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Three years experience in a Dutch public awareness campaign on photovoltaic system performance

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Abstract: To raise awareness on the importance of monitoring photovoltaic (PV) systems in the Netherlands, a public campaign was organised in three consecutive years. During 1 week in the spring of 2014, 2015, and 2016, as part of the Dutch Solar Days, participants were asked to measure or determine the amount of energy generated by their PV systems. All in all over 8000 participants were recruited via social media and a national television show. This study analyses the variation of weekly yield and performance ratio (PR) of the systems of the participants for 3 years. On average, for each year, a PR was found of 0.74 with a left-skewed distribution, indicating that most systems perform well. Further analysis was made, which showed the ineffectiveness of an undersized inverter in low radiation conditions. It was also found that the performance difference between mono- and multicrystalline silicon panels was small, and that micro-inverters are effective in reaching high performance for PV systems that suffer from shading. Generally, this work demonstrated the usefulness of citizen science approaches in PV system performance analysis.

1 Introduction

As in many countries, also in the Netherlands deployment of photovoltaic (PV) technology is growing fast. A total installed capacity of ∼2 GWp is expected at the end of 2016, while it is has been doubling for the past 5 years (see Fig. 1) due to fast decreasing prices that have led to levelised cost of electricity lower than retail electricity prices: consumer grid parity has been reached [2]. This growth is requiring reliable information on amongst other the performance of PV systems, which is to be shared with the various actors in the market. For example, accurate PV performance data allows net operators to manage high penetration levels of PV into distribution grids when linked to forecasting and storage options.

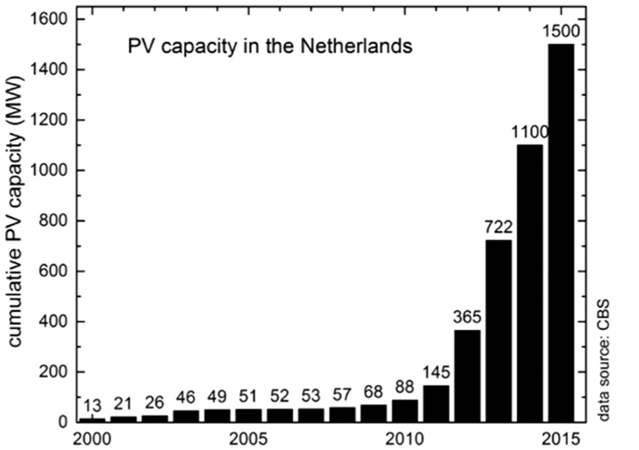


Fig. 1 *Cumulative installed PV capacity in the Netherlands, 2000–2015 (data from Centraal Bureau voor de Statistiek (CBS) [1])*

However, performance data are not readily available, though some reports exist [3–7]. Nowadays, effort by platforms such as SolarLog and PVOutput.org target to disclose performance data. Installers that have performance data at their disposal tend to be reluctant to share this information. This is particularly true if detailed numbers in question allow for financial insights. Legal contracts that restrict partners to secrecy on financial details often prohibit data sharing, even if they are highly motivated to share data, in general, terms. In contrast, and perhaps unintended, PV owners are contributing to 'citizen science' [8], by sharing monitoring data over the Internet. These data can be analysed by anyone, but the level of detail and the unknown measurement accuracy may prohibit a proper analysis. We therefore have applied statistical principles for analysis and visualisation of these data [9].

To raise public awareness on monitoring of PV performance, a campaign was organised in the Netherlands named 'Tel de Zon' ('Counting the Sun') [10], for the first time in Spring 2014, and repeated in 2015 and 2016. During 1 week, which is part of the Dutch Solar Days, the 'Solar Week' (12–18 May 2014, 1–7 June 2015, and 30 May–5 June 2016) participants were asked to measure or determine the amount of generated energy by their PV systems. After substantial social media activity and exposure via the national television network consumer show 'Kassa' over 5000 participants were recruited in 2014. These shared their performance as well as PV system information: system location, orientation, tilt, and system and inverter capacity. In addition, remarks were added regarding suspected problems with shading from nearby objects. Participants received feedback on performance of their PV system, which required automation of yield and performance calculations using in-house developed *Python* scripts.

This paper will first describe the approach and methodology used, followed by main results on weekly yield and performance ratio (PR), and an analysis of spatial variations. Subsequently, a detailed statistical analysis of yield and PR in relation to system

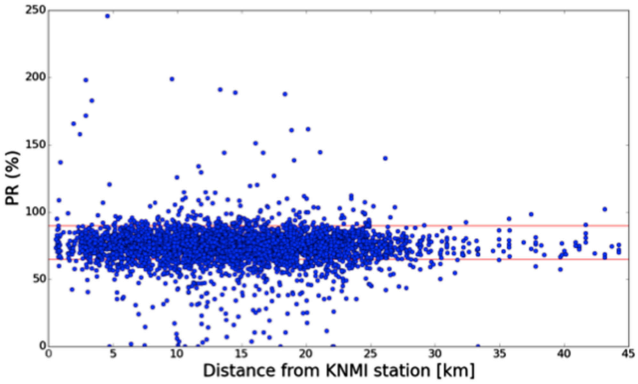


Fig. 2 *Calculated PR values as a function of distance of systems to the nearest KNMI station*

components is presented. This paper closes with a discussion and general conclusions.

2 Approach

The campaign for the public was set-up using a web-based interface that first required participants to register, where after the actual web-form opened into which participants had to input system location (postal code), system capacity (Wp), number of panels, brand and type of panels, inverter capacity, inverter brand and type, orientation, tilt, and year of installation. At the start of the campaign week, participants had to input a value for the cumulative amount of energy generated up to that day, which could be read from the inverter display (or by other means). At the end of the week, they had to input the cumulative energy, from which a weekly energy yield is calculated. Alternatively, they could input the weekly energy yield themselves. After analysis of yield and PR, participants received feedback on the performance of their systems, using a five-Sun scale, with five Suns for excellent [11] performance ratio PR > 0.8, four Suns for 0.8 < PR < 0.7, three Suns for 0.7 < PR < 0.6, two Suns for 0.6 < PR < 0.5, and one Sun for PR < 0.5.

3 Analysis methodology

To determine performance of systems, we used the two most common indicators for PV system performance: the final system (weekly) yield Y_f, and the performance ratio PR. Final system yield is the net energy E delivered for the specific period divided by the DC-rated power output P_0 of the installed array and it has units kWh/kWp [12]

$$Y_f = \frac{E}{P_0} \tag{1}$$

It conveniently allows comparing performance of different PV systems and has the advantage that only the actual produced energy is required. It varies widely by climate, by the length of the calculation period and by how the two parameters are defined (e.g. array DC level or inverter AC output).

The PR describes the relationship between the actual and theoretical or reference energy output of the PV system. The actual energy yield is the utilisable AC electricity, which is divided by the amount of energy that could be generated if the system were to operate under standard test conditions (1000 W/m^2, AM1.5 solar spectrum, 25°C cell temperature). The difference between 100% and the PR value aggregates all the possible energy losses including inverter efficiency, cabling losses, panel degradation, mismatch, shading effects, dust, thermal inefficiencies, and system failures [11]. PR is defined as the ratio of final system yield Y_f and reference yield Y_r

$$\text{PR} = \frac{Y_f}{Y_r} \tag{2}$$

For the calculation of reference yield irradiance data is required. Global horizontal irradiance (GHI) values from 31 meteorological ground stations in the Netherlands (Royal Netherlands Meteorological Institute, KNMI [13]) were available. The reference energy yield for each PV system was calculated using the system information provided by the participants by determination of the irradiance values in the plane of the panels [plane of array (POA)], for every hour, using a model by Olmo *et al.* [14]. This model was selected as it depends only on the clearness index and avoids the separation of the solar beam into direct and diffuse components. Moreover, in a comparison of a number of models for determining the solar global irradiation on inclined surfaces derived from GHI, the Olmo model was found to have the best match between the predicted and the experimental values [15].

The fact that the used irradiance data are taken from the 31 meteorological stations of KNMI may induce incorrect POA irradiance data, as the distance between station and PV system may be substantial, while weather conditions may very well vary on a much smaller scale. However, as Fig. 2 shows, a dependence of PR of the Solar Week 2014 on the distance between the PV system and the closest meteorological stations most probably are absent, as most of the calculated PR values are within a band of 60–90%, and no distance-dependent behaviour is observed. Note that unrealistic values of PR most probably result from incorrect data supplied by participants. Also, most of the systems are at maximum 25 km from a meteorological station.

4 Results

4.1 Participation and system sample

The measurement campaign was considered successful in that it raised awareness among PV system owners regarding performance of their system. Some participants already were well aware of the performance of their system, others clearly not, as evidenced by several e-mail exchanges. Some found out that, for example, strings were not functioning well, due to malfunctions such as disconnected cables, others encountered unexpected shading. Especially, early Saturday evening live coverage on national television to announce the measurement week as well as after the week was very good for raising awareness, not only of PV system owners, but also to the general public; nearly 1,000,000 viewers were counted for the first broadcast and about 800,000 viewers for the second broadcast. These numbers constitute ∼15–20% of all Dutch television viewers. This second broadcast showed that performance, in general, was quite good, which was illustrated with recordings of interviews with participants of three well-functioning systems. Also results were discussed in front of an audience, which was broadcasted live. In addition, press releases and the use of social media further added to dissemination of the results.

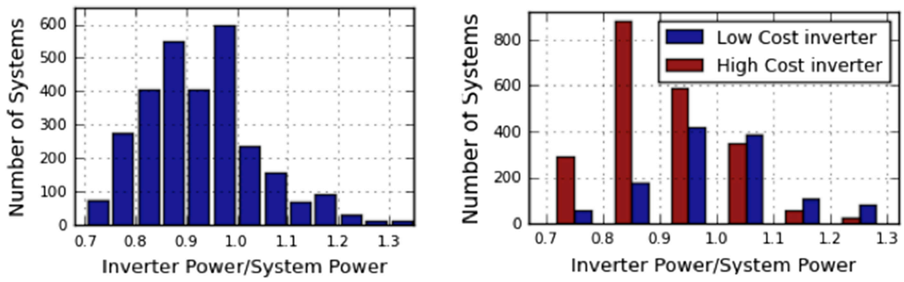
The total number of participants varied in 3 years, with a clear high number in 2014 as a result of the coverage of the measurement campaign on national public television: 5019, 1901, and 1548 participants in 2014, 2015, and 2016, respectively, see also Table 1. Of these participants, 466 participated all 3 years. In the following, we analyse results for all participants, and also separately for these 466 ones. The total capacity of the participating systems in 2014 was 16.2 MWp, with an average installation size of 3.5 kWp. This constituted ∼2% of the total amount of PV capacity at that time in the Netherlands.

Crystalline silicon is the most popular module technology, since in 4926 known systems in the dataset, 46.7% (i.e. 2300 systems) mono-crystalline silicon modules are used, while 43.0% consist of multicrystalline silicon modules. Thin film technology is only marginally used: amorphous silicon 0.5%, copper–indium–selenide 1.8%. Interestingly, 7.4% (362) of the participants are not aware of the PV technology on their roof.

Analysis of the ratio of inverter AC nominal power and system DC-rated power revealed an interesting fact. An average ratio of 0.93 ± 0.11 was found, while it is somewhat lower for relatively high-cost inverters (0.90 ± 0.11), and somewhat higher for relatively low-cost inverters (0.99 ± 0.12); a distribution is shown in Fig. 3. As participants shared their brand inverter, we could

Table 1 Overview of system data and results

Parameter	2014	2015	2016	Whole dataset
Participants	5019	1901	1548	
participants with PR > 25%	4866	1732	1361	
participants all year				466
mono-crystalline silicon systems				46.7%
multicrystalline silicon systems				43.0%
DC power ratio inverter/system (all inverters)				0.93 ± 0.11
DC power ratio inverter/system (low-cost inverter)				0.99 ± 0.12
DC power ratio inverter/system (high-cost inverter)				0.90 ± 0.11
average GHI, kWh/m^2	41.9	43.7	31.9	
average PR, %	74.6 ± 9.6	74.5 ± 9.4	74.0 ± 10.8	
average PR, % (466 participants)	75.0 ± 9.5	75.4 ± 7.9	74.6 ± 10.2	



a b

Fig. 3 *Distribution of inverters based on the ratio of AC inverter power and DC systems power; (left) all systems; (right) distinction between low- and high-cost inverters*

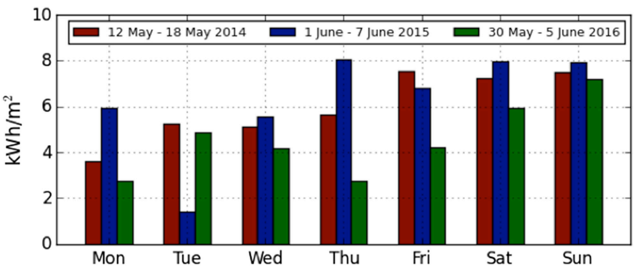


Fig. 4 *Average radiation per day (source: Koninklijk Nederlands Meteorologisch Instituut (KNMI) [13]). Clearly, the radiation during Solar Week 2016 was worst than the previous years. Furthermore, during both Solar Weeks of 2014 and 2015 at the end of the week the weather was better than at the beginning*

distinguish between low- and high-cost inverters, using cost data from [16]. Usually, as a rule-of-thumb, a ratio of ∼0.8 is used in PV system design. This is based on the fact that maximum DC output of a PV system in practise will never be reached due to temperature effects, i.e. the negative temperature coefficient of PV technology [17]. This rule-of-thumb has been criticised as it was based on hourly irradiation data, while especially in partly overcast situations, irradiance variations can be fast so that using a higher ratio of ∼1 will actually lead to lower inverter-related losses in the PV system [17]. The rule-of-thumb was also inspired by the cost of inverters in the past. With cheaper inverters on the market, a ratio of 1 or larger still is economically attractive.

4.2 Weekly irradiation

The total GHI on a national level was similar during the Solar Weeks of 2014 and 2015 (41.9 and 43.7 kWh/m^2, respectively), but significantly lower (31.9 kWh/m^2) during the Solar Week of 2016. In the triple bar chart of Fig. 4 the average radiation per day is presented for every Solar Week. Both for 2014 and 2015 the first days showed some cloud cover and rain, whereas the last days of each Solar Week were clear. On the other hand, during the Solar Week of 2016 the weather was much worst with partially clear skies only on Tuesday, Saturday, and Sunday.

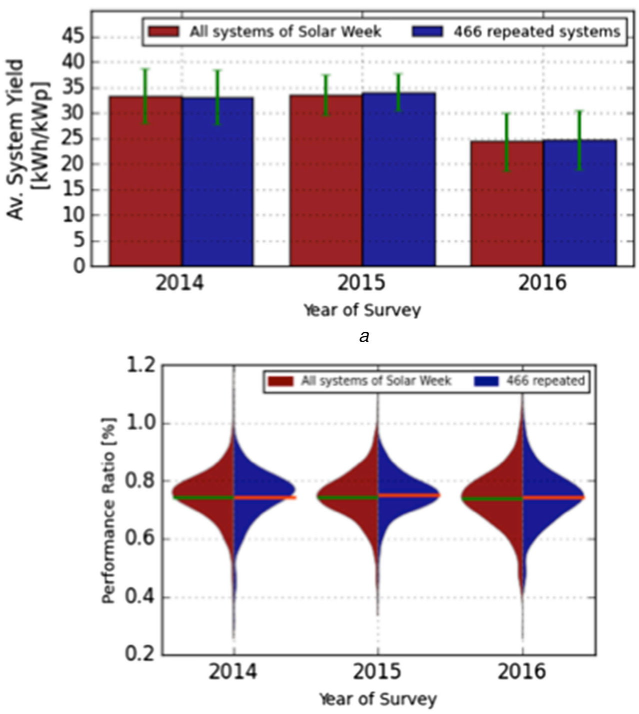


Fig. 5 *(top) System yield and (bottom) PR of all systems in this paper, compared with the systems that participated in all 3 years*

4.3 Weekly yield and PR

As a result of the weather dependency, the average system yield differs for the 3 weeks. This is shown in Fig. 5 (top). This is not different for the 466 systems that participated all 3 years.

The average PR of the full dataset, as depicted by the green line on the left-hand side of the violins of the violin plot [18] in Fig. 5 (bottom) does not differ between 2014, 2015, and 2016, as PR was found to be 74.6, 74.5, and 74%, respectively, with standard deviation of the mean of ∼10% point (see Table 1). In addition, the

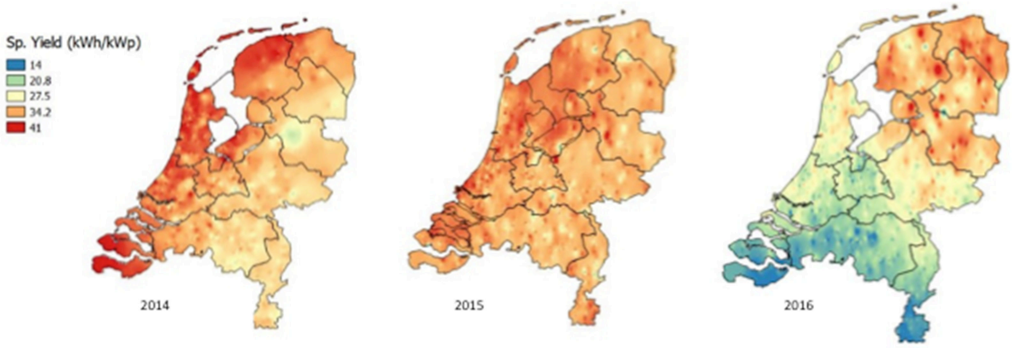


Fig. 6 *Spatial variation of weekly yield over the country for the 3 years*
(a) 2014, ***(b)*** 2015, ***(c)*** 2016

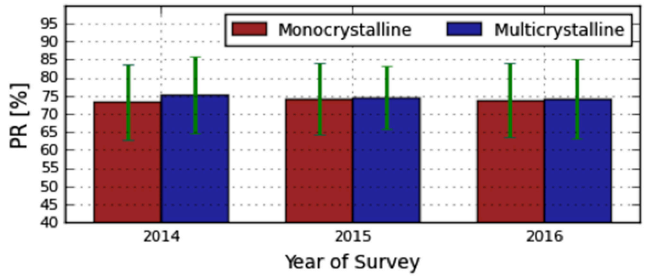


Fig. 7 *PR in relation to panel technology*

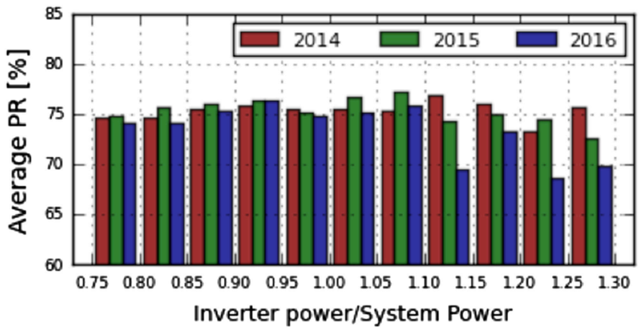


Fig. 8 *PR in relation to the ratio of AC inverter power to DC system power*

average PR of the 466 PV systems does not differ either from year to year (right half of the violins of Fig. 4 (bottom, red line).

Both weekly yield and PR do not differ between the full dataset and the smaller set of 466 systems. This illustrates that the smaller amount of systems is representative for the determination of yield and PR.

4.4 Spatial variation

As irradiance varies over the country also the weekly yield does. This is illustrated in Fig. 6, in three different ways, using geographical information systems (GISs) mapping. Using GIS for performance mapping has been described recently as a good means to quickly see which systems are malfunctioning and where they are located [19]. In 2014, systems located on the coastal part of the country had on average 23% higher yields during the Solar Week, as shown in Fig. 6*a*, where data interpolation for the yield was used for colour coding. In 2015, the spatial differences were much smaller, as evidenced in Fig. 6*b*. For the most recent Solar Week systems located in the Northeast experience much higher yield (up to 50% more than the average) compared with the systems in the South (Fig. 6*c*). According to the Köppen–Geiger climate classification the whole of the Netherlands is described as ‘Cfb’, or a temperate climate without a dry season and a warm summer [20]. Irradiation data typically show; however, that the coastal zone receives ∼10% annual irradiance, leading to higher yields [13]. Finally, we found that the PR did not show any spatial variation over the country for any of the years (not shown here).

4.5 Analysis of system components

4.5.1 Panel technologies: Crystalline silicon was the most popular module technology with ∼90% of the systems, as was shown above (Table 1). We found a slight difference in performance of systems with mono- and multicrystalline silicon panels, with an average PR of 73 and 75% for mono- and multicrystalline panels, respectively, considering the 2014 dataset (see Fig. 7). Interestingly, PR for mono- is lower than for multicrystalline silicon panels. Note, that differences are very small for the systems in the later years 2015 and 2016, i.e. only 0.5% point. Consequently, the same small difference holds for the energy yield. The year of installation may also be of importance as panels installed more recently may have improved efficiencies. In our complete 3 year dataset, 49.8% of the systems have been installed in 2013, 23.7% in 2012, 22.3% in 2014, 3.6% in 2015, and 0.6% in 2016. This means that mono- and multicrystalline silicon panels from 2013 are most dominant in the results.

4.5.2 Ratio of inverter AC nominal power and system DC-rated power: The ratio of inverter AC nominal power and system DC-rated power was on average 0.93 (Table 1), which is substantially higher than the 0.8 rule-of-thumb ratio [17]. These high values of the ratio are expected to lead to lower PR values, as a result of the lower inverter efficiency at low irradiation. This can indeed be seen in Fig. 8, where the systems with higher ratio have significantly lower PR in 2016 than the other ratios of the same year and similar ratios of the previous years. This is caused by the lower irradiance in the 2016 Solar Week compared with the other years. Fig. 8 also shows that inverters with nominal AC capacity 1.2 times larger than the DC system capacity are ineffective in low-irradiance conditions.

4.5.3 String and micro-inverters on shaded rooftops: The occurrence of shade is quite common on the rooftops in the Netherlands as systems are predominantly installed in residential areas. For the year 2014, the participants have been asked to specify whether their system would be affected by any kind of shading such as due to dormers and chimneys. In this way, information from 1450 PV systems was collected: 749 PV systems are reported to be shaded and 701 are not. Interestingly, from the shaded systems, 542 have string inverters, while 207 have micro-inverters or power optimisers, which in theory should be performing better than the string inverters under shading conditions. We indeed have found, as shown in Fig. 9, that micro-inverters have higher, albeit only somewhat and with appreciable standard deviation, values of PR and system yield, i.e. $73 \pm 11\%$ and 32.61 ± 5.53 kWh/kWp, respectively, while string inverters show lower PR and system yield of $71 \pm 12\%$ and 31.37 ± 5.52 kWh/kWp. Such a small difference between the use of string inverters and module level power electronics was also shown by others in a rigorous outdoor testing environment [21].

5 Discussion

Collecting data from a large amount of participants was not without problems. Many erroneous inputs were given such as mistakes in

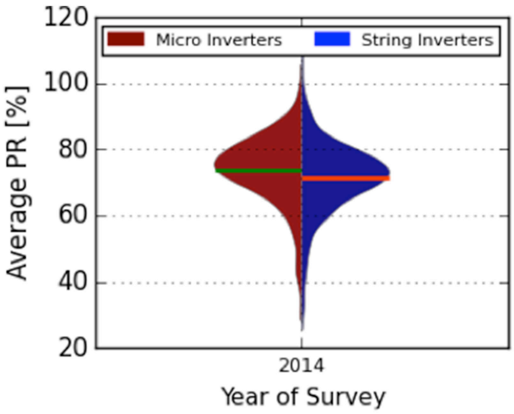


Fig. 9 *PR for systems with micro-inverters and string inverters, with suspected shading*

system power. An obvious mistake was inputting a value of '4', where '4000' would have been correct for a 4 kWp system. This could be easily corrected using the input 'number of panels', in our analysis software. In some cases, cumulative energy was read from a smart meter instead of from the inverter directly. This leads to low weekly yields, as smart meter readings are net energy fed back to the grid. Also, inverter AC-rated capacity was not always known, while the brand and type were; from specification sheets the correct information could be derived.

With this citizen science approach, the accuracy of measurements may be difficult to assess. Inverter displays show energy generated, but not all inverters measure energy correctly. The use of the Olmo model to calculate POA irradiance added to the accuracy of the PR. While this is difficult to overcome, the shear amount of data and a statistical analysis would allow for a proper determination of average yield and PR, while standard deviation in the means are substantial, but acceptable for analysis.

6 Conclusions

The measurement campaign was successful and it raised awareness not only among PV system owners regarding performance of their system, but also among the general public. Considering all 3 years, over 8000 participants generously supplied data, which allowed analyses of weekly yield, PR, also in relation to system components. Results show that PV systems in the Netherlands, in general, are performing well, with PR values of 74.6 ± 9.6, 74.5 ± 9.4, and $74.0 \pm 10.8\%$, for the weeks of 2014, 2015, and 2016, respectively, which is evenly spread over the country. Only some (∼15%) of the systems suffer most probably from some kind of shading. Furthermore, no significant degradation is observed on the 466 repeated participants. This fact can be expected, since all these systems were installed on late 2013 and early 2014, thus they are younger than 3 years, and degradation would be limited to ∼1% only.

Further analysis on system components shows that the actual average ratio of inverter AC nominal power and system DC-rated power was substantially larger (0.93) than the rule-of-thumb of 0.8; this ratio is somewhat higher for low-cost inverters. This illustrates that with decreasing inverter cost the rule-of-thumb may be relaxed, especially, due to the fact that the oversized inverters are performing less in conditions with lower radiation.

Furthermore, component analysis revealed that the use of a proper inverter technology can improve the PV yield, since the shaded systems with micro-inverters or power optimisers are performing better that the shaded systems with string inverters.

7 Acknowledgements

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