One-year comparison of different thin film technologies at Bolzano Airport Test Installation

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Abstract

The performance and behaviour of four different photovoltaic thin film technologies are evaluated for a period of one year at the Alpine latitudes of Bolzano, in the north-east of Italy.

The monitored modules are based on: single and double junction amorphous silicon (a-Si), copper indium gallium diselenide (CIGS) and micromorph silicon (a-Si/μc-Si). They are mounted on fixed racks as part of the multi-technological outdoor test installation at Airport Bolzano Dolomiti (ABD). The energy production and electrical parameters under operating conditions are registered by string inverters, while the temperature of modules, the in-plane and horizontal irradiance and the ambient temperature are measured through sensors installed at the meteo station placed next to the PV plant.

The irradiance frequency, the energy production distribution, the monthly final yield as well as the monthly performance ratio are calculated in order to assess and compare the investigated technologies. A polycrystalline silicon (pc-Si) is added to the comparison as a reference technology.

Keywords: thin film behaviour; outdoor operating conditions; performance ratio; final yield; irradiance frequency; energy production distribution

1. Introduction

PV modules based on thin film technology have been developed since early 1990s. The last few years have seen an increase in their diffusion due to different factors. The progress in materials research has increased the stable cell efficiency up to 20.1% [1]. The relative low manufacturing costs, the high versatility of modules and the introduction of feed-in tariffs in many countries have encouraged more designers and installers to use these technologies mostly for BIPV applications. In 2009, the market share of thin film had reached some 15% [2].

Due to the variety in materials and deposition techniques the thin film PV modules technologies exhibit different behaviours under real conditions. This paper aims to evaluate four thin film technologies which are very common on the market: single and double junction amorphous silicon (a-Si), copper indium gallium diselenide (CIGS) and micromorph silicon (a-Si/μc-Si). The modules are installed at the ground-mounted plant at Airport Bolzano Dolomiti (ABD). They have the same orientation and tilt angle, which allows their comparison. The data are elaborated in terms of: produced energy, final yield and performance ratio on the monthly base. In order to better understand their outdoor behaviour, a polycrystalline silicon (pc-Si) based module is also taken into consideration as a reference one. The monitored period ranges from February 2011 to March 2012. The first 6 months of plant operation are not taken into consideration since strong degradation processes take place in this period, especially on a-Si modules.

2. Experimental setup

The multi-technology ground-mounted photovoltaic test facility installed at ABD is divided into a 662 kW_p commercial part and a 62 kW_p experimental installation [3]. The facility is owned by ABD and developed with a co-financing of the European Regional Development Fund (ERDF). EURAC´s Institute for Renewable Energy is responsible for the testing, analysis and performance evaluation of the different photovoltaic modules. The experimental part is composed of 24 different types of modules, for a total of 39 groups ranging between 1 and 2 kW_p each, and was connected to the medium voltage (MV) network on August 10th, 2010. The technologies considered in this paper are mounted on a 30° fixed rack, have an orientation of 8.5° West of South, and are placed at an altitude of 262 m above the sea level. The DC-side electrical parameters such as maximum power and energy production of each group are registered directly by the inverter every 15 minutes. The in-plane and horizontal irradiance are measured with pyranometers installed at the meteo station; the ambient temperature as well as the back-of-module temperature of each group of module types are recorded by a Pt100 sensors. Measurements are performed every one minute, and averaged on a 15-minutes time interval.

3. Results and discussion

3.1 Irradiance frequency and energy production distribution

The main characteristics of the modules and their arrays considered in this paper are summarized in Table 1. They include the nominal module power given by the manufacturer, the number of modules in each array as well as the array nominal power and total surface.

Table 1 Characteristics of the monitored thin film and reference polycrystalline modules and arrays.

Type of technology	Module nominal power (W_p)	Number of modules	Array nominal power (W_p)	Array surface (m^2)
single junction a-Si	50	20	1000	18.78
double junction a-Si	33	36	1188	21.60
CIGS	55	20	1100	16.55
micromorph	135	8	1080	11.37
pc-Si	210	20	4200	29.70

These parameters are used to define the final yield, energy production and performance ratio of the investigated module technologies.

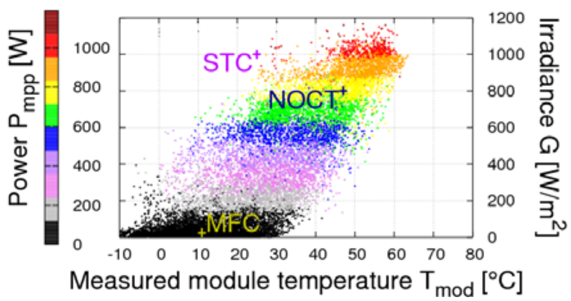

Fig. 1 Performance matrix, standard test condition (STC), normal operating cell temperature (NOCT) and most frequent condition (MFC) of the CIGS technology, for the period March 2011 – February 2012.

A first indication of how a technology performs under the whole range of module temperature and irradiance is given by the performance matrix, which is shown in Fig. 1 for the CIGS array. The standard test condition (STC), normal operating cell temperature (NOCT) and most frequent condition (MFC) are also displayed. It is clear that the array never works close to STC. On the other hand, NOCT lies in the centre of the measured points and is therefore more representative of PV module operating conditions under outdoor exposure. The most frequent condition encountered by the array is at irradiances lower than 100 W/m^2. The performance matrices of the other monitored technologies are not displayed, since they show similar results.

In order to investigate the behaviour of the monitored technologies under different levels of irradiance the irradiance frequency and energy production are calculated.

Irradiance frequency is the number of hours, normalized to 100%, during which the PV array operates under a certain class of irradiance *G*. It indicates which irradiance conditions are more often or more rarely met during outdoor operation.

Energy production distribution indicates how the energy production of a PV plant, normalized to 100%, is distributed along the irradiance classes, i.e. under which irradiance conditions the plant produces more or less energy.

Figure 2 shows the two above mentioned parameters for the monitored thin film and reference pc-Si technologies. As discussed above, irradiance conditions between 0 and 100 W/m^2 are met most frequently - one third of the times. The reason of this high amount of low irradiance could be explained by the shading effects by the close mountain located at the east side of the plant and due to the fact that all outdoor climate conditions are taken into consideration. The irradiance frequency between 100 W/m^2 to 1000 W/m^2 does not vary significantly and has an average value of 7.1%. Very high irradiance conditions (1000 - 1200 W/m^2) are met just 2.2% of time.

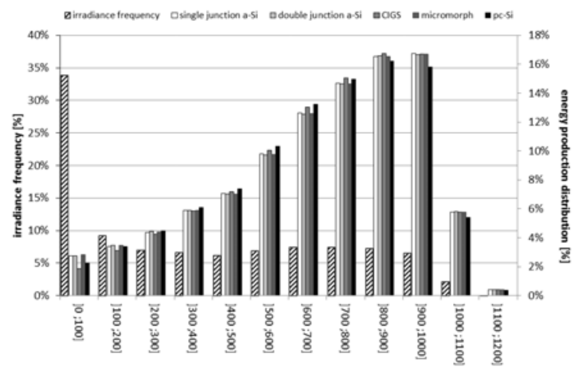

Fig. 2 Irradiance frequency (upward diagonal pattern) and energy production distribution (solid fill) of the monitored thin film and reference pc-Si arrays, for the period February 2011 – March 2012.

The energy production distribution shows a different trend and it increases with irradiance up to 1000 W/m^2. In general, under irradiance values lower than 100 W/m^2, the amount of energy output is just 2.5%. On the other hand, 48% of energy production is encountered at irradiances between 700 and 1000 W/m^2 (frequency of 21.1%). Very high irradiance conditions are not frequent, but produce alone about 6% of total energy.

At irradiances lower than 100 W/m^2, which correspond to a high percentage of diffuse-on-global radiation (turbidity), micromorph modules produce a higher share of energy, followed by double junction and single junction a-Si modules. The energy outputs of pc-Si and CIGS are lower. This situation changes at irradiances between 100 and 400 W/m^2. Compared to a-Si based and micromorph modules, here the energy productions of pc-Si and CIGS tend to be closer, with the latter giving the lowest values. On the other hand, double junction a-Si perform better than the other thin film technologies. At intermediate irradiances (between 400 and 700 W/m^2) pc-Si modules produce more energy than the other technologies, since the percentage of direct-on-global radiation is higher. CIGS modules follow the same trend because their spectrum response is similar to pc-Si modules [4], and present a higher share of energy than the other thin film technologies. At the same irradiance range, the energy outputs of single junction a-Si modules are higher than those of double junction a-Si and micromorph modules. At irradiances between 700 and 800 W/m^2 pc-Si modules start being affected by high temperatures, thus decreasing their performance. On the other hand, all the thin film technology have less negative temperature coefficients, and are not as affected as pc-Si by temperature. CIGS gives the highest values of energy production. The effect of temperature coefficient increases at irradiances higher than 800 W/m^2, where pc-Si modules show lower levels of energy production compared to the other technologies. Under the same ranges of irradiance, CIGS modules show an energy production which is similar to single/double junction a-Si and micromorph modules.

3.2 Final yield, Y_f

The final PV system yield is defined by the standard IEC 61724 [5].

Figure 3 presents the values of final yield for the monitored technologies, calculated on a monthly base. The average daily yield is also represented which shows how many hours per day a PV array would need to work at its rated power in order to produce the same amount of energy within a month. This value is the average of the monitored arrays.

The months with the highest energy production were May, July and August, with the lowest was December. The most productive month resulted May, which was characterized by clear sky every day with an average monthly turbidity of 0.56. On the other hand, energy production in June was not as high as expected for this period of the year. It was actually a cloudy month, with a turbidity value of 0.74. A large difference between the production values of February and March 2012 occurred because the latter was characterized by exceptionally clear sky conditions, with a turbidity coefficient of 0.49 (turbidity of March 2011 was 0.67).

The period February – March 2011 saw a higher specific energy production of pc-Si and CIGS modules, followed by single junction a-Si modules. This trend started changing during April, when the gradual increase of temperatures began to affect the performance of pc-Si and CIGS modules. The same effect occurred in a-Si based and micromorph modules but less pronounced, due to the less negative temperature coefficient of these technologies.

The warm period May – September 2011 was characterized by the highest outputs of specific energy given by single-junction a-Si, followed by double-junction a-Si modules. During the same period, micromorph modules produced less specific energy than single and double junction a-Si, but more than CIGS and pc-Si (with the exception of May). The reason for these higher values of specific energy of a-Si based modules could be explained by two concurrent effects: lower temperature coefficients than the other monitored technologies and the well-known thermal annealing effect. The latter becomes visible after a long period of exposure at high temperatures [6]. During the period October 2011 – February 2012 the same situation as during the cold months February - March 2011 occurred. pc-Si modules produced more specific energy than the other technologies. Amongst thin film technologies, CIGS modules were better performing, followed by single junction a-Si. Double junction a-Si and micromorph modules had similar values of specific energy output, the lowest compared to the other technologies.

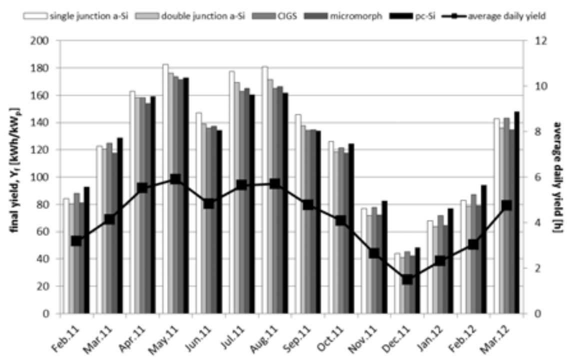

Fig. 3 Final yield, Y_f (columns) and average daily yield (line) of the monitored thin film and reference polycrystalline arrays, for the period February 2011 – March 2012.

The values of average daily yield ranged between a minimum of 1.5 hours in December and a maximum of more than 5.5 hours in spring and summer. This confirms the overall favourable climatic conditions for PV plants in Bolzano area.

The total in-plane solar radiation measured during the one-year period March 2011 - February 2012 resulted 1720 kWh/m^2. This is in a good agreement with the value of 1756 kWh/m^2 given by GeoModel Solar [7] for the period 2005 - 2011 and calculated through a translation algorithm from global horizontal irradiance data measured by satellite.

The total energy per unit area produced during the period March 2011 - February 2012 was: 80.8 kWh/m^2 for single junction a-Si, 79.5 kWh/m^2 for double junction a-Si, 96.9 kWh/m^2 for CIGS and 135.1 kWh/m^2 for micromorph.

3.3 Performance Ratio, PR

The performance ratio of a PV system is defined by the standard IEC 61724 [5].
This parameter helps evaluating the performance of a PV array, and is influenced by the overall effect of losses.

Figure 4 shows the performance ratio of the monitored technologies. In general, the performance ratio of the monitored technologies over the selected period is always above 0.8, with the exception of the period January – February 2012 for the single junction a-Si technology and the period November 2011 - March 2012 for double junction a-Si and micromorph modules.

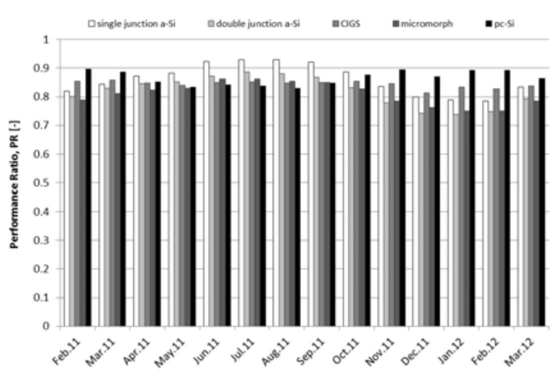

Fig. 4 Monthly Performance Ratio, PR for the monitored technologies (period February 2011 – March 2012).

Table 2 shows the minimum, maximum, average and standard deviation of PR values for the monitored technologies.

Table 2 Minimum, maximum, average and standard deviation of performance ratio of the monitored technologies, for the period February 2011 – March 2012.

	single junction a-Si	double junction a-Si	CIGS	micromorph	pc-Si
Min.	0.79	0.74	0.81	0.75	0.83
Max.	0.93	0.89	0.86	0.86	0.90
Average	0.86	0.82	0.84	0.81	0.87
St. dev.	0.052	0.052	0.012	0.040	0.025

The average PR value of single junction a-Si modules is almost the same as that of pc-Si modules, which is the highest. They are followed by CIGS (0.84), double junction a-Si (0.82) and micromorph (0.81) modules. These values confirm the good design and the overall favourable conditions at ABD PV installation.

Single and double junction a-Si modules show the same values of standard deviation σ, which is also the highest amongst the monitored technologies. Micromorph modules show a 23% less standard deviation than a-Si based modules, while CIGS performance ratio is much more stable than the other technologies with a 77% less standard deviation than a-Si based modules.

4. Conclusions

This study considered the behavior and performance of different thin film technologies: single- and double-junction amorphous silicon (a-Si), copper indium gallium diselenide (CIGS) and micromorph silicon (a-Si/μc-Si). They are installed at the Alpine latitudes of Bolzano, in the north-east of Italy. A comparison was carried out by means of irradiance frequency, energy production distribution, final yield and performance ratio.

The most frequent condition encountered by the monitored arrays is at irradiances lower than 100 W/m^2, which occur 33% of time but contribute just for a 2.5% of the overall energy production. On the other hand, very high irradiance conditions (1000 - 1200 W/m^2) are met just 2.2% of time but produce about 6% of the total energy. The irradiance frequency is equally distributed between irradiances between 100 W/m^2 to 1000 W/m^2 with an average value of 7.1%. 48% of energy production is encountered at irradiances between 700 and 1000 W/m^2.

The average daily yield of the monitored technologies ranges between a minimum of 1.5 hours in December and a maximum of more than 5.5 hours in spring and summer. With a measured value of total yearly in-plane radiation of 1720 kWh/m^2, the climatic conditions of Bolzano area can be considered favourable for the installation of PV plants in the Alpine region.

Single junction a-Si and pc-Si modules have the highest average values of performance ratio, and very close to each other. They are followed by CIGS, double junction a-Si and micromorph modules. All the monitored technologies show a seasonal variation of performance ratio values, which is higher in a-Si based modules (σ = 0.052). An exception is represented by CIGS technology which is less dependent on seasonal effects, thus showing a low variation of performance ratio values throughout the year (σ = 0.012).

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References

[1] Green MA, Emery K, Hishikawa Y, Warta W. Solar cell efficiency tables. *Progress in Photovoltaics*. Res. Appl. 17 (2009) 85–94

[2] Avrutin V, Izyumskaya N, Morkoç H. Semiconductor solar cells: Recent progress in terrestrial applications. *Superlattices and Microstructures* 49, n. 4 (2011): 337–364.

[3] Colli A, Sparber W, Armani M, Kofler B, Maturi L. Performance monitoring of different PV technologies at a PV field in Northern Italy. 25th European Solar Energy Conference and Exhibition, Valencia, 2010, 4344 - 4349.

[4] Reich NH, van Sark WGJHM, Alsema EA, eds. Weak light performance and spectral response of different solar cell types. 20th European Solar Energy Conference and Exhibition, Barcelona, 2005.

[5] IEC. Photovoltaic System Performance monitoring – Guidelines for Measurement, Data Exchange, and Analysis. IEC Standard 61724, Geneva, Switzerland, 1998.

[6] Nikolaeva-Dimitrova M, Kenny RP, Dunlop ED. Long term stability of a-Si:H thin film modules. 21th European PV Solar Energy Conference and Exhibition, Dresden, 2006, 2565-2569.

[7] SolarGis radiation data. 2012 GeoModel Solar s. r. o.. Available at www.solargis.info.