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Outdoor efficiency analyses and comparison of on-grid CdTe and μc-Si/a-Si thin-film PV systems for three years in Ankara – Turkey

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The present paper is mainly a comparison of the performances of two PV systems under outdoor conditions in Ankara. The systems are grid connected and consist of two PV arrays. The types of these PV arrays are CdTe thin film and amorphous silicon/micro-crystalline-based (μc-Si/a-Si) arrays. They are operated for 3 years; 2012-2014. Yearly averages of monthly efficiencies of these two systems working under the same ambient conditions are 6.88%, 6.65%, 6.80% and 6.64%, 5.86%, 5.25% for μc-Si/a-Si and CdTe, respectively. Using these values, simple calculation results for the degradation rates per year are about 0.39%/year and 6.98%/year, respectively for these two types of systems.

1 Introduction and methodology Outdoor testing of PV arrays in the long term at different climates is now important as such evaluations are very helpful in both determining the long term performance and degradation problems and also in planning environmentally friendly energy policies [1,2]. In this context, comparative outdoor testing at different climates and under the same outdoor climatic conditions is also important to yield additional information. Although some outdoor testing of too many years (longer than 10 years) appeared in the literature [2,3], testing in shorter terms (a few years) seem also very informative and in this respect, especially analysis for different climates are very evaluative [4-8]. Two of such researches appeared in the literature are summarized below.

Ishii et al. [1] analysed the performance degradation of 14 PV modules after 4 years of outdoor operation under moderate climatic conditions in Mongolia and India. They observed that the performance difference of single crystalline silicon modules was changing between 1.9%/year and 2.8%/year. However, their observation yielded that the performance of polycrystalline silicon cells decreased by 0.7%/year in the same time interval. They investigated and presented the long term performances of 14 PV modules manufactured by six different companies.

Eke and Senturk reported performance results of a grid-connected 40 kWp building integrated photovoltaic (BIPV) systems in Mugla Sıtkı Kocman University in Turkey after 36 months of operation [9]. Monitored systems consist of single junction (with 10.24 kWp nominal power and vertically oriented on two towers) and triple junction (with 30.15 kWp nominal power and 60^o fix tilt) amorphous silicon PV modules. They measured total generated electricity of the BIPV system as 103,702 kWh for 36 months of operation between July 2008 and June 2011. They found that the average efficiency is 5.58% during the monitoring period for the single junction amorphous silicon PV modules and 5.99% for the triple junction amorphous silicon PV modules.

Present study is the comparison and efficiency analyses of two different types of grid connected PV system which are installed as a project of The Center for Solar Energy Research and Applications (GÜNAM), and are located on the roof of Department of Physics at METU. The systems consist of two PV arrays, namely, CdTe thin film and amorphous silicon/micro-crystalline-based (μc-Si/a-Si) arrays (Fig. 1). PV arrays have a fixed tilt angle of 32°. The panels are cleaned once in every week.

The aim of the research is to analyze and to compare long term (3 years; 2012-2014) performances of these two systems working under the same ambient conditions.

Figure 1 CdTe and μc-Si/a-Si thin film on-gird PV systems.

The inverters are identical and the outputs are directly connected to the grid of the Middle East Technical University (METU). Tables 1 and 2 give the details of the system specifications of the systems under consideration.

Table 1 CdTe and μc-Si/a-Si thin film PV systems properties.

Specifications	CdTe	μc-Si/a-Si
Module brand	Abound	Kaneka
Module type	AB1-67B	U-EA105
P_{MAX} [W]	67.5	105
V_{OC} [V]	46.6	71
I_{SC} [A]	2.2	2.4
V_{MPP} [V]	36.1	53.5
I_{MPP} [A]	1.9	1.96
Connection	6 series x 3 parallel	4 series x 3 parallel

Monthly averages of ambient temperatures of the location of installations are summarized as follows. Maximum values for the three years are 26.43, 25.65 and 25.41 °C, which are for the months August, July and July, respectively. During noon and afternoon hours, the temperature can reach up to 40 °C. Therefore, the temperature of panels can reach well around 60 °C during summer months. However, winter months are quite cold and the lowest monthly average temperature is -2.0 °C for the month February of the year 2014. During spring and autumn the monthly average temperatures are around 13 °C and rather more stable.

The measurements of solar irradiation by the diode sensor built in the installed PV systems have very low accuracy and unreliable outputs. Another fact about these reference cell sensor is its degradability, which introduce extra inaccuracies in the performance calculations. In this respect, accuracy of measurements of the input is very important for improved outdoor testing of PV arrays [10]. Therefore, we used the measurements of solar irradiation carried out by State Meteorological Service of Turkey (MGM).

We firstly estimated the daily values of global solar irradiation on horizontal surface using daily bright sunshine hours (sunshine duration) data which are obtained from MGM. Although MGM is 20 km away from the location where the systems are installed, we believe that use of a universally applicable formula to estimate daily or monthly global solar irradiation [11] is good enough for the locations at that distance away of the measuring station [12].

In the estimation of daily solar irradiation we used a universal quadratic model which was tested extensively before [13]. The model uses measured daily or monthly average daily bright sunshine hours n to estimate the daily global solar irradiation H:

$$H / H_o = 0.145 + 0.845(n / N) - 0.280(n / N)^2 , \qquad (1)$$

where N is the day-length and H_0 is the daily extraterrestrial solar irradiation on horizontal surface. Using H values one can estimate the hourly global and diffuse component of solar irradiation using the model of Collares-Pereira and Rabl [14] and the model of Erbs et al. [15]. The details of these calculations are given in Duffie and Beckmann [16].

Table 2 Inverter properties.

Specifications	Energy Input Values [DA]	Energy Output Values [AA]
Inverter Brand	SMA	
Inverter type	SB 1200	
V_{MAX} [V]/V_{nom} [V]	400	105
V_{MPP} [V]/f_{nom} [Hz]	100-320	50/60
I_{MAX} [A]/I_{nom} [A]	12.6	5.2
–/P_{nom} [V]	---	1200
–/cos φ	---	1

As mentioned above we also used the measured values of hourly global solar irradiation on horizontal surface by MGM from which we calculated hourly global and diffuse component of solar irradiation as explained above.

In the calculations of hourly solar irradiation on tilted PV arrays we used isotropic sky model of Liu and Jordan [17]. Their expression is given as

$$I_T = I_b R_b + I_d \left(\frac{1+\cos\beta}{2}\right) + I \rho_g \left(\frac{1-\cos\beta}{2}\right) , \qquad (2)$$

where I_b and I_d are hourly beam and diffuse irradiation respectively, I ($I = I_b + I_d$) is hourly global horizontal irradiation, R_b is the ratio of beam radiation on the tilted surface to that on a horizontal surface, β is tilt angle and ρ_g is the ground reflectance. We used a value of 0.20 for ρ_g, which is a typical average value for cultivation sites [18]. We note that the use of anisotropic models (for example

Perez model [19]) does not change our results of the performances of PV systems significantly. As mentioned above, the details of such calculations are outlined in Duffie and Beckman [15]. We first calculated daily values from hourly calculations and take the averages for monthly average of daily values.
Next section gives and discusses the results of three years of outdoor measurements. In Section 3 we conclude and give a future prospect.

2 Results and discussion The estimated monthly total values of solar irradiation on the tilted PV arrays are shown in Fig. 3, for three years. Also in this figure we presented the calculated values of monthly total solar irradiation on the tilted panels, using the measured daily global solar irradiation on horizontal surface which we obtained from MGM.

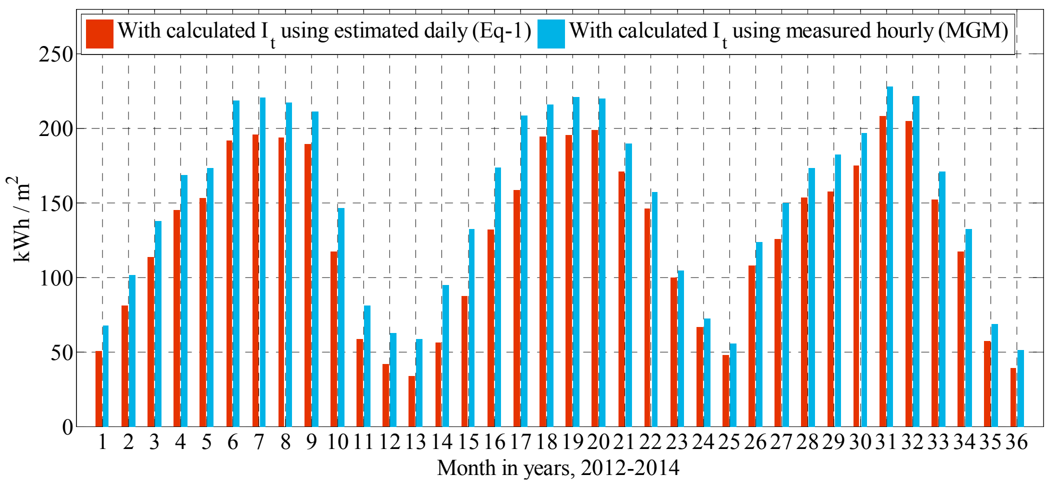


Figure 2 Input of the PV systems.

The calculated monthly values (Fig. 2) using measured data of MGM (blue bars) are higher than those calculated from the estimated solar irradiation using Eq. (1) (red bars); during summer and fall the difference is around 10% (~20 kWh/m^2). The difference is around 6% (~10 kWh/m^2) for the winter and spring months. Although similar trends can be observed for all the years, the differences seem larger for the year 2013.

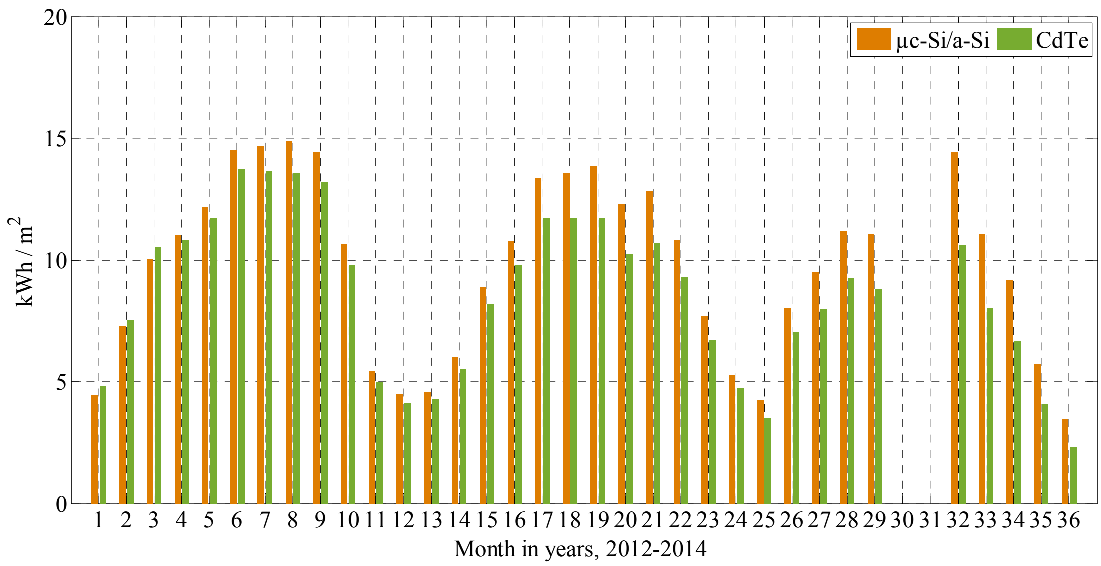
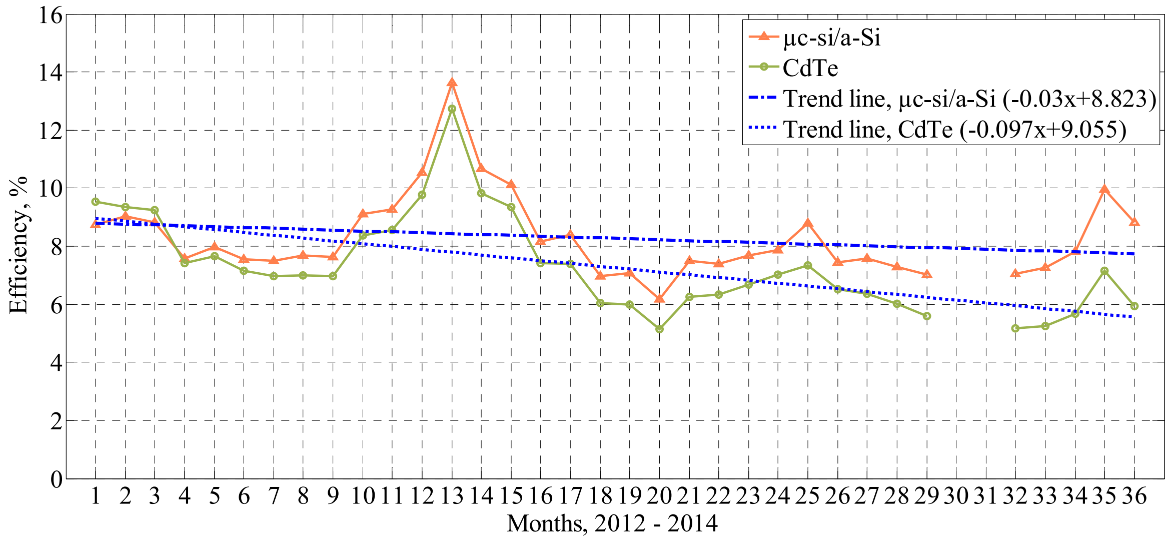


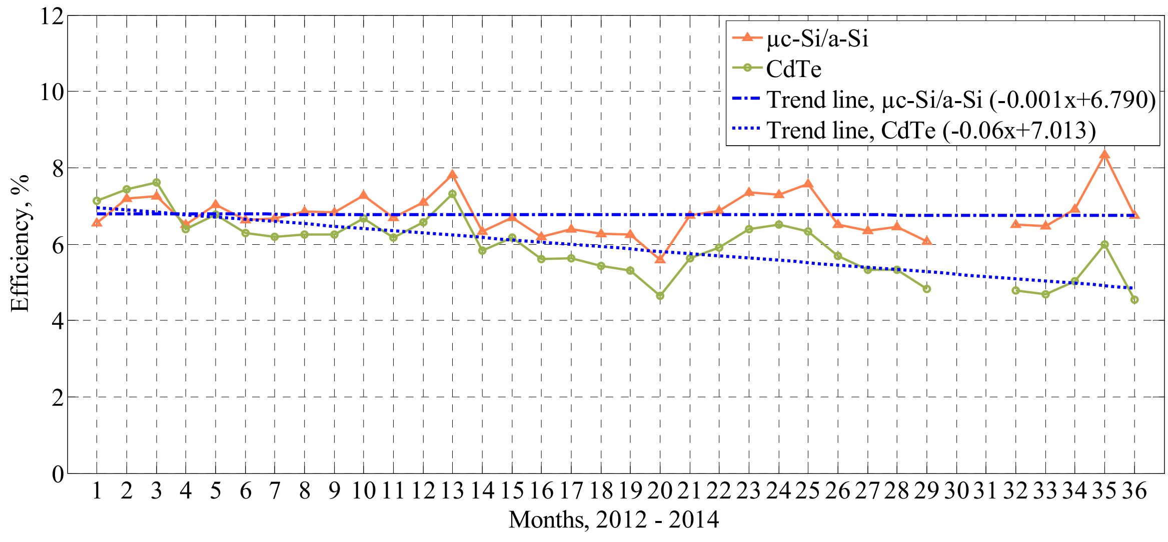
Figure 3 The energy harvested by the two PV systems for the three years 2012-2014.

Our preliminary results showed that the amount of annual energy harvested is quite the same from two PV systems (Fig. 3). Figure 3 depicts the monthly harvested energy values from two types of PV arrays for three years. This is the energy measured by our recording system which is the energy directly given to the grid of METU.

The difference between the amounts of energy harvested by the two types of arrays can clearly be seen; that is, the annual sums are 122.3 kWh/m^2 for CdTe PV array and 128.0 kWh/m^2 for μc-Si/a-Si array. Note that two months are missing in the last year since the number of days that the recorders failed is high for these two months.



(a) With the calculated I_t using estimated daily



(b) With the calculated I_t using measured hourly

Figure 4 Efficiencies of grid connected μc-Si/a-Si and CdTe systems

The monthly efficiencies calculated by the estimated global horizontal solar irradiation using bright sunshine hours from MGM and Eq. (1) (Fig. 4a), and by the hourly data of global horizontal solar irradiation taken from MGM (Fig. 4b), for the two systems are presented in Fig. 4. As can be seen the monthly efficiencies follow about the similar trends. It is important to note that although the efficiency of CdTe system is being a little higher for 3 months (January-March) of the first year, it is always lower than μc-Si/a-Si array in the following years. This seems due to a higher degradation rate for CdTe system as will be discussed below. The efficiencies calculated from the estimated and measured global horizontal solar irradiation are quite the same in their values and in their monthly trends.

However the degradation rates calculated using least square regression lines (i.e. the slopes of the least square regressions; see the results in the inset of the Fig. 4a and b) are quite different for these two different calculation procedures. That is, the degradation rates for CdTe and μc-Si/a-Si array are 0.097/month and 0.03/month, respectively for the calculations from the estimated solar irradiation by Eq. (1) (Fig. 4a); while they are quite lower as 0.06/month and 0.001/month for the calculations using the measured data of MGM (Fig. 4b). We should note that the yearly degradation rate of our CdTe system is quite higher (6.98%/year with MGM data) compared to the average values of around 1.9%/year reported in the literature [6]. On the other hand, the degradation rate of μc-Si/a-Si array (0.39%/year with MGM data) is rather closer to the reported average values of around 1.4%/year. For the installed system after 2000, in reference [6], the average value of the reported degradation rates for a-Si thin film array is around 1%/year. This figure is higher than our observation of 0.39%/year which is the result that we obtained by the measured hourly data of solar irradiation of MGM. (Here, we should note that our system is μc-Si/a-Si but the results presented in [6] are for a-Si thin films.) Another issue in this context is, although it is still high, rather lower degradation rate of 6.98%/year (0.06/month) that we obtained for CdTe using the data of MGM, seem rather closer to the reported highest values of around 3.5%/year for CdTe. This suggests that our results, calculated by the measured solar irradiation of MGM are more accurate than those calculated using estimated solar irradiation by bright sunshine hours using Eq. (1), as expected. In addition, one might also conclude that the inaccuracy in the degradation rates calculated by estimated solar irradiation using Eq. (1) might be as high as 20-30%. However, these conclusions should be further tested and this is our future research of interest.

The variation of the solar irradiation for a specific month from year to year, for these three years, is rather low. Therefore, dependence of the efficiency variation on incident solar irradiation is negligibly smaller than the rates of degradation of the arrays. Thus, one can conclude that the degradation is mainly due to intrinsic changes in the cells themselves.

3 Conclusion In this article we summarized the three years outdoor testing results of two PV systems in Ankara, Central Anatolia. Our results showed that yearly averages of monthly efficiencies are 6.88%, 6.56%, 6.80% and 6.64%, 5.86%, 5.25% for μc-Si/a-Si and CdTe, respectively. The degradation rates are calculated to be 0.39%/year, and 6.98%/year, respectively. It is observed that the degradation rate of CdTe system is quite higher than those reported in the literature.

We note that to measure solar irradiation using more accurate thermopile pyranometers at the installation site will give more accurate measurements of efficiencies and thus degradation rates. Therefore, to determine the more accurate results of the efficiencies and thus for the final comparisons we plan to install more accurate solar irradiation measuring devices nearby to the arrays. Further research of interest is therefore to renew our outdoor testing facilities. Analysis for another system (mono crystalline) which worked under the same conditions is future topic of research. In addition, comparisons using the data of a new automatic meteorological station installed recently are ongoing further research subjects.

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