UNIVERSITY OF TURKU

Outdoor aging experiments of perovskite solar cells

Department of Mechanical and Materials engineering

Bachelor's thesis

Author(s):

Frans Lind

09.04.2025

Turku

The originality of this thesis has been checked in accordance with the University of Turku quality assurance system using the Turnitin Originality Check service.

Bachelor's thesis

Subject: Materials Engineering
Author(s): Frans Lind
Title: Outdoor aging experiments of perovskite solar cells
Supervisor(s): M.Sc. Rustem Nizamov
Number of pages: 22 pages
Date: 09.04.2025

Perovskite solar cells (PSCs) are a hot topic in photovoltaic field due to the high level of power conversion efficacy that can be reached. With the technology being relatively new there are few long-term outdoor experiments conducted. This thesis takes a dive into what kinds of tests have been conducted on PSCs, what parameters have been measured, how outdoor environment can affect the aging speed of PSCs and how outdoor testing results compare to indoor testing. The purpose of this thesis is to create understanding on previously stated subjects.

This thesis was conducted as a literature review utilizing mainly academic articles discussing for example perovskite as itself and about PSCs. Existing study results in that are referred in this thesis were conducted in different geological areas.

From these studies it was found that most of the studies follow the ISOS protocol for the experiment setup but with the same protocol the testing setup looked very different to each other. With this conclusion comes the need for a stricter standard. There is also a research gap regarding both northern geological areas and panel size specimens. For comparability with indoor testing it was determined that the more testing mimics the outdoor environment the more comparable it is. There still needs to be a lot of experimenting done with PSCs in outdoor setting and it should start by creating a credible standard to make different studies comparable

Key words: Perovskite solar cell, Aging, Outdoor aging, Outdoor experiment

Kandidaatintutkielma

Tutkinto-ohjelma, oppiaine: Materiaalitekniikka
Tekijä(t): Frans Lind
Otsikko: Outdoor aging experiments of perovskite solar cells
Ohjaaja(t): M.Sc. Rustem Nizamov
Sivumäärä: 22 sivua
Päivämäärä: 09.04.2025

Perovskiittiaurinkkokennot (PSC) ovat paljon puhuttu aihe, kun puhutaan aurinkoenergiasta. Niiden avulla pystytään saavuttamaan huomattavasti perinteisiä aurinkokennoja korkeampi hyötysuhde. Teknologia on kuitenkin suhteellisen uutta, eikä sitä ole tutkittu paljoa pitkäaikaisessa ulkoilmakäytössä. Tässä tutkielmassa syvennytään millaisia tutkimuksia kennoille on tehty ulkoilmaympäristössä, minkä laisia koejärjestelyjä on käytetty, mitä eri parametrejä on seurattu ja miten, miten eri ulkoilman muuttujat vaikuttavat aurinkopaneelin ikääntymisen nopeuteen ja ovatko ulkoilmassa tehtyjen tutkimusten tulokset verrattavissa sisätiloissa tehtyihin.

Tämän kandidaatintutkielman tarkoitus on luoda ymmärrys jo tehdyistä tutkimuksista ja havainnoista. Kandidaatintutkielma toteutettiin kirjallisuuskatsauksena, jossa pääasiallisena lähteenä toimivat tieteelliset artikkelit. Artikkelit käsittelivät yleisesti perovskiitin ja perovskiittiaurinkokennojen luonnetta ja ominaisuuksia. Näiden artikkelien lisäksi käsitellään myös kolmea erillistä artikkelia tutkimuksista, jotka on toteutettu toisistaan eroavissa geologisissa sijainneissa.

Tutkielmassa kävi ilmi, että tehdyt tutkimukset ovat noudattaneet samaa ISOS-protokollaa koejärjestelyissään, mutta silti järjestelyissä oli huomattavia eroja. Ulkoilman muuttujat kuten kosteus ja lämpötila ovat vaikuttavia tekijöitä ikääntymisen nopeuteen. Tutkimusaukkoja löytyy niin korkealta pohjoiselta pallonpuoliskolta, kuin paneelikoossa tehdyissä kokeissakin. Tutkielmassa todettiin myös, että ulko- ja sisäilmakokeiden verrattavuus paranee, mitä enemmän ulkoilmasta tuodaan sisäilmakokeisiin muuttujia, kuten kosteus. Kennoille tulee siis tehdä vielä paljon tutkimuksia ulkoilmassa, jotta saadaan parempi ymmärrys niiden käyttäytymisestä. Ensimmäinen askel olisi kuitenkin luoda standardi, joka määrittää koejärjestelyt tarkasti eikä mahdollista erilaisia koejärjestelyitä kuten ISOS-protokolla. Laajasti tunnustettu ja käytetty standardi siis parantaisi tutkimustulosten vertailua.

Avainsanat: Perovskiittiaurinkokenno, Ikääntyminen, Ikääntyminen ulkona, Perovskiitti

Table of contents

1 Introduction

1.1 Introduction

Perovskite solar cells are currently a hot topic in the area of solar cells. PSCs have seen tremendous advancement in their power conversion efficiency also known as PCE over the past decade. In 2009 a PCE of 3,8% was achieved for PSCs [1] and then as recent as July of 2024 a study was released where a PCE of 26,7% for perovskite cell on a very small surface area of only $0{,}05\ cm^2$ and a slightly smaller PCE of 22,6% with surface area of $20{,}25\ cm^2$. [2] So where PSCs have a high PCE there is a problem with scaling up the cells to the panel size and maintaining the high level of PCE. [3]

There are multiple parameters to follow when evaluating the aging of PSCs. The already mentioned PCE is a parameter for evaluating speed of degradation or in other words the length of operational lifetime. Continuously monitoring the PCE allows us to determine the T_{80} and T_{50}. Should the T_{80} or T_{50} be the cornerstone of the requirements in the standards for PSCs aging in outdoor setting in hand with the PCE percentage at start. [4]

And the main problem with PSCs currently is the rapid degradation that comes along with lack of stability and how it can be studied. The problem with the lack of stability is that the T_{80} time is not long enough for the commercially viable PSCs because the cells age so fast that the panels are not cost efficient and would need to be replaced almost weekly throughout the year. For commercially viable PSCs, the T_{80} should be in years and not days or weeks. There have been tests conducted in the outdoor setting for example in Israel, where tested devices were set to a wall in different times of the year. The longest T_{80} time on average were achieved in the spring time which was approximately 300 hrs and lower averages in different seasons. [5]

The problem lies on how new the technology is that the requirements and protocols for testing the PSCs in outdoor setting are still being built. It needs to be studied what kind of effects different conditions like rain, temperature, air humidity and the sun have on the panels and how different geological areas affect the solar panels. There is also an unmet need for the test to be conducted on PSCs in panel size, not just in module or cell size.

1.2 Definitions

1.2.1 Perovskite

The so-called father of perovskite is calcium titanate ($CaTiO_3$), which was discovered at Ural mountains in 1839 by Aleksander Kämmerer, [6] However, over the years the structure of calcium titanate has come to be the definition of material that can be called perovskite. For example organometal halide perovskites have emerged in the recent years as the top contenders for being the best material for PSCs. As materials they are cost effective and achieve high power conversion energy. [7]

There are two criteria that are more widely agreed on. First and the most agreed on is that the material must have a stoichiometry of ABX_3 or at least the same ratio. In the mentioned structure A stand for the larger cation - for example calcium in the calcium titanate - and B stands for the central cation which is in this case titanium. This leaves us with the X anion which is in this case oxygen. The second criterion is that the cubic network must be a corner sharing BX octahedra. [8, 9]

In picture 1 we can see three different ways to present the perovskite structure with perovskite material $SrTiO_3$. In example figure 1a we can see the corner shared BX octahedra which is one of the requirements for material to be perovskite.

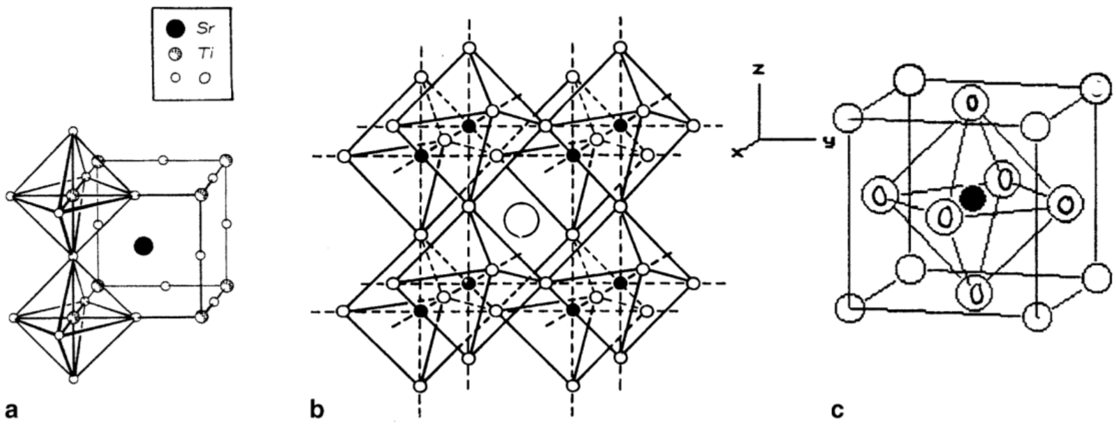

Figure 1 Perovskite structure A.S Bhalla [10] published in Taylor & Francis

1.2.2 Terms and abbreviations

When it comes to talking about perovskite and the usage of them in solar cells there are multiple terms and abbreviations of those terms that are used. Perovskite solar cells are regularly referred to as PSCs in academic literature. When talking about the efficacy of PSCs one parameter that is one of the most important is power conversion efficiency (PCE) which is displayed as a percentage and it tells how efficiently the PSC converts the incoming solar power to electrical output of the cell. The other widely used parameter is open circuit voltage, V_{OC}. V_{OC}, which stands for the maximum voltage that solar cell can produce when there is no current flowing.

When it comes to measuring the aging of PSCs the most important parameter is the T_{80}, which indicates the time it takes for a solar cell's PCE to drop down to 20% of the original value. A relatively similar parameter to PCE is the fill factor, also referred to as FF%. FF is the ratio of maximum power output and open circuit voltage and short circuit current. It is also usual to perform J-V measurements. In J-V measurements the curve that is formed represents correlation between current density.

1.2.3 Aging

In this thesis aging is talked regarding the degradation of the of the solar cells. Aging is determined by certain parameters. One and the most reliable parameter to follow the degradation is PCE. With PCE, we can see in real time how the PSCs lose their efficiency and the PCE heads towards T_{80}. PCE is simply an undeniable parameter to tell how much the solar cell has aged and if PCE is followed regularly we can also find the speed of degradation and see if it is linear or not. Decreases in short-circuit current and open-circuit voltage are also viable parameters to follow regarding aging to support the data of power conversion energy.

Aging can also be observed visually by the changes in the solar cells appearance. So in summary there are many ways to evaluate the aging of the PSCs. But in all its simplicity aging of the PSCs means noticeable decrease in their performance and changes in visual appearance.

2 Outdoor testing and parameters

When it comes to testing the properties and observing aging in outdoor settings, not much testing has been done. PSCs are still emerging and making their way towards commercial market so there still is not an established standard for how tests should be conducted in outdoor settings. There need to be standards on how the panels are mounted in relation to sun, will the panels be stationary during the testing or will they be mounted on solar trackers so that the duration of direct sunlight is longer. And during the testing will it be allowed to maintain the solar panels for example cleaning them as they would be cleaned when used commercially.

2.1 Study one - Israel

In this study [5] the solar cells were mounted outdoors on dual axis solar trackers which follows the sun as the day goes on. The testing was done periodically between August 2022 and December 2023 in Israel.

Stability tests of the perovskite were done under the ISOS-O-2 protocol. ISOS is the International summit on photo organic PV stability and the O stand for outdoors and the number 2 stands for the protocol that uses natural sunlight. [11] The protocol aims to provide framework on how the tests should be conducted so that the results can be reliably compared with other test results. The ISOS-O-2 Protocol includes keeping the test specimen in either open-circuit conditions which means that there should be no external load or maximum power point tracking (MPP) which means operating the optimal power output that simulates real life situations. Protocol also requires collecting environmental data throughout the tests for example intensity of sunlight, ambient temperature, humidity and the temperature of specimen. And lastly the protocol determines that parameters of which data should be regularly collected are PCE, current-voltage characteristic, fill factor, short-circuit voltage and open-circuit voltage

Test specimens were cell sized in this experiment and they were mounted outdoors in different points of the timeline mentioned before. For data collection regarding the time frame the year was divided to summertime from June to August, fall from October to November, winter just December and lastly spring February to April. The solar cells were mounted outdoors continuously also during the night to mimic commercial usage, but the paper does not tell if the cells are cleaned during the test or if they take the cleanliness of the cells into consideration.

In this experiment there were few indicators determine the speed of aging and lifetime of the solar cell was power conversion efficacy. Current and voltage data was collected in intervals differing in time between 30-300s intervals. In addition to current and voltage the ambient temperature and solar irradiation were recorded continuously as the ISOS-O-2 protocol demands. The temperature was recorded using type-K thermocouple on the solar tracker plate and solar irradiation was measured using Eppley Precision Spectral.

With the continuous following of power conversion efficacy T_{80} and T_{50} could be determined. The T_{80} and T_{50} were determined by the last time that power conversion efficacy went under the 50% and 80% value of initial power conversion efficacy. It means that if on one day the PCE was under the value needed but on the next day it was over the minimum value, the T_{80} or T_{50} time was not yet determined.

In the experiment all the results were not measured fully because some of the results are estimations made by using different methods. For example in case the T_{80} or T_{50} values were not reached the measurements was extrapolated to get an estimation for the times.[5]

2.2 Study two - Germany

The second study examined the outdoor stability of PSCs in cell size using two different types of encapsulating methods and comparing the differences in performance and the speed of degradation. The outdoor testing of this study was conducted in Germany between time period of November 2020 and September 2021. The first method was glue-based encapsulation also referred to as “LAB” encapsulation. In this method there was a glass plane that was glued on top of the PSC using a UV light curing adhesive. The second method used was Lamination-based encapsulation, also referred to as “COM”. This method utilises polyolefin and butyl edge sealant as encapsulation materials. Pictures of both methods can be seen below in picture 2. Where d in LAB and e is COM encapsulation methods.

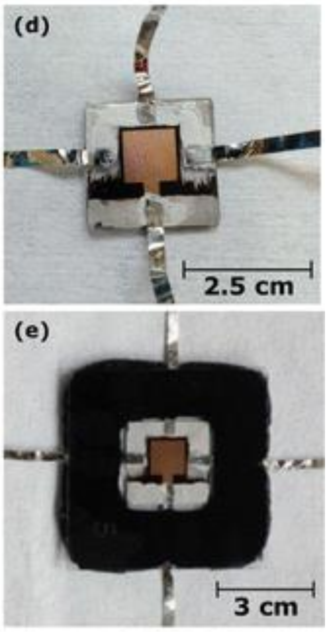

Figure 2 test specimen from Quitere Emerry [12] Copyright The authors. Published by American Chemical Society

In this study there were total of six PSCs used. Three cells of both encapsulating methods. The cells were mounted to stationary stand unlike in study one. The tilt of the solar cells was 35° and they were facing south for the whole study. All the solar cells were placed in the stand on the same time and were kept there for the whole time period or taken away after they were not usable anymore apart from the periodical dismounts to conduct J-V and electroluminescent tests indoors.

This study was conducted in MPP conditions. The study followed PCE, V_{OC} and FF% hence why the cells are periodically detached from the stand for the J-V measurements. In addition the irradiance was measured every 2 seconds with a EKO ML-02 Si-pyranometer. Temperature of the solar cell was recorder by a sensor attached to the backs of the solar cells. The parameters not directly linked to the solar cells that were measured were the ambient temperature, relative humidity and precipitation. These parameters were measured with a meteo station which was located in the vicinity of the solar cells.

The biggest differences with the study one is that on this study there was two kinds of encapsulation methods used, the testing was done in Germany where the sun exposure is not as intensive as in Israel and the ambient conditions vary greatly specially during wintertime. In this study [12] there was done also indoors lab tests in on-shelf conditions and also in damp heat conditions for specimens identical to the ones that were tested outdoors which helps to compare the results more reliably. In this study there is also visual evaluation done for the specimen which widens the possibility to understand the degradation behaviours of perovskite solar cells in commercial use. [12]

2.3 Study three - Mediterranean

The third study is significantly shorter than the others, lasting only approximately 30 days, and was done using carbon-based PSCs. The biggest difference C-PSCs have with traditional PSCs is that the former use carbon-based electrodes and hole transport layers, such as carbon nanotubes instead of expensive metal electrodes and organic hole transport layers. The experimental portion in this study is done in two different locations, on different timelines and different setups. Unfortunately, the specimens from different sites are not identical and they are mounted in a different way to each other so the results are not straight comparable. The specimen size was the same in both location which was cell size and there were two samples were used per site.

On of the sites was located in Paola, Malta and the time period for the tests was from May to June 2020. The specimens were mounted to a stationary stand and there was no UV filters used. The second site was in Barcelona, Spain and the time period for tests was from April to May 2020. In Barcelona the specimens were mounted onto the two axis solar tracking stand which is capable of following the sun similar to the one used in Israel in the study one. In the Barcelona sites UV filters were used. Both test sites did the test according to the ISOS-O-2 protocol again similar to the study one. In both sites the tests were done in MPP conditions.

The parameters surrounding the solar cell that were followed during this experiment were determined by the ISOS-O-2, irradiance, ambient temperature and PV parameters. From the parameters where we can determine the aging of PSCs were measured the PCE, FF%, Open-circuit voltage and Short-circuit current. The values in results graph were taken during midday and in addition in Barcelona the solar cell was followed from morning to evening with J-V curves performed every 45 minutes allows to make comprehensive graphs of different parameters during the day and makes it possible to examine performance parameters throughout the day in correlation with irradiance and ambient temperature. [13]

3 Stability test results

The results certainly differ from one study to another because of the constant evolution of PSCs, which use different kinds of material and as a big differentiating factor, different kinds of encapsulating methods. By compiling results from different studies the one thing that sums up the aging speed of the PCE is T_{80}. Therefore it is suggested one combining factor for all studies to have in the centre of their studies is efficiency and stability. [14]

3.1 Study one - Israel

In total there was 36 different specimens used in this experiment. The results for T_{80} and T_{50} have been grouped for the time periods of which they were mounted in the outdoors. These results we can see in the picture 3.

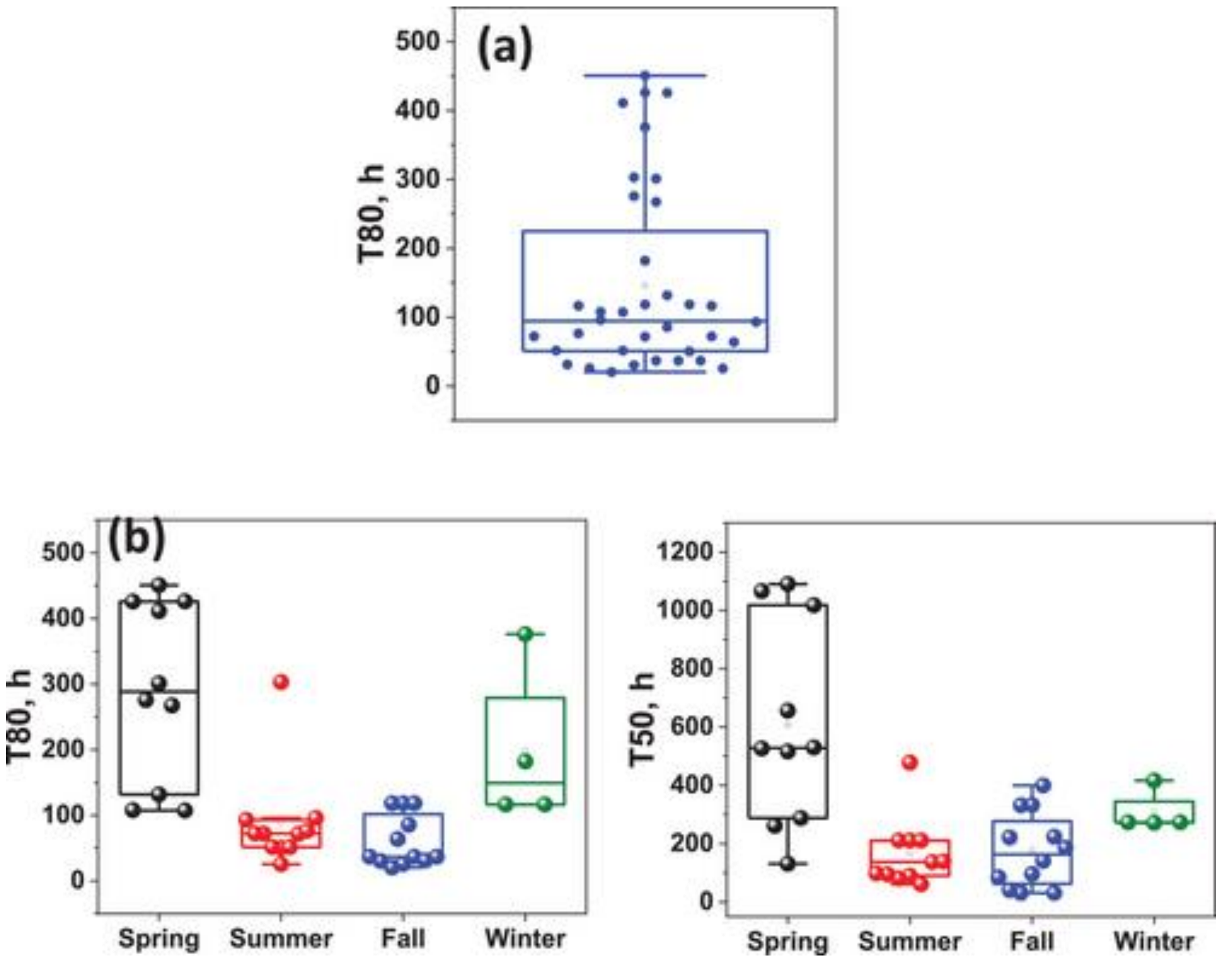

Figure 3 test results from Ritesh Kant Gupta, D [5] Copyright The authors. Advanced energy materials published by Wiley-VCH GmbH

In the picture above we can see that in this experiment there was difference between the points of time that the solar cells were mounted outdoors. Specially springtime is the one that stands out positively from the results. The differences seem to be bigger with spring versus other season when looking at the T_{80} time. When we look at the table for T_{50} times the spring time is the clear winner still but specially summer and fall time are much closer to spring time in T_{50} time. The differences of average temperatures during the day and the daily maximum solar irradiance are also displayed. Results show that during winter and fall the average daily max approximately 33°C and min approximately 15°C temperature are lower than summer max 45° and min 25°C and in fall max 38° and min 20°. This alone may explain the fact that the degradation is slower during colder months because the sun is not as intensive, not as much UV-light and not as much thermal stress on the cells.

Even though temperatures are lower in spring and winter, the maximum solar irradiance is higher. This is possibly caused by other environmental changes depending on season. Despites similar measured ambient conditions during winter the T times differ significantly from each other. The study does not suggest causes for this but one reason that the PSCs degrade faster during winter might be the rain season.

The fact of T_{50} time differences getting smaller with longer times indicates that the effects are bigger and more radical in the beginning of the test and when the times go on the speed of aging slows down. The effects of the deration slowing down is also displayed in the study report, showing the decreasing of power conversion efficacy, where we can see that in the summer and fall time aging speed is greater at first but slows down to quite minimal when closing the T_{50} value. With springtime test specimens we can more clearly see how the initial burn-in is short timewise and steep PCE degrading. After that we can see slow degrading all the way down to T_{50} and after that fast decoration. [5]

3.2 Study two - Germany

As previously mentioned in this study there was tests done with identical specimens in indoor setting in on-shelf conditions and in damp heat. With these experiments done in the same study it makes it possible to truly reflect and compare the results with outdoor testing to determine how they are comparable with each other and if it is possible to achieve the same test results indoor as achieved in outdoor testing. As mentioned, the outdoor experiment of this test was conducted using three LAB and three COM encapsulated solar cells. The results for PCE tracking can be seen in picture 4.

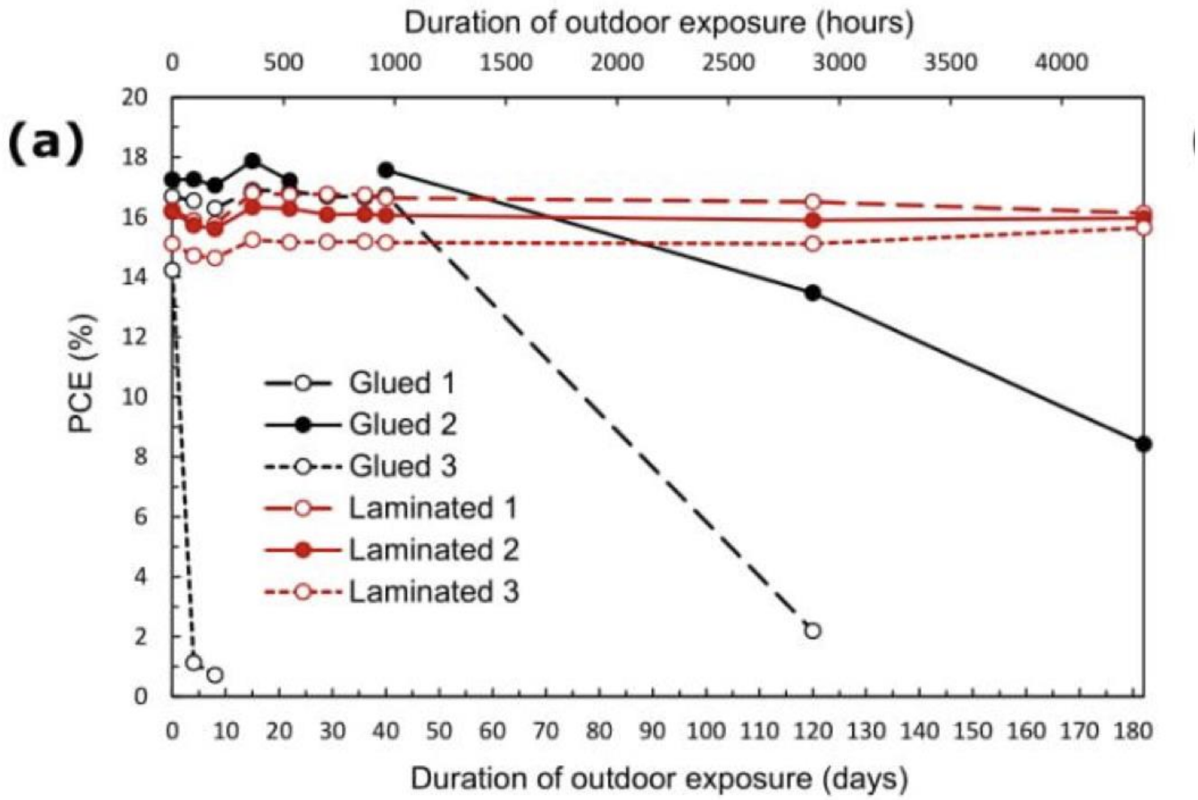

Figure 4 test specimen from Quitere Emerry [11] Copyright The authors. Published by American Chemical Society

As we can see from picture 4 there is clear difference between LAB meaning glued and COM meaning laminated encapsulated PSCs. In this experiment we can see that the PSCs with COM encapsulation achieved notable reliability the level of PCE. From the graph it is also possible to see that LAB encapsulated PSCs are quite unreliable regarding the average degradation time and also not even nearly stable enough to be considered for commercial usage. The graphs of V_{OC}, J_{SC} and FF% closely mimic the visuality of picture 4. As said the test were conducted from November 2020 to September 2021 in Germany. The location is visible for example in the average PSC temperatures being -10°C to 10°C in wintertime and from 5°C to almost 40°C. Solar irradiance did not achieve the levels of study one and unlike in study one the irradiance levels closely mimicked the cell temperature.

Considering the reasons for the poor stability of LAB encapsulated PSCs one affecting factor could be humidity and rain. Here the indoor testing data with identical specimens is useful. The data show that in on-shelf conditions LAB encapsulated PSC kept its PCE levels as well as its COM counterpart. But in the damp heat conditions the LAB encapsulated PSC failed almost identically to the worst performing PSC in the outdoor tests as the COM counterpart did not significantly age. Indoor tests were conducted for 1500 hours and during that time all the PSCs except one kept their stability and did not degrade significantly. With just one specimen per test the results cannot be interpreted too reliably but they show some kind of correlation to the outdoor tests.

This study also followed the electroluminescent of PSCs. Electroluminescent is the effect of applying electric current in this case to the PSC and the parts where there are active electric transporters illuminates light. [15] In results sections of the study is shown electroluminescent test photos taken every time that there is a datapoint marked in picture 4. From pictures the darkening of LAB encapsulated PSCs is quick towards the end. In addition in the two PSCs that aged slower than the worst performer has visible slowly growing groves in the edge of cell. This may be an indication of possible slow progressing failure of encapsulation from different parts of the cell. Whilst the COM encapsulated PSCs electroluminescent stayed quite stable during the experiment and there was no significant aging detected visually. [12]

3.3 Study three - Mediterranean

In the third study there was potential to compare two slightly different geological locations given one experiment was carried out in Malta and one in Spain, Barcelona to be more precise but because of different measurement setups that is not completely possible but in some level it is. The sample size for this study was low. Only two specimens were tested in each location which puts the reliability of the study into consideration. This small sample size is very vulnerable to having two defective PSCs. Though in this experiment the data regarding aging and degradation looks like data from other studies which gives confidence. In this experiment from the Barcelona test site was also reported more accurate data from day level which allows us to understand correlation between temperature, irradiance and power conversion efficacy. Results from both tests are visible in picture 5 below.

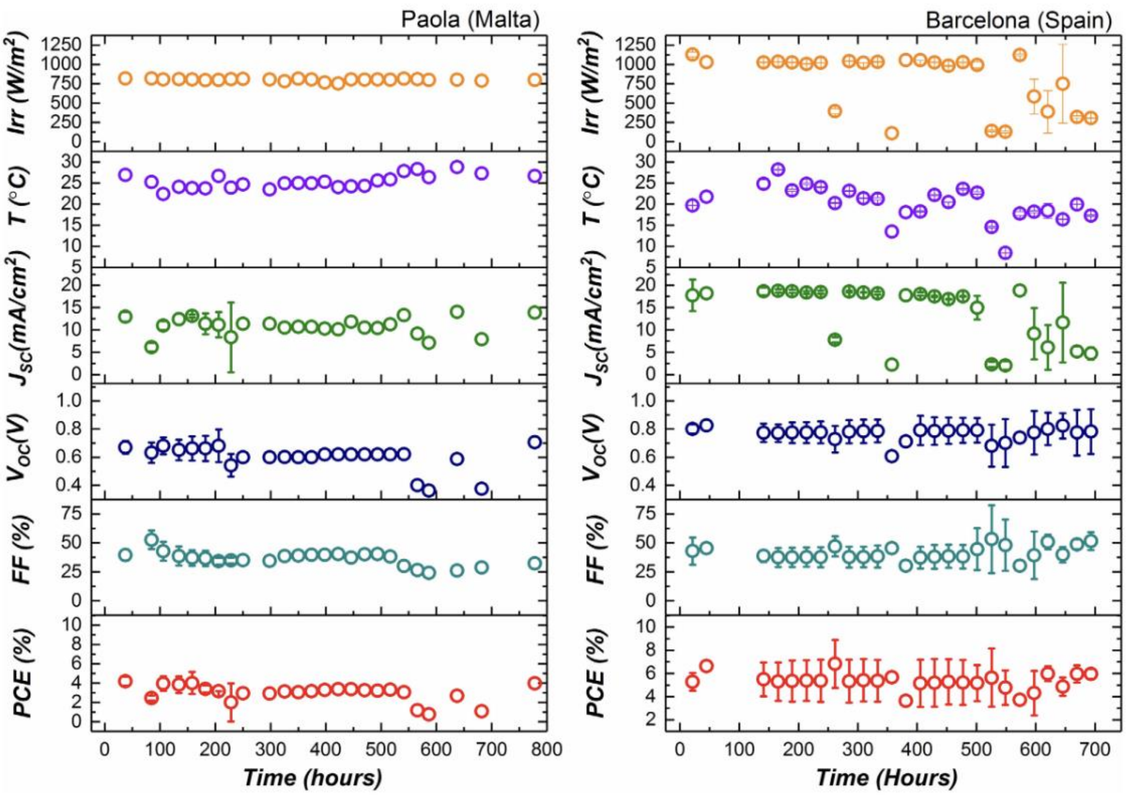

Figure 5 test results from Fransesca De Rossi [13] Copyright The authors. Published by Wiley-VCH Verlag GmbH

From picture 5 we can see the results measured and calculated during experiment. Results from Malta site on the left and Spain results on right. Subject worthy of noting is that one of the PSCs in Malta site stopped working at 250 hours which is the cause for there being no standard deviations in results after that. There was no significant aging seen during the experiment which was quite short. We can also notice in Malta test records that there are very bad days compared to other days towards to the end of the experiment.

An interesting part in the daily values measured reported for three days from Barcelona in the experiment is that the PCE differs quite a lot during the day. The data collection of the three-day data was measured from eight in the morning to eight in the evening. At morning when the sun is rising it can be seen from the graph that the PCE is approximately 20% smaller than the highest value of the day on two of the three days. We can also see the ambient temperature and irradiance rise and lower hand to hand with temperature. But as they rise PCE simultaneously lowers slightly and towards evening when temperature and irradiance come back down PCE on the other hand rises. This may indicate that higher temperatures age the PSCs faster which supports opinions from other studies. [16]

The study comments on how the PSC degrade faster during constant illumination but in light cycles, for example the outdoors PSCs can recover and the degradation can be slightly reversible during nighttime. This is an interesting finding that also complicates the question of whether we can test PSCs in one geological location and say that the test results are viable all around the world even though the sunny time is different in different locations around the world. During the short testing period it cannot be seen how the light cycle length affects the aging speed of PSCs. Longer version of this experiment could give answers to this if the UV cover is taken of in Spain but the PSCs will be mounted in sun tracker. When the stand follows sun during the day the direct light time is noticeably longer than on the stationary stand in Malta. [13]

4 Comparability between tests

Conditions in different geographical locations differ from each other, and conditions change locally due to seasonal variations. Especially here in Finland, winters are normally cold with freezing temperatures, in springtime weather is dusty and sunny, summer is hot and sunny and lastly, the fall is mostly wet and humid.

From the study one a clear difference in the speed of aging can be seen in different seasons. The correlation between temperature and T_{80} time can be seen from results both in outdoor testing and indoor light cycling test. At lower temperatures, the speed of aging is significantly slower. Also, large differences in temperatures between seasons can cause the PSCs to age significantly faster, at least in indoor testing. [5, 16] Therefore temperature can be named as one of the factors on which the speed of PSCs aging depends.

Studies have investigated how correlations between sunlight exposure and dark periods may affect the aging speed of PSCs. This is because during shorter periods of sunlight the degradation is not as severe, and the during longer dark periods, PSCs have more time for self-healing, which has been found possible. [17] This factor is significant, especially considering that in some regions, during summer the sun does not set at all. Given the current results, where cycle time is found as one factor in aging speed the differences, in sunlight exposure make it harder to compare results. For example, the test two conducted in Germany during winter when the daily sunlight duration is shorter than in Israel, Spain and Malta the sites of test one and three. Germany also showed the best stability results. One factor in this could be the longer dark time granted for self-healing ability of PSCs. [17]

In the study two, as mentioned there was indoor testing done on identical PSCs as in the outdoor setting. In the indoor testing, it was found that humidity is one environmental factor that affects the aging speed of PSCs. There were significant visual changes during damp heat testing. Also, the differences in aging speed could be seen from the drop of PCE during on-shelf and damp heat testing. [12] Thus, from these facts the comparability between outdoor and indoor testing is greatly dependent how closely the indoor experiment mimics the outdoor environment conditions, such as light cycling duration, ambient temperature, light intensity and humidity.

It would be beneficial to conduct studies, for example in Finland, where weather conditions around the year change drastically, as previously mentioned. Experiments would bring more understanding on if and how freezing temperatures affect aging speed of PSCs outdoors and if the temperature changes going from + to -°C from day to night would be drastic and fast enough to duplicate the results in sped up aging much like achieved in indoors setting. [16] There is significant temperature changes during the day in studies mentioned in this thesis, but the temperatures have not gone into freezing temperatures, excluding some days in Germany studies.

In the end, the study one and study three Barcelona sites test results are most comparable, as they share similar geological location regarding latitude and utilized similar testing setups. Otherwise, between all three studies best approach in comparing them with each other is to identify similarity in different environmental factors and investigating whether they have similar effects on PSCs. This helps everyone regardless of PSC type and test setup, if it is known which environmental factors need to be taken into account and what possible effects the factors have to PSCs.

5 Conclusion

There has been significant number of studies conducted on PSCs in recent years. With the most of tests done in cell-sized cells there is still noticeable lack of outdoor testing done with module size without even talking about panels size. Another gap in the research data is that geological areas where the weather can go from 30°C to -20°C have no prominent studies conducted. It would be very critical in my opinion to conduct series of tests that many different latitudes from up north do down south. This would give better understanding on how quickly PSCs age in different environments and what different factors like humidity and temperature affect the PSCs and on how they affect the aging speed.

Big percentage of the outdoor test have been done in compliance with ISOS standard keeping the PSCs in open circuit or MPP conditions with mounts varying from stationary to solar trackers. The outdoor tests have taken anywhere from couple days to half a year. To get better understanding of PSC outdoor aging speed and of factors that affect PSCs it is better to conduct longer experiments.

With better knowledge and understanding on the affecting elements and the mechanics that speed aging can indoor testing be developed to closer resemble the outdoor aging tests. From the results of studies discussed previously it is clearly visible that environmental factors like the ambient heat and in correlation with PSCs temperature and humidity affect the speed of PSCs aging quite significantly whether it is speeding up or preventing aging

There is no standard above all else determined at the moment which is problematic. As it can be seen from the results of different studies the geological location affects the speed of PSCs aging due to environmental factors. So the standard for performance at this point should be constructed for each different kind of environment. But for the testing setup there should be a stricter standard. As previously discussed there is the ISOS protocols. However protocols are just that, protocols that are more suggestions than rules set in stone like rules are in standards. For example in study two it was possible to conduct experiment under the same ISOS protocol on stationary mount without UV blockers and in other location on two axis mount with UV blockers. This is not a viable option to compare study results with each other because of the different kind of setups even though both are complying the same ISOS protocol. Stricter and universally accepted standard must be constructed that for example determines the mounts type, angle to sun, direction the specimen faces, parameters that are measured, how they are measured and how often.

References

[1] H. Zhang, X. Ji, H. Yao, Q. Fan, B. Yu, and J. Li, 'Review on efficiency improvement effort of perovskite solar cell', *Sol. Energy*, vol. 233, pp. 421–434, Feb. 2022, doi: 10.1016/j.solener.2022.01.060.

[2] M. A. Green *et al.*, 'Solar cell efficiency tables (Version 64)', *Prog. Photovolt. Res. Appl.*, vol. 32, no. 7, pp. 425–441, Jul. 2024, doi: 10.1002/pip.3831.

[3] Y. Galagan, E. W. C. Coenen, W. J. H. Verhees, and R. Andriessen, 'Towards the scaling up of perovskite solar cells and modules', *J. Mater. Chem. A*, vol. 4, no. 15, pp. 5700–5705, 2016, doi: 10.1039/C6TA01134A.

[4] M. O. Reese *et al.*, 'Consensus stability testing protocols for organic photovoltaic materials and devices', *Sol. Energy Mater. Sol. Cells*, vol. 95, no. 5, pp. 1253–1267, May 2011, doi: 10.1016/j.solmat.2011.01.036.

[5] R. K. Gupta *et al.*, 'Seasonal Effects on Outdoor Stability of Perovskite Solar Cells', *Adv. Energy Mater.*, vol. 15, no. 8, p. 2403844, Feb. 2025, doi: 10.1002/aenm.202403844.

[6] E. A. Katz, 'Perovskite: Name Puzzle and German-Russian Odyssey of Discovery', *Helv. Chim. Acta*, vol. 103, no. 6, p. e2000061, Jun. 2020, doi: 10.1002/hlca.202000061.

[7] Y. Cheng and L. Ding, 'Pushing commercialization of perovskite solar cells by improving their intrinsic stability', *Energy Environ. Sci.*, vol. 14, no. 6, pp. 3233–3255, 2021, doi: 10.1039/D1EE00493J.

[8] J. Breternitz and S. Schorr, 'What Defines a Perovskite?', *Adv. Energy Mater.*, vol. 8, no. 34, p. 1802366, Dec. 2018, doi: 10.1002/aenm.201802366.

[9] Q. A. Akkerman and L. Manna, 'What Defines a Halide Perovskite?', *ACS Energy Lett.*, vol. 5, no. 2, pp. 604–610, Feb. 2020, doi: 10.1021/acsenergylett.0c00039.

[10] A. S. Bhalla, R. Guo, and R. Roy, 'The perovskite structure—a review of its role in ceramic science and technology', *Mater. Res. Innov.*, vol. 4, no. 1, pp. 3–26, Nov. 2000, doi: 10.1007/s100190000062.

[11] M. V. Khenkin *et al.*, 'Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures', *Nat. Energy*, vol. 5, no. 1, pp. 35–49, Jan. 2020, doi: 10.1038/s41560-019-0529-5.

[12] Q. Emery *et al.*, 'Encapsulation and Outdoor Testing of Perovskite Solar Cells: Comparing Industrially Relevant Process with a Simplified Lab Procedure', *ACS Appl. Mater. Interfaces*, vol. 14, no. 4, pp. 5159–5167, Feb. 2022, doi: 10.1021/acsami.1c14720.

[13] F. De Rossi *et al.*, 'An Interlaboratory Study on the Stability of All-Printable Hole Transport Material–Free Perovskite Solar Cells', *Energy Technol.*, vol. 8, no. 12, p. 2000134, Dec. 2020, doi: 10.1002/ente.202000134.

[14] M. U. Ali, H. Mo, Y. Li, and A. B. Djurišić, 'Outdoor stability testing of perovskite solar cells: Necessary step toward real-life applications', *APL Energy*, vol. 1, no. 2, p. 020903, Sep. 2023, doi: 10.1063/5.0155845.

[15] M. Cirio, S. De Liberato, N. Lambert, and F. Nori, 'Ground State Electroluminescence', *Phys. Rev. Lett.*, vol. 116, no. 11, p. 113601, Mar. 2016, doi: 10.1103/PhysRevLett.116.113601.

[16] J. A. Schwenzer *et al.*, 'Temperature Variation-Induced Performance Decline of Perovskite Solar Cells', *ACS Appl. Mater. Interfaces*, vol. 10, no. 19, pp. 16390–16399, May 2018, doi: 10.1021/acsami.8b01033.

[17] W. Nie *et al.*, 'Light-activated photocurrent degradation and self-healing in perovskite solar cells', *Nat. Commun.*, vol. 7, no. 1, p. 11574, May 2016, doi: 10.1038/ncomms11574.