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# Review of the performance of residential PV systems in Belgium

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ABSTRACT

The main objective of this paper is to review the state of the art of residential PV systems in Belgium by the analysis of the operational data of 993 installations. For that, 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? This work brings answers to these questions. A middling commercial PV system, optimally oriented, produces a mean annual energy of 892 kWh/kW$_p$. As a whole, the orientation of PV generators causes energy productions to be some 6% inferior to optimally oriented PV systems. The mean performance ratio is 78% and the mean performance index is 85%. That is to say, the energy produced by a typical PV system in Belgium is 15% inferior to the energy produced by a very high quality PV system. Finally, on average, the real power of the PV modules falls 5% below its corresponding nominal power announced on the manufacturer's datasheet. Differences between real and nominal power of up to 16% have been detected.



**Contents**



## 1. Introduction

The main objective of this paper is to review the state of the art of residential PV systems in Belgium by the analysis of the operational data of a representative sample of 993 installations, totalizing a peak power of approximately 4 MW (5% of the total power in French speaking part of Belgium [1]), and installed between 2007 and 2010. The paper focuses the analysis on the following three questions:

a) How much electricity do PV systems produce in terms of kWh per installed kWp.
b) How good is this electrical production? The PV systems quality is analyzed using different performance indicators such as the performance ratio (PR), the performance ratio at STC conditions (PR$_{STC}$) and the performance index (PI).
c) Which are the key aspects that influence the quality of PV systems? Statistical tools are applied to find them out.

For the first question, we have used the monthly energy production data supplied by the PV systems' owners through two Websites [2,3]. Although Belgium is composed of three regions, the data come from Wallonia and Brussels and not from Flanders, due to

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availability reasons. Nevertheless, the data is still representative of the state of the art, since typologies are very similar. Flanders has developed towards both residential PV and solar plants. 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 [4,5]. The PV power connected to the grid consequently jumped from 200 kW in 2007 to 50 MW at the end of 2009 [1]. That power is distributed among more than 10,000 PV installations [6].

For the second question, the quality is evaluated using the aforementioned performance indicators, all of them consisting on comparing the actual production of each of the systems with the simulated electrical production of a hypothetical corresponding system used as a reference.

For the third question, we have investigated the main causes of the quality differences that are observed by applying an Analysis-of-Variance (ANOVA) to the PI. 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 paper allow extracting conclusions about the expected energy production of PV residential systems, about the energy production losses due their orientation and about the state of the art and the quality of residential PV systems. The important quantity of PV systems analyzed makes it possible to extend the results not only to the Belgian market, but also to the European one and, hence, they are of general interest. In fact, the conclusions 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 [7–10], and can be useful for important works that are presently ongoing [11] and whose main purpose is the assessment of the performance and reliability of PV systems.

## 2. Belgian residential PV market

In Wallonia, there is a fairly stable relation between installed PV power per province, the number of habitants and the net annual income per habitant. However, the Region of Brussels-Capital, with a population nearly equivalent to one third of the Walloon population, owns only 6% of the PV power installed among the two regions. Urbanization style very likely explains this marked difference. In Wallonia, an important proportion of the population lives in a house that offers the surface necessary to install 1–5 $kW_p$ of PV modules, while in Brussels-Capital people generally live in urban buildings with no individual roof where to install solar panels.

Fig. 1 shows that residential PV systems of less than 10 kW account for 98% of the total installed PV power. The power of nearly three fourths or the PV systems is comprised between 3 and 5 kW [6]. 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 total market shares [6]. The rest of the market is distributed, by order of importance, among copper indium (di)selenide (CIS) (3%), heterojunction with intrinsic thin layer (HIT) (3%), and amorphous silicon (aSi) (1%).

The database presents the number of PV market actors as follows: 85 PV modules manufacturers, 25 inverters manufacturers and 210 PV systems installers. Fig. 2 shows their relative market share. The relative market penetration within each of those three categories of actors 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 by one inverter manufacturer alone of more than 50% of the market (the point corresponding to that inverter manufacturer is not represented in Fig. 3 because it is out of scale, but is taken into account in the power-law equation).

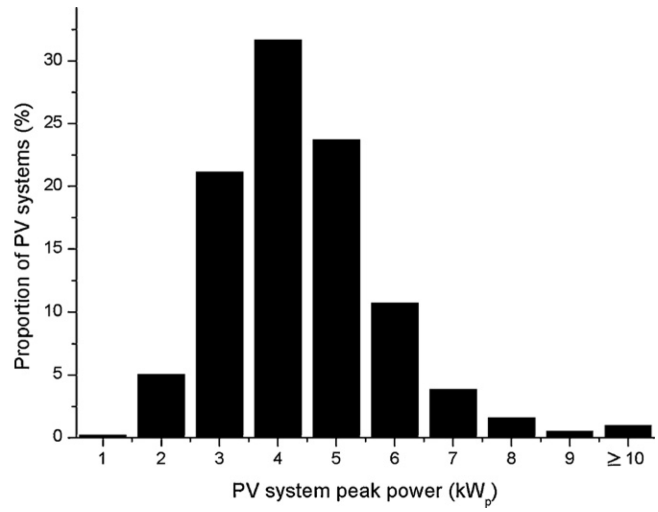



**Fig. 1.** Histogram of the peak power of PV systems. Powers lower than 10 $kW_p$ account for 98% of the total installed power. The power of nearly three fourths or the PV systems is comprised between 3 and 5 $kW_p$.

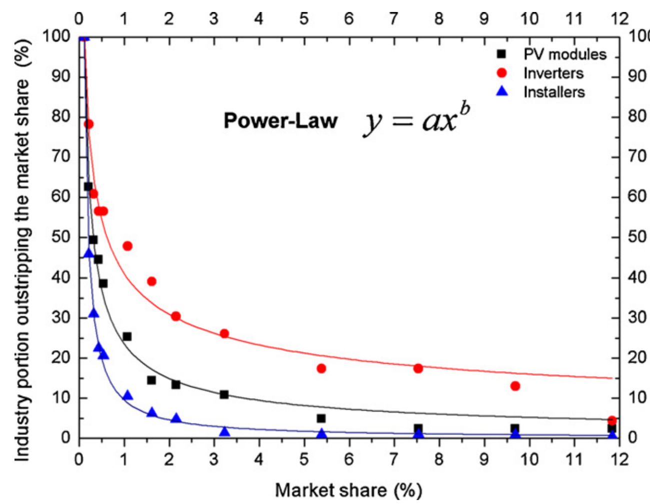



**Fig. 2.** Relative portion of the PV industry outstripping a given market share. The industry is presented through the manufacturers of PV modules and inverters, and the installers. The relative market penetration within each indicator is satisfactorily modeled by a power-law. The *R*-squares of the fits yield 99.8% for the installers, 99.1% for the PV modules, and 96.9% for the inverters.

## 3. Performance analysis methodology

### 3.1. Energy production

As mentioned before, 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

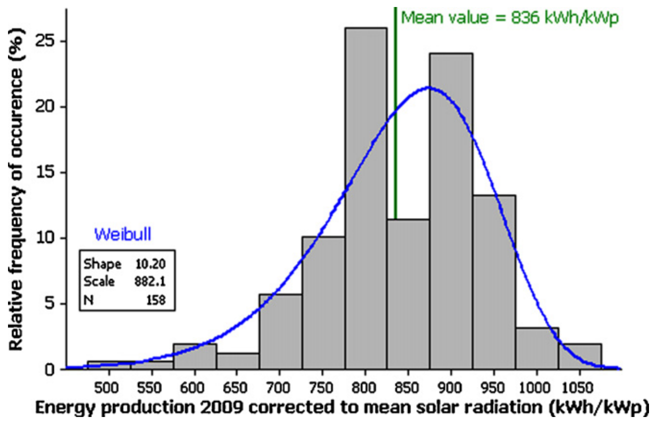



**Fig. 3.** Histogram of the production of the PV systems in 2009, corrected to mean solar radiation on the last decade.

equip the systems, and the installers. The net energy production is reported on a monthly basis, and is read at the inverter (95% of the data base), or at the meter (20%), or at both sources (15%). The PV owners also communicated the annual energy that they expected to produce, which was generally estimated by the installer. Not all the PV owners reported the energy production corresponding to each month, and only 35% 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. The ratio $E_{inverter}/E_{meter}$ shows a typical standard deviation of 3–4%, and a range of mean value of 1–1.07, depending on the inverter manufacturer. The ratios superior to 1 indicate that the inverters systematically overestimate the energy produced, up to 7% for some inverter manufacturers. In the present study, the data provided by the inverter is adjusted by comparison with the data provided by the energy meter.

### 3.2. Technical quality

The energy production of the reference PV system that is required for the calculation of the performance indicators is simulated with a tool developed at IES-UPM and based on widely accepted models, whose details have been described elsewhere [12–19]. 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 [20] and PVGIS [21] respectively. The solar radiation received on the surface of each of the PV generators is estimated using widely accepted solar radiation models [22–24].

The energy performance indicators that are used to qualify 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. Table 1 describes three different possibilities.

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. 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

**Table 1**
The quality of a PV system for producing energy can be described through three different performance indicators: PR, $PR_{STC}$ or PI.

| Indicator | Definition | Reference system |
|---|---|---|
| Performance ratio | $PR = \frac{E_{produced}}{(P_{STC}/G_{STC})\int Gdt}$ | Free of any kind of system losses and whose solar cells are always kept at 25 °C |
| STC performance ratio | $PR_{STC} = \frac{E_{produced}}{(P_{STC}/G_{STC})\int G(1-\Delta P_{STC})dt}$ | Free of any kind of system losses and whose solar cells operate at the same temperature than the ones of the system to be compared with |
| Performance index | $PI = \frac{E_{produced}}{(P_{STC}/G_{STC})\int G(1-\Delta P_{STC})(1-\Delta P_{DC/AC})dt}$ | High quality PV system. Almost free of system losses, except mainly the DC/AC losses corresponding to a good inverter and considered somewhat unavoidable |

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. $PR_{STC}$ takes away such thermal losses, which requires to consider (measure or estimate) the temperature of operation of the solar cells. 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, a further step can still be done by taking away 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 [25]. 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. Because of that, this paper pays particular attention to the analysis of PI values. Table 2 summarizes step by step the methodology used to calculate the performance indexes.

### 3.3. Statistical analysis on the parameters affecting energy performance

To investigate furthermore the main causes of the quality differences among the PV systems, they have been compared by grouping them by common properties. The statistical tool 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 first realized according to four criteria: PV modules manufacturer, inverters manufacturer, installer, and PV system peak-power.

**Table 2**
General methodology used for the assessment of the performance of residential PV systems.

| |
|---|
| **I. Data collection at each location** |
| -Monthly global horizontal radiation [20] |
| -Monthly $T_{\max}$ and $T_{\min}$ [21] |
| -PV systems monthly real energy production [2,3] |
| -PV systems main characteristics: PV generator peak power, surface, tilt and orientation, PV modules and inverters models, installer, general comments about the system [2,3] |
| **II. Solar radiation on PV generators** |
| -Clearness indexes for global and diffuse radiation [20] |
| -Daily global, direct and diffuse radiation [21] |
| -Anisotropic decomposition model for diffuse radiation [22] |
| -Global radiation on PV generator surface [2,3] |
| **III. Calculation of performance ratio (PR)** |
| -Rated power under STC [2,3] |
| -IV curve under outdoor conditions [13] |
| -PR = ratio (real energy production/energy production without system losses) |
| **IV. Calculation of performance index (PI)** |
| -Losses due to cell temperature [14] |
| -Spectral losses [15,16] |
| -Inverter electrical model [17] |
| -PI = ratio (real energy production/energy production for reference system) |

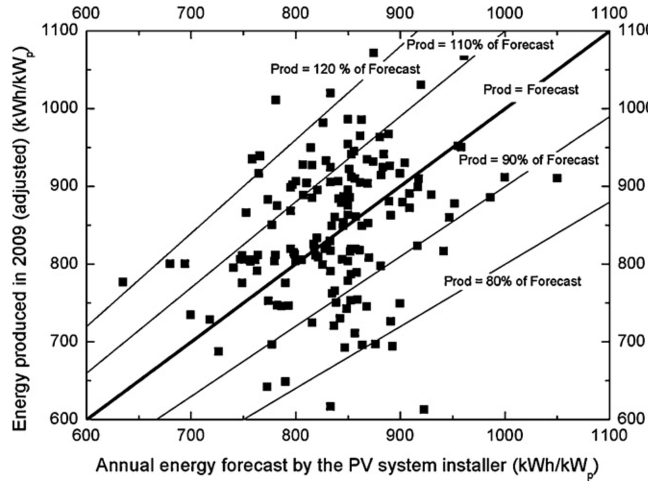



**Fig. 4.** Regression analysis between the energy produced in 2009 by the PV systems and the corresponding production expected by the PV system owner. No significant correlation is visible.

## 4. Results

### 4.1. Energy production

The energy production analysis is carried out for the year 2009 and for the 158 PV systems from which the monthly production was reported for the 12 months of the year. On average, the PV systems produced in 2009 a net annual energy of 902 kWh/kW$_p$.

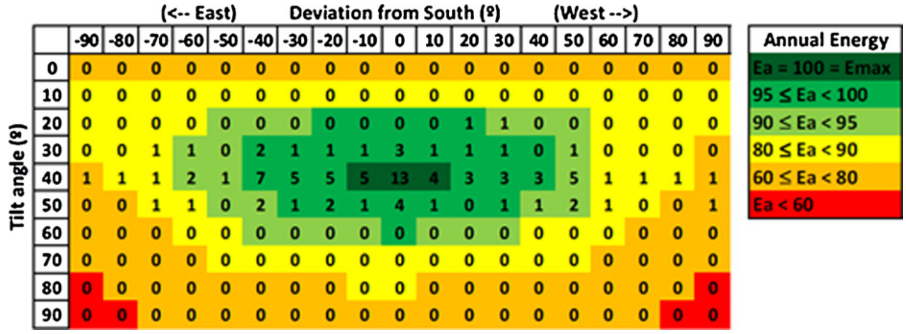
In order to compare this production with other previous studies in the literature, we have adjusted the production in 2009 by the ratio of the solar radiation received in 2009 and the mean solar radiation of the last decade according to SoDa database, resulting in a value of 836 kWh/kW$_p$. Fig. 3 shows a histogram of the corrected productions. 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 [7].

Fig. 4 shows a linear regression between the annual energy production expected by the PV system owner (generally estimated by the installer, on the basis of the mean solar radiation corresponding the last decade) and the energy really produced during the year 2009 (adjusted to the mean solar radiation for the last decade as explained previously). Somewhat surprisingly, the linear regression shows no significant correlation between forecast and real production. The ratio $E_{\mathrm{Forecast}}/E_{\mathrm{Produced}}$ has a mean value of approximately 0.99, very close to 1, which indicates that the energy production is not overestimated taken as a whole. Nevertheless, the standard deviation of that ratio is close to 14%, which indicates that the installers generally do not estimate the energy production accurately.

### 4.2. Tilt and orientation energy losses

The vast majority of PV generators have a tilt angle between 20° and 50°, which generally corresponds to the configuration of the roofs on which they are mounted. At latitudes close to 50° North, a PV generator maximizes its annual energy produced when it faces South and benefits from a tilt angle around 40°. This would be the optimal orientation. When the orientation is different, which is usual in residential PV, the energy produced diminishes by an amount that is shown in Fig. 5. The 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 10° have been reported to keep hold of important quantities of dust [18]), but Fig. 5 shows that it is not frequent to find those low tilt values.

Fig. 6 shows the relation between the energy losses due to orientation and the proportion of PV systems installed. It is satisfactorily described by a power-law. Almost 70% of the PV systems lose less than 5% of their annual energy due to orientation, and less than one fifth lose more than 10%. As a whole, the orientation of residential PV causes energy productions to be 6% inferior to optimally oriented PV systems, which can be interpreted as the price to pay, in terms of energy losses, for installing PV systems on roofs instead of installing PV farms.


(<-- 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 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | 0 | 0 | 1 | 1 | 0 | 2 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 40 | 1 | 1 | 1 | 2 | 1 | 7 | 5 | 5 | 5 | 13 | 4 | 3 | 3 | 3 | 5 | 1 | 1 | 1 | 1 |
| 50 | 0 | 0 | 1 | 1 | 0 | 2 | 1 | 2 | 1 | 4 | 1 | 0 | 1 | 1 | 2 | 1 | 0 | 0 | 1 |
| 60 | 0 | 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 |
| 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 |

| Annual Energy |
|---|
| Ea = 100 = Emax |
| 95 ≤ Ea < 100 |
| 90 ≤ Ea < 95 |
| 80 ≤ Ea < 90 |
| 60 ≤ Ea < 80 |
| Ea < 60 |

**Fig. 5.** Relative distribution, in percent, of the number of PV systems installed, in function of the orientation and tilt, together with the corresponding net annual energy produced by a PV system in Belgium respect to the optimal inclination, in percent.

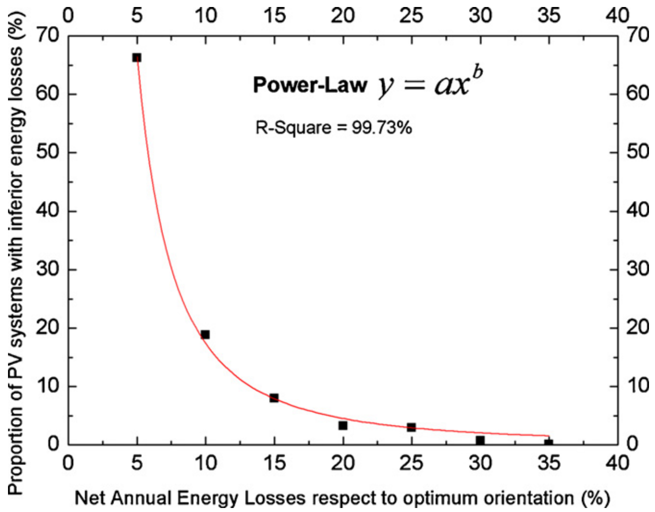



**Fig. 6.** Proportion of PV systems (in percent) oriented so that they lose less than a given percentage of net annual energy respect to the optimum orientation. Almost 70% of the PV systems lose less than 5% of annual energy due to their orientation, and less than one fifth lose more than 10%.

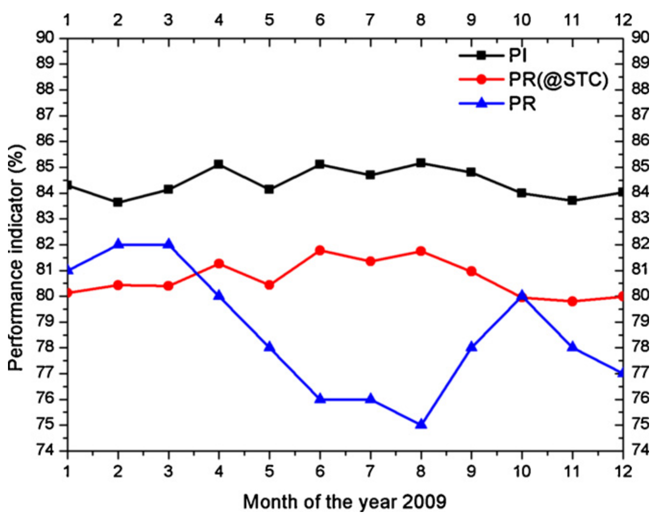



**Fig. 7.** Evolution of PI, $PR_{STC}$ and PR for a PV system during the year 2009.

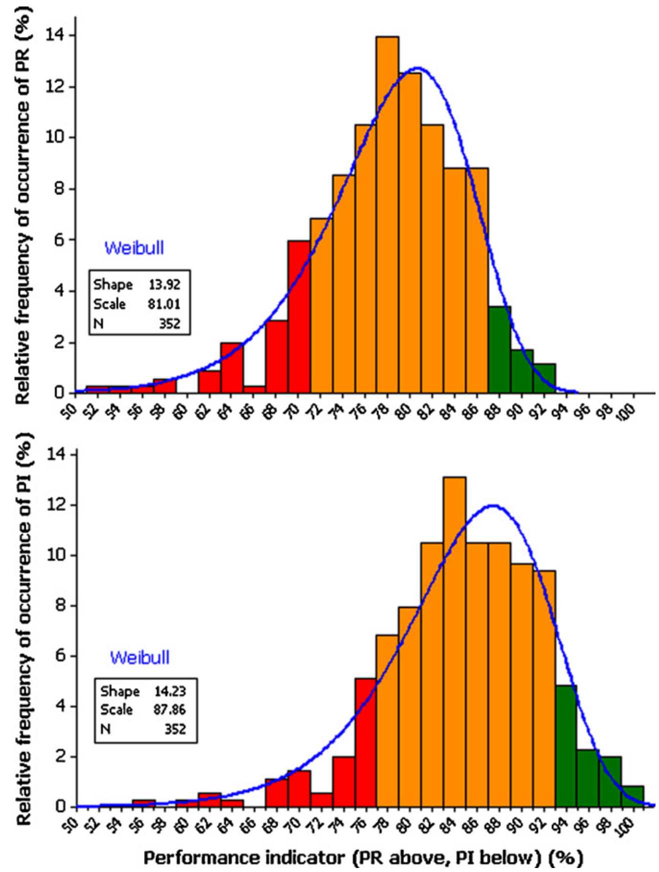



**Fig. 8.** Histogram of the performance ratio (above) and performance index (below) of the PV systems analyzed. The distribution is nearly normal between a PI value of 70% and 100%. The distribution is left skewed. The skewness is modeled through a Weibull distribution. The histogram of the performance ratio is very similar to the PI histogram because almost all the PV systems analyzed are subject to similar installation and climatic conditions.

### 4.3. Technical quality

Fig. 7 shows the evolution during the year 2009 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 85%, whose $PR_{STC}$ is 80.5% and whose PR is 78%. 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.

Fig. 8 presents the histogram of PR and PI yearly values of 352 PV systems that provided at least 12 monthly produced energy data between January 2009 and August 2010. The mean value of PI is slightly under 85%, which indicates that, on average, the PV systems are producing an annual energy that is 15% inferior to the reference system. Therefore, a PV system optimally oriented, located at Namur, and receiving the mean annual global horizontal solar radiation indicated by SODA for this location, 975 kWh/m$^2$, would produce nearly 892 kWh/kW$_p$. This is the value that seems the most representative of the state of the art.

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 modeled through a Weibull distribution. Further probability assessment plots of the PI have demonstrated that, at a confidence level of 95%, the distribution can be approximated by a Weibull (Anderson-Darling goodness of fit = 0.823) or normal (Anderson-Darling goodness of fit = 1.224) distribution. The Weibull fits better for extreme values, while the normal fits better for the central values.

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 with the more widely spread concept of PR, Fig. 8 shows its corresponding histogram. The mean value of PR is 78%. As a comparison, values of PR between 48% and 93% have been reported in other works [26,27].

Both histograms show relative distributions that are very similar in the present case, because almost all the PV systems analyzed are subject to similar installation and climatic conditions.

In order to look for the causes that explain the PI differences among the different PV residential systems, we have applied an ANOVA to our database. It did not allow associating significant variations of PI to the nominal power of the installations, the inverters manufacturers or the installers. This failure to identify significant trends does not imply the absence of differences, but simply suggests that the PI differences cannot be statistically attributed to any of these parameters.

**Table 3**
ANOVA on PV modules present at least on 10 PV installations. *N* indicates the number of installations. The ANOVA analysis on PV modules shows significance differences between the mean power of several groups of PV modules.

| PV modules | *N* | Mean of PI (%) | StDev of PI (%) |
|---|---|---|---|
| bcSi | 31 | 85.9 | 6.2 |
| CIS | 16 | 73.6 | 6.6 |
| HIT | 29 | 86.8 | 5.1 |
| xSi1 | 26 | 87.8 | 6.6 |
| xSi2 | 19 | 88.9 | 5.8 |
| xSi3 | 11 | 88.9 | 5.6 |
| xSi4 | 26 | 85.8 | 6.4 |
| xSi5 | 58 | 83.8 | 6.2 |
| xSi6 | 17 | 81.2 | 4.2 |
| xSi7 | 10 | 84.6 | 5.7 |

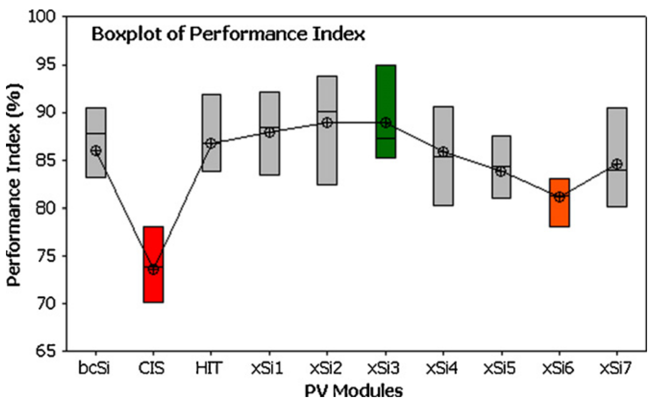



**Fig. 9.** Boxplot of performance index for PV modules present at least on 10 PV installations. The boxes show the first, second and third quartiles, represented respectively by the lower, medium and upper horizontal lines. The second quartile is also the median.

The ANOVA did however allow to establish strong evidence that the PV modules explain the majority of the dispersion of PI ($F = 9.94$ and $P$-value <0.001). The results of this ANOVA for PV modules present on at least 10 installations are detailed in Table 3. Manufacturers' names have been hidden under symbols for reasons of confidentiality: 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). The systems equipped with the PV module tagged as "CIS" clearly show a PI pretty low respect to all the other groups.

Fig. 9 shows a boxplot that allows visualizing the PI variations among and within the groups of PV modules.

In order to estimate the real power of the PV modules, we assume that 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% [18,19]. The average inverter has a yield 2% lower than the high quality inverter that equips the reference system [28]. PV generator mismatch and wiring losses can typically be 2% higher than in the reference system [29]. 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 Belgium [30]. Other losses, such as the ones due to the availability of the system, can account for 1% [31]. 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.

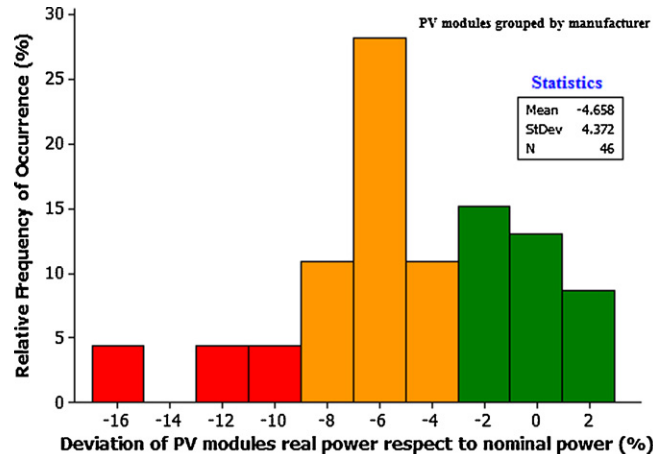



**Fig. 10.** Histogram of the deviation of the real power of the PV modules respect to their nominal power. On average, the PV modules real power falls 4.7% below the corresponding nominal power. Some PV modules manufacturers provide very good quality modules. Some manufacturers deliver PV modules of poor quality, with a real power up to 16% below the nominal power.

Under those assumptions, the deviation of the real power of the PV modules, grouped by model, respect to the announced nominal power, is distributed as shown in Fig. 10. In this figure, the analysis is extended to 46 different models of PV modules. It is worth mentioning that the PV modules analyzed here have a mean exposure time of 2 years.

On average, the real power of PV modules falls 4.7% below their corresponding nominal power. Other authors have reported the real nominal power of PV modules to be on average 5% inferior to the nominal power stated by the manufacturer [32,33]. The presence of PV modules showing a real power higher than their nominal power corresponds 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. The majority of the PV modules have a real power between 2% and 8% lower than their nominal power. Some models of PV modules show poor quality, with a mean real power up to 16% below the nominal power. The gap between the poorest qualities and the rest corresponds to a change of technology between CIS-based modules and silicon-based modules. 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. 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 [34,35].

## 5. Conclusions

The objective of this paper is to review the state of the art of residential PV systems in Belgium by analyzing the operational data of 993 PV systems. Although the available data are from installations in the regions of Wallonia and Brussels, the results are of general interest to understand the state of the art of residential PV in Belgium and Europe.

The PV market in Wallonia and Brussels developed towards residential PV systems 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 PV industry (manufacturers of PV modules and inverters, and installers) is dominated by a reduced number of actors.

A middling commercial PV system, optimally oriented, produces a mean annual energy of 892 kWh/kW$_p$. As a whole, the orientation of residential PV causes energy productions to be some 6% inferior to optimally oriented PV systems. These orientation losses are generally low enough to ensure that the PV systems installed on buildings are a viable alternative to solar plants optimally oriented.

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 78% and the mean performance index of the PV systems is 85%, 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 4.7% below their corresponding nominal power announced on the manufacturer's datasheet. However, some modules show a real power 16% below the nominal power announced by their manufacturer.

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