OVERVIEW OF TEMPERATURE COEFFICIENTS OF DIFFERENT THIN FILM PHOTOVOLTAIC TECHNOLOGIES

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ABSTRACT: The operating temperature of a PV module or system is a crucial parameter for its energy output. PV modules are in fact usually rated at Standard Test Conditions (STC = 1000 W/m^2, AM1.5, 25°C), but their operating temperatures are usually significantly higher. In order to have an idea of their temperature behavior- an information which may result useful in optimizing the output of a PV system under particular conditions - in the present work we have compared indoor measured temperature coefficients values of several thin film technologies (a-Si based single or multi-junctions, CdTe, CIS, thin-film silicon) with typical TCO's of a conventional c-Si wafer-based module. With the exception of the thin film Si device (γ_{rel} = -0.48 %/°C), all thin film technologies have lower values for the γ_{rel} temperature coefficient for power compared to the c-Si wafer-based module (γ_{rel} = -0.45 %/°C), with the a-Si single-junction (γ_{rel} = -0.13 %/°C) device showing the less pronounced decrease with temperature, followed by CdTe (γ_{rel} = -0.21 %/°C). The microcrystalline and CIGS device investigated in this work have TCO values for power very close (γ_{rel} = -0.36 %/°C). At least for the single-junction devices, the magnitude of the power temperature coefficient seems to be strongly correlated to the band gaps of the corresponding absorber materials. TCO values presented in this work are in line with data coming from the literature and or from manufacturer's datasheets. It should, however, be noted that for a given technology a significant spread for TCO values may exist.
Keywords: Module, Thin Film, Thermal performance

1 INTRODUCTION

The operating temperature of a photovoltaic (PV) module or system is a crucial parameter for its energy output. PV modules are in fact usually rated at Standard Test Conditions (STC = 1000 W/m^2, AM1.5, 25°C), but their operating temperatures are usually significantly higher.

The Nominal Operating Cell Temperature (NOCT) gives an indication of the operating temperature of a PV device and is therefore a useful parameter for the PV system designers. NOCT of open-rack mounted modules is measured – according to IEC 61215 and 61646 design qualification and type approval standards - at 45^o tilt, 800Wm^{-2} with a wind speed of 1ms^{-1}, an ambient temperature of 20^{o}C, and in open-circuit [1 , 2]. Typical NOCT values lay approximately around 50°C and may be a few degrees lower for devices with a polymer/glass structure (conventional c-Si modules) and slightly higher for glass/glass devices, as thin film devices usually are [3].

However, real operating temperatures of PV devices may by far exceed NOCT values - particularly in summer days - depending on several factors, as wind speed, irradiance, ambient temperature, etc.

Moreover, in the case of Building Added/Integrated PV installations, the assembly method will largely affect the rear ventilation of the module consequently determining the heat-exchange mechanisms and the average and maximum operating temperatures of the PV modules.

As described in [3], during summer days thin film glass/glass modules may reach - depending on their assembly method - temperatures up to 70°C, 79°C, and 92°C for open-rack mounted, and for installations simulating BAPV, and BIPV conditions, respectively.

Whereas a decade ago only *"conventional"* crystalline and amorphous Si technologies were commercially available for terrestrial installations, the massive growth of the photovoltaic (PV) market worldwide is nowadays accompanied by a large number of *novel* technologies and concepts entering the market. Among them several thin film (TF) technologies.

Due to the fact that different PV technologies have different temperature coefficients (TCO's), the loss of power due to higher operating temperatures - compared to STC conditions - will be more pronounced for some technologies and less for others.

In order to have an idea of their temperature behavior- an information which may result useful in optimizing the output of a PV system under particular conditions - , in the present work we compare indoor measured TCO values of several thin film technologies (a-Si based single or multi-junctions, CdTe, CIS, thin-film silicon).

Moreover, as discussed in detail in [4, 5], several energy rating models use temperature coefficients TCO to predict the energy output of a PV device. The present overview may provide a useful input to some of these models.

2 EXPERIMENTAL SET-UP

In the present work we tested the temperature coefficients of a set of thin film modules commercially available on the European market. The technologies investigated are: single junction amorphous silicon (a-Si SJ), tandem micromorph (a-Si/μc-Si), CdTe, CIGS ($Cu(In,Ga)Se_2$), and thin film c-Si (TF-Si). The technologies are listed on an anonymous basis in Table 1. For comparison, TCO's of a conventional single-crystal c-Si wafer-based module were tested as well.

The TCO measurements were realized by placing the device under test into a thermostatic chamber (shown in Fig. 1) with a high-transmittance window (low-Fe content) and by realizing IV curve measurements by using a PASAN IIIB pulsed solar simulator (10-ms pulse duration) in the range 25 – 60 °C, with 5°C steps.

Though the measurement of Temperature Coefficients is a relative one, properly matched reference cells were used as reference devices. TCO's were tested according to IEC 61646 and 61215 standards at an irradiance of 800 W/m^2.

Moreover, according to the relevant standards all modules – with the exception of the CdTe one - were subjected to Outdoor Exposure (OE) prior to the measurements. In IEC 61646 (design qualification and type approval standard for thin film devices), the TCO measurement follows an outdoor exposure of 60kWh/m^2 under a resistive load, whereas the corresponding standard for c-Si devices (IEC 61215) foresees prior to the TCO measurement only 5 kWh of pre-conditioning in open circuit conditions.

An identification of the main uncertainty contributions leads to an estimation of the measurement uncertainty. The measurement error for each temperature coefficient is expressed in Table1.

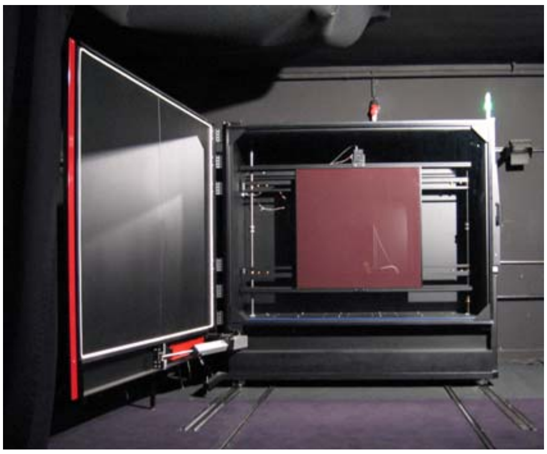

Figure 1:. The thermostatic chamber used to realize temperature coefficient (TCO) measurements of the thin film devices.

2 RESULTS

For the set of devices under test, the values as a function of the temperature for the module's maximum power, the open-circuit voltage, the short-circuit current, and the fill factor – after a proper outdoor exposure – are shown in Figure 2, 3, 4, and 5, respectively. In order to facilitate a fair comparison between different technologies the values are normalized to STC values. The temperature coefficients of Table 1 were obtained from linear fits to these data.

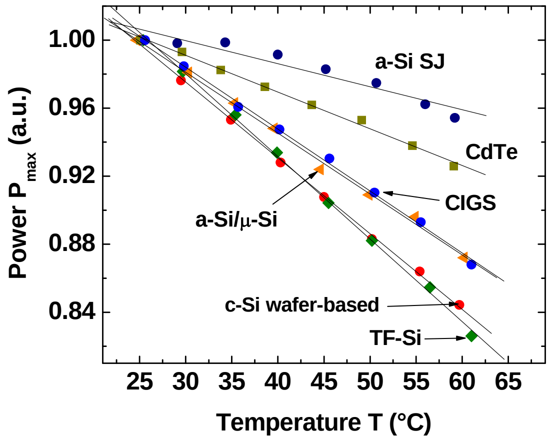

Figure 2:. Modules' maximum power P_{max} as a function of the temperature for the different technologies under test. The values are normalized to STC values to facilitate a fair comparison between different technologies. Linear fits to these data provide the relative temperature coefficients for P_{max}. (γ_{rel}).

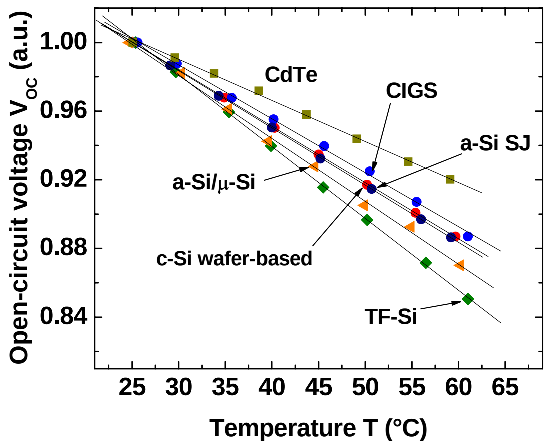

Figure 3:. Modules' open-circuit voltage Voc as a function of the temperature. The values are normalized to STC values. Linear fits to these data provide the relative temperature coefficients for Voc (β_{rel}).

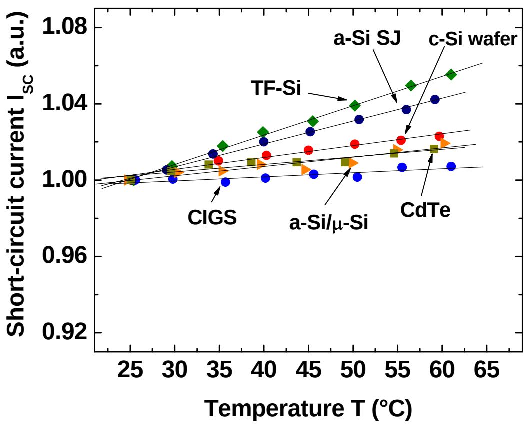

Figure 4:. Modules' short-circuit current Isc as a function of the temperature. The values are normalized to STC values. Linear fits to these data provide the relative temperature coefficients for Isc (α_{rel}).

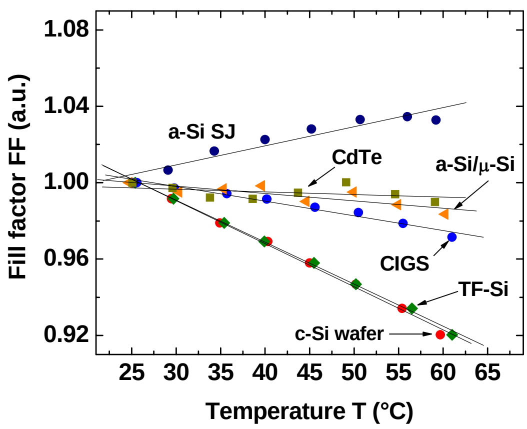

Figure 5:. Modules' fill factor FF as a function of the temperature. The values are normalized to STC values. Linear fits to these data provide the relative temperature coefficients for FF (κ_{rel}).

Table 1 provides an overview of the measured relative Temperature Coefficients (γ_{rel} for power, β_{rel} for the open-circuit voltage, α_{rel} for the short-circuit current, and κ_{rel} for the fill factor) for the set of thin-film modules under test and – for comparison - for a traditional c-Si wafer-based module. With the exception of CdTe, the values shown in Table 1 refer to the TCO measurements performed after an outdoor exposure of the modules according to the relevant standards (Outdoor Exposure 60 kWh for TF's and Pre-Conditioning of 5kWh for c-Si).

The data presented in Table 1 refer to a single module, but, in most cases, are representative of a set of devices of the same type. The values are listed in ascending order for the γ_{rel} temperature coefficient for power.

Table1: Relative temperature coefficients (TCO's) of a set of thin-film modules and of a traditional c-Si wafer-based module for comparison. With the exception of the CdTe device, the modules were subjected to an outdoor exposure (according to relevant IEC standards) before testing.

TCO's	**Pmax** γ_{rel} (%/°C)	**Voc** β_{rel} (%/°C)	**Isc** α_{rel} (%/°C)	**FF** κ_{rel} (%/°C)
Error	**± 0.027**	±0.021	±0.019	-
a-Si (SJ)	**-0.13**	-0.33	+ 0.12	+ 0.10
CdTe	**-0.21**	-0.24	+ 0.04	- 0.01
Microm. (a-Si/µcSi)	**-0.36**	-0.37	+ 0.05	- 0.04
CIGS	**-0.36**	-0.31	+ 0.02	- 0.08
c-Si wafer-based	**-0.45**	-0.33	+ 0.06	- 0.19
TF - Si	**-0.48**	-0.41	+ 0.15	- 0.22

For some technologies (CIGS, micromorph, and a-Si) the TCO's were tested before, and after an outdoor exposure to light. While the exposure to light may have a strong impact on the performance (P_{max}) of these devices, the relative temperature coefficients do not seem to be strongly influenced by the exposure to light (often differences lay between the estimated measurement uncertainty). Nevertheless, further investigations are required to verify whether TCO's may be influenced by a prolonged exposure to light and other effects, e.g. seasonal variations, which may alter the temperature behavior of these devices over the time.

4 DISCUSSION

With the exception of the a-Si and of the micromorph device, the measured PV parameters of all other technologies have a linear behavior with increasing temperature. The non–perfect linear behavior of a-Si (P_{max}, and FF) may be explained by two competitive effects which increasing temperature has on the performance of the cell, i.e. *i)* a regenerative effect promoted by the annealing of the cell (Stabler-Wronsky effect), and *ii)* an intrinsic drop of the cell's conversion efficiency as temperature increases.

Whereas the less pronounced non-perfect linear behavior (P_{max}, Isc, FF) of the micromorph device may arise from current-matching constraints for the series-connected multi-junction cells that are not seen for single-junction devices.

As Figure 2 clearly shows, all solar devices have conversion efficiencies that drop when the temperature increases. The technology which experiences the less reduction in power is the a-Si single-junction one, whereas the thin film c-Si module is the one experiencing the most significant reduction of power due to exposure at higher temperatures. This device experiences a loss of power at e.g. 60°C which is slightly higher, but comparable, to the one of the c-Si based module taken as a reference.

At least for the single-junction devices, the magnitude of the power temperature coefficient seems to be strongly correlated to the band gap of the corresponding absorber material, which vary from 1.1 eV for crystalline silicon, to approximately 1.8 for amorphous silicon (~1.2 eV for CIGS and ~1.44 eV for CdTe).

Micromorph (a-Si/μc-Si) tandem silicon solar modules have a γ_{rel} temperature coefficient for P_{max} which lies somewhere between the temperature coefficients of the two sub-cells (amorphous silicon and microcrystalline).

The temperature behavior of the micromorph device under test in the present work seems to be dominated by the behavior of the bottom (mycro-cristalline) sub-cell.

The spread between different technologies is less pronounced if we consider the decreasing and the increasing behavior as a function of temperatures for the Voc and the Isc, respectively.

On the contrary, when considering the temperature behavior of the FF, we observe an increasing trend for a-Si (likely due to the beneficial annealing process), a slightly decreasing trend for CIGS, CdTe, and the micromorph devices, respectively, and a pronounced decrease for thin film Si and the wafer-based c-Si modules.

In order to have an idea of the influence of temperature on the output power of a PV module (and system), Table 2 uses the values contained in Table 1 to show the reduction of the module's power - compared to STC (25°C) - when operating at a temperature of 60, 70, and 80 °C. These temperature are easily reached during clear-sky days in summer time by open-rack mounted modules, by modules with a reduced rear ventilation (BAPV, Building Added PV), and by modules with a fully isolated rear-side (BIPV, Building Integrated PV), respectively.

Table2: Reduction of the module's power - compared to STC (25°C) - when operating at 60, 70, and 80°C. This temperatures. are easily reached during clear-sky days in summer by open-rack (OR) mounted modules, by modules with a reduced rear ventilation (BAPV), and by modules with a fully isolated rear-side, respectively.

Power' loss compared to STC (%)	At 60°C ΔT=35°C (OR)	At 70°C ΔT=45°C (BAPV)	At 80°C ΔT=55°C (BIPV)
a-Si SJ	-4.6%	-5.8%	-7.2%
CdTe	-7.4 %	-9.4%	-11.6%
Microm.	-12.6	-16.2%	-19.8%
CIGS	-12.6 %	-16.2%	-19.8%
c-Si wafer-based	- 15.7 %	-20.3%	-24.8%
TF Si	-16.8%	-21.6%	-26.4%

Overviews of TCO's from the literature (see for example [6]) and from different producers show that for a given PV technology (thin film or wafer-based) temperature coefficients may vary quite significantly from manufacturer to manufacturer and also within modules coming from the same production line. Therefore, the values expressed in Table 1 do not pretend to express "*absolute*" TCO values, but only to give a generic overview of the temperature behavior of different TF technologies, compared to crystalline silicon. In order to provide a more complete figure, Table 3 compares the values for the power temperature coefficient γ_{rel} measured in this work, with additional data coming from our internal (SUPSI-ISAAC) database and with data coming from a partial overview of manufacturers' datasheets and from the literature.

Table3: Values for the power temperature coefficient γ_{rel} measured in this work, with additional data coming from our internal (SUPSI-ISAAC) database and with data coming from a partial overview of manufacturers' datasheets and from the literature. For a-Si based devices SJ, DJ, TJ stand for single-, double-, and triple-junction devices, respectively.

TCO for Pmax γ_{rel}, (%/C)	This work	Internal database (SUPSI)	Manufac. Datasheets + Literature
a-Si	**-0.13 (SJ)**	-0.1 to -0.3 (SJ, DJ, TJ)	-0.1 to - 0.3 (SJ, DJ, TJ)
CdTe	**-0.21**	-0.2 to -0.22	-0.18 to -0.36
Microm. (a-Si/μc-Si)	**-0.36**	-0.26 to -0.38	-0.24 to -0.29
CIGS	**-0.36**	-0.26 to -0.36	-0.33 to -0.5
c-Si wafer-based	**-0.45**	-0.41 to - 0.57	-0.37 to -0.52
Thin film Si	**-0.48**	-	- 0.58 to -0.62

The TCO values presented in this work are in line with data coming from the literature and/or from manufacturer's datasheets. However, it should be noted that for a given technology a significant spread for TCO values may exist.

5 CONCLUSIONS

The operating temperature of a PV module or system is a crucial parameter for its energy output. PV modules are in fact usually rated at Standard Test Conditions (STC = 1000 W/m^2, AM1.5, 25°C), but their operating temperatures are usually significantly higher.

In order to have an idea of their temperature behavior- an information which may result useful in optimizing the output of a PV system under particular conditions - in the present work we have compared indoor measured temperature coefficients values of several thin film technologies (a-Si based single or multi-junctions, CdTe, CIS, thin-film silicon) with typical TCO's of a conventional c-Si wafer-based module.

With the exception of the thin film Si device, all thin film technologies have lower values for the γ_{rel} temperature coefficient for power, with the a-Si single-junction device showing the less pronounced decrease with temperature, followed by CdTe. At least for the single-junction devices, the magnitude of the power temperature coefficient can be correlated to the band gap of the corresponding absorber material.

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