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# Consensus stability testing protocols for organic photovoltaic materials and devices

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ABSTRACT

Procedures for testing organic solar cell devices and modules with respect to stability and operational lifetime are described. The descriptions represent a consensus of the discussion and conclusions reached during the first 3 years of the international summit on OPV stability (ISOS). The procedures include directions for shelf life testing, outdoor testing, laboratory weathering testing and thermal cycling testing, as well as guidelines for reporting data. These procedures are not meant to be

*Abbreviations: OPV*, organic photovoltaics; *JV*, current–voltage characteristics; $J_{sc}$, short circuit current; $V_{oc}$, open circuit voltage; *FF*, fill factor; *PCE*, photoconversion efficiency; *MPP*, maximum power point; *IPCE*, incident- photon-to-electron conversion efficiency; $T_{80}$, period of time when device has decayed 20% from initial measurement; AM1.5G, standard solar spectrum at the Earth's surface; *SMU*, source measure unit; *RTD*, resistive thermal detector; *NOCT*, nominal operating cell temperature

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Protocol
Reporting

qualification tests, but rather generally agreed test conditions and practices to allow ready comparison between laboratories and to help improving the reliability of reported values. Failure mechanisms and detailed degradation mechanisms are not covered in this report.



## 1. Introduction

In contrast to devices from more mature photovoltaic (PV) technologies, organic solar cells still suffer from a relatively non-static performance as a function of time. Most other PV technologies offer some constancy in power output over time and methodologies for their qualification have been developed and are well described in standards [1–3]. At the root of each of these standards are decades of field and laboratory experience associated with failure modes of silicon devices in both semiconductor and photovoltaic industries. Interestingly, it is commonly the case that the majority of the failures of crystalline silicon PV modules are associated with solder joints, busbars and other interconnects [4,5]. Other technologies suffer from different failure modes that may or may not be applicable to organic photovoltaics (OPV). For instance, high levels of light concentration in concentrator PV cause thermal degradation and yellowing of encapsulants, which also leads to non-uniform illumination of the PV cell [6,7]. Thin-film technologies like a-Si, CdTe, and CIGS have reported problems with electrochemical corrosion of $SnO_2$:F or notable sensitivity of the ZnO-based transparent conducting oxide to moisture, as well as shunt hot spots at scribe lines and weak diodes/hot spots due to non-uniformities in processing [8–10]. While some of the lessons learned in these other technologies may aid understanding of degradation modes in OPV systems, the proposed fabrication and usage coupled with the wide variety of non-standard material systems and device architectures presently being considered by the OPV community indicate that a new set of guidelines may be needed. Due to their low cost, limited thermal stability, and little if any efficiency improvements under higher irradiation levels, it is unlikely that OPVs will be employed in high concentration PV systems ($\geqslant$ 10 suns). Additionally, monolithic architectures that generally avoid solder joints and busbars, roll-to-roll solution processing and vacuum evaporation that may permit large area uniformity not achievable by sputtering, and the consideration of a wider variety of transparent contacts that may prove to have different stability, all present potential differences with the existing standards. Furthermore, OPV systems may have other failure modes than inorganic systems including photo-oxidation, change in morphologies of the active layer, and chemical degradation of the electrodes and interfaces [11]. For this reason, a new set of guidelines is being developed, which aim at being able to compare data and claims obtained by different laboratories. The complexity of developing testing procedures to evaluate stability stems from the fact that unlike inorganic technologies, organic photovoltaics is a highly diverse technology with cells that can be prepared with different architectures, using many different materials and combinations thereof, processed by many different methods. All these variables enter as parameters that influence the overall stability performance of the final device. Very often the intrinsic reasons for device breakdown are poorly understood and the alleviation of the device failure is achieved through packaging and encapsulation or other means that empirically remove the problem or reduce it as much as possible. To illustrate the problem, a plot of the power conversion efficiency over time can take virtually any shape before ending with device degradation. Some typical examples are shown in Fig. 1. The time of operation until 80% ($T_{80}$) and 50% ($T_{50}$) of the initial performance are extracted for a device exhibiting a linear decay. In the context of organic solar cells this does present some challenge due to the many different curve shapes that can be encountered and a dogmatic reporting of values cannot be recommended unless the general shape of the curve is known. An agreement has to be made on how decay data have to be evaluated and reported.

In this work we describe the guidelines that through discussions and breakout sessions have been reached during the first three ISOS meetings: ISOS-1 in 2008 (Denver, USA), ISOS-2 in 2009 (Amsterdam, The Netherlands) and ISOS-3 in 2010 (Roskilde, Denmark). The purpose is to enable reasonable accuracy in the comparison of reported stability and lifetime data for organic solar cells produced from polymers and small molecules. Furthermore, rather than establishing qualification tests that tend to be pass/fail protocols, with more limited data collection, the guidelines attempt to coordinate efforts to gather as much information in a controlled manner such that qualification tests may eventually be developed. A very rigorous set of recommendations might be optimal for ensuring the maximum of information that could be extracted from the tests and allowing others to duplicate and compare results. This would however restrict the number of people in the community who could participate to a few certified laboratories and in reality exclude other groups and lead to less general acceptance and development of substandard procedures. Instead of one rigorous standard that could exclude some research groups, three levels of procedures are recommended for each of the main types of testing regimes: Basic (Level 1), Intermediate (Level 2) and Advanced (Level 3), with the last one having a higher level of sophistication and accuracy. If reports on stability measurements were labeled according to this scheme, this would immediately allow others to assess the value of the data and confirm that a known minimum set of operational procedures was followed. Basic (Level 1) procedures should require minimum instrumentation and protocol requirements. This could mean only measuring simple parameters using inexpensive equipment (such as No-Source-Measure Unit and an

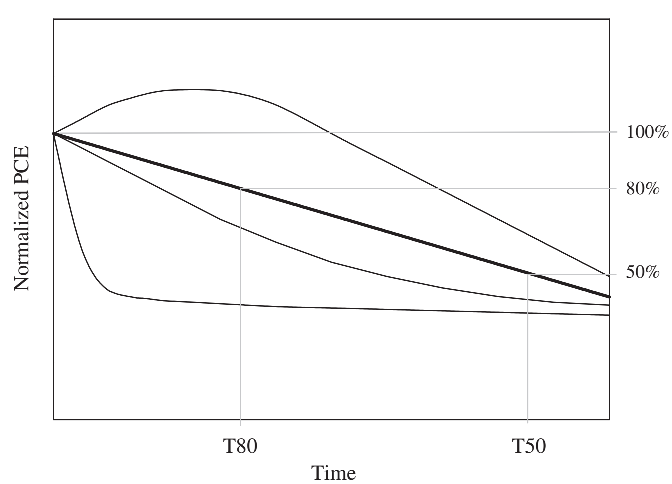


**Fig. 1.** Examples of how the power conversion efficiency for an organic solar cell can evolve with time during operation. The $T_{80}$ and $T_{50}$ are shown for a device showing linear decay. Three other examples of commonly observed decay curves are also presented (an increase in performance followed by decay, some degree of exponential decay and fast initial decay followed by a stable period).

inexpensive light source or natural sunlight). Limited, but potentially useful, results could be obtained. Intermediate (Level 2) procedures should require equipment available at most laboratories, such as source measure units (SMU) to obtain full JV-curves and calibrated solar simulators. In this case, the protocols should allow other groups to reproduce the results with confidence. Advanced (Level 3) procedures should require additional equipment and/or more involved protocols that might be outside the scope of many laboratories. One could also argue that laboratories eligible for the advanced category would naturally invent high level testing and comply with rigorous standards. The procedures described here would therefore mainly be of benefit for laboratories performing at basic and intermediate levels. Although protocols with three different levels of sophistication are recommended, it may be assumed that some of the laboratories will not have the capabilities to entirely fulfill any of the protocols or will be "caught in between" the levels by having conditions used from two different levels. In such a case, it is recommended that the experimenter carefully records all the deviations from the recommended procedure and reports these together with the lifetime data.

## 2. Measuring and reporting device operational stability

An important part of understanding degradation mechanisms is the proper evaluation of the solar cell performance as a function of time. In order to evaluate the stability of a device one has to be able to compare the lifetime measurement results with the results of other devices (with different geometries or produced by different groups). However, it is not as easy a task as it may seem, since there are no standards defined for stability evaluations of OPVs. As a result different groups have reported varying levels of detail, which makes comparisons of different types of devices challenging. For example, some types of solar cells might deliver high efficiencies for a short time, while others will have low efficiencies but can steadily perform at the same level for a long time. In the former case focus often is on the absolute efficiency of encapsulated devices and in the latter case on normalized values of unprotected devices, sometimes without mention of the absolute efficiency. As a consequence of this there is some inconsistency among the stability reports by different groups. In addition some OPV systems are very sensitive to the environmental conditions and the effects of slight changes in the

**Table 1**
Overview of different types of test protocols.

| Three levels | |
|---|---|
| **Basic (Level 1)** | "Hand held" measurements using the simplest equipment and few conditions |
| **Intermediate (Level 2)** | Fixed conditions and protocols suited for most labs |
| **Advanced (Level 3)** | Standardized tests applied in certified labs. Extended range of parameters to monitor, etc. |

| **Test type** | **Dark** | | | **Outdoor** | | |
|---|---|---|---|---|---|---|
| **Test ID** | ISOS-D-1 Shelf | ISOS-D-2 High temp. storage | ISOS-D-3 Damp heat | ISOS-O-1 Outdoor | ISOS-O-2 Outdoor | ISOS-O-3 Outdoor |
| **Light source** | None | None | None | Sunlight | Sunlight | Sunlight |
| **Temp.**[a] | Ambient | 65/85 °C | 65/85 °C | Ambient | Ambient | Ambient |
| **Relative humidity (R.H.)**[a] | Ambient | Ambient (low) | 85% | Ambient | Ambient | Ambient |
| **Environment**[a] | Ambient | Oven | Env. chamber | Outdoor | Outdoor | Outdoor |
| **Characterization light source** | Solar simulator or sunlight | Solar simulator | Solar simulator | Solar simulator | Sunlight | Sunlight and solar simulator |
| **Load**[b] | Open circuit | Open circuit | Open circuit | MPP or open circuit | MPP or open circuit | MPP |

| **Test type** | **Laboratory weathering testing** | | | **Thermal cycling** | | |
|---|---|---|---|---|---|---|
| **Test ID** | ISOS-L-1 Laboratory weathering | ISOS-L-2 Laboratory weathering | ISOS-L-3 Laboratory weathering | ISOS-T-1 Thermal cycling | ISOS-T-2 Thermal cycling | ISOS- T-3 Thermal cycling |
| **Light source** | Simulator | Simulator | Simulator | None | None | None |
| **Temp.**[a] | Ambient | 65/85 °C | 65/85 °C | Between room temp. and 65/85 °C | Between room temp. and 65/85 °C | −40 to +85 °C |
| **Relative humidity (R.H.)**[a] | Ambient | Ambient | Near 50% | Ambient | Ambient | Near 55% |
| **Environment/setup** | Light only | Light & Temp. | Light, Temp. and R.H. | Hot plate/oven | Oven/env. chamb. | Env. chamb. |
| **Characterization light source** | Solar simulator | Solar simulator | Solar simulator | Solar simulator or sunlight | Solar simulator | Solar simulator |
| **Load**[b] | MPP or open circuit | MPP or open circuit | MPP | Open circuit | Open circuit | Open circuit |

| **Test type** | **Solar-thermal-humidity Cycling** | | |
|---|---|---|---|
| **Test ID** | ISOS-LT-1 solar-thermal cycling | ISOS-LT-2 solar-thermal-humidity cycling | ISOS-LT-3 solar-thermal-humidity-freeze cycling |
| **Light source** | Simulator | Simulator | Simulator |
| **Temp.** | Linear or step ramping between room temp. and 65 °C | Linear ramping between 5 and 65 °C | Linear ramping between −25 and 65 °C |
| **Relative humidity (R.H.)** | Monitored, uncontrolled | Monitored, controlled at 50% beyond 40 °C | Monitored, controlled at 50% beyond 40 °C |
| **Environment/setup** | Weathering chamber | Env. chamb. with sun simulation | Env. chamb. with sun simulation and freezing |
| **Characterization light source** | Solar simulator | Solar simulator | Solar simulator |
| **Load**[b] | MPP or open circuit | MPP or open circuit | MPP or open circuit |

[a] The ambient conditions are defined as 23 °C/50%RH in general, and 27 °C/65%RH accepted in tropical countries according to ISO 291(2008): Plastics—Standard atmospheres for conditioning and testing.

[b] Open circuit refers to a simply disconnected device or device connected to a sourcemeter set to 0 current.

conditions are still unclear. It is possible that these seemingly small changes might cause some of the dramatic differences in the device decay features discussed above. Operational lifetimes have been measured under different incident light intensities, with varying spectra (i.e. AM1.5G, real sun or unspecified), under continuous or intermittent illumination, in the dark, encapsulated, inert atmosphere or in air, outside under real conditions, at different temperatures, at specified or unspecified levels of humidity, and the conditions between measurements are usually not stated. Are the devices kept in the dark or under illumination, under short or open circuit or under some bias voltage? A round robin study [12] with the involvement of eighteen different laboratories presented measurements on roll-to-roll coated flexible large-area polymer solar-cell modules that have been measured at one location (Risø DTU) followed by transportation to a participating laboratory for performance measurement and returned to the starting location for re-measurement of the performance. While the main purpose of the project was to demonstrate that with the current OPV technology it is possible to share devices and obtain consistent data even over long periods of time, the results also showed that the conditions (light intensities and spectrum, device temperatures, relative humidity, etc.) of device testing vary from one lab to another. A second round robin or inter-laboratory study with a special focus on comparing OPV stability between laboratories has been carried out in conjunction with ISOS-3 and this has highlighted the complexities associated with agreeing on OPV stability even when the devices are initially prepared and tested at the same location [13]. Therefore, a standardized method of reporting data is an important requirement for further development of the field. The three International Summits on Organic Photovoltaic Stability (ISOS) held since 2008 resulted in some general measurement practices for OPVs that we summarize below.

## 3. Stability measurement protocols

There are different categories of test protocols: dark, outdoor, simulated light & stress testing and thermal cycling. Each of these is subdivided in three levels: Basic (Level 1), Intermediate (Level 2) and Advanced (Level 3). In each of these categories the main test parameters (temperature, humidity, environment, light and electrical load) have been specified (see Table 1). The list of the abbreviations commonly used throughout the protocols can be found in the abbreviations list. Each of the main categories of test protocols is described in more detail in later sections. The word "characterization" will henceforth be used for describing the periodic JV testing of devices. For example, the lowest level of a shelf life test has completely uncontrolled temperature and humidity whereas the most advanced is a damp heat test.

**Table 2**
Overview of dark testing.

| | | ISOS-D-1 (Shelf) | ISOS-D-2 (high temperature storage) | ISOS-D-3 (damp heat) |
|---|---|---|---|---|
| **Test setup** | Light source | None (Dark) | None (Dark) | None (Dark) |
| | Load | Open circuit | Open circuit | Open circuit |
| | Storage temperature | Ambient | 65/85 $\pm$ 2 °C | 65/85 $\pm$ 2 °C |
| | Storage R.H. | Ambient | Ambient (Low) | 85 $\pm$ 3% |
| | Characterization light source | Solar simulator or natural sunlight | Simulated AM1.5G[a] | Simulated AM1.5G[a] |
| **Testing protocol** | Storage temp./R. H. | Monitor ambient values | Control and monitor specimen temp. and monitor R.H. | Control and monitor specimen temp. and R.H. |
| | JV characterization | Refer to Section 3.8 | Refer to Section 3.8 | Refer to Section 3.8 |
| | Min. measurement intervals | Daily to weekly (adjust to device performance) | Daily to weekly (adjust to device performance) | Daily to weekly (adjust to device performance) |
| | Characterization temperature | Monitor | Monitor | Use standard reporting conditions in IEC 60904-3/ ASTM E948 (i.e. 25 $\pm$ 2/ 25 $\pm$ 1 °C) |
| | Characterization irradiance level | Monitor | Control (800–1100 W/m$^2$) | Control (800–1100 W/m$^2$) |
| | IPCE (at $T_0$, $T_{80}$, $T_s$, $T_{s80}$ see Section 4.1) | Optional | Optional | Measure |
| **Output** | Time/date | Report | Report | Report |
| | Characterization light source | Report type and irradiance level | Report type and irradiance level | Report type and irradiance level |
| | Storage temp./R.H. | Report | Report | Report |
| | Instantaneous performance parameters | Report $J_{sc}$ and $V_{oc}$ (report FF and PCE/MPP if applicable) | Report $J_{sc}$, $V_{oc}$, FF, PCE/MPP; JVs optional | Report $J_{sc}$, $V_{oc}$, FF, PCE /MPP; JVs optional |
| | Stability performance parameters | Refer to Section 4 | Refer to Section 4 | Refer to Section 4 |
| | Description of measurement protocol and testing setup | Report | Report | Report |
| **Required equipment** | Characterization light source | Solar simulator (close to AM1.5G) | Solar simulator with AM1.5G | Solar simulator with AM1.5G |
| | Temperature monitoring | Ambient temperature measuring unit | RTD preferred, other device with $\pm$2 °C acceptable | RTD preferred, other device with $\pm$2 °C acceptable |
| | Humidity monitoring | Ambient R.H. measuring unit | Sensor with $\pm$5% capability | Sensor with $\pm$5% capability |
| | JV characterization | Refer to Section 3.8 | Refer to Section 3.8 | Refer to Section 3.8 |
| | Storage | Drawer, etc. | Oven, environmental chamber | Environmental chamber |
| | IPCE measuring system | Optional | Optional | Required |

[a] AM 1.5G stands for the reference solar spectral irradiance at air mass 1.5 Global, given in Table 1 of IEC 60904-9 Photovoltaic devices—Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data. Any other standardized definition of daylight is valid.

**Table 3**
The three different suggested levels of outdoor testing.

| | | ISOS-O-1 (outdoor) | ISOS-O-2 (outdoor) | ISOS-O-3 (outdoor) |
|---|---|---|---|---|
| **Test Setup** | Light source | Direct sunlight in outdoor conditions. Choose a place away from possible shadows | Direct sunlight in outdoor conditions. Choose a place away from possible shadows | Direct sunlight in outdoor conditions. Choose a place away from possible shadows |
| | Mounting | Static: front side oriented towards the equator, at latitude angle<br>Tracking: front side facing sun | Static: front side oriented towards the equator, at latitude angle<br>Tracking: front side facing sun | Static: front side oriented towards the equator, at latitude angle<br>Tracking: front side facing sun |
| | Load (refer to Section 3.9) | MPP tracking—preferred. Open circuit—optional | MPP tracking—preferred. Open circuit—optional | MPP (resistor, passive) or MPP tracking (active) |
| | Temperature | Ambient | Ambient | Ambient |
| | R.H. | Ambient | Ambient | Ambient |
| | Characterization light source | Inside with simulated light | Outside under sunlight | Outside regularly and inside at certain periods |
| **Testing protocol** | Temp./R.H. | Monitor ambient values | Monitor NOCT and ambient R.H. | Monitor NOCT and ambient R.H. |
| | Solar irradiance (in $W/m^2$) and irradiation (in $MJ/m^2$) | Monitor irradiance and calculate accumulated irradiation | Monitor irradiance and calculate accumulated irradiation | Monitor irradiance and calculate accumulated irradiation |
| | JV characterization | Refer to Section 3.8 | Refer to Section 3.8 | Refer to Section 3.8 |
| | Min. measurement intervals | Daily to weekly (adjust to device performance) | 1/15 min–1/1 h recommended to establish variations across the day | Outside: 1/15 min–1/1 h to establish variations across the day; Inside: weekly or monthly |
| | Characterization temperature | Monitor specimen temperature on backside | Monitor specimen temperature on backside | Monitor specimen temperature on backside |
| | Characterization irradiance level | Monitor | Monitor irradiance | Monitor irradiance |
| | Wind monitoring | Optional | Optional | Monitor wind speed down to 0.25 m/s. The system should be installed ca. 1.2 m to the east or west of the devices under test and 0.7 m higher |
| | IPCE (at $T_0$, $T_{80}$, $T_s$, $T_{s80}$ see Section 4.1) | Optional | Optional | Measure |
| | Note data taken in ranges | Optional | Ambient temperature outside of range $20 \pm 15$ °C<br>Irradiance below 400 $W/m^2$ | Ambient temperature outside of range $20 \pm 15$ °C<br>Irradiance below 400 $W/m^2$<br>Wind speeds outside of range $1 \pm 0.75$ m/s<br>For 10 min following wind speeds exceeding 4 m/s<br>Wind direction within $\pm 20°$ east or west |
| **Output** | Location/time | Report latitude, longitude and date | Report latitude, longitude and date | Report latitude, longitude and date |
| | Irradiance and irradiation | Refer to Section 3.2.2 | Refer to Section 3.2.2 | Refer to Section 3.2.2 |
| | Exposure temp./R.H. | Report ambient values | Report NOCT and R.H. | Report NOCT and R.H. |
| | Instantaneous performance parameters | Report $J_{sc}$ and $V_{oc}$ (FF and PCE/MPP and/or full JVs if possible) | Report $J_{sc}$, $V_{oc}$, FF, PCE/MPP; JVs optional | Report $J_{sc}$, $V_{oc}$, FF, PCE/MPP; JVs optional |
| | Stability performance parameters | Refer to Section 4 | Refer to Section 4 | Refer to Section 4 |
| | Characterization light source | Report type and irradiance level | Report sunlight irradiance | Report type and irradiance level |
| | Wind | Optional | Optional | Report |
| | IPCE | Optional | Optional | Report |
| | Description of measurement protocol and setup | Report | Report | Report |
| | Load type | Report | Report | Report |
| **Required equipment** | Characterization light source | Solar simulator (close to AM1.5G) | Sunlight under clear sky conditions | Sunlight under clear sky conditions and solar simulator with AM1.5G |
| | Temperature monitoring | Ambient temperature measuring unit | RTD preferred, other device with $\pm 2$ °C acceptable | RTD preferred, other device with $\pm 2$ °C acceptable |
| | R.H. monitoring | Ambient R.H. measuring unit | Sensor with $\pm 5\%$ capability | Sensor with $\pm 5\%$ capability |
| | Irradiance monitoring | Pyranometer and/or photodiode | Irradiance monitoring unit (for example, pyranometer) | Matched photodiode for solar simulator and sunlight irradiance monitoring unit (for example, pyranometer) |
| | Load | Refer to Section 3.9 | Refer to Section 3.9 | Refer to Section 3.9 |
| | Fixture | Tracking system preferred, stationary acceptable; bottom edge $> 0.6$ m above horizontal surface | Tracking system preferred, stationary acceptable; bottom edge $> 0.6$ m above horizontal surface | Tracking system preferred, stationary acceptable; bottom edge $> 0.6$ m above horizontal surface |
| | Wind monitoring | Optional | Optional | Required, weather station |

**Table 3** (*continued*)

| | ISOS-O-1 (outdoor) | ISOS-O-2 (outdoor) | ISOS-O-3 (outdoor) |
|---|---|---|---|
| JV characterization | Refer to Section 3.8 | Refer to Section 3.8 | Refer to Section 3.8 |
| IPCE measuring system | Optional | Optional | Required |

The goal of this set of recommended procedures is to increase the amount of data that can readily be compared between different laboratories. As determining the effect of different variables is still in the process of being investigated, it is unclear which variables must be carefully controlled. However, due to the unknown relationship of different stress conditions on device stability it has been suggested that the number and variety of standardized tests should be limited to a set of likely testing conditions until a more sophisticated and relevant set of testing conditions can be identified based on the data provided by inter-laboratory comparisons. For instance, since the quantitative effect of temperature and humidity has not been well established, limiting the number of damp heat conditions to two should aid in more direct comparisons. Due to various types/rates of degradation processes it might be required that the logging interval is adjusted to the timescale of performance variations especially at the beginning of the test in order to correctly establish the initial and stabilized performances of the device. Moreover, despite the fact that $T_{80}$ is considered as the lifetime of the device, it can be useful to totally degrade the sample in order to establish the full character of the degradation process.

The nominal operating cell temperature (NOCT) used in the protocols may be determined by affixing a small temperature sensor such as a resistive thermal detector (RTD) like a PT-100 probe on the back of a representative device or sample.

### 3.1. *Dark storage*

Shelf life studies are carried out by leaving samples in the dark with no load. These can range from leaving a sample at ambient conditions ISOS-D-1 (shelf) to controlling the temperature with a hotplate or oven, ISOS-D-2 (high temperature storage) to carefully control both the temperature and humidity with an environmental chamber ISOS-D-3 (damp heat). The different elements of the recommended practices are provided in Table 2.

If a testing of the specimen under low temperatures is required in order to simulate winter conditions such as when the specimen is covered by a snow layer, the experimenter is advised to proceed according to the ISOS-D-2 protocol with storage temperature being set to $-18\,^{\circ}$C. For more advanced low temperature testing however, thermal cycling ISOS-T-3 (described in Section 3.4) or solar thermal humidity freeze cycling (described in Section 3.5) is advised.

### 3.2. *Outdoor*

#### 3.2.1. *Standards for outdoor testing*

The seemingly most straightforward manner of testing photovoltaic devices is to expose them outdoors and monitor their performance either *in situ* under natural sunlight or indoors with a solar simulator at periodic intervals. While *in situ* monitoring is the most convenient and perhaps scalable, it can raise several issues, including the effects due to temperature coefficients, cloud cover, non-linearity between performance and irradiance, and wind and seasonal variation of energy dosage received by the specimen. Furthermore, the variations associated with different climates, latitudes, and altitudes should all be presented to try to allow for ready comparison between different geographic locations.

Thus, three categories of outdoor testing were established, such as ISOS-O-1, where devices are kept outside and periodically measured inside under solar simulation, ISOS-O-2, where devices are kept outside and measured outside under daylight and ISOS-O-3, where devices are kept and measured outside, but also from time to time measured inside for improving the accuracy of measurements. The suggested procedures are outlined in Table 3.

#### 3.2.2. *Irradiation measurements and reporting of normalized data*

When carrying out outdoor measurements of performance there are a number of issues that can influence the accuracy of the measurements, such as the inconsistency between irradiation level measured by a sensor and actual irradiation received by specimen (due to shadowing effects) or time delay between measurements of irradiation level and JV. Thus, precautions have to be taken to avoid such errors. Specimens have to be placed away from any possible shadowing. The precise times of irradiation measurement and JV testing need to be recorded and correlated. Additionally, continuous measurement of irradiation level is required to establish the total energy dose received by the specimen during the test (can possibly also be obtained from available databases). When reporting degradation curves of normalized photo-current and PCE, it is recommended that only data measured in the irradiation range of 800–1100 W/m$^2$ is taken to avoid any nonlinear effects. However, full data of photo-current and PCE together with the irradiance should be provided as well. The parameters should be plotted versus the accumulated energy dose and the corresponding time range should be provided as well.

### 3.3. *Laboratory weathering testing*

The stability of organic solar cells strongly depends on the spectral distribution of the light source they are being exposed to [13,14]. The cells are especially sensitive towards the quantity of UV light and can thus perform differently depending on the type of the light source [13]. In Section 3.7 a number of light sources are presented, which are commonly used in the OPV community for device characterization. The list contains setups with various spectral distributions (and UV quantities). For accurate comparison of indoor stability testing with real life, a light source that closely matches the spectral distribution of daylight has to be chosen. Thus, in Table 4 we chose to leave a freedom of choice of light source for the ISOS-L-1 test, provided that the spectral distribution is reported, while restrictions are put on the type of light source used for ISOS-L-2 & L-3. The light sources should closely match the solar spectrum such as xenon arc with daylight filter, or calibrated metal halide lamps with daylight filter. Lamps with class A for spectral mismatch in the range of 400–1100 nm including a significant level of UV radiation down to 300 nm can also be used. It is crucial for these types of tests that the light source intensity is monitored over time, since the spectra of the lamps can change with aging. Standard equipment for laboratory weathering monitors either the UV intensity at 340 or 420 nm, or in the range 300–400 nm, and adjusts the lamp power to keep this intensity constant. This is of particular importance in the context of polymers as their degradation is closely related to the amount of UV-radiation received, and for OPV a similar effect is expected.

### 3.4. Thermal cycling (TC)

Final product certification typically requires thermal cycling with a temperature range well outside the limits of normal use in order to show that thermal cycling will not be a degradation mechanism

**Table 4**
Suggested levels of laboratory weathering testing.

| | | **ISOS-L-1 (laboratory simulations)** | **ISOS-L-2 (laboratory simulations)** | **ISOS-L-3 (laboratory simulations)** |
|---|---|---|---|---|
| **Test Setup** | Test setup | Constant light source (spectrum preferably close to AM1.5G). Can include environmental chambers | Weathering chamber with AM 1.5G[a] light source, ±10% irradiance uniformity at exposure area level. | Weathering chamber with AM 1.5G[a] light source, ±10% irradiance uniformity at exposure area level. |
| | Mounting | Specimen's surface normal to light beam, continuous illumination | Specimen's surface normal to light beam, continuous illumination | Specimen's surface normal to light beam, continuous illumination |
| | Load | MPP tracking – preferred open circuit – optional | MPP tracking – preferred open circuit – optional | MPP (resistor, passive) or MPP tracking (Active) |
| | Temperature | Monitored, uncontrolled | Controlled (65/85 °C), monitored | Controlled (65/85 °C), monitored |
| | R. H. | Uncontrolled, monitored ambient | Uncontrolled, monitored ambient | Controlled (50%) |
| | Irradiance level | 400–1200 W/m$^2$ | 600–1200 W/m$^2$ | 600–1200 W/m$^2$ |
| | Performance measurement | *In situ* or with additional characterization setup | *In situ* or with additional characterization setup | Under calibrated AM1.5G solar simulator |
| **Testing protocol** | Temp./R.H. | Monitor specimen temperature and ambient R.H. | Monitor specimen temperature and ambient R.H. | Monitor specimen temperature and ambient R.H. |
| | Light intensity | Monitor | Control at constant level of UV and monitor | Control at constant level of UV and monitor |
| | JV characterization | Refer to Section 3.8 | Refer to Section 3.8 | Refer to Section 3.8 |
| | Min. measurement intervals | Daily to weekly (adjust to device performance) | Daily to weekly (adjust to device performance) | Daily to weekly (adjust to device performance) |
| | Characterization temp. and irradiance | Monitor specimen temperature on backside | Monitor specimen temperature on backside | Monitor specimen temperature on backside |
| | IPCE (at $T_0$, $T_{80}$, $T_s$, $T_{s80}$ see Section 4.1) | Optional | Optional | Measure |
| **Output** | Time | Report date | Report date | Report date |
| | Instantaneous performance parameters | Report $J_{sc}$ and $V_{oc}$ (FF and PCE/MPP and/or full JVs if possible) | Report $J_{sc}$, $V_{oc}$, FF, PCE/MPP (full JVs optional) | Report $J_{sc}$, $V_{oc}$, FF, PCE/MPP (full JVs optional) |
| | Stability performance parameters | Refer to Section 4 | Refer to Section 4 | Refer to Section 4 |
| | Irradiance | Report irradiance level during exposure and characterization. For large area modules measure/report uniformity of illumination | Report irradiance level during exposure and characterization. For large area modules measure/report uniformity of illumination | Report irradiance level during exposure and characterization. For large area modules measure/report uniformity of illumination |
| | Spectrum | Report light spectrum | Report light spectrum | Report light spectrum |
| | Temperature/R.H. | Report specimen temperature during storage and measurement; report ambient R.H. | Report specimen temperature during storage and measurement; report ambient R.H.. | Report specimen temperature during storage and measurement; report ambient R.H. |
| | IPCE | Optional | Optional | Report |
| | Description of measurement protocol and setup | Report | Report | Report |
| **Required equipment** | Temperature | RTD preferred, other device with ±2 °C acceptable | RTD preferred, other device with ±2 °C acceptable (e.g., BST/BPT) | RTD preferred, other device with ±2 °C acceptable (e.g., BST/BPT) |
| | R.H. monitoring | Ambient R.H. measuring unit | Required, ±5% capability | Required, ±5% capability |
| | Irradiance monitoring | Photodiode/pyranometer | Photodiode/pyranometer | Photodiode/pyranometer |
| | Load | Refer to Section 3.9 | Refer to Section 3.9 | Refer to Section 3.9 |
| | Artificial light source (weathering chambers) | Constant light source (spectrum preferably close to AM1.5G) | Weathering chamber with AM 1.5G[a] light source, ±10% irradiance uniformity at exposure area level. | Weathering chamber with AM 1.5G[a] light source, ±10% irradiance uniformity at exposure area level. |
| | JV measuring setup (refer to Section 3.8) | Required | Required | Required |
| | IPCE measuring system | Optional | Optional | Required |

[a] AM 1.5G stands for the reference solar spectral irradiance at air mass 1.5 Global, given in Table 1 of IEC 60904-3 Photovoltaic devices—Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data. Any other standardized definition of daylight is valid.

during the life of the product. However, this test may be inconvenient because it requires advanced equipment and can provide limited data during development, especially when samples are susceptible to damage from thermal cycling. In other words, one cycle between 85 and −40 °C may damage a cell completely and this test serves the function of a pass/fail test instead of a more gradual degradation test that could discern between cells with similar but different resistances to damage from thermal cycling. Therefore there are several categories of tests that depend both on the level of equipment available and the resistance of the cell itself towards damage caused by thermal cycling (Table 5).

Basic (ISOS-T-1) category is an initial test in which a sample is cycled from a high temperature (65/85 °C) to room temperature using a hot plate set to the high temperature and a clock-actuated switch to turn the hot plate on/off. Intermediate (ISOS-T-2) cycling is similar except that more advanced equipment such as

**Table 5**
Suggested levels of thermal profile testing.

| | | ISOS-T-1 (thermal cycling) | ISOS-T-2 (thermal cycling) | ISOS-T-3 (thermal cycling) |
|---|---|---|---|---|
| **Testing setup** | Test environment | Dark | Dark | Dark |
| | Load | Open circuit | Open circuit | Open circuit |
| | Storage temperature | Cycle between room temperature and 65/85 °C by cycling on/off hot plate | Cycle between room temperature and 65/85 °C. Follow the recommended thermal cycle on Table 6. | Cycle from −40 to 85 °C with 1–8 cycles per day. Follow the recommended thermal cycle on Table 7 and Fig. 2. |
| | Storage R.H. | Ambient | Ambient, monitored | Controlled (55%), monitored |
| | Characterization light source | Solar simulator or natural sunlight | Simulated AM1.5G[a] | Simulated AM1.5G[a] |
| **Testing protocol** | Temperature | Monitor specimen temperature | Monitor specimen temperature | Monitor specimen temperature |
| | JV measurement | Refer to Section 3.8 | Refer to Section 3.8 | Refer to Section 3.8 |
| | Min. measurement intervals | Every 1–10 cycles for first 50 cycles, then once every 50 cycles (adjust to specimen performance) | Every 1–10 cycles for first 50 cycles, then once every 50 cycles (adjust to specimen performance) | Every 1–10 cycles for first 50 cycles, then once every 50 cycles (adjust to specimen performance) |
| | Characterization temperature | Monitor specimen temperature on backside | Monitor specimen temperature on backside | Monitor specimen temperature on backside |
| | Characterization irradiance level | Monitor | Control (800–1100 W/m$^2$) | Control (800–1100 W/m$^2$) |
| | IPCE (at $T_0$, $T_{80}$, $T_s$, $T_{s80}$ see Section 4.1) | Optional | Optional | Required |
| **Output** | Time | Report | Report | Report |
| | Characterization light source | Report type and irradiance level | Report type and irradiance level | Report type and irradiance level |
| | Instantaneous performance parameters | Report $J_{sc}$ and $V_{oc}$ (FF & PCE/MPP and/or full JVs if possible) | Report $J_{sc}$, $V_{oc}$, FF, PCE/MPP (full JVs optional) | Report $J_{sc}$, $V_{oc}$, FF, PCE/MPP (full JVs optional) |
| | Stability performance parameters | Refer to Section 4 | Refer to Section 4 | Refer to Section 4 |
| | Storage temperature/R.H. | Report specimen temperature and ambient R.H. | Report specimen temperature and ambient R.H. | Report specimen temperature and ambient R.H. |
| | IPCE | Optional | Optional | Report |
| | Description of measurement protocol and setup | Report | Report | Report |
| **Required equipment** | Characterization light source | Refer to Section 3.7 | Refer to Section 3.7 | Refer to Section 3.7 |
| | Temperature | RTD preferred, other device with ±2 °C acceptable | RTD preferred, other device with ±2 °C acceptable | RTD preferred, other device with ±2 °C acceptable |
| | R.H. monitoring | Ambient R.H. measuring unit | Required, ±5% capability | Required, ±5% capability |
| | Storage | Hot plate or oven with capability to cycle between ambient temperature and (65/86 °C) | Oven or env. chamber with capability to cycle between ambient temperature and (65/85 °C) with a controlled/gradual change in temperature over time, see Table 6 | Chamber with capability to cycle between −40 and 85 °C with a controlled/gradual change in temperature over time, see Table 7 and Fig. 2 |
| | JV measuring setup | Refer to Section 3.8 | Refer to Section 3.8 | Refer to Section 3.8 |
| | IPCE measuring system | Optional | Optional | Required |

[a] AM 1.5G stands for the reference solar spectral irradiance at air mass 1.5 Global, given in Table 1 of IEC 60904-3 Photovoltaic devices—Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data. Any other standardized definition of daylight is valid.

**Table 6**
Recommended thermal profile for Intermediate (ISOS-T2) thermal cycling. 6–9 cycles are performed in one day.

| | TIME (min) | 0 | 15 | 30 | 45 | 60 | 75 | 90 | 105 | 120 | 135 | 150 | 165 | 180 | 195 | 210 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max temp. = 65 °C | Temp. (°C) | 25 | 25 | 32 | 38 | 45 | 52 | 52 | 58 | 65 | 65 | 58 | 52 | 45 | 32 | 25 |
| Max temp. = 85 °C | Temp. (°C) | 25 | 25 | 35 | 45 | 55 | 65 | 75 | 75 | 85 | 85 | 75 | 65 | 55 | 35 | 25 |

an environmental chamber or a hot plate with the ability to automatically vary temperature over time is used to precisely cycle the temperature gradually over the course of the cycle period (see Table 6 for recommended cycle profile). Advanced (ISOS-T-3) category requires the most advanced equipment where the temperature can be cycled from 85 to $-40$ °C and controlled during the course of the cycle (see Table 7 and Fig. 2 for recommended cycle profile).

### 3.5. Solar thermal humidity cycling/solar thermal humidity freeze cycling (STH/STHF)

Solar thermal humidity cycling (STH) and solar thermal humidity freeze (STHF) cycling are enhanced types of thermal cycling that enables simulation at the laboratory scale the natural diurnal and seasonal variations in solar radiation, temperature and humidity experienced by OPVs in service conditions. These can be classified in the Advanced (Level 3) category as well. An example of STHF cycle is shown in Fig. 3.

The combined effects of light/dark cycling, temperature cycling and moisture cycling, as in the real world, add stresses to specimens that are crucial for good correlation. In particular, the addition of light accounts for two important effects:

- In contrast to dark oven convective heating that ensures a uniform specimen temperature, the unidirectional IR heating from incident light induces a temperature gradient through the material from the exposed surface to the back, which creates additional thermo-mechanical stress and may alter the rate of the various diffusion processes.
- The current generation is a source of electrically induced stresses that enhance failure modes such as the corrosion of metallic parts [11].

**Table 7**
Recommended cycle for advanced (ISOS-T3) thermal cycling. 6–9 cycles are performed in one day.

| Time (min) | 0 | 47 | 62 | 152 | 167 | 210 |
|---|---|---|---|---|---|---|
| Temp. (°C) | 25 | $-40$ | $-40$ | 85 | 85 | 25 |

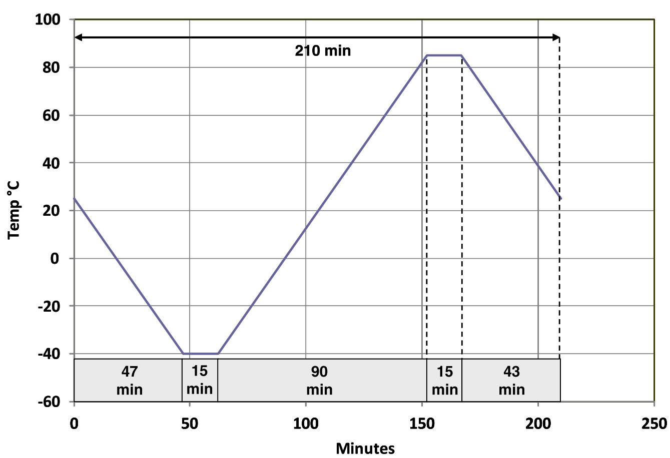


**Fig. 2.** Graphic representation of the recommended thermal cycling profile.

### 3.6. Low light measurements

An important advantage of OPV is their good performance under low-light and indoor conditions. Since this fact is receiving more and more attention these measurements require standardization as well. Low-light measurements can be classified in two general categories with regards to their target application for indoor or outdoor use. There is a fundamental difference between the measurement and qualification of solar cells with the purpose for indoor or outdoor applications since the spectra of indoor light sources differ significantly in both spectral distribution and irradiance level.

For outdoor applications the reference spectrum is the AM1.5G spectrum of the sun, and lamps should match this spectrum most closely or should at least be corrected with a mismatch factor that can be calculated from the external quantum efficiency of the OPV cell and knowledge of the measurement spectrum. To perform low-light measurements under the AM1.5G spectrum a standard solar simulator should be used. The irradiance level can then be decreased either through the use of neutral density filters or through the use of wire mesh or slotted/punched metal sheets, which decrease the intensity through shadowing. This second

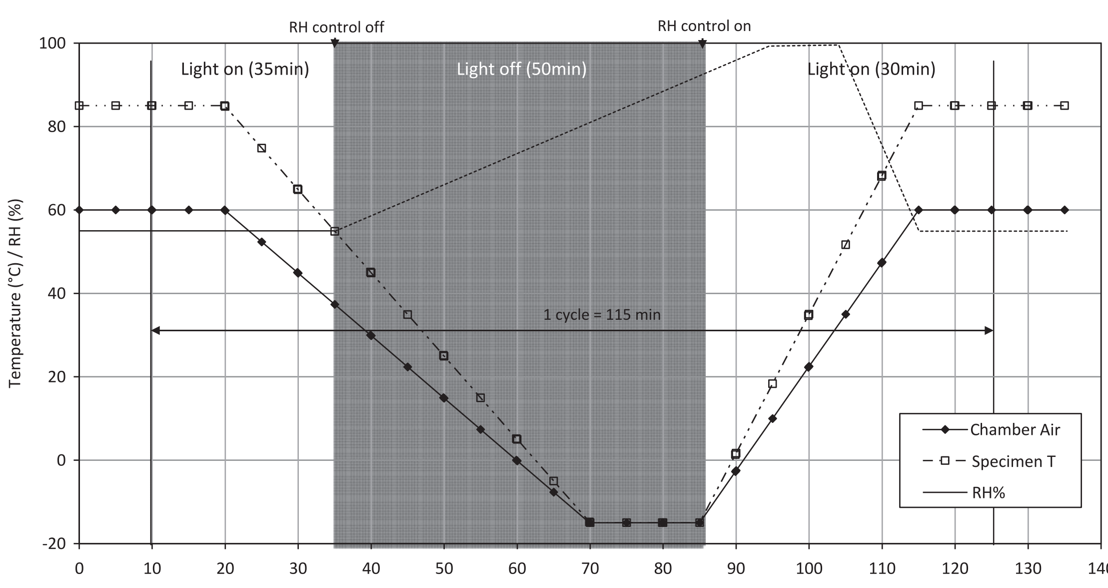


**Fig. 3.** Graphic representation of a possible solar thermal humidity-freeze cycling profile.

approach is useful for measuring larger area devices, and care should be taken that the distance between the sample and the slotted metal is much larger than the separation of the holes in the metal plate used. Apart from that the procedure for measurement is identical to the measurement procedure for JV-characterization as outlined in Section 3.8. For indoor applications, e.g., the use of solar cells inside buildings, artificial light sources like fluorescent lamps, incandescent lamps and LEDs are used. Since in offices and large rooms mostly fluorescent lamps are used we suggest the use of fluorescent lamps for indoor performance characterization. Note that the types of the fluorescent lamps discussed here are different from the UV type fluorescent lamps presented in Section 3.7. A fluorescent lamp for conventional light testing converts UV-light into visible light and the spectrum of one lamp to the other varies depending on the fluorescent materials used and is completely different to the AM1.5G spectrum of the sun. For comparison the spectrum of a fluorescent lamp and the AM1.5G spectrum are shown in Fig. 4. The illuminance of a fluorescent lamp is measured in lx and is weighted by the sensitivity of the human eye. Typical values of the illuminance requirements for offices range between 200 and 1000 lx, which is approximately a factor 100–500 lower than the 1000 W/m$^2$ of the AM1.5G spectrum.

From a practical point of view, the JV characteristics can be measured according to the procedures outlined in Section 3.8. The lower current under low light compared to measurements at 1 sun (a factor of 100–500) results in a lower signal to noise ratio (SNR), which can be improved by increasing the integration time. The illuminance can be adjusted by varying the distance between the lamp and the solar cell. The distance between the solar cell and the light source should be chosen $>30$ cm to guarantee a homogeneous illumination. The fluorescent lamps should warm up for $>15$ min until a constant illuminance is reached. We emphasize that the performance of solar cells under low light conditions and 1 sun illumination might be significantly different. Good OPV cells under 1 sun illumination might be limited in performance under low light conditions and vice versa since the parallel resistance is of predominant importance for low light applications [15], while the impact of transport limitations is less severe in low light conditions (Table 8).

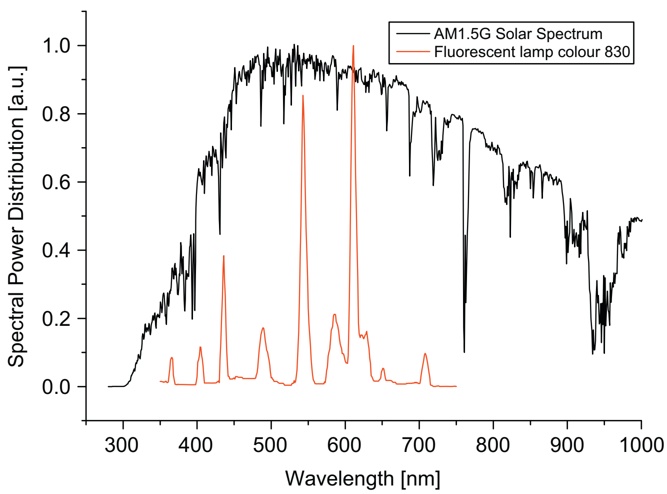


**Fig. 4.** Comparison of the spectrum of a fluorescent lamp with the light color 830 and the AM1.5 spectrum of the sun.

### 3.7. Light source options

Aside from enabling electricity production, natural daylight affects OPV cells in a number of ways. For instance, the UV range (between 290 and 400 nm) and the short wavelengths of the visible radiation range induce photochemical processes in organic materials, such as chain scissions, cross-linking, photo-discoloration and photo-bleaching, at various rates depending on the nature and morphology of the polymer. These processes lead to a decrease in mechanical, electrical and cosmetic properties. The visible range (400–800 nm) accounts for differences in surface temperatures depending on the color of the exposed parts, resulting in different degradation rates. The production of photocurrent within the device may generate damaging electrical and/or electrochemical stresses that affect the metallic contacts [11]. Most organic materials absorb the infrared component of daylight (beyond 800 nm) and release the absorbed energy as heat, raising the temperature. It is expected that in future generations of OPVs, a portion of the IR range will be used to generate photocurrent as

**Table 8**
Recommended test procedures for low light level or Fluorescent lamp stability and JV testing.

| | | Basic (Level 1) | Advanced (Level 3) |
|---|---|---|---|
| **Testing Protocol** | Light source | Fluorescent lamp | Fluorescent lamp |
| | Illuminance | Measured (1000 lx suggested) | Measured (1000, 500 and 200 lx). Illuminance can be adjusted by distance from lamp to solar cell. |
| | Spectrum | Light color 830 recommended. Report light color and manufacturer | Light color 830 recommended. Report light color and manufacturer. Measure spectrum. |
| | JV measurement | Refer to Section 3.8 | Refer to Section 3.8 |
| | Temperature | Measure | Measure |
| | UV-light prior measurement. | Optional | 5 min |
| **Output** | Measurement light source | Report type and irradiance level | Report type and irradiance level |
| | Performance parameters | Report $J_{sc}$ and $V_{oc}$ (FF and PCE and MPP (power density) and/or full JVs if possible) | Report $J_{sc}$, $V_{oc}$, FF, PCE and MPP (power density) (full JVs optional) |
| | Temperature | Report | Report |
| | IPCE | Optional | Report |
| | Description of measurement protocol and setup | Report | Report |
| **Required equipment** | Light source | Fluorescent lamp (light color 830 suggested) | Fluorescent lamp (light color 830 suggested) |
| | Luxmeter | Required | Required |
| | Calibrated spectrometer | Optional | Required |
| | JV measuring setup | Refer to Section 3.8 | Refer to Section 3.8 |

this is the case for inorganic PV technologies. These photochemical, thermal, and electrical stresses cannot be accounted for in laboratory tests that do not involve light or that use light that does not provide a good match to daylight. In order to reproduce the same failure modes and property changes as produced by daylight under laboratory conditions, it is important that the artificial light source simulates as closely as possible the characteristics of daylight in all spectral ranges (i.e. UV, visible and near IR). Since the intensity and spectral power distribution of daylight varies depending on the geographical location, the time of the day, the season, the angle of exposure, the climatic conditions and the altitude, it is recommended to use a standardized definition of daylight, such as the AM 1.5G reference spectral irradiance (according to IEC 60904-3 and IEC 60904-9 in Table 1). Despite the variety of artificial light sources used for OPV stability testing, a limited number match AM 1.5G (Table 9). Light sources used for PV performance measurements emit mainly between 400 and 1100 nm. These include xenon arc, metal halide, sulfur plasma, tungsten halogen, and combinations of LED lamps. Among them, only xenon arc and metal halide emit a significant amount of UV radiation to induce photodegradation processes and their emission spectrum can be tuned to match the daylight spectral distribution [16,17]. Other light sources such as fluorescent UVA and UVB tubes, widely used in the plastic and paint industry, emit in the UV range only. While UVA sources present a good match to daylight between 290 and 340 nm, they do not emit significantly beyond 380 nm. UVB sources exhibit a maximum of emission at 313 nm, which decreases at longer wavelength; beyond 350 nm, no significant radiation is measured. Mostly due to the important proportion of radiation emitted below 290 nm, UVB tubes are known to be unsuitable to simulate the photochemical effect of daylight [18,19].

Filtered medium pressure mercury arc is a source emitting monochromatic radiation in the UV and visible range up to 560 nm used for photo-aging experiment [20,21]. Although this source bears little resemblance to daylight, in particular in the visible and IR ranges, it has been shown to induce the same photodegradation reactions as daylight for a large number of polymers [20]. Although carbon arc has been historically used for artificial weathering since 1910, when no other laboratory source was available, their spectral distribution poorly matches daylight. In Figs. 5 and 6, the typical spectral power distributions of some of the artificial light sources discussed above are shown, together with the AM 1.5G reference solar spectral irradiance. Among the variety of light sources used at the laboratory scale, only filtered xenon arc [22] and some types of metal halide sources reproduce fairly well the daylight spectrum. These sources also represent the vast majority of light sources used in solar simulators, justifying the use of solar simulators to perform short-term weathering experiments.

### 3.8. *Suggested JV measurement techniques for different levels*

*The basic procedure for JV measurement*. In the simplest possible measurement the open circuit voltage ($V_{oc}$) and the short circuit current ($I_{sc}$) can be recorded. If a simple voltmeter is used it should present a high input impedance ( $>10^{12}\ \Omega$) when measuring open circuit voltage. If the equipment capacity permits however it is strongly recommended to follow procedures of JV measurements described for the intermediate level (Level 2). It is recommended that the measurements are repeated until 3% stability is obtained within the measurements. *Intermediate procedure for JV measurement*: It is recommended to employ a source meter such that the full JV-plane can be mapped. The JV-curve should be swept over the voltage range for the junction(s) that avoids shorting the devices. For single-junctions this will typically be in the $\pm 1$–2 V range. For serially connected devices or multi-junctions the voltage range is the multiple of the number of junctions with the voltage range. A useful investigation of failure mechanisms requires measurement into the reverse bias and the forward injection range. In general a reasonable rule of thumb for the measurement range is to measure from $-2V_{oc}$ to $+3V_{oc}$. The operator should ensure that sweeping the voltage from both positive to negative and negative to positive gives the same result and that the test setup is not subject to capacitive loading

**Table 9**
Overview of artificial light sources used in the OPV field and relevance to AM1.5G spectral power distribution.

| Type of light source | Comments | Comparison to AM 1.5G |
|---|---|---|
| **Sulfur plasma** | Broad continuous spectrum in the visible and IR range, cannot reach class A designation for spectral match between 400 and 1100 nm<br>No significant emission in the UV range | Does not match AM 1.5G |
| **Tungsten halogen** | Broad continuous spectrum in the visible and IR range, cannot reach class A designation for spectral match between 400 and 1100 nm<br>No significant emission in the UV range<br>Spatial uniformity issues to be expected | Does not match AM 1.5G |
| **LED lamps** | Tunable colors. Large array of LEDs can simulate light approaching AM1.5G (see for example, [23]), but single LEDs cannot presently reach Class A designation from 400 to 1100 nm | Does not match AM 1.5G |
| **UVA and UVB fluorescent tubes** | UVA lamps: good match to daylight between 290 and 340 nm, no emission in the visible and IR ranges<br>UVB lamps: important emission below 290 nm, no emission in the visible and IR ranges | Do not match AM 1.5G |
| **Medium pressure mercury arc** | Discrete emission of nearly monochromatic radiation between 290 and 560 nm. No radiation emitted beyond 560 nm | Does not match AM 1.5G |
| **Xenon arc** | Very good match to AM1.5G with appropriate filtering, can meet class A requirements for spectral match<br>Lamp aging tends to affect more UV range over other ranges, so monitoring in UV range is critical to maintain proper irradiance level | Good match AM1.5G (with correct filter system) |
| **Metal halide** | Very good match to AM1.5G with appropriate filtering, can meet class A requirements for spectral match (metal halide global types), require stable source of electrical power for stability of emission spectrum | Good match AM1.5G (certain types) |

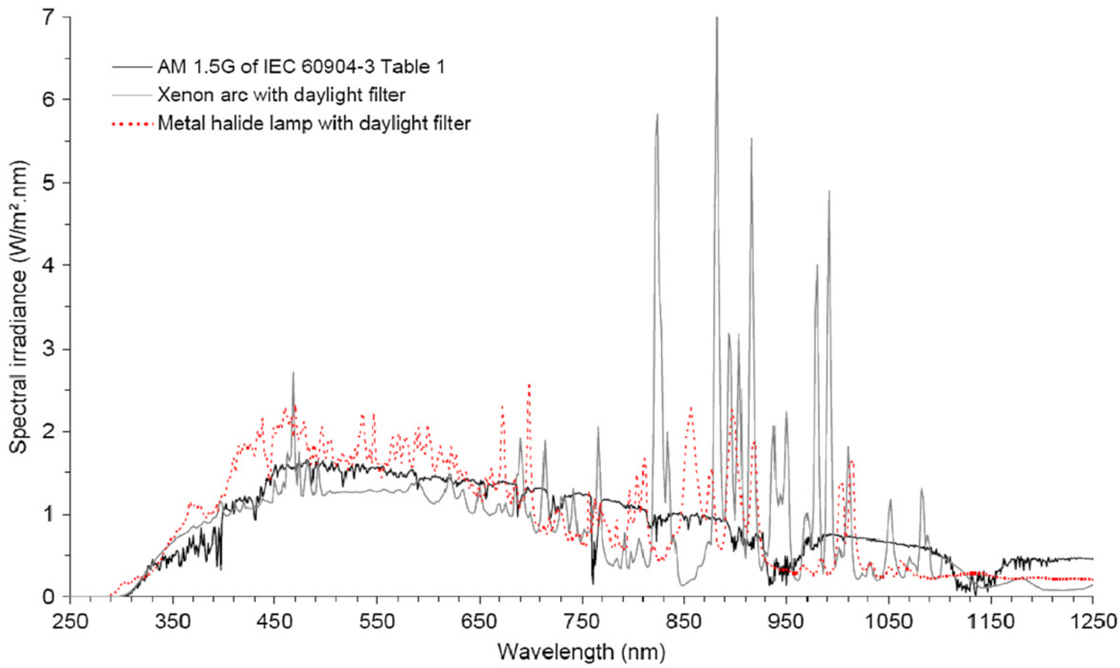


**Fig. 5.** Typical spectral power distributions of xenon arc and metal halide lamps with daylight filters. AM1.5G defined in IEC 60904-3 Table 1 is also shown for comparison.

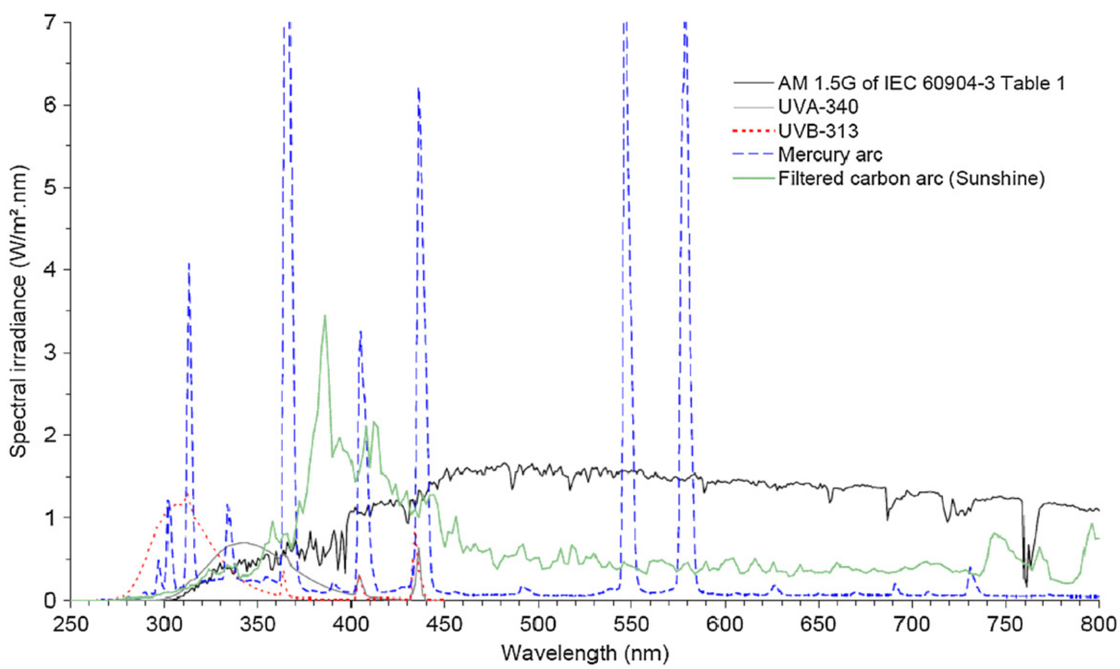


**Fig. 6.** Typical spectral power distributions of UVA-340 and UVB-313 fluorescent lamps, filtered carbon arc and medium pressure mercury arc. AM1.5G defined in IEC 60904-3 Table 1 is also shown for comparison.

or dielectric charging/polarization phenomena. Four-point measurements are encouraged but not mandatory. The swept voltage range should at least consist of 100–200 data points to enable accurate determination of the JV-characteristics ($V_{oc}$, $I_{sc}$, MPP and FF). The time interval between individual data points should be longer than the response of the device (capacitive loading and dielectric response). Typically 10–100 ms per data point should be employed (i.e. a few seconds for the recording of a JV-curve). The dark curve should be taken prior to the measurement under light and should present zero current and zero voltage. The JV-curves under illumination should be recorded repeatedly until the JV-curve is stable within 3%. Typically the device will need a few minutes of equilibration when placed under the solar simulator (to reach stable temperature, filling of traps, photo-doping, etc.). There are no requirements on the type of instrument employed, but a source-meter with a reasonable accuracy is required (nA/mV current–voltage resolution). *Advanced procedure for JV measurement*: Refer to IEC 60904-1 (2006) Photovoltaic devices. It is generally recommended that any JV characterizations are carried out at irradiances close to 1000 W/m$^2$, since the dependence of generated photo-current on irradiance might vary along the course of the device lifetime.

### 3.9. Loading conditions

In order to assure simulations that are the closest to actual service conditions for OPVs a load has to be applied to the specimen during daylight or artificial light testing, which will keep the device under constant operation at or near MPP. Thus, the following procedures are recommended to fulfill the minimal requirements for loading:

#### 3.9.1. Level 1

*Passive load*: Apply a resistor that will keep the device near MPP at $t_0$ starting point or keep the device open circuited (device disconnected or connected to SMU set to 0 current).

#### 3.9.2. Levels 2 and 3

Although for Level 2 open circuit conditions are possible, it is recommended to follow the procedures below:

*Passive load*: Apply a resistor that will keep the device at MPP ($\pm$10% deviations). Periodically adjust the load by substituting the resistors to keep the device at MPP ($\pm$10% deviations).

*Active load*: Use a computer controlled SMU to measure and to keep the device at MPP. The initial value of the MPP parameters is obtained from a JV scan. The SMU is then set to source at the MPP with small periodic variations to calculate if and how the MPP changes (MPP tracking). These updated values are then used to adjust the source voltage to keep the device at MPP. The interval between MPP tracking/calculation operations will depend on the test employed. If rapid changes in test conditions are expected such as intermittent cloud cover in outdoor testing the interval should be set accordingly. The object is to keep the device at MPP much more precisely than possible with a passive load and to automatically adjust to variations in the test conditions.

### 3.10. General examples of equipment: laboratory weathering devices

Commercially available equipment used to carry out laboratory weathering tests fall into two main categories, depending on the exposure type. In static exposure devices, specimens are exposed in a static fashion on a flat exposure area. The other category of device uses rotating racks onto which test specimens are mounted, the rotation offering better temperature and irradiance uniformity across the exposed specimens. Most rotating rack devices enable control of irradiance (most often between 600 and 1200 W/m$^2$ in the total spectral range), air chamber temperature, the temperature of a reference body (insulated or non-insulated black panel) and relative humidity, with the possibility to use water sprays. Among static exposure instruments, high range models provide similar capabilities to rotating rack devices. Lower range static exposure models enable irradiance and black panel temperature control as well as monitoring of relative humidity and air chamber temperature. Both flat bed and rotating rack instruments are available with xenon arc sources, one of the two light sources closely matching AM1.5G. Instruments using metal halide lamps (the other type of lamp simulating AM1.5G) and fluorescent lamps are only available in the static exposure technology type. While rotating rack devices enable the simultaneous exposure of a large number of specimens with limited sizes (e.g., 7 cm $\times$ 13 cm), some static exposure devices offer the possibility to expose large area specimens. Customized static exposure systems using metal halide lamps enable the exposure of any number of specimens with no limit in size. Because of these differences, rotating rack weathering devices are better suited for detailed stability studies of individual materials or OPV cells, while static exposure weathering devices may be used to assess the stability of full size products such as OPV modules and arrays.

## 4. Reporting the operational lifetime

There exist several quantities that nominally describe the operational lifetime of a device or module. The most widely used metric is the so-called "$T_{80}$". The definition of operational lifetime is in traditional engineering terms given as the period of time that elapses between the initial stabilized performance and the point where 80% of the initial performance has been reached. Because $T_{80}$ is so universally used, it is recommended at a minimum to report the $T_{80}$ value for any degradation study. This approach is advised especially when considerations of qualification for a particular application are desired.

It should be kept in mind that $T_{80}$, as a single number, cannot completely describe the degradation process, in particular the rate of degradation as a function of time. The $T_{80}$ will also omit any "burn in" period, where performance may be decreasing or increasing before initial stabilization. Omitting this information, opportunities for device improvement may be missed, or the potential of the device may be underestimated. It is recommended, therefore, that the full device or module performance data as a function of time be reported. This reporting could include pre-stabilization data if it is not thought to be sensitive or misleading. It is quite important to report variation in degradation across multiple devices. The number of devices required to assess reproducibility will depend on the devices themselves and the uniformity and reproducibility of the testing environment. In general we recommend reporting uncertainty in $T_{80}$ to 95% confidence. If the data are well-behaved, it may be possible to present full device or module performance data as a function of time, with individual error bars at each time describing the uncertainty in module performance to 95% confidence. A choice must be made on how to handle catastrophic device failure, especially if such failure does not occur at a regular time in the degradation study. With a sufficient number of tested devices, it may be possible to report a catastrophic failure rate or probability as a function of time, and separate these failed devices from the functioning ones that are aging "normally." If there is a large amount of catastrophic failure among the devices from which statistics are drawn, it may not be possible to calculate meaningful uncertainties for $T_{80}$ or device performance parameters. If there is a small amount of catastrophic failure, it may be possible to include these devices in the full cohort and still arrive at meaningful statistics. Whichever course is chosen must be fully disclosed and discussed with the results.

### 4.1. Representing the stability data

To accurately describe the decay performance of an OPV device over time, there are two representations of the data that should be included. The first of these representations is the time evolution of a given parameter of an OPV device. Within this representation there are four (4) pairs of necessary parameters needed to accurately describe the decay pattern (Table 10). In Fig. 7, the representation of the four pairs of parameters related to power conversion efficiency (PCE) are shown, including $E_0$ and $T_0$, $E_S$ and $T_S$, $E_{80}$ and $T_{80}$, and $E_{S80}$ and $T_{S80}$, and used to establish definitions for when and how each measurement should be made. However, other parameters such as FF, $V_{oc}$, $J_{sc}$, etc. can also be included using the same established protocol.

The first measurement point, $E_0$, is the initial testing measurement of an OPV device immediately after final fabrication of the device, at time $t=0$, $T_0$. This measurement should represent the

**Table 10**
Summary of the definition of the four pairs of parameters needed to define OPV device stability.

| | |
|---|---|
| $E_0$, $T_0$ | $E_0$ is the initial testing measurement of an OPV device immediately after final fabrication of the device, at time=0, $T_0$. |
| $E_S$, $T_S$ | $E_S$ is a second testing measurement of an OPV device, defined arbitrarily by the user as some time, $T_S$, after the fabrication of a device. |
| $E_{80}$, $T_{80}$ | $E_{80}$ is the testing measurement of an OPV device after the device has decayed 20% from the initial testing measurement, $E_0$. $T_{80}$ is the time it took to decay to $E_{80}$. |
| $E_{S80}$, $T_{S80}$ | $E_{S80}$ is the testing measurement of an OPV device after the device has decayed 20% from the second testing measurement, $E_S$. $T_{S80}$ is the time it took to decay to $E_{S80}$. |

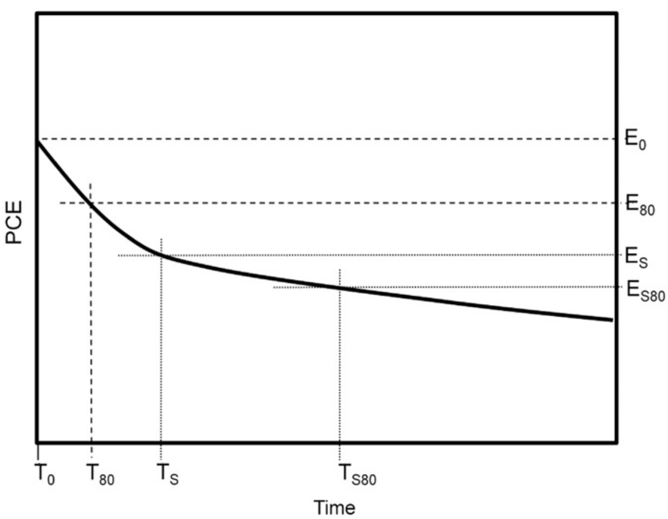


**Fig. 7.** Representative figure defining the parameters to be included in the reporting of OPV stability data. The time evolution of a given parameter of an OPV device, illustrating the four (4) pairs of necessary parameters to describe the decay pattern, including $E_0$ and $T_0$, $E_S$ and $T_S$, $E_{80}$ and $T_{80}$, and $E_{S80}$ and $T_{S80}$. Each parameter is defined in text.

pristine device most accurately. The second parameter, $E_S$, is a second testing measurement of the OPV device, defined arbitrarily by the user as some time, $T_S$, after the fabrication of a device. Defining the second parameter, $E_S$, allows the representation of cases where an OPV device is not immediately subjected to the stability testing conditions, or if a device is first 'stabilized' before subjecting it to further aging conditions. The third and fourth parameters, $E_{80}$ and $E_{S80}$, represent the performance of an OPV device after it has decayed 20% from its initial or second testing measurement, after some time, $T_{80}$ or $T_{S80}$, respectively. While the time evolution of a given parameter will capture the decay behavior of an OPV device, it is also necessary to report the JV curve for each of the four time points highlighted in the decay curve.

### *4.2. Device protection and "handling" history*

Due to the complexity of comparing stability data among laboratories with different testing and stability setups it is recommended that any nuances in device construction, handling and/or testing procedures that could contribute to systematic or random variations in the stability data should be reported. In particular, below there are a number of factors, which based on initial observations have been significantly influencing device stability:

(1) Device encapsulation
The encapsulation of a device (including the substrate, the barrier material, any UV filters and getter materials that have been incorporated) and the ratio between the encapsulation area and the active area of the device, play an important role in performance stabilization. Therefore they should be carefully described. Spectral absorption changes of the intrinsic device due to encapsulation should be noted as well. In addition, devices that have been prepackaged (for example, for shipping to elsewhere), and the packaging has been removed prior to measurements, have to be specified. The shelf-life is considered from the time the packaging was removed.

(2) Substrates and electrodes
Types and thicknesses of substrates and front and back electrodes used for device preparation can significantly affect the stability of the device and therefore should be reported.

(3) Device layout, active area size and masking
Commonly, the OPV community defines the device active area by the overlap of front and back electrodes. This definition, however, is not very accurate and in some cases can lead to incorrect quantification and reporting of device efficiencies. It does not take into account, for example, the input from the edges of the device, known as edge effects. Often there is some contribution into a photocurrent from the edges outside the area of the overlapped electrodes and it can vary significantly depending on the device size and layout. Also, the area defined by the electrodes cannot be used in the case when one or both electrodes have a grid structure. Accurate masking of the device functional area during characterization can both solve the issue of the edge effects and define the area of the tested device (especially in the case of grid electrode structures). Discussions on the device layout and active area effects, as well as descriptions of accurate measurements of device performance, can be found in the literature (see, for example, [24,25]).
Although, the accurate determination of device active areas is only critical during the correct quantification of device PCEs, it may also play some minor role during the measurements of device lifetimes. Therefore, the experimenter is advised to accurately mask the tested device during characterization and report the device active area defined by the mask together with the stability data. The layout of tested devices should be reported as well.

(4) Contacting for measurements
Contacting during measurements is another source of instabilities and therefore should be described. Effects of contacting are especially pronounced when materials such as conducting glue are used for long term measurements.

(5) Device handling
If JV-curves are not measured *in situ*, detailed descriptions of the periodic handling, such as times between removing from stability testing and JV testing, frequency of measurements, methods of fixing specimen on outdoor platforms, contacting, etc. should be provided.

The list can be more exhaustive and therefore, it is recommended that the experimenter determine and reports all the additional parameters that can possibly influence the device lifetime.

## 5. Acceleration studies (Arrhenius type behavior)

Presently, most organic solar cell devices have detectable degradation of performance in the range of hours to months, which is feasible to measure directly. As organic solar cells become more stable this is no longer possible: An alternative method is accelerated testing, where the degradation is artificially accelerated by applying increased levels of stress such as elevated temperatures, cyclic or periodic mechanical and/or electrical stresses, concentrated light, etc. The rationale is that the decay process, which may be chemical in nature, can have an Arrhenius-type behavior and thus, can be described using the Arrhenius model where the rate of decay is determined by an exponential function:

$$k_{deg} = A\, exp\left(\frac{-E_a}{RT}\right) \tag{1}$$

where $E_a$ is the activation energy for the process in eV, $R$ is gas constant, $T$ the temperature in K, and $A$ is a reaction dependent constant. If the decay follows this simple equation, it is evident that the rate of decay $k_{deg}$ is very temperature dependent and thus, the model allows calculating the acceleration factor from Eq. (2):

$$K = \frac{k_{deg}(T_1)}{k_{deg}(T_2)} = exp\left[\frac{E_a}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right] \tag{2}$$

The acceleration factor $K$ is the ratio between the rates of degradation ($k_{deg}$) at the two temperatures ($T_1$ and $T_2$). The Arrhenius model is also utilized for calculating effective exposure temperature $T_{\text{eff}}$, which represents a constant temperature that creates the same amount of photo-degradation as the naturally varying temperature in outdoors and provides a benchmark temperature for making lifetime predictions from accelerated laboratory exposures (see, for example, [26]). There have been a few reports of using the Arrhenius model for accelerated studies of OPV devices [27–29]. However, this approach is rather complex and has not been well studied by the OPV community and certainly cannot be referred to as a standardized procedure for device stability characterization. The purpose of this section is to introduce the concept to the interested reader and initiate further studies of the applicability of the model in the lifetime assessment of OPVs [30].

## 6. Conclusions

Approaches to measurements of organic solar cell devices were detailed with particular focus on establishing standard procedures for accurate lifetime determination. The descriptions are given as the consensus reached during the first three international summits on OPV stability (ISOS 2008–2010). Four different categories of test protocols: Shelf Life, Outdoor, Indoor and Thermal Cycling were agreed upon, each being subdivided into three levels: Basic (1), Intermediate (2) and Advanced (3).

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