LONG-TERM OUTDOOR TESTING OF POLYCRYSTALLINE SILICON AND MICROMORPH SILICON THIN-FILM TANDEM TECHNOLOGY MODULES IN GREECE

Kyritsis Anastasios, Tselepis Stathis, Rikos Evangelos, Nikoletatos John, Halambalakis George
Centre for Renewable Energy Sources and Saving (CRES), Pikermi, Greece
Corresponding author: stselep@cres.gr

ABSTRACT: This paper presents a comprehensive comparison between a poly-Si and a-Si/μ-Si thin-film tandem PV module under outdoor conditions in Greece. Both modules are produced by Greek vertically integrated manufacturing companies and installed at CRES facilities in a tilt angle close to latitude optimum, facing south. The testing period is more than a year and thus the influences from climate conditions to module electrical characteristics are recorded too. The testing setup and the measurement equipment follow the DERlab technical guidelines for long-term outdoor testing. Our long-term outdoor testing scope, which will continue for several years, is to investigate the performance of the two different technology PV modules in term of energy yields, efficiency fluctuation, module degradation evolution and PV modules thermal behavior (with respect to ambient conditions). Last but not least results from the modules initial stabilizing period is presented too.

Keywords: PV module, outdoor testing, field testing, system performance, energy yield, poly-Si, a-Si/μ-Si

1 INTRODUCTION

Nowadays, grid-connected PV systems form important part in the electricity generation of Greece, serving the National Action Plan 20-20-20 for the promotion and use of energy from renewable sources (Directive 2009/28 EC). According to the most recent statistics the PV capacity in Greece reaches the 3GW at the first half of 2013, when the entire renewable and conventional sources installed electricity capacity is almost 16GW. As it concerns PVs reliability aspect, it has been established that an accurate prediction of PV system power output over time is needed in order to predict the real power delivery. Thus, comprehensive investigation of PV modules performance (in term of energy yields, efficiency fluctuation and power reduction over time) is essential not only to investors but also to utility companies.

Outdoor field testing of PVs plays significant role in the investigation of the PVs long-term behavior for at least two reasons: it is the typical operating environment for PV systems, and it is the only way to correlate indoor accelerated testing to outdoor results to forecast field performance [1].

This paper presents a comprehensive comparison between a poly-Si and a-Si/μ-Si thin-film tandem PV module under outdoor conditions in Greece. The testing setup and the measurement equipment follow the DERlab technical guidelines [2, 3]. The PV modules outdoor testing started at 1st November 2011 for the case of poly-Si module and at 21st December for the micromorph thin-film tandem (a-Si/μ-Si) PV module respectively. Both modules are installed at CRES facilities in Pikermi-Greece (37°59.57’19’’N, 23°55.38’ 60’’E) in tilt angle close to latitude optimum of 30° facing south and are monitored until now. According to the module manufacturers, the power output and the temperature coefficient of power output (α-P_{MPP}) values are respectively 220W and -0.5%/K for the poly-Si module and 120W and -0.29%/K for the a-Si/μ-Si. The a-Si/μ-Si cells are encapsulated within a glass/glass structure without frame, while the poly-Si cells are laminated with glass only in the front side and have an aluminum frame. An availability of 99.7% of the PV modules potential operation time for the first testing year is achieved.

2 CRES MEASURING SYSTEM FOR LONG TERM PV MODULES EVALUATION

Two PV module pairs (up to 350W each one and with maximum current and voltage values 12A and 145V respectively) are monitored in parallel field tests. Every fifteen seconds the I_{SC}, V_{OC}, I_{MP} and V_{MP} values are measured and recorded by sweeping the PV module I-V curves. Then the electrical characteristic data are averaged to one minute values. The rest raw data of the I-V curve are recorded too. The power at the MPP is calculated by multiplying the I_{MP} and V_{MP} values, and thus the energy production values are independent of the inverter topology, the maximum power point tracking (MPPT) accuracy and the B.O.S. characteristics (e.g. cable diameter or material). The field test meteorological conditions (irradiance at PV modules plane, global horizontal and diffuse irradiance, PV and ambient temperatures, wind speed, humidity etc) are measured, recorded and averaged to one minute values too. Between two successive measurements the PVs are forced to work near the MPP for high irradiation levels. Thus the PV module temperature profile and aging degradation are similar to an actual system installation.

Figure 1 presents the testing field, the weather station equipment and the measuring system that was designed and realized by CRES for long-term PV module testing. The same figure highlights the under test PV modules (in general 4 modules are served). CRES measuring system is equipped with two electronic load predefined ranges in order to serve poly-Si, mono-Si modules (40V/12A small range electrical load) and a-Si, a-Si/μ-Si modules (140V/ 2A large range electrical load).

Figure 1: CRES long-term PV module testing field, weather station and measuring system equipment.

3 DATA COLLECTION AND PROCESSING

Figure 2 presents the irradiance at PV modules plane, ambient and PVs temperatures, as well as both modules short-circuit current and open circuit voltage values for one clear and low wind day per every month of 2012. The daily data recording period is starting at 05:00AM and ends at 21:00PM. For the remaining time interval of the day, the CRES electronic recorder system is shut down. Similar graphs were generated for each day of months for more meteorological and electrical parameters. This month-by-month analysis provides information about the influences from climate effects to module electrical characteristics.

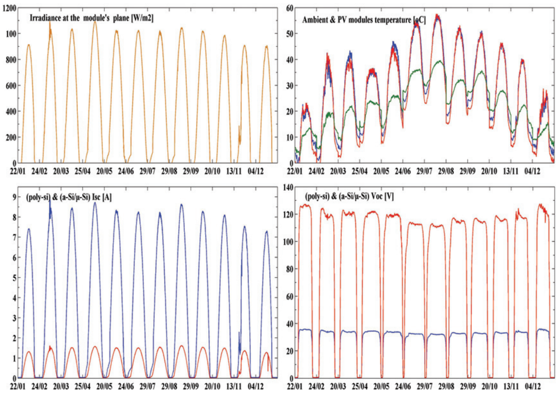

Figure 2: Field test meteorological conditions and electrical characteristic data of both modules for one clear and low wind day for every month of 2012.

In order to compare the poly-Si and a-Si/μ-Si modules energy production, both modules energy production is normalized to a DC PV array of 1kWp-label. Table I summarizes the measured monthly production of each module and the calculated monthly DC production for normalized 1kW$_{\text{p-label}}$ PV arrays.

Table I: 2012 Energy production statistics

	Poly-Si module		α-Si/μ-Si module	
2012	Module production [kWh]	Normalized production [kWh/kWp]	Module production [kWh]	Normalized production [kWh/kWp]
Jan	19.949	90.677	10.063	83.858
Feb	18.506	84.118	9.446	78.717
Mar	33.591	152.686	17.945	149.542
Apr	37.461	170.277	20.442	170.350
May	37.153	168.877	21.524	179.367
Jun	42.041	191.095	25.123	209.358
Jul	42.164	191.655	25.716	214.300
Aug	40.321	183.277	24.427	203.558
Sep	36.853	167.514	21.719	180.992
Oct	27.811	126.414	15.885	132.375
Nov	19.479	88.541	10.441	87.008
Dec	19.279	87.632	9.681	80.675

Figure 3 shows the normalized PV modules monthly and cumulative energy production for the year 2012, while figure 4 illustrates the normalized energy production ratio and the normalized energy production balance of both modules for the year 2012. According to Table I and figures 3 and 4, the a-Si/μ-Si module energy production is almost 4.7% - 11.8% higher during May to October and 1.7% - 7.9% lower from January to March as well as for November and December, compared to the corresponding poly-Si module (in terms of normalized DC PV array power), for the specific location and the specific module manufactures. The cumulative energy production values for the year 2012 were 374.61kWh and 212.41kWh for the poly-Si and the a-Si/μ-Si modules respectively, while the annual normalized power output values were 1.7MWh/kWp and 1.77MWh/kWp. Thus the poly-si module normalized energy production was lower by approximately 3.95% compared to the micromorph thin-film tandem module.

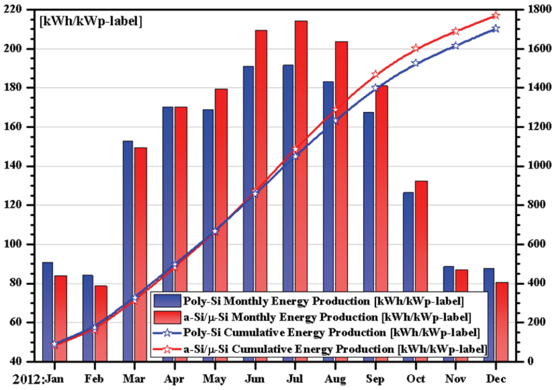

Figure 3: Normalized poly-Si and a-Si/μ-Si monthly and cumulative energy production for the year 2012.

After the first three months of 2013 the total normalized power output values become 2.04MWh/kWp and 2.09MWh/kWp respectively and the normalized energy production diverge lessens to 2.39%, proving that the a-Si/μ-Si module energy production is lower compared to the corresponding poly-Si PV module during the first three months of a year. Finally at the end of June the normalized cumulative power output values become 2.547 MWh/kWp and 2.628 MWh/kWp respectively and the normalized energy production diverge increased to 3.08%. Taking into account that the first six months of 2013 the ambient conditions were approximately the same with the corresponding months of 2012 (slightly cooler and less sunny testing period) we conclude that for the specific location the under test a-Si/μ-Si module produced more energy compared to the specific poly-Si module during the hottest months of the year. In order to prove the aforementioned result figure 5 is presented.

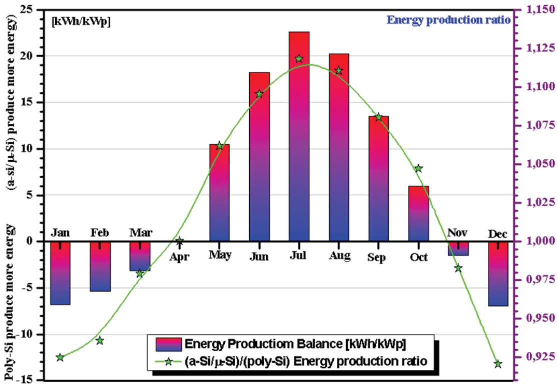

Figure 4: Normalized energy production ratio and energy production balance between the two modules.

Figure 5 shows the available sun irradiation at the PV module plane [kWh/m^2] and the monthly ambient and PV modules average temperatures [°C] for the 2012 testing period (the monthly average temperature values are based on 16 hours daily recording period). Considering the lower a-Si/μ-Si temperature coefficient as well as that the PVs maximum temperature values are 1.5-1.7 times higher than the recorded average temperature values, we conclude that during May to October of 2012 the a-Si/μ-Si module energy production decreases less than the poly-Si technology module (hottest months of the year with medium and high sunny irradiation profile). For example during clear sunny and low wind middays of June to August of 2012, the poly-Si real module output power was only 78-82.5% of the module nominal output power, while a-Si/μ-Si module real output power reaches the 87-89.9% of the STC module output power.

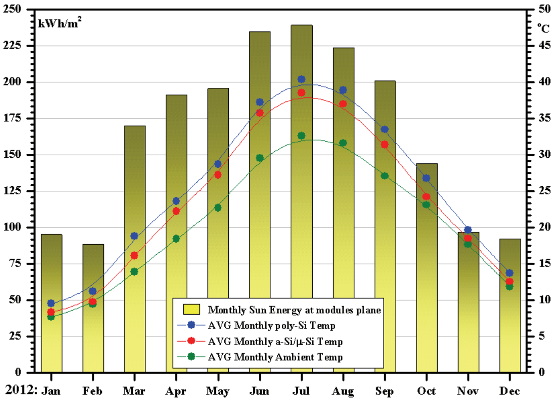

Figure 5: Poly-Si and a-Si/μ-Si modules monthly average temperatures, ambient temperature and available sun irradiation at the modules plane for the year 2012.

It is worth noticing that, during April both modules produce equivalent energy amounts in terms of normalized DC PV array power (according to figure 4 and Table I). Last but not least, during May the modules energy production values were different although that April and May present almost the same sunny irradiation profile (191.1kWh/m^2 and 195.6kWh/m^2 respectively). Taking into account that during May the PVs temperatures were significant increased compared to April (roughly by 5°C according to figure 5), it is proven that poly-Si module energy production decreases more than the a-Si/μ-Si module when the temperature values are increased beyond a certain value.

Figure 6 presents the average monthly efficiency of both under test PV modules. By studying this figure we conclude that the poly-Si module average monthly efficiency presents high variation, fluctuating from 10.81% for July (similar low values obtained the June and August) to 13.16% for February (similar high values obtained the January and December too). On the other hand the a-Si/μ-Si average monthly efficiency fluctuates from 7.06% for December (similar low value obtained the January) to 7.63% for October (similar high values were obtained in May, August and September too). Beyond that, the average annual efficiency values were 7.42% and 12.05% for the case of a-Si/μ-Si and poly-Si module respectively. According to the same figure the poly-Si module average monthly efficiencies follow a heavy parabola shape (with vertex at hottest summer month), while a-Si/μ-Si modules average monthly efficiencies present almost a constant profile. Figures 7 and 8 attempt to further investigate this issue.

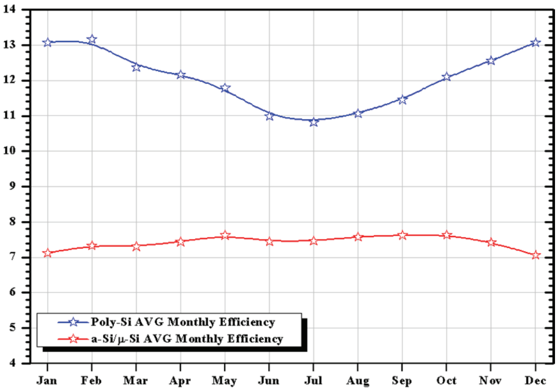

Figure 6: Poly-Si and a-Si/μ-Si modules average monthly efficiencies variation for the year 2012.

Figure 7 shows both modules efficiency values relative to the modules temperatures for the year 2012, while figure 8 shows the poly-Si and a-Si/μ-Si PV modules efficiency fluctuation relative to the available sun irradiation at the PV module plane for the same calendar year (different colour is used for each month). The irradiance and the modules temperature values are averaged to 1 minute values.

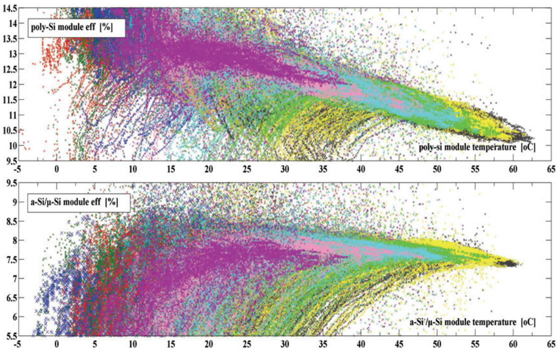

Figure 7: poly-Si and a-Si/μ-Si PV modules efficiencies relative to the modules temperatures.

By studying figure 7 we conclude that for the specific location and the specific module manufacturers, the poly-Si module efficiency is strongly affected by the high ambient temperature values during the summer months, while a-Si/μ-Si module efficiency is almost constant and according to figure 8, it is diminished depending on irradiance (particularly for irradiance values above 400W/m^2) and temperature variation during a calendar year. The aforementioned conclusions derived from the two figures trend line.

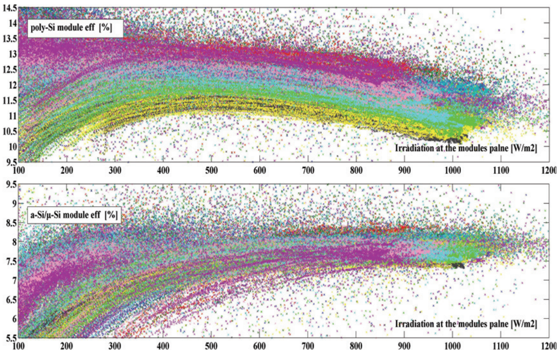

Figure 8: poly-Si and a-Si/μ-Si PV modules efficiencies relative to the available sun irradiation at PV's plane.

In order to measure the modules electrical characteristic and their efficiency at STC as well as to investigate the module degradation mechanisms in outdoor conditions, CRES applied the following methodology. Every month, one clear and low wind day is selected, and the raw data of the I-V curve (for irradiation level above 850W/m^2) are retrieved and corrected for Standard Test Conditions (irradiance of 1000 W/m², estimated solar spectrum of AM 1.5 global and PV module temperature of 25°C) according to IEC 60891. This month-by-month analysis provides information about the module electrical characteristics evolution, and also provides an accurate estimation of the PV module performance at STC.

Figure 9 and 10 present the poly-Si and a-Si/μ-Si P_{mp}, V_{OC}, I_{SC} and efficiency values for STC, month by month according to IEC 60891. It is worth noticing that the accuracy for the current and voltage measurements are ±0.91% and ±1.4% for the large range electrical load and ±1.3% and ±1.6% for small range electrical load respectively. The irradiance measurement accuracy is ±2% (by using Kipp&Zonen pyranometer CM11) and ±4% (by using ISET poly-Si Sensor) while the ambient and PV module temperature measurements are performed using Delta OHM-HD9009TR and 4 wire PT100 sensor respectively.

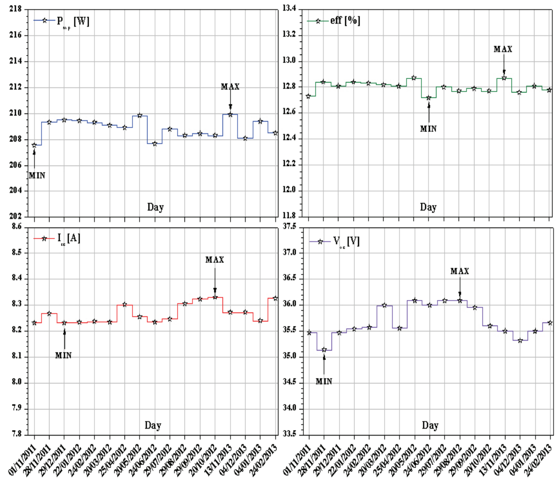

Figure 9: Month by month poly-Si basic electrical characteristics and efficiency calculations for STC.

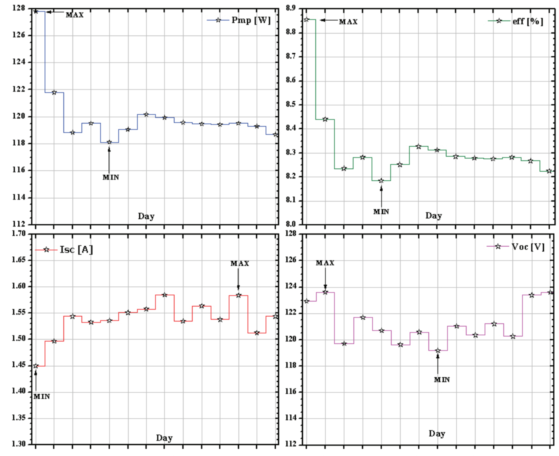

Figure 10: Month by month a-Si/μ-Si basic electrical characteristics and efficiency calculations for STC.

Moreover, Figures 11 and 12 present the P_{mp}, V_{OC} and I_{SC} monthly deviation from the initially recorded values (207.54W, 35.47V, 8.23A for the poly-Si module and 127.80W, 122.94V, 1.45A for the a-Si/μ-Si module) when monitoring started at CRES. The olive colour line indicates the initial values (initial P_{mp}, V_{OC} and I_{SC} measurements), while positive value implies improvement. According to figures 11 and 12, poly-Si basic electrical characteristics follow a slightly positive trend deviation, while micromorph thin-film tandem technology module shows a negative P_{mp} and V_{OC} deviation trend (in contrast to I_{SC} trend), caused by light-induced degradation of a-Si and an increase in series resistance [6, 4].

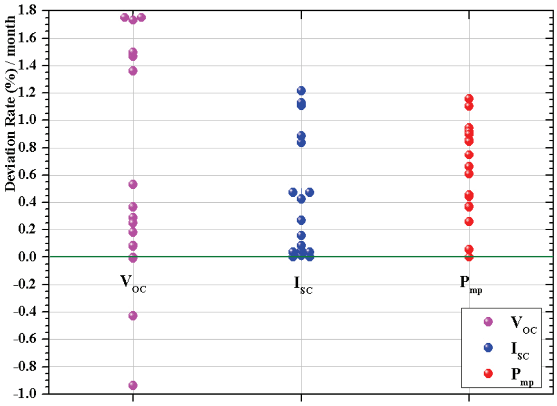

Figure 11: Month by month poly-Si V_{OC}, I_{SC} and P_{mp} deviation from the initial record values.

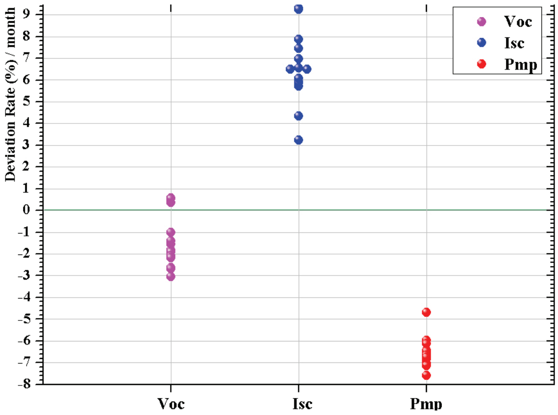

Figure 12: Month by month a-Si/μ-Si V_{OC}, I_{SC} and P_{mp} deviation from the initial record values.

The standards for design qualification and type approval of terrestrial PV modules IEC 61215 for crystalline silicon and IEC 61646 for thin-film suggest an initial outdoor irradiation exposure to the test modules of 60 kWh/m² in order to achieve modules electrical characteristics stabilization. Although the exposure time is very short for detecting long-term effects like degradation (irradiation exposure value is reached before the end of the first testing month for both modules), the standards require no visible damages after the exposure time and the maximum output power may not be under 5% of the measured value in the initial measurements for crystalline silicon and under manufacturer tolerance for thin-film. After the first exposure month the P_{mp} value of the poly-Si module were 209.32W and 121.8W for the a-Si/μ-Si module. Considering that the deviation of a-Si/μ-

Si module peak power was 4.69% we conclude that only the poly-Si module fulfills the aforementioned rule since the a-Si/μ-Si module manufacturer tolerance is ±3% (referring to the stabilized operation). After the initial irradiation exposure deviation of a-Si/μ-Si module peak power lessens to 1.5%.

Tables II and III present both modules electrical characteristics and efficiency values for STC: (i) at the beginning of the test period (ii) the calculated values for STC one year later (applying averaging model), (iii) the corresponding manufacturers values, (iv) and finally the signed difference between case (i) and (ii).

Table II: Poly-Si electrical characteristics and eff(%) for STC at the beginning of the test period and one year later, difference between them and manufacture values

Poly-Si module						
	P_{mp} [W]	I_{mp} [A]	V_{mp} [V]	I_{sc} [A]	V_{oc} [V]	eff [%]
i	207.54	7.593	27.33	8.233	35.47	12.73
ii	208.90	7.610	27.45	8.270	35.69	12.80
iii	220.00	7.580	29.04	8.200	36.67	13.49
Iv	+0.65%	+0.22%	+0.44%	+0.45%	+0.62%	+0.07%

Table III: a-Si/μ-Si electrical characteristics and eff(%) for STC at the beginning of the test period and one year later, difference between them and manufacture values

a-Si/μ-Si module						
	P_{mp} [W]	I_{mp} [A]	V_{mp} [V]	I_{sc} [A]	V_{oc} [V]	eff [%]
i	127.80	1.268	100.77	1.45	122.94	8.86
ii	119.57	1.270	94.25	1.54	121.44	8.29
iii	120.00	1.240	99.00	1.44	130.00	8.39
iv	-6.44%	+0.16%	-6.47%	+6.21%	-1.22%	-0.57%

Figure 13 and 14 show the poly-Si and a-Si/μ-Si modules I-V curves corrected for STC using IEC 60891 from the first day of expose to February 2013. According to figures 9 and 13 and Table II the changes at poly-Si module electrical characteristics (as a result of module degradation over time) are insignificant since the measurements fluctuation is less that the data measurement accuracy. This was an expected result, since the matured crystalline Si technology usually leads to average degradation rate of 0.5-0.8% per year for most crystalline Si products manufactured after 2000 [5-6].

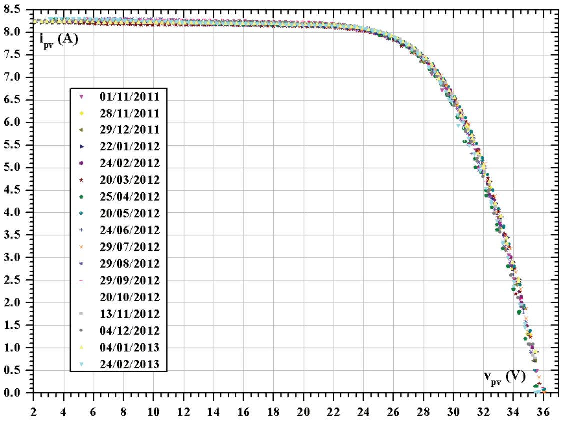

Figure 13: poly-Si module I-V curves corrected for STC, from the first day of expose to February 2013.

On the contrary, the a-Si/μ-Si module I-V curves follow a clockwise rotation depending on the exposure month of the year, leading to higher sort circuit current values and lower open circuit voltage values. Beyond that, the electrical characteristics changes were higher than the accuracy of the electrical measurements reported in figures 10, 14 and Table III. Thus, a significant decrease at initial P_{mp}, V_{mp} and efficiency values were recorded, as well as an equivalent increase at initial I_{SC} values were noticed. Taking into account that the testing period started during the December of 2011 and by studying figure 14, it is concluded that I_{SC} and V_{OC} are strongly influenced from seasonal changes possibly as a result of pre-annealing of module material prior to exposure [7]. In more details the I_{SC} increase and the V_{OC} decrease are forced during the hotter months of the year while they converge as to the initial recorded values during the winter. However, after initial degradation, modules P_{mp} value appears to be stable. Lastly, the seasonal changes seem to affect the PV system design (number of series connected modules) and not the nominal power of a-Si/μ-Si modules.

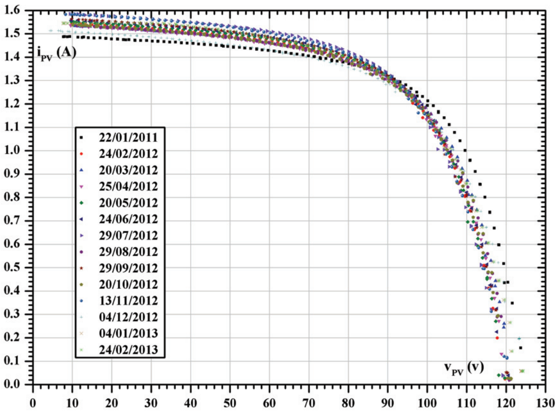

Figure 14: a-Si/μ-Si module I-V curves corrected for STC, from the first day of expose to February 2013.

Furthermore, at the beginning of both modules testing period, the poly-Si and the a-Si/μ-Si modules shunt resistances were calculated to be ~220 Ω and ~1100 Ω respectively. The above values of the shunt resistances are relatively high, indicating that there were no leakage currents due to defects or to micro-cracks in the PVs.

4 CONCLUSION

This paper studies the performance of two different technologies, poly-Si and a-Si/μ-Si thin-film tandem PV modules in term of energy yields, efficiency fluctuation, and module degradation evolution from the beginning of their operational life. Further investigation of the modules electrical parameters is needed for more years in order to define the correlation between power degradation mechanisms and internal defects. In the near future further results in the effect of the shunt resistance in a long time operation of the PV modules of both technologies under real environmental conditions will be presented. More results by using different techniques such as dark I-V traces and thermocamera pictures will be presented too.

5 REFERENCES

[1] Dirk C. Jordan and Sarah R. Kurtz: “Photovoltaic Degradation Rates — An Analytical Review”,

NREL/JA-5200-51664, June 2012.

[2] European Distributed Energy Resources Laboratories e.V., "Technical Guidelines on Long-term Photovoltaic Module Outdoor Tests", Reference No. 100-01, February 2012

[3] Craciun D., Helmbrecht V., Tselepis S., Kyritsis A., Hatziargyriou N., Latoufis K., Misara S., Funtan P., Strauss P., Ellis A., Bründlinger R.: "Harmonized procedures on Photovoltaic Modules Long-Term Energy Yield Measurements and Performance evaluation under Outdoor Conditions", proceedings of the 27th EU PVSEC, Frankfurt, Germany, 24-28 September 2012, rpaper no 4CO.12.5.

[4] J.A. del Cueto et al., Stability of CIGS Modules at the OTF over 2 Decades, 33rd Photovoltaic Specialists Conference, San Diego, 2008, 1.

[5] D.C. Jordan et al., Photovoltaic Degradation Rates – an Analytical Review, Prog. Photovolt: Res. Appl., 2011.

[6] Dirk C. Jordan, John H. Wohlgemuth, and Sarah R. Kurtz: "Technology and Climate Trends in PV Module Degradation", proceedings of the 27th EU PVSEC, Frankfurt, Germany, 24-28 September 2012.

[7] I. J. Muirhead: "Long term performance modelling of amorphous silicon photovoltaic modules", Proc. PVSEC-7, Nagoya, Nov 22-26 1993, 99 461-462.