, several French and one Belgian PV modules manufacturers present in the database perform below average, while several Chinese manufacturers perform better than average.

Other authors have reported the real nominal power of PV modules to be on average 5% inferior to the nominal power stated by their manufacturer[26,29]. Globally, those differences between real power and nominal power suggest that it is profitable to implement quality control procedures to verify and improve the quality of PV systems[32,33].

4.4 Validation of the results against on-site measurements

The results of the present work have been compared to on-site measurements realized by the IES-UPM during the last years on more than 200 MW of PV modules equipping solar plants in Spain, Italy and France[28]. Among the modules manufacturers present on more than 25 installations of the database of BDPV, it was possible to identify 9 that were also measured by the IES-UPM. The relation between their real and nominal powers has thus been estimated through two different, independent methods, and is shown on table 2. The difference is generally lower than 2.3%. This is well within the uncertainties of those kinds of measurements. Additionally to the uncertainties on the measurements and on the estimations used in both methods, other sources of uncertainties are present from the fact that the PV modules that were rated here were not all installed at the same time, nor under the same climatic conditions, which possibly implies that some modules have already lost more power than others due to the light soaking process ongoing since they were exposed to outdoor conditions. Such agreements can thus be considered as very satisfactory. It is important to note that these conclusions are drawn only for PV modules present on at least 25 installations. The sources of uncertainties related to the methodology used in the present work are too high to be able to draw any reliable conclusion on smaller samples. These uncertainties are emphasized by the relatively high standard deviations associated to individual PI estimations on table 1. The method described in the present work is thus not accurate, but it is sufficiently precise when considering large samples. The comparisons between the method used here and on-site measurements also suggest that the method does not introduce any significant positive of negative bias on the conclusions.

Table 2: Comparisons between real and nominal powers estimated in this work, and measured by IES-UPM on solar plants in Spain, Italy and France.

PV Module (Veiled)	ΔP (%) [This work]	ΔP (%) [Measured]	Diff (%)
PV1	-6.2	-7.1	0.9
PV2	-4.6	-3.1	-1.5
PV3	-10.7	-12.3	1.6
PV4	-1.3	-2.1	0.8
PV5	-6.1	-4.7	-1.4
PV6	-2.9	-5.2	2.3
PV7	-2.1	-2.2	0.1
PV8	-4.1	-3.2	-0.9
PV9	-6.4	-6.6	0.2

5 CONCLUSIONS AND DISCUSSIONS

The objective of this paper is to review the state of the art of residential PV systems in France and in Belgium, which is done analyzing the operational data of 10650 PV systems.

The PV market in France and Belgium developed towards residential PV systems as a consequence of limiting the most interesting public financial support to systems of 3 kW_p. The PV industry (manufacturers of PV modules and inverters) is dominated by a reduced number of actors, while an important fraction of installations are realized by small installers, working at a regional scope.

On average, the PV systems produced in 2010 a net annual energy of 1163 kWh/kW_p in France and 852 kWh/kW_p in Belgium. As a whole, the orientation of residential PV causes energy productions to be some 7% inferior to optimally oriented PV systems.

The quality of the PV systems is quantified using the Performance Ratio (PR), and the Performance Index (PI). After a mean exposure time of 2 years, the mean value of Performance Ratio is 76% in France and 78% in Belgium, and the mean Performance Index of the PV systems is 85% in both countries, which implies that the typical real PV system produces 15% less than a very high quality PV system (or reference PV system). On average, the real power of the PV modules falls 4.9% below their corresponding nominal power announced on the manufacturer's datasheet. A brief analysis by PV modules technology has lead to relevant observations about two technologies. On the one hand, the PV systems equipped with HIT modules show performances higher than average. On the other hand, the systems equipped with the CIS modules show a real power that is 16 % lower than nominal value.

6 ACKNOWLEDGMENTS

This work would never have been possible without the thousands of altruistic people who generously and freely provided us the data corresponding to the energy production of their PV system. Catherine Praile, owing to her programmer talents, was absolutely essential to the success of this work. Eduardo Lorenzo brought invaluable feedback and insight.

7 REFERENCES

[1] Statistiques EDF, *Installations de production raccordées au réseau géré par ERDF à fin mars 2011.*

[2] *Renouvelle*, n°29, december 2010, p.12 (http://www.apere.org/).

[3] BDPV: *Base de Données PhotoVoltaïque* (http://www.bdpv.fr/).

[4] SolarWeb.be (http://www.solarweb.be/).

[5] Jahn, U. and Nasse, W. (2004), *Operational performance of grid-connected PV systems on buildings in Germany.* Progress in Photovoltaics: Research and Applications, 12: 441–448. doi: 10.1002/pip.550.

[6] Oozeki, T., Yamada, T., Otani, K., Takashima, T. and Kato, K. (2010), *Performance trends in grid-connected photovoltaic systems for public and industrial use in Japan.* Progress in Photovoltaics: Research and Applications, 18: 596–602. doi: 10.1002/pip.992.

[7] J.C. Wiles et al., *PV installations, a progress report*, IEEE Photovoltaic Specialists Conference, 2002.

[8] Furkan Dincer, *The analysis on photovoltaic electricity generation status, potential and policies of the leading countries in solar energy*, Renewable and Sustainable Energy Reviews, Volume 15, Issue 1, January 2011, Pages 713-720, ISSN 1364-0321, DOI: 10.1016/j.rser.2010.09.026.

[9] IEA, *PVPS Task 13: Performance and Reliability Of Photovoltaic Systems.* Ongoing.

[10] SoDa (http://www.soda-is.com/).

[11] PVGIS (http://re.jrc.ec.europa.eu/pvgis/).

[12] D.G. Erbs et al.,, *Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation*, Solar Energy, Elsevier, 1982.

[13] B. Liu, R.C. Jordan, *The interrelationship and characteristic distribution of direct, diffuse, and total solar radiation*, Solar Energy 1960;4:1–9.

[14] J.E. Hay, *Calculating solar radiation for inclined surfaces: Practical approache*s, Solar Energy, Elsevier, 2003.

[15] Narvarte, L. and Lorenzo, E. (2008), *Tracking and ground cover ratio.* Progress in Photovoltaics: Research and Applications, 16: 703–714. doi: 10.1002/pip.847

[16] B. Marion, *A method for modeling the current–voltage curve of a PV module for outdoor conditions*, Progress in Photovoltaics: Research and Applications, Volume 10, Issue 3, pages 205–214, 2002.

[17] E. Skoplaki, J.A. Palyvos, *On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations*, Volume 83, Issue 5, 2009, Pages 614-624.

[18] M. Simon, E.L. Meyer, *The effects of spectral evaluation of c-Si modules*, Progress in Photovoltaics, 2011.

[19] N.J. Christian et al, *Influence of spectral effects on the performance of multijunction amorphous silicon cells*, PV Conference and Exhibition, Rome, 2002.

[20] Schmid J, Schmidt H, *Inverters for photovoltaic systems*, Proceedings 5th Contractor's Meeting of the Photovoltaic Demonstration Projects, Ispra, 1991.

[21] R. Hammond et al., *Effects of soiling on PV module and radiometer performance*, AZ Photovoltaic Specialists Conference, 1997.

[22] N. Martin, *J.M.* Ruiz, *Annual angular reflection losses in PV modules,* Progress in Photovoltaics, 2006.

[23] Behnke, Erdman, and Whitaker Engineering, Inc., Commonwealth Energy Biogas/PV Mini-Grid, Renewable Resources Program, *Interim Exposure and Operations Report for the Comprehensive Large PV System Comparison*, 2005.

[24] F. Martínez et al., *Testing of PV arrays in large grid-connected PV plants installed in Spain*, 23rd EUPVSEC, 2008.

[25] Decker B, Jahn U. *Performance of 170 grid connected PV plants in northern Germany—analysis of yields and optimization potentials.* Solar Energy 1997;59:127–33.

[26] D.K. Munro, G. Blaesser, *The performance of PV systems and components in the THERMIE programme*, Renewable Energy, Volume 5, Issues 1-4, Climate change Energy and the environment, August 1994, Pages 172-178, ISSN 0960-1481, DOI: 10.1016/0960-1481(94)90368-9.

[27] Muñoz, J., Martínez-Moreno, F. and Lorenzo, E. (2011*), On-site characterisation and energy efficiency of grid-connected PV inverters.* Progress in Photovoltaics:

Research and Applications, 19: 192–201. doi: 10.1002/pip.997

[28] Martínez-Moreno, F., Lorenzo, E., Muñoz, J. and Moretón, R. (2011), *On the testing of large PV arrays.* Progress in Photovoltaics: Research and Applications, 19: n/a. doi: 10.1002/pip.1102.

[29] F. Martinez-Moreno, J. Munoz, E. Lorenzo, *Experimental model to estimate shading losses on PV arrays*, Solar Energy Materials and Solar Cells, Volume 94, Issue 12, December 2010, Pages 2298-2303, ISSN 0927-0248, DOI: 10.1016/j.solmat.2010.07.029.

[30] B. Bletterie, *Sensitivity of photovoltaic inverters to voltage sags — Test results for a set of commercial products*, e & i Elektrotechnik und Informationstechnik, Volume 122, Number 10, 349, 2007.

[31] Fraunhofer-Institut Für Solare Energysysteme ISE, *Annual Report, Achievements and Results*, 2007.

[32] E. Caamaño et al., *Quality control of wide collections of PV modules: lessons learned from the IES experience*, Progress in Photovoltaics: research and applications 7, 137-149, 1999.

[33] J. Coello at al., *Quality control during the supply of PV modules: Fundamental key to guarantee the profitability of PV installations*, Proceedings 23rd European Photovoltaic Solar Energy Conference, 2008.