Monitoring 30,000 PV systems in Europe: Performance, Faults, and State of the Art

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ABSTRACT: We have tried to cast some light on some of the numerous questions concerning the performance of solar PV systems in Europe. We have based our analysis on the operational data monitored at more than 31,000 PV systems in Europe. These installations comprise residential and commercial rooftop PV systems distributed over 9 different countries, including multi-megawatt PV plants installed in the South of Europe. The PV systems were installed between 2006 and 2014. The mean Energy Yield of the PV systems located in the four reference countries are 1115 kWh/kWp for France, 898 kWh/kWp for the UK, 908 kWh/kWp for Belgium, 1450 kWh/kWp for the PV plants in Spain mounted on a static structure, and 2127 kWh/kWp for those mounted on a solar tracker in Spain. We suggest that the typical PR value for the PV systems installed in 2015 is 0.81. We have observed that the performance of the PV systems tends to increase when the peak power of the PV systems increases. We have found significant performance differences as a function of the inverter manufacturer, and the PV module manufacturer and technology. We have found an improvement of the state-of-the-art, in the form of an increase in performance in the yearly integrated PR of around 3 to 4% over the last seven years, which represents an increase of about 0.5% per year.
Keywords: PV system, Performance Ratio, Energy yield, UK, France, Belgium, Spain, State of the art

1 INTRODUCTION

The number of solar photovoltaic (PV) systems installed in Europe has drastically increased over the last few years, mostly thanks to the advantageous feed-in tariffs set in by each country's government. A relatively little fraction of the energy production data of these PV systems has been analysed [1-6], and as a consequence, there still remain wide gaps in the knowledge of the real-world performance of these PV systems. This feedback from the field is nevertheless important for the future development of the PV industry and for the establishment of new renewable energy development programmes by the respective governments.

In this work, we have tried to cast some light on some of the numerous remaining questions about the performance of PV systems in Europe. To do so, we have based our analysis on the operational data monitored at more than 31,000 PV systems in Europe. These installations comprise residential and commercial rooftop PV systems distributed over 9 different countries, and multi-megawatt PV plants installed in the South of Europe. These PV systems were installed between 2006 and 2014, and the data have been measured at time resolutions varying from minutely to monthly.

We have carried out an assessment of the energy production and the performance of all of these installations, from their commissioning date until the end of 2014.

We have looked for important trends on these installations, such as the decrease in performance with the time of operation, or the increase in performance due to improvements in the quality of PV system components and installation practices. We have also studied the distribution of the installed power per region, as a function of the type of installation and the external incentives.

We have characterised the state of the art of the PV installations, both in terms of PV system components, installation topology, orientation, and peak power, differentiating from the small residential PV market in northern and mid-latitude Europe and the PV plants in the southern and sunnier countries. We have applied statistical analyses on the whole database, which has allowed us to analyse the main parameters that explain the important differences that were observed among the installations in terms of performance, such as the PV module technology and manufacturer, the PV inverter, the region and year of installation.

2 DATA AND METHODS

This work is based on the data collected at more than 31,000 PV systems in Europe (See Figure 1). Most of them are located in the UK, Belgium and France. Spain has few PV systems, but they are important ones because most of them are large PV plants, which sum up a larger total peak power than the rooftop installations from any other country. About 300 PV systems are located in other countries from Europe. This study is therefore mostly based on the analysis of the data of 4 reference countries: France, UK, Belgium (mostly small rooftop PV systems) and Spain (mostly large PV plants). The diversity in climates and installation types among these 4 countries allows to reach a representative picture of the state of the art in PV systems in Europe. The data on which this work is based are publicly and freely available in a condensed form from a web repository [7].

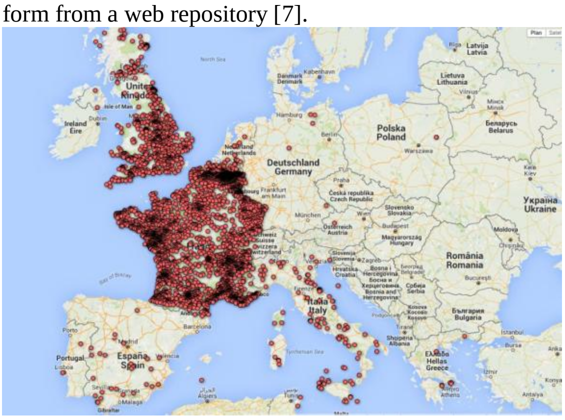

Figure 1: Location of the 31,000+ PV systems in our database. Most of them are located in the UK, Belgium and France.

The geographical distribution and type of these data are summarized in table I.

Table I: Geographical distribution and type of the PV systems in our database. Most of the PV systems in Spain are large PV plants. 300 PV systems are located in other countries from Europe.

Country	# systems	Pp [MWp]	Type
France	17672	65	Rooftop
Belgium	7648	50	Rooftop
UK	5835	23	Rooftop
Spain	29	116	PV plant
Others	307	3	Rooftop
TOTAL	31491	255	

Most of the data for the UK have been provided by Sheffield Solar and were acquired through the Microgen Database (MgDB) website [8]. Most of the data for France and Belgium were provided by BDPV through its free public website for PV system owners[9], and Rtone through its commercial monitoring service Rbee Solar [10]. The data from the PV plants in Spain have been provided by several PV plant operators through Instituto de Energía Solar - Universidad Politécnica de Madrid (IES-UPM). The data for the rest of Europe have been provided by Rtone and BDPV.

The data that were used as input for these analyses can be divided into three main categories: PV systems characteristics, PV energy production and solar irradiation.

Some of the PV system characteristics were available for most of the PV systems: latitude, longitude, azimuth and tilt angles, and peak power. Some other characteristics were available, depending on the data provider: PV module manufacturer and model, inverter manufacturer and model, installer, year of installation, PV cell/module technology.

The PV energy production data provided by MgDB were collected via the MgDB website, with PV owners using the site as a portal to upload readings and in return receiving free monthly Performance Ratio (PR) analysis and peer-to-peer performance checking in the form of interactive maps and nearest neighbour comparisons. The majority of data is measured by the energy meters of the inverters and is collected from commercial data donors who own/monitor hundreds of systems using automated data transfers. PR calculations interact directly with the MgDB so as to provide regular updates to the live website.

The PV energy production data provided by Rtone have been monitored using the Rbee Solar monitoring product, which measures the energy production with a smart energy meter at a 10-min time interval. The installations provided by Rbee Solar have been installed from 2008 to 2014.

The PV energy production data provided by BDPV have been collected through a free, public website for PV system owners, where individuals can manually enter the monthly reading of their energy meter or inverter through an HTML web interface, or if their equipment allows for it, make use of an Application Program Interface (API) to automatically upload their data, at any time resolution.

The PV energy production data provided by the PV plant operators have been provided to IES-UPM in several different formats, mostly in the form of text/csv files. The oldest of these PV plants was commissioned in 2005, but most of them date from the years 2006-2010.

Figure 2 represents the relative distribution of the azimuth and tilt angles of all the PV systems on a heatmap. The figures are given in the format of a percentage. Most of the installations have an azimuth between South-East (-45º) and South-West (45º) and with a tilt between 20º and 50º, which correspond to the orientations for which the annual yearly yield is the highest.

(<--East) Azimuth 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	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.2	0.1	0.0	0.1	0.1	0.4	0.2	0.2	0.2	0.6	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0
20	0.9	0.4	0.5	0.7	0.5	2.3	1.2	1.9	2.3	6.8	2.0	1.8	1.3	1.2	2.0	0.5	0.4	0.3	0.6
30	0.5	0.3	0.4	0.6	0.3	2.0	1.0	2.0	2.2	6.4	1.8	1.5	1.0	1.2	1.8	0.3	0.2	0.2	0.5
40	0.9	0.4	0.7	0.7	0.5	3.2	1.5	2.2	2.5	7.6	1.9	1.9	1.2	1.5	3.5	0.3	0.3	0.2	0.4
50	0.3	0.1	0.2	0.3	0.4	1.7	0.6	0.8	1.1	2.9	1.1	1.0	0.7	0.5	1.0	0.4	0.2	0.1	0.3
60	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	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	0.0	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	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 2: Relative distribution of the azimuth and tilt angles of all the PV systems on a heatmap. The figures are given as a percentage. Most of the installations have an azimuth between South-East (-45º) and South-West (45º) and with a tilt between 20º and 50º, which correspond to the orientations for which the annual yearly yield is the highest.

Figure 3 shows the frequency of the peak power of the PV systems in Europe. Most of them have a peak power between 1 and 6 kWp. A pronounced peak in frequency is visible around 3 kWp. This peak is mostly explained by more than 50% of installations in our database coming from France, where the government has set up a public incentive mechanism that makes it uneconomical to install a PV system with a peak power higher than 3 kWp. As a consequence, most of the PV systems in France have a peak power of exactly 3 kWp or slightly lower (see Figure 4).

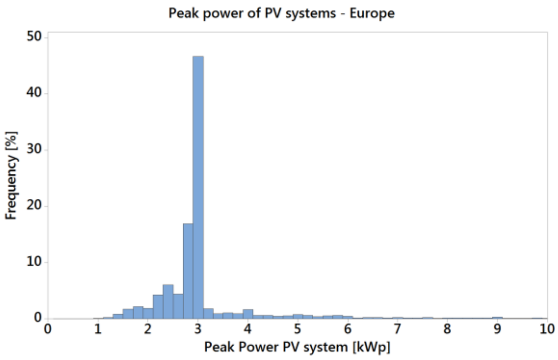

Figure 3: Frequency of the peak power of the PV systems in Europe. There is a pronounced peak around 3 kWp. This is a direct result of the public incentive mechanism set up by the French government such that it is uneconomical to install a PV system with a peak power higher than 3 kWp. As a consequence, most of the PV systems in France have a peak power of exactly 3kWp or slightly lower. As a comparison, Figure 5 shows the frequency of the peak power of the PV systems in Belgium, where the public incentives have been established following a very different mechanism. The feed-in tariff set-up by the government establishes that the owner of a PV system can sell as much PV-generated electricity as the amount of electricity that he/she consumes per year (annual net-balance mechanism). The distribution of the peak power shows a wider dispersion, with most of the PV systems between 1 kWp and 10 kWp, and it roughly follows a lognormal law, which arises as the product of several independent positive random variables, the most relevant being the annual energy consumption of the owner, the surface available

on the roof to install PV modules, and the capital that the owner is willing/able to invest in a PV system. The feed-in tariff in Belgium was so attractive that numerous households have also found it economical to voluntarily increase their annual electricity consumption in order to be able to sell more PV electricity. They often did so by switching to electricity for water heating, space heating, or cooking.

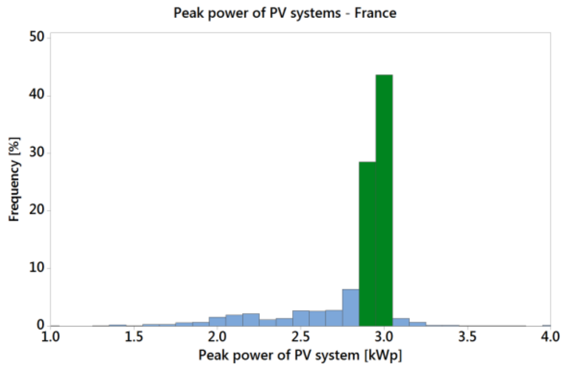

Figure 4: Frequency of the peak power of the PV systems in France. There is a pronounced peak around 3 kWp.

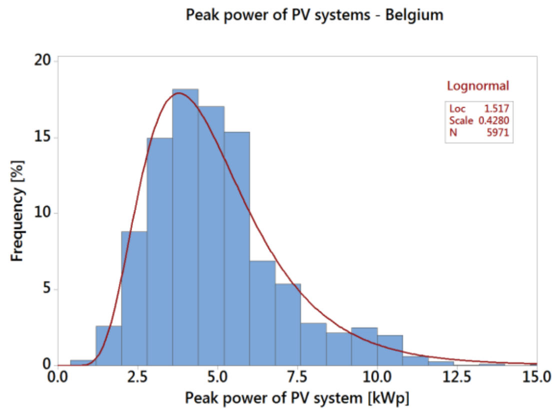

Figure 5: Frequency of the peak power of the PV systems in Belgium. The distribution of the peak power shows a wider dispersion, with most of the PV systems between 1 kWp and 10 kWp, and it roughly follows a lognormal law.

The monthly solar irradiation data have been provided by the solar irradiation data provider Synermet [11]. The monthly Global Horizontal Irradiation (GHI) data were acquired from CM SAF [12], and they have been translated into monthly Global Tilted Irradiation (GTI) data using a decomposition and translation model.

The information reported by the data providers is not always very accurate. We have observed these inaccuracies in the information on some key parameters such as the azimuth angle, the tilt angle, or the peak power. We have also observed inaccuracies and inconsistencies in the energy production data and in the solar irradiation data. This leads to some important uncertainties in our results, although we have tried to minimise their impact, by applying filtering procedures, and by using analyses methods that are robust against erroneous data and outliers. As an example, Figure 6 shows the tilt angle information for all the PV systems in our database as reported by the data providers. The systematic peaks around values that are multiples of 5º are an indicator that most of the data have been rounded. Moreover, many tilt angles were reported as 0º, but they do not appear on the figure, because they corresponded to PV system orientations reported as 0º in tilt and 0º in azimuth, which for some data providers is a convention used as default when they do not know that information. As very few PV generators are installed completely horizontally, we have removed all of these data. It would in any case be very bad practice to install the PV modules horizontally, because they would tend to accumulate soiling, and their energy yield would be greatly affected.

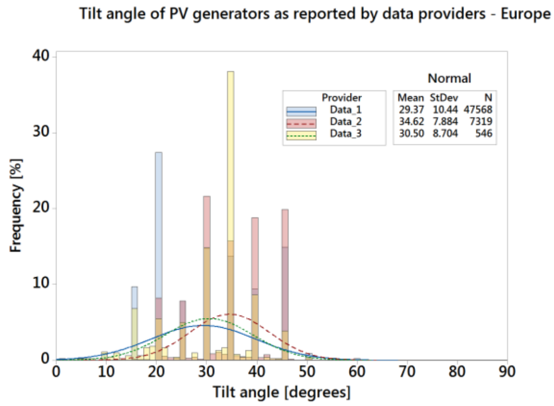

Figure 6: Tilt angle of all the PV systems in Europe as reported by the data providers. The systematic peaks around values that are multiples of 5º are an indicator that most of the data have been rounded.

We have filtered out all the monthly integrated PR data that were higher than 1.1, because these values are very unlikely, and they are the consequence of uncertainties on some of the input data. On the other hand, we chose not to be too restrictive in the filterings in order to avoid to skew our results by eliminating some points that would look like outsiders but are due to other causes that are physically sound. We have filtered out all the yearly integrated PR data every time that at least one of the months of this year for a given installation had been filtered out.

We have applied a simple statistical filtering on the yearly integrated PR. To do so, first we calculate the median of the whole population ($\mu_{1/2} = median(PR)$). We then calculate the Median Absolute Deviation (MAD) of the whole population, defined as: $MAD = median(|PR - \mu_{1/2}|)$ and filter out any yearly integrated PR value that is higher than $\mu_{1/2} + 3 \times (1.5 \times MAD)$ and lower than $\mu_{1/2} - 6 \times (1.5 \times MAD)$. The application of this method leads us to filter out all the PR values lower than 39.5% and higher than 95.5%.

We have analysed the annual energy yield of the PV systems, and we have calculated and represented its mean value and dispersion for all the PV systems in Europe and for four of the reference countries.

We have used the Performance Ratio (PR) to analyse the overall performance of the PV systems.

The PR is defined as:

$$PR = \frac{Y_f}{Y_r}$$

with final yield Y_f defined by E_{pv}/P^{STC} and the reference yield Y_r defined by GTI/G^{STC} where:
E_{pv} is the net electrical energy produced by the PV system during a given period of time, P^{STC} is the rated power of the PV generator under Standard Test Conditions (STC), G^{STC} is the global solar irradiance under STC (i.e. 1000 W/m2), and GTI is the Global Tilted Irradiation received by the PV generator.

We have analysed all the monthly integrated PR of all the PV systems, and for all the months for which the data were considered to be correct after filtering on a month-by-month basis.

We have analysed the yearly integrated PR of all the PV systems, and for all the years for which there were 12 consistent monthly data for the PV system.

We have used histograms and box plots to visualize the data, and we have used an Analysis of Variance (ANOVA) procedure to assess the statistical soundness of our results for the comparisons of the PV systems' performance as a function of several key parameters such as the inverter manufacturer, the PV module manufacturer, the PV module technology, the year of installation, or the country where it is located. This allows to test whether the differences observed between different populations are significant enough relative to the overall dispersion among the populations that is due to uncertainties and/or the other parameters. We have used multi-ANOVA procedures in order to analyze the effects of one parameter on performance, while normalizing as much as possible for the other relevant effects. For example, when analyzing whether there is a statistically significant relationship between a PV module manufacturer and the performance of the PV systems equipped with its PV modules, we have applied a multi-ANOVA to verify that the results obtained regarding the PV modules were not due to systematic associations between one PV module and one inverter, where one poorly performing inverter model or manufacturer could negatively influence the results for the PV modules associated with it.

3 RESULTS

3.1 Annual energy yield

Figure 7 shows the distribution of the annual energy yield for Belgium, France, Spain, and the UK. The distributions in Belgium and in the UK are very similar, with a mean annual energy yield around 900 kWh/kWp. This holds true in our database because a small proportion of the systems from the UK are located in the northern regions. The annual energy yield in France is around 1,100 kWh/kWp, with a wide distribution that largely reflects the difference in solar resource between the north and the south of the country. The mean annual energy yield in Spain appears to be around 1,900 kWh/kWp, but very few PV systems are encountered around that value, which corresponds to a valley between two peaks rather than to a peak. The explanation resides in the existence of two types of PV plants: static and trackers (See Figure 8). The mean annual energy yield for static PV plants is around 1450 kWh/kWp, and the corresponding value for PV plants with trackers is around 2,100 kWh/kWp. There is a wide variation in the annual energy yield in Spain which, as with France, is largely due to the difference in solar resource between the north and the south of the country, but in the case of the PV plants with trackers, these differences also reflect the diversity in the tracking mechanisms.

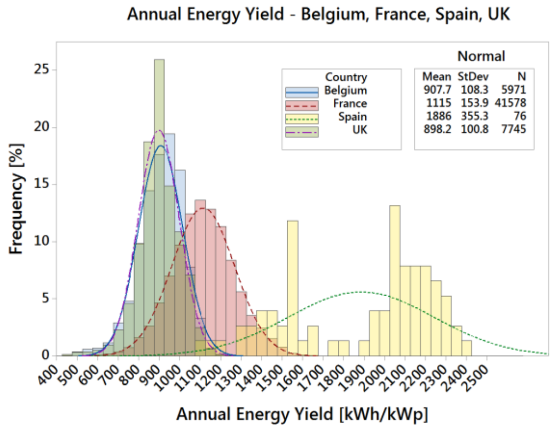

Figure 7: Distribution of the annual energy yield for Belgium, France, Spain, and the UK. The differences observed are mainly due to the differences in the solar resource available. In the case of the PV plants in Spain, this also reflects the differences between static structures and tracking mechanisms.

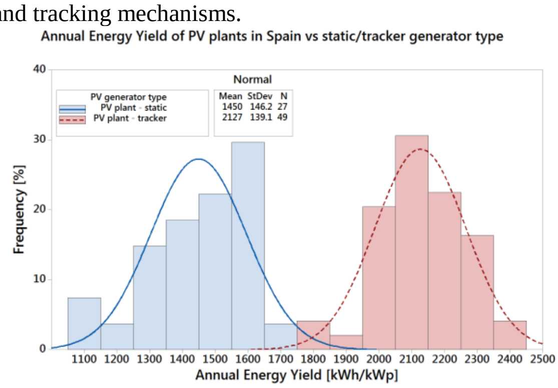

Figure 8: Distribution of the annual energy yield for PV plants in Spain. The differences are largely due to the difference in solar resource between the north and the south of the country, but in the case of the PV plants with trackers, these differences also reflect the diversity in tracking mechanisms.

Table II summarizes the mean annual energy yield for the 4 reference countries.

Table II: Mean annual energy yield data for the four reference countries.

Country	Mean yield (kWh/kW$_{p)}$
France	1115
UK	898
Belgium	908
Spain – PV plant – Static	1450
Spain – PV plant – Tracker	2127

3.2. Yearly integrated Performance Ratio

The yearly integrated PR has been calculated for all the PV systems, and for all the years for which data were available. Figure 9 shows the distribution of these yearly integrated PR. The distribution does not follow a normal (or gaussian) distribution, because an important fraction of the PV systems show an overall performance lower than average, and others are clearly subject to faults, which skews the distributions towards the low PR values. The distribution is better explained with a Weibull distribution, which often arises when the range of variation of a population is physically limited at one extremity, but not at the other. In the case of PV systems, it is very difficult to reach yearly integrated PR higher than 0.9, while it is much more likely that a PV system will have a PR much lower than average, because of performance problems.

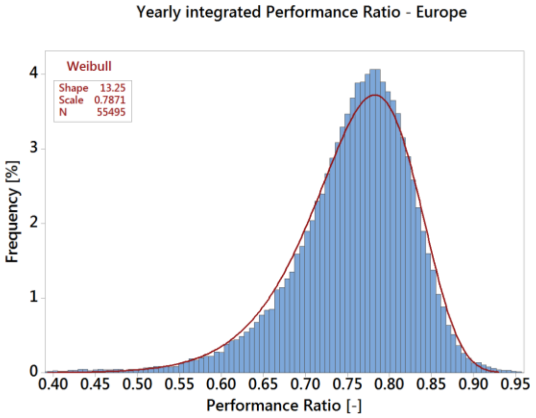

Figure 9: The distribution does not follow a normal (or gaussian) distribution, because it is skewed towards the low PR values. The distribution is better fit by a Weibull distribution.

We have tested the goodness of the Weibull distribution on our data. To do so we have carried out a probability plot, whose result is shown on Figure 10. The probability plot shows that the Weibull explains very well the PR distribution from PR values ranging from 0.6 to 0.9. This range of values represents the majority of the PV systems. On the contrary, the Weibull distribution does not explain the data for PR values lower than 0.6 and higher than 0.9, which is clearly visible from the probability plot, and also from the P-value and from the result of the Anderson-Darling (AD) test. For PR values that are lower than 0.6, there is a significant departure of the Weibull fit from the data, which shows that these data belong to a different population. These PV systems are subject to severe performance problems and to faults. On the other hand, the Weibull law does not explain the PR values that are higher than 0.9, which also suggests that these PV systems belong to a different population. It is very likely that these PR values are simply not real, and that they are caused by uncertainties on solar irradiation data, as well as on the azimuth and tilt angles and the peak power of the PV systems. This probability plot allows us to suggest that the yearly integrated PR values ranging from 0.6 to 0.9 are representative of the state-of-the-art for PV systems in Europe. We suggest to take the scale (or peak or most frequent value) of the Weibull distribution as the typical value that represents the whole population. The shape of the Weibull fit to the data of all the PV systems from Europe is around 0.79, and we therefore suggest that this value is representative of the typical PV system in Europe installed over the last few years. Given the shape (the asymmetry) of this Weibull distribution, the mean value of the PR is some 3% lower than the most frequent value.

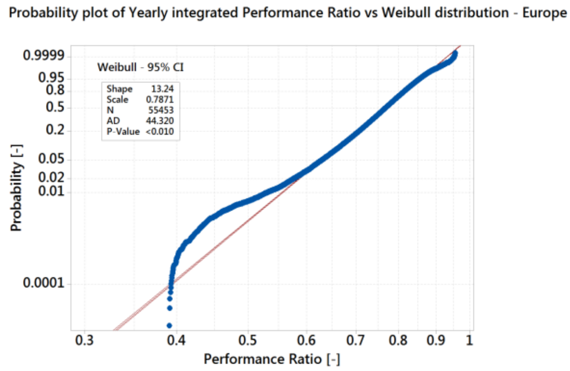

Figure 10: Probability plot of the yearly integrated PR against a fit on the data using a Weibull law. The probability plot shows that the Weibull law explains very well the PR distribution from PR values ranging from 0.6 to 0.9. This range of values represents the majority of the PV systems, and could represent the start of the art of the PV systems installed in Europe over the last few years.

Figure 11 represents the distribution of the yearly PR for the three reference countries whose installations are predominantly rooftop-mounted: France, UK, and Belgium. We take the typical (peak) values for yearly PR are 0.81 in the UK, 0.80 in Belgium, and 0.78 in France.

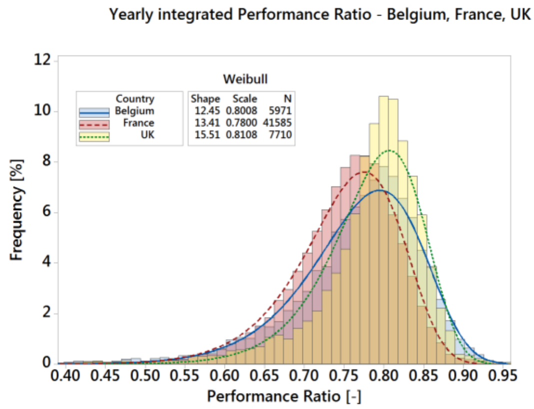

Figure 11: Distribution of the yearly PR for the three reference countries whose typology corresponds to rooftop installations: France, UK, and Belgium. The typical (peak) values for yearly PR are 0.81 in the UK, 0.80 in Belgium, and 0.78 in France.

Figure 12 shows the distribution of the yearly integrated PR for PV plants in Spain (both with static structures and trackers). The typical value of PR is 0.81. PV systems in Spain are more affected by thermal losses in the PV cells than the PV systems in the other countries of Europe. Notwithstanding, the PR obtained for the PV plants in Spain is still high when compared to the other countries in Europe. This high value for the PV plants in Spain relatively to the other countries reflects the higher efficiencies of larger PV installations, that take benefit from scale effects.

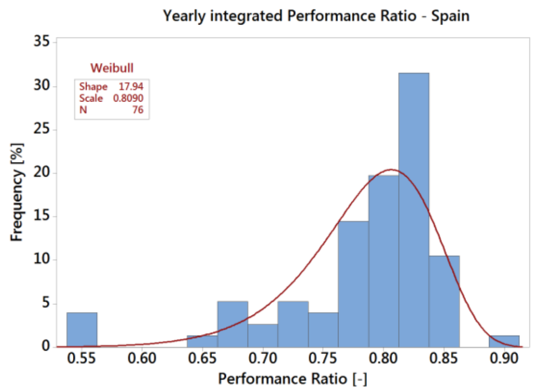

Figure 12: Distribution of the yearly PR for PV plants in Spain. The typical value is 0.81.

Figure 13 shows the comparison of the yearly integrated PR of the 4 reference countries on a boxplot. The middle line of the boxes represents the median, or the 50th percentile of the distribution. The bottom line represents the 25th percentile, whilst the upper line represents the 75th percentile. The whiskers indicate the dispersion among the rest of the population, excluding outliers. The PV plants in Spain and the rooftop installations in the UK appear to have the higher median value, followed by Belgium, and then France. The PR in France is some 3% lower than in the UK, and 2% lower than in Belgium.

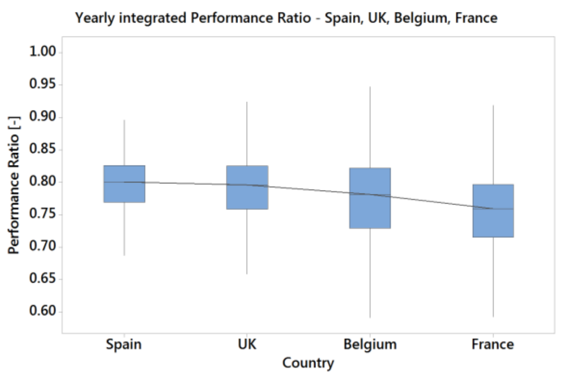

Figure 13: Comparison of the yearly integrated PR of the 4 reference countries using boxplots. The PV plants in Spain and the rooftop installations in the UK appear to have the highest median value, followed by Belgium, and then France. The PR in France is some 3% lower than in the UK, and 2% lower than in Belgium.

Table III summarizes the result of the yearly PR calculations for the 4 reference countries.

Table III: Yearly PR for the four reference countries.

Country	Mean PR [-]	Typical [-]
France - Rooftop	0.75	0.78
UK - Rooftop	0.78	0.81
Belgium - Rooftop	0.77	0.80
Spain - PV plant	0.78	0.81

3.3. Influence of the peak power on performance

Figure 14 shows the relationship between the yearly integrated PR and the peak power of the PV system. We observe an increase in performance along with the increase in the peak power of the PV system. This is in particular true for PV systems whose peak power is lower than 4 kWp. This is mostly explained by the increasing yield of the inverter as a function of their nominal power, but in some cases, in particular for large PV installations, the higher performance also arises from more demanding quality controls. This advocates for more quality control procedures in small rooftop installations. This also suggests that when the policymaker decides to shape the PV landscape towards small systems, such as it was the case in France with systems limited to 3 kWp, this is done at the price of lower PV system performance. An ANOVA allowed us to confirm that the trend observed is independent of external factors.

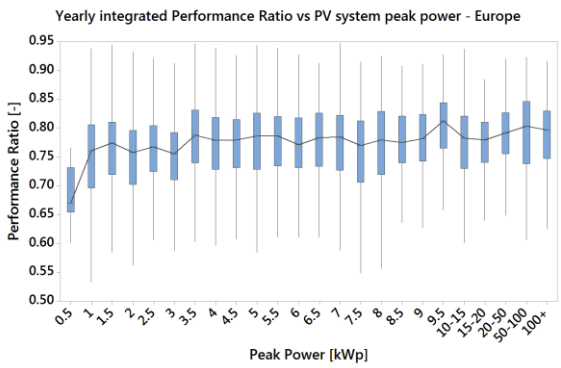

Figure 14: Relationship between the yearly integrated PR and the peak power of the PV system. We observe an increase in performance along with the increase in the peak power of the PV system. This is in particular true for PV systems whose peak power is lower than 4 kWp.

3.4. Influence of the inverter on performance

We have attempted to assess whether there was a significant difference in performance between PV systems equipped with inverters produced by different manufacturers. To do so, we have grouped the PV systems by inverter manufacturer, and we have calculated the yearly integrated PR for each one of these sub-groups. Figure 15 presents the result of this exercise, for the inverters that equip at least 100 PV systems in our database.

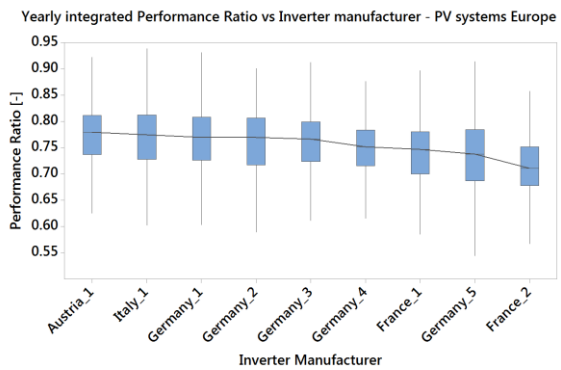

Figure 15: Boxplot representing the yearly PR of the inverters present on at least 100 PV systems in our database. We observe that there is a difference in the median value of PR of some 5% between the best performer and the worst performer.

We observe that there is a difference in the median value of PR of some 5% between the best performer and the worst performer. This seems to be partly in line with the datasheets of the inverter manufacturers, some of which deliver higher energy yields than others, but it also suggests that under real conditions, the real performance of some inverters depart more from their nominal performance than others. An ANOVA allowed to confirm that the differences observed between the best and the worst inverter manufacturers had enough statistical power.

3.5. Influence of the PV module on performance

We have also attempted to assess whether there was a significant difference in performance between PV systems equipped with PV modules produced by different manufacturers (except for the thin-film technologies, that are dealt with later on). Figure 16 presents the result of this exercise, for the PV modules that equip at least 100 PV systems in our database. The names of the manufacturers have been masked under a hidden code. The country of the manufacturers corresponds to the headquarters of the company, and not necessarily to the location of the manufacturing, which in some cases may be different. We observe that there is a difference in the median value of PR of some 6% between the best performer and the worst performer. This seems to be partly in line with the datasheets of the PV module manufacturers, most of which have a nominal power tolerance of +- 3%. Therefore, these differences could arise if some manufacturers sell their PV modules with a tolerance that is very close to + 3%, while some others sell with tolerances very close to - 3%. An ANOVA allowed to confirm that the differences observed between the best and the worst PV module manufacturers had enough statistical power. From the figure, we can also observe that there is no clear correlation between the geographical origin of a PV module manufacturer and the quality of the PV module.

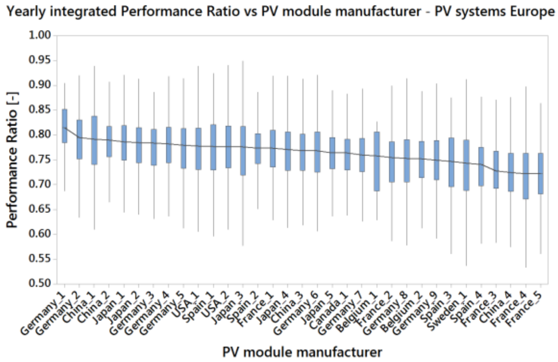

Figure 16: Boxplot representing the yearly PR for the PV modules that equip at least 100 PV systems in our database (excluding thin-film technologies). We observe that there is a difference in the median value of PR of some 6% between the best performer and the worst performer.

We have also attempted to study the impact of the PV cell/module technology on the performance of the PV systems. The results are shown on Figure 17. The classic and most common crystalline silicon technology, marked as xSi, can serve as a reference to assess the performance of the other technologies relatively to it. We observe that two technologies perform slightly better than the xSi technology. These technologies are the Heterojunction with Intrinsic Thin layer (HIT), and the back-contact silicon (bcSi). Other technologies show performances that are lower than the ones of the xSi. Immediately after the xSi technology comes the Saturn silicon (xSi-Sat). Then comes the Cadmium Telluride (CdTe). The dispersion of its performance appears to be higher, but this is mostly because the information that we possess on this technology comes from PV plants in Spain rather than in rooftops in Europe. The sample therefore appears as composed of less elements in the statistical analysis, although the total peak power represents around 30 MW. Furthermore, the dispersion mostly arises from one single PV plant that has been subject to severe performance problems for several years, related with the PV modules themselves (this PV plant appears at the lowest PR in Figure 12, with a value of 0.55). Nevertheless, as it can be observed, the median value of the entire technology is not much lower than for the xSi-Sat technology, and it is probably more representative of the newer modules made using this technology. Then comes the Upgraded Metallurgical Grade Silicon (UMGSi). The last two boxplots are for thin-film technologies and show a performance that is considerably lower than the rest of the technologies. The second poorest performer is the amorphous silicon (aSi). The worst performer is the Copper Indium Selenide (CIS) and the Copper Indium Gallium (di)selenide (CIGS). Nevertheless, in this last case, the information that we had at our disposal only came from two PV module manufacturers, and both have now ceased their activities in PV, so our result should not be taken as representative of the latest CIS/CIGS technologies. An ANOVA allowed to confirm that the differences observed as a function of the PV module technology had enough statistical power.

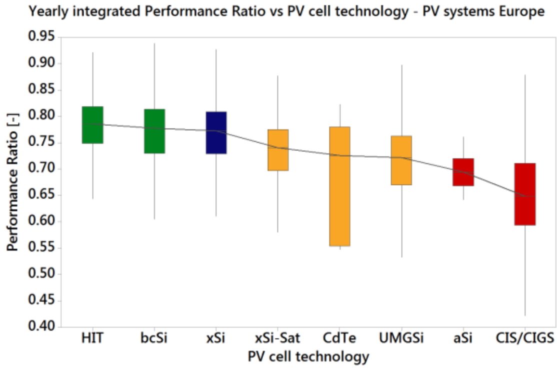

Figure 17: Boxplot representing the yearly PR as a function of the PV cell/module technology. HIT = Intrinsic Thin layer; bcSi = back-contact silicon; xSi = classic crystalline silicon; xSi-Sat = Saturn silicon; CdTe = Cadmium Telluride. UMGSi = Upgraded Metallurgical Grade Silicon; aSi = amorphous silicon; CIS/CIGS = Copper Indium Selenide (CIS)/Copper Indium Gallium (di)selenide (CIGS).

3.6. Evolution of the state of the art

We have investigated whether it was possible to observe any improvement in the state of the art of PV systems over time that would directly translate into an increase in overall performance. To do so, we have grouped the PV systems as a function of their year of installation. We have compared the yearly integrated PR of these groups during 2013 as a reference year. The result is shown on Figure 18, where we observe a remarkable increase in systems' performance over time, with an increase in yearly PR around 3 to 4% over the last seven years, which represents an increase of about 0.5% per year. For this result, we can also suggest that the state of the art of PV systems in Europe installed today is probably some 2% higher than the mean results that we have obtained with our data ranging from 2007 to 2014. Therefore, because the typical yearly PR for that period was assessed to be around 0.79, we can probably assert that the state of the art for PV systems installed in 2015 corresponds to a typical yearly PR around 0.81.

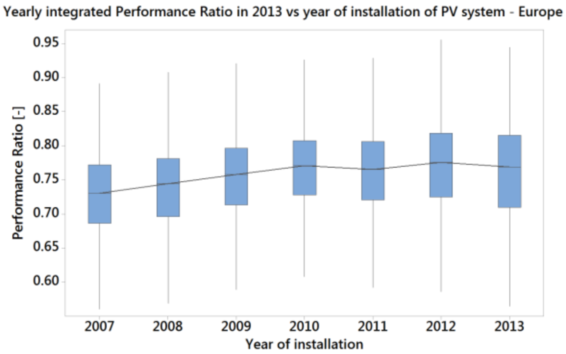

Figure 18: Yearly PR in 2013 for all the PV systems, grouped as a function of their year of installation. We observe an increase in systems' performance over time, with an increase in yearly PR around 3-4% over the last seven years, which represents an increase of about 0.5% per year.

3.7. Degradation of PV system performance

We have attempted to assess whether it is possible to observe any relevant degradation of the PV systems' degradation over time. We have done so by analysing the yearly integrated PR of all the PV systems installed in the year 2008, as a function of the year of production from 2009 to 2014. We chose the systems installed in 2008 because it is the first year for which we have at least 1000 PV systems with yearly energy production data that that have passed the filterings. The result is shown on Figure 19, where we can observe that the degradation in PV systems' performance over the last six years ranges from unnoticeable to very low. The decrease in performance from 2009 to 2014 appears to be around 1.5%. Nevertheless, an ANOVA that was carried out on these results showed that it was not possible to conclude with a high statistical power that this observed decrease was not merely the effects of the uncertainty, or reversely that the mean degradation is accurate. Therefore we have not been able to quantify the degradation.

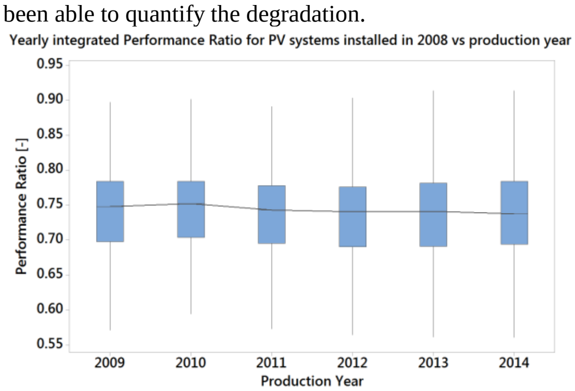

Figure 19: Yearly integrated PR of all the PV systems installed in the year 2008, as a function of the year of production from 2009 to 2014. We can observe that the degradation in PV systems' performance over the last six years ranges is very low, and we have not been able to quantify it.

4 DISCUSSION

Apart from our analyses carried out on yearly integrated data, whose objective was to reach a global understanding of the performance of the PV systems in Europe, we have analysed the distribution of the monthly integrated PR for all the PV systems in Europe to investigate whether other complementary observations could be obtained from them. The result is shown on Figure 20. The dispersion in the monthly integrated PR is much higher than that observed for the yearly integrated PR for several reasons. Firstly the uncertainty on PR is higher during the winter months, which is made more explicit when monthly data are analysed independently. Secondly, any performance problems that span one month or less are much more visible on the monthly data than on the yearly data. This dispersion is therefore a strong indicator of the presence of performance problems or faults on some of the PV systems. More evidence of short-lived faults appears when we move towards higher temporal resolutions e.g. hourly data. The description of these kinds of performance problems and faults are out of the scope of this work, but the evidence of their presence suggest that they should be studied more carefully in future works.

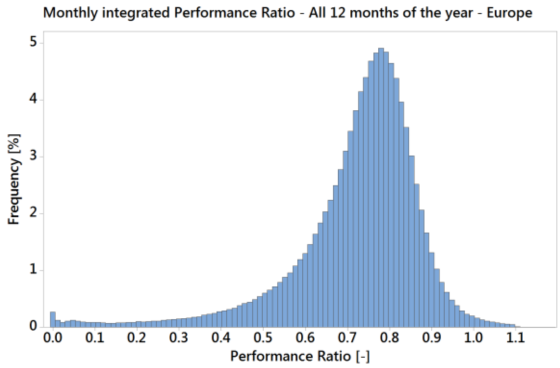

Figure 20: Dispersion in the monthly integrated PR. It is much higher than the one observed for the yearly integrated PR.

Even though we have analysed more than 30,000 PV systems in Europe, these were mostly located in four countries. We have analysed many PV module and inverter manufacturers and technologies, but not all of them. Furthermore, new technologies have recently appeared in the market, and it would be interesting to analyse them in order to update our results. The uncertainties around many of our analyses are important, and we further development may enable us to reduce them in order to obtain more accurate and more in-depth conclusions. We still have many gaps to cover to achieve a comprehensive understanding of the state-of-the-art of PV systems in Europe. With this in mind, we welcome any future collaboration that might improve our outlook, whether by completing our database with other countries and technologies, or by comparing methods and results. By definition, a review of the state-of-the-art of PV systems requires regular iterations in order to continue to incorporate the latest advances.

5 CONCLUSION

We have analysed the data from more than 31,000 PV installations in Europe. The mean Energy Yield of the PV systems located in each of the four reference countries is 1115 kWh/kW_p for France, 898 kWh/kW_p for the UK, 908 kWh/kW_p for Belgium, 1450 kWh/kW_p for the PV plants in Spain mounted on a static structure, and 2127 kWh/kW_p for those mounted on a solar tracker in Spain.

We have shown that the distribution of the yearly integrated PR can be modeled well using a Weibull distribution for PR values ranging from 0.6 to 0.9. This range of values represents the majority of the PV systems, and we suggest that they are representative of the state-of-the-art for PV systems in Europe. We suggest that the typical PR value for the PV systems installed in Europe over the last few years is 0.79, and that the value for the PV systems installed in 2015 is 0.81. The corresponding mean values are respectively 0.76 and 0.78.

We have observed that the performance of the PV systems tends to increase when the peak power of the PV systems increases, in particular for PV systems whose peak power is lower than 4 kW_p.

We have grouped the PV systems as by inverter manufacturer and we found significant performance differences, up to 5%, between the best performer and the worst.

Similarly, we have grouped the PV systems as a function of the PV module manufacturer, and have found significant performance differences, up to 6%, between the best performer and the worst.

We have found significant differences in performance as a function of the PV module/cell technology.

We have found an increase in performance in the yearly integrated PR around 3 to 4% over the last seven years, which represents an increase of about 0.5% per year.

We have qualitatively observed some performance degradation of the PV systems over the last few years but we were not able to reliably quantify it without further investigation.

We still have many gaps to cover to reach a comprehensive and accurate understanding of the state-of-the-art of PV systems in Europe. We therefore welcome any future collaboration towards this goal.

ACKNOWLEDGMENTS

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