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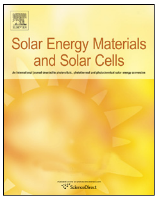

# Worldwide outdoor round robin study of organic photovoltaic devices and modules

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## ABSTRACT

Accurate characterization and reporting of organic photovoltaic (OPV) device performance remains one of the important challenges in the field. The large spread among the efficiencies of devices with the same structure reported by different groups is significantly caused by different procedures and equipment used during testing. The presented article addresses this issue by offering a new method of device testing using “suitcase sample” approach combined with outdoor testing that limits the diversity of the equipment, and a strict measurement protocol. A round robin outdoor characterization of roll-to-roll coated OPV cells and modules conducted among 46 laboratories worldwide is presented, where the samples and the testing equipment were integrated in a compact suitcase that served both as a sample transportation tool and as a holder and test equipment during testing. In addition, an internet based coordination was used via plasticphotovoltaics.org that allowed fast and efficient communication among participants and provided a controlled reporting format for the results that eased the analysis of the data. The reported deviations among the laboratories were limited to 5% when compared to the Si reference device integrated in the suitcase and were up to 8% when calculated using the local irradiance data. Therefore, this method offers a fast, cheap and efficient tool for sample sharing and testing that allows conducting outdoor measurements of OPV devices in a reproducible manner.

## 1. Introduction

12% record efficiency [1] is the number that represents the organic photovoltaic (OPV) technology today. However, in the OPV community today, the constantly reported efficiencies of different OPV technologies are scattered along a wide scale with an average performance much below the current record efficiency [2–3] creating concerns whether the technology is mature for industrialization. Besides the challenges of reproducible manufacturing of devices, the large spread in the reported efficiencies is often generated by the inaccuracy of testing procedure. Given the costly and time consuming process of device performance certification at accredited laboratories, many researchers choose to test their device in their own laboratories using the equipment on hand and procedures attuned to the equipment and device architectures. Since OPVs are sensitive towards the testing conditions, the reported results are linked to the local testing procedures and thus, become irreproducible in other laboratories. Therefore, the field is in need of common testing procedures and protocols (for example according to International Electrotechnical Commission standards) that can allow more harmonized procedures and can deliver reproducible results. This issue is currently one of the primary focuses within the OPV topic in the Project of European Research Infrastructure (SOPHIA) and the European Energy Research Alliance (EERA).

One of the best techniques for establishing common testing methods is the round robin or interlaboratory study, where the set of test samples is shared among a number of laboratories and testing and intercomparisons are performed [4–11]. A round robin is a useful tool that allows reaching consensus on best practices for both designing device architectures, utilizing the most suitable test equipment, and creating common test protocols. Within the OPV field, a number of different round robin studies have already been presented for both initial power output [12–14] and lifetime [15–18] measurements, which addressed the issue of large spread of data among different laboratories.

While many lessons have been learned this article presents a new characterization method for photovoltaic devices that involves an innovative approach of “suitcase samples”. The samples are integrated in a special compact suitcase that provides sample protection and at the same time allows easy transport, mounting, electric contacting, and testing of the samples with virtually no use of external equipment and therefore, allows sample sharing and round robin characterization using low cost tools and equipment. The method was tested in an outdoor round robin study conducted for roll-to-roll produced OPVs among 45 laboratories (+ 1 coordinator) worldwide. To cover such large scale study, an internet based coordination was used. A website infrastructure was created to allow central coordination and communication between all the laboratories, transportation of the samples, and reporting of the results in a controlled format. The manuscript describes in detail the sample development, the web based coordination process and the control of the reporting procedures. It further analyzes the results of the measurements and discusses the advantages and shortcomings of the new method.

## 2. Experimental

### 2.1. Sample and suitcase preparation

Roll-to-roll coated OPV modules produced at the Technical University of Denmark (DTU) were used for the tests. The devices had an ITO free structure of Ag grid/PEDOT:PSS/ZnOx/P3HT:PCBM/PEDOT:PSS/Ag grid/PET substrate. The two PEDOT:PSS layers on both sides have different chemical alterations and therefore have different energy levels. The devices were encapsulated using flexible Amcor packaging barrier foil and epoxy adhesive (DELO LP655) and fixed on a rigid platform. The device terminals were connected to easily accessible electric plugs as shown in Fig. 1. Three sample designs were used with correspondingly serially connected 1, 3 and 6 stripes of solar cells in each module. The terminals of the modules were additionally sealed by epoxy to prevent the diffusion of oxygen or water inside the device. Si photovoltaic modules were additionally used as references. A thermocouple was glued on the backside of one of the OPV samples for temperature measurements. Table 1 shows the ID and the average performance of the samples (together with standard deviations) tested under solar simulator in DTU with the sample temperatures set close to 60 °C and the light intensity calibrated to 1 sun using photodiode with a KG5 filter. Such calibration provides good accuracy for P3HT:PCBM devices, but not for the Si module and therefore, significantly lower values were obtained for Si compared to AM1.5G. This, however, is not critical, since the same conditions were used for post-ageing measurements to record any changes. Figs. S1–S4 in the supporting material additionally shows typical IV curves for each type of sample.

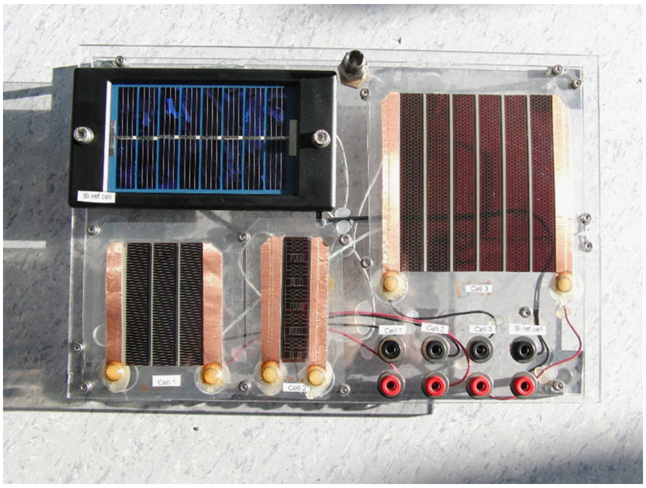


**Fig. 1.** Three OPV modules and one Si reference module fixed on a rigid platform.

The compact suitcase (36 × 29 × 17 cm) used for sample transportation was customized to serve also as a sample holder during testing. Fig. 2(a–e) shows the mounting of the sample platform both inside the suitcase (for transportation) and on top of the suitcase (for testing). Both the platform and the lid contained integrated magnets to allow easy fixing of the platform inside the lid (Fig. 2a) and on top (Fig. 2 b and c). The threaded rod allowed fixing of the angle of the lid at a certain position. The "angle adjustment tube" easily mounts on the platform and allows for determination of the angle for direct incidence of sun irradiation (Fig. 2 d and e). Fig. 2a also shows the components provided in the suitcase, such as the multimeter for measuring open circuit voltage $V_{oc}$, short circuit current $I_{sc}$ and temperature of the samples, cables for electrical measurements and an angle measuring scale.

### 2.2. Measurement procedures

The suitcase contained a copy of the detailed protocol (also made available at the round robin website) describing the testing procedure of the samples and the reporting of the data. The protocol contained detailed instructions on setting up the samples, soaking the samples under light for 30 min followed by performance testing. The experimenter was recommended to perform both full *I–V* testing (depending on locally available equipment) and measure $I_{sc}$ and $V_{oc}$ of each sample using the provided multimeter. The Si reference device was used both as a test sample and as a reference for irradiance. The experimenter was also recommended to use local sensors (if available) to record the local irradiance level. The temperature of the samples was recorded via the thermocouple attached to one of the samples and the multimeter. 5 measurements for each parameter of each cell were required. Reporting of the results was done via the electronic form set up on the website. A copy of the original protocol is provided in the Supporting document (S2). The website used for coordination and data reporting is described in the Supporting document (S6).

### 2.3. Participating laboratories

The participants were originally recruited at the International Summit on OPV Stability (ISOS-5). The studies were additionally advertised at http://plasticphotovoltaics.org/roundrobin and a few participants were engaged this way. Finally a number of laboratories were contacted directly in an attempt to fill out the world-map. The finalized list of participants can be seen in Table 2 and the geographic location in the map in Fig. 3. To carry out the round robin among such a large number of participants within a

**Table 1**
Description and the average performance of different samples. The values represent the average of four samples tested under solar simulator with light intensity close to 1 sun and sample temperature of 60 °C.

| Sample ID | Description | Active area (cm$^2$) | $V_{oc}$ [V] (STD %) | $I_{sc}$ [mA] (STD %) | FF [%] (STD %) | PCE [%] (STD %) |
|---|---|---|---|---|---|---|
| Cell 1 | OPV module with 3 stripes | 21.32 | 1.52(2.3) | 33.3(10) | 57(3.2) | 1.35(13) |
| Cell 2 | OPV cell with 1 stripe | 6.9 | 0.54(1.4) | 38.8(3.6) | 52(5.1) | 1.58(5.5) |
| Cell 3 | OPV module with 6 stripes | 67 | 2.93(1.1) | 56.9(4.7) | 52(4) | 1.3(5.7) |
| Cell 4 | Si reference module | 47.4 | 4.14(0.5) | 160(0.4) | 72(1) | 10.1(0.8) |

**Fig. 2.** a) General view of the suitcase and its content, b) mounting of the sample platform on top of the suitcase, c) adjusting the angle of the lid via a rod with a thread, d) adjusting the angle to sun altitude and e) measuring the angle.

reasonable time, four identical suitcases were circulated at the same time in four loops. Certain labs (marked blue in the map in Fig. 3) volunteered to perform more than one test. Due to time constrains, however, each participant eventually received the samples only once.

## 3. Results and discussion

### 3.1. Logistics

Four loops were organized among 45 laboratories with four suitcases circulating in parallel. Fig. 4 shows the map with the tracking lines of the suitcase routes and a table with the numbers of laboratories in each loop and the total time of measurements. While 2 weeks were originally set for testing and transportation for each participant the actual average time reached 3.5 weeks and the total test period lasted around 10 months. Such an extension was mainly caused by custom clearance procedures at the country borders, especially when the suitcase was traveling across continents. Express services were used to accelerate the transportation. However, it was later discovered that using regular posting service did not require slow and expensive custom clearances and therefore had a much better result.

While 6 of the participants had to perform the measurements in a cloudy day with no direct sunlight, in most cases a clear sky measurement was achieved. Although the “cloudy” measurements gave a good insight on the linearity of the devices versus the irradiance, the overall deviations were somewhat larger and therefore these data were not taken into account during the calculation of the average performance. In addition, in some cases the testing was performed under unusual conditions, such as at 3000 m elevation in Armenia or at −15 °C air temperature in Russia, the former not having significant effect on data deviations, while the latter resulting in reduced performance of the OPVs compared to the Si reference device. The participants were also recommended to perform the testing as close to noon time as possible, to reduce the spectral mismatch effects of sunlight.

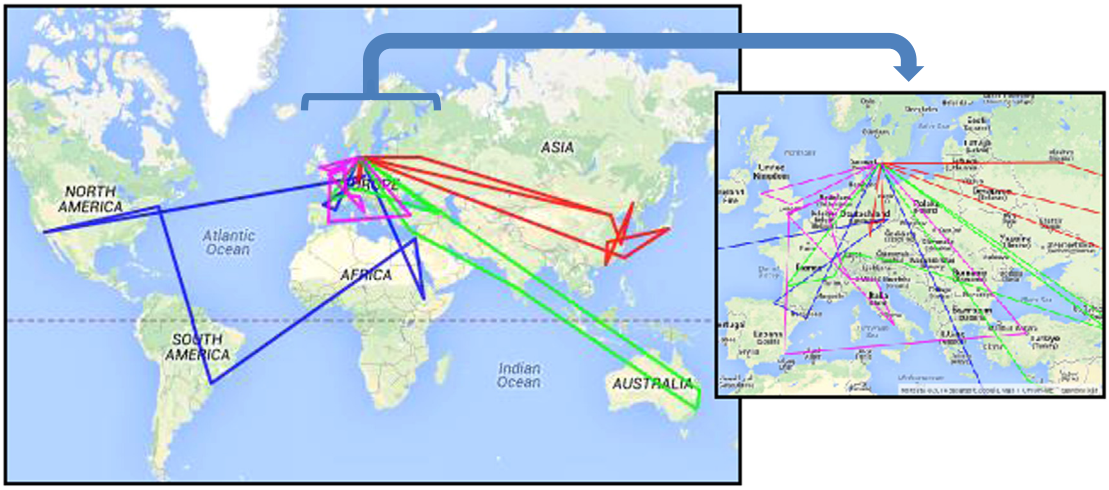
### 3.2. Degradation and failure of samples

The samples were tested before and after the experiments at the host laboratory (DTU) to record possible degradation effects during transportation and tests. Fig. 5 shows the performance of all the samples after the experiments, normalized to the initial values. Three out of twelve OPV samples showed degradation (marked with black circle in Fig. 5) caused mostly by the drop of fill factor FF, but for some also by $V_{oc}$ and $I_{sc}$. However, for the cell 3 in the suitcase 4 the lower FF was recorded only at the laboratory of origin upon return, while the actual round robin measurements did not show patterns of degradation. Since the encapsulation of devices was entirely automated (made by R2R machinery), which secures good reproducibility of lifetimes, the reason of degradation was assigned to the sealing of device terminals, which was performed manually and possibly imperfect in some cases, resulting in diffusion of oxygen and water inside the barrier, which is a common failure mechanism as was reported earlier [18–19]. Visual inspection of the samples did not reveal any failures. The reported measurements that showed degradation patterns were not used in the calculations of the average performance.

**Table 2**
The full list of participants in the study.

| | University/organization | Contact person | Country |
|---|---|---|---|
| 1 | Belelectric | Hans-Joachim Egelhaaf | Germany |
| 2 | Ben-Gurion University of Negev | Eugene Katz | Israel |
| 3 | CEA-INES OPV group | Matthieu Manceau | France |
| 4 | Cin2 | Monica Lira Cantu | Spain |
| 5 | CSEM | Ton Offermans | Switzerland |
| 6 | ECN | Jan M. Kroon | Netherlands |
| 7 | ENEA | Pasquale Morvillo | Italy |
| 8 | University of Erlangen-Nuremberg | Florian Machui | Germany |
| 9 | Inside2Outside | Robert Carpenter | England |
| 10 | IAPP | Martin Hermenau | Germany |
| 11 | IKERLAN | Roberto Pacios | Spain |
| 12 | Ilmenau | Roland Roesch | Germany |
| 13 | Imperial College | Sachetan Tuladhar | England |
| 14 | IMS | Guillaume Wantz | France |
| 15 | Fraunhofer ISE | Birger Zimmermann | Germany |
| 16 | Joint Research Centre | Giorgio Bardizza | Italy |
| 17 | KAST | Katsuhiko Takagi | Japan |
| 18 | Cyprus University of Technology | Marios Neophytou | Cyprus |
| 19 | NPL | Fernando Araujo de Castro | England |
| 20 | National Taiwan University | Jr-Hau He | Taiwan |
| 21 | Northearstern Univeristy | Latika Menon | USA |
| 22 | Pomona College | Gretta Mae Ferguson | USA |
| 23 | University of Groningen | L. Jan Anton Koster | Netherlands |
| 24 | Bangor University | Jeff Kettle | Wales |
| 25 | Siano | Changqi Ma | China |
| 26 | Holst Centre | Yulia Galagan | Netherlands |
| 27 | TU Chemnitz | Chaitanya Bapat | Germany |
| 28 | Graz University of Technology | Thomas Rath | Austria |
| 29 | University Hasselt | Jean Manca | Belgium |
| 30 | Tübitak | Elif Alturk Parlak | Turkey |
| 31 | University of Wollongong | Ziqi Sun | Australia |
| 32 | University of Southern California | Barry Thompson | USA |
| 33 | Wuhan University | Jiangbin Xia | China |
| 34 | American University of Armenia | Artak Hambarian | Armenia |
| 35 | The University of Queensland | Mike Hambsch | Australia |
| 36 | Jawaharlal Nehru Centre for Advanced Scientific Research | Giridhar U. Kulkarni | India |
| 37 | CSIRO Energy Technology | Chris Fell | Australia |
| 38 | International Laser Center & Faculty of Physics, M.V.Lomonosov Moscow State University | Dmitry Paraschuk | Russia |
| 39 | Federal University of Paraná | Lucimara Stolz Roman | Brazil |
| 40 | Technical University of Cartagena | Antonio Urbina | Spain |
| 41 | Addis Ababa University | Teketel Yohannes | Ethiopia |
| 42 | Changchun Institute of Applied Chemistry | Zhiyuan Xie | China |
| 43 | Department of Polymer Science and Engineering, Zhejiang University | Hongzheng Chen | China |
| 44 | Peking University | Xiaowei Zhan | China |
| 45 | Dipartimento di Ingegneria dell Informazione, Universita di Padova | Andrea Cester | Italy |
| 46 | Technical University of Denmark (Coordinator) | Morten V. Madsen/Suren Gevorgyan | Denmark |

**Fig. 3.** Flags in the google map correspond to the locations of the 46 participants. Blue colored locations were the sites intended for multiple measurements. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



| Suitcase ID (line color) | Number of participants | Total time of testing (days) |
|---|---|---|
| S1 (Blue) | 9 | 232 |
| S2 (Red) | 12 | 310 |
| S3 (Green) | 10 | 259 |
| S4 (Pink) | 14 | 309 |

**Fig. 4.** Routes of the four suitcases. The table below shows the number of participants and total time of experiments for each loop.

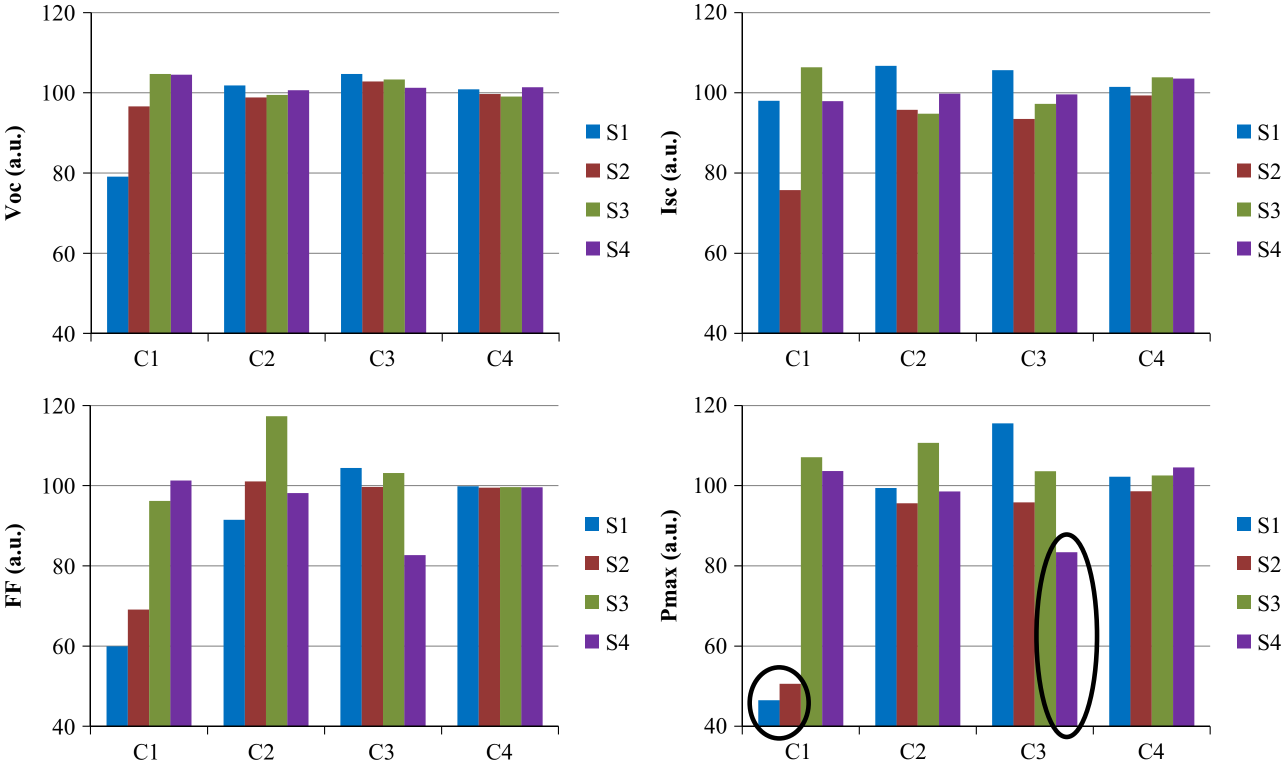


**Fig. 5.** Performance of all the samples after the experiments normalized to the initial values. C1 to C4 refer correspondingly to Cell 1 to Cell 4 in each suitcase (Table 1). The three samples which showed degradation are marked with a black circle.

Some of the participants additionally reported a weak contact of the terminal of cell 1 in suitcase 3, which was resolved by pressing on the contact. Detachment of the thermocouple from the back of the samples was also recorded. The issue was resolved by re-attaching the sensor with new epoxy adhesive.

### *3.3. Spread of data*

According to the test protocol the participants were required to record the photocurrent of the reference Si (Si devices were not calibrated prior to the studies) during testing of each sample, as

**Table 3**
Temperature coefficients of $I_{sc}$ and $V_{oc}$ of the test samples.

| Device | $I_{sc}$ temp. coeff. (%/°C) | $V_{oc}$ temp. coeff. (%/°C) |
|---|---|---|
| Si device | 0.12 | −0.26 |
| OPV device | 0.17 | −0.041 |

well as record the local irradiance, if a local sensor was available. 17 labs reported locally recorded global irradiance data, which was typically recorded using a pyranometer positioned in the same plane as the samples. The reported irradiance data was used to normalize the reference Si $I_{sc}$ data to 1000 Wm$^{-2}$, which was then used to estimate the temperature coefficient for Si devices (the data for all Si devices from four suitcases were combined to improve the statistics and outliers were not taken into account) and normalized the data to temperature. Sample temperature of 40 °C was used for normalization. The same procedure was performed for OPV samples. For the latter, however, the OPV $I_{sc}$ was normalized to the already temperature corrected Si $I_{sc}$. To do so the average 1 sun value of Si $I_{sc}$ was identified, which was 183 mA and this value was used for normalization. Exception was made for the data of the Joint Research Center that reported the accurately calibrated and normalized data including the spectral mismatch calibration. In the case of $V_{oc}$ only the data above 600 Wm$^{-2}$ were used ($V_{oc}$ was not corrected to irradiance) for estimation of the temperature coefficients for both OPVs and Si. Table 3 shows the determined coefficients. This method has a number of underestimations, such as:

- Spectral mismatch in different geographic locations and between Si and OPV devices is not taken into account.
- In some cases, there is a time delay between measured $I_{sc}$ and temperature values.
- Temperature is measured only on one OPV sample per suitcase and while valid for the other OPV samples, it may not reflect accurately the temperature changes in the Si device.
- The temperature range is mostly limited to 20–50 °C.
- $V_{oc}$ values are not normalized to irradiance.

Despite these deviations, the large quantity of the data is believed to give sufficient precision for temperature corrections. To confirm this, *P*-values were calculated for the different parameters, which represents the statistical significance of the data trend. The results revealed very low *P*-values for the three coefficients in Table 3, while a value of 0.07 was observed for the temperature coefficient of Si $I_{sc}$ suggesting that the data for the former is statistically significant, while for the latter the significance is low. Taking the aforementioned underestimations the obtained values must not be treated as generic, but rather as values that describe the sample behavior under different temperatures for the given method of temperature and device performance measurements.

In order to calculate the deviations among the reported measurements, first the data were corrected to a common temperature of 40 °C with the temperature coefficients in Table 3. Then these were filtered for any outliers caused by device failure or extreme testing conditions (irradiance below 600 Wm$^{-2}$ or air temperatures below 0 °C). As a next step the average of 5 measurements was calculated for each laboratory (as there were 5 measurements performed for each sample by each laboratory). This was followed by calculation of the weight average of the data among laboratories for the same sample and then re-calculation of a new weighted average using only the data within 10% deviation from the first weighted average. The weighted average was chosen since some of the laboratories reported less than 5 measurements per sample. Fig. 6 shows the distribution of the deviations of all the laboratories for all the cells in each suitcase. The following labeling is used to identify the large deviations:

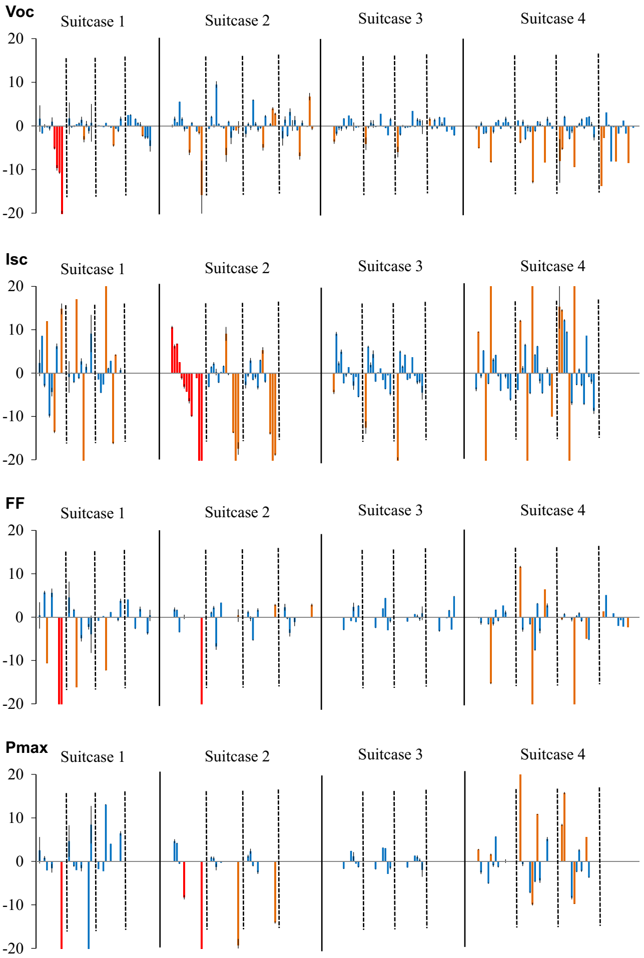


**Fig. 6.** Deviations of reported PV parameters for all the laboratories for each suitcase. The orange columns represent the data that was qualified as an outlier due to extreme testing conditions. The red columns represent the data of degraded devices. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- The orange columns represent the data that were either qualified as outliers due to extreme testing conditions or were above a deviation of 10%.
- The red columns represent the degraded samples.
- The black solid lines separate the measurements of each suitcase and the dotted line separates the samples.
- The error bars represent the standard deviation of the 5 measurements.

The actual values of all the deviations are presented in S3 in the supporting document.

Fig. 7 shows the standard deviation among the data presented in Fig. 6 for each sample. Results are shown for both the filtered data (dark blue) and the data with the outliers (light blue). The degraded devices are marked by red. While the calculations of $I_{sc}$ and $V_{oc}$ are based on at least 9 and more measurements/labs, for FF and maximum power $P_{max}$ fewer data points are available (since only some performed IVs or reported FF) and thus may not represent the true spread accurately. According to the results, the agreement among the data is not affected by device failure or

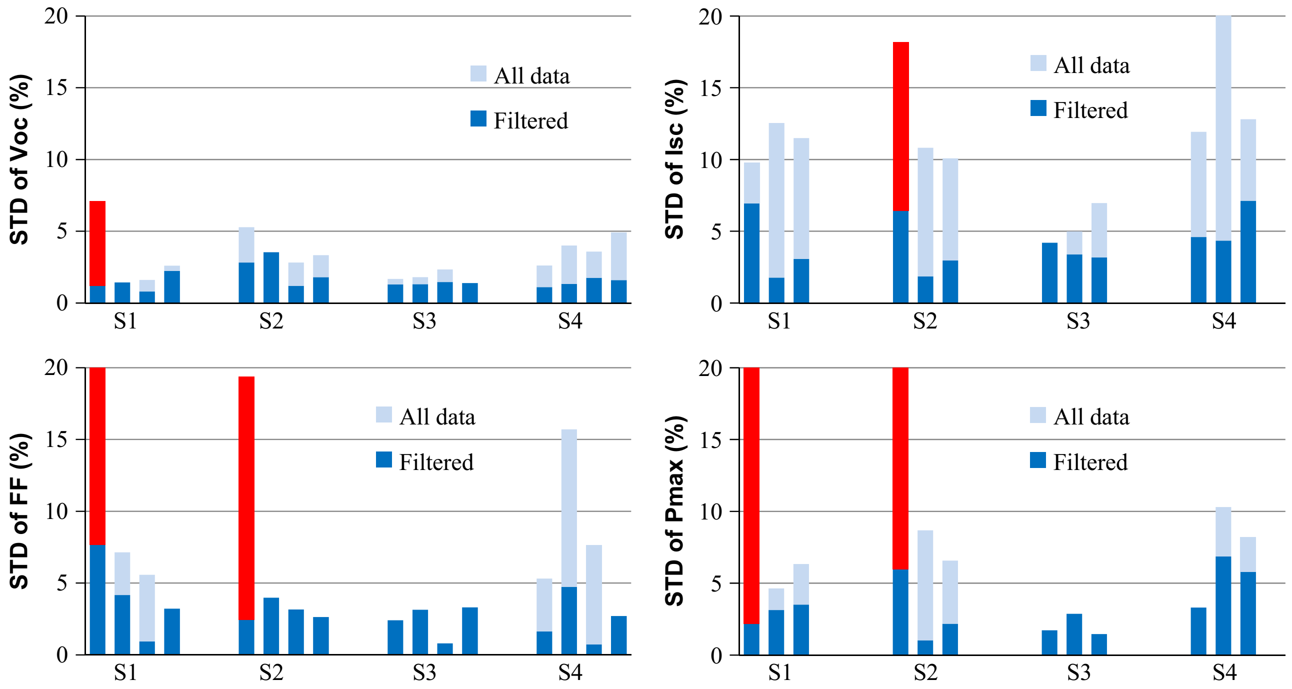


**Fig. 7.** Standard deviation for all the devices in each suitcase among the laboratories. Results are shown for both the filtered data (dark blue) and the data including the outliers (light blue). The degraded devices are marked by red. Since $I_{sc}$ (and consequently $P_{max}$) was normalized to the measured reference Si module there is only 3 columns in $I_{SC}$ and $P_{max}$ plot. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

critical weather conditions and is somewhere at 5% and less, which is a rather small spread, given the nature of the testing conditions and the device sensitivity towards testing conditions. The data are presented for the case in which $I_{sc}$ (consequently also $P_{max}$) was normalized to the measured reference Si module. The same calculations made with $I_{sc}$ normalized to the locally reported irradiance values (with less statistical data, since limited number of laboratories reported irradiance) gave up to 8% average standard deviations for both $I_{sc}$ and $P_{max}$ (the plots of standard deviations of those are provided in Supporting document S4). All the values of the standard deviations are given in Supporting document S5.

In addition, $V_{oc}$ and $I_{sc}$ values were compared between the measurements performed by the provided multimeter and the local measuring units, which did not reveal significant differences.

## 4. Discussion

A number of conclusions can be drawn from the results:

1. The internet based coordination allowed the realization of a round robin at a massive scale involving 45 laboratories from all populated continents (excluding Antarctica). The internet based platform allowed having efficient communication with many participants in parallel and quickly resolving any issues and saving time. In addition, the internet based reporting allowed controlling the format of the data and significantly eased the analyses of the immense amount of data. The online method therefore suggests a novel format of round robin coordination with significantly improved speed and quality of experiments and data reporting.
2. The customized “suitcase” design of the sample holder allowed having good protection of the samples, easy transportation and most importantly did not require special external tools for mounting the samples for measurements. The approach saved both significant amount of time and possible extra costs for installation and measurements of the samples for participants. This also allowed a larger number of participants (especially groups with limited budgets) and therefore, significantly increased the “OPV consortium” for improved and harmonized testing of OPV devices.
3. It is well established that OPVs are rather sensitive to the light spectrum and therefore for sample characterization it is recommended to use light sources as close to real sun light as possible [20]. In addition, solar simulators often have the problem of limited spatial uniformity of illumination and therefore put constrains on the dimensions of samples that can be accurately characterized [21,22]. Obviously, using the real sun helps avoid costly equipment with aforementioned limitations. The results presented in this manuscript suggest that the accuracy of outdoor testing is not inferior to earlier reported indoor tests [14] and even more accurate in some cases. The spread is confined within approximately 5% if considering only the tests under reasonable weather conditions (clear sky and above 0 °C air temperature) and if a reference Si module is provided as a reference. If local irradiance data is used then the spread can be up to 8%, which is still a relatively good value.
4. The tests additionally allowed the participants to address the accuracy of the local irradiance measurements and the procedures of OPV power output measurements.

Based on the aforementioned results it can be concluded that the described approach offers fast and cheap technique for testing and reporting photovoltaic device performances in a reproducible manner using only basic equipment on hand and sharing the samples with a number of laboratories. One has to bear in mind that this regards the consistency of results between laboratories, but does not make a statement about the deviations from the (unknown) true performance of the devices.

### 4.1. Shortcomings

1. The main shortcoming of the technique is linked to the weather conditions and possibly cannot be used in winter season especially in countries with limited amount of sunny days.
2. The provided multimeter has limited accuracy and thus, needs to be rechecked and calibrated with an accurate source meter prior to and after such studies. In addition, the multimeter is only suitable for extracting $V_{oc}$ and $I_{sc}$ parameters, while an appropriate source meter is required for full $I$–$V$ scan and determination of power output of the device.
3. While the aim of this study was to investigate the deviations among the laboratories, in order to accurately determine the tested sample performance the provided Si reference devices need to be traceably calibrated (including temperature coefficient) and must also contain an integrated temperature sensor. Furthermore spectral mismatch corrections need to be performed.

## 5. Conclusions

The article presented a new method of OPV characterization in outdoor conditions using a suitcase sample approach, where the test samples and the testing equipment were packaged in a compact suitcase, which served both as a transportation tool and as a holder for the samples during outdoor round robin testing. Outdoor round robin characterizations of roll-to-roll coated OPV modules were conducted among 45 laboratories worldwide using this method. The study additionally involved internet based coordination via a common portal that allowed centralized and efficient communication among the partners and a controlled reporting format of the results. The OPV sample performances were tested at each laboratory and compared with a reference Si module. The results revealed a standard deviation of around 5% and less for measurements performed on clear sky days. When the data was normalized to local irradiance values, the standard deviations reached up to 8%, which is still reasonably low compared to earlier reported indoor round robin studies.

Although the technique is applicable only in good weather conditions, based on the aforementioned facts it may offer fast and cheap testing and reporting of performance of organic photovoltaic devices and modules in a comparable and reliable manner and therefore can improve the interoperability among the different groups.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.solmat.2014.07.021.

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