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Thin-film CdTe photovoltaics – The technology for utility scale sustainable energy generation

Amit H. Munshi[a,*], Nikhil Sasidharan[b], Subin Pinkayan[b], Kurt L. Barth[a], W.S. Sampath[a], Weerakorn Ongsakul[b]

[a] Department of Mechanical Engineering, Colorado State University, Fort Collins, CO 80523, USA
[b] Department of Energy, Environment and Climate Change, Asian Institute of Technology, Bangkok 12120, Thailand

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ABSTRACT

Photovoltaics is an important energy technology for large scale energy generation. In the past few years cost of photovoltaic module manufacturing and installation as well as electricity generation has substantially decreased while the production volume has seen a steep increase. These changes can be attributed to improvement in solar cell efficiencies as well as better manufacturing practices. There are several photovoltaic technologies available in the market but the two primary technologies commercially manufactured for large scale installations are polycrystalline thin-film CdTe and crystalline silicon. Crystalline Si is the oldest and the most widely installed technology while thin-film CdTe is the technology that has demonstrated the largest growth and lowest LCOE (levelized cost of energy). In this study, commercial modules from both these technologies are installed side by side for an accurate comparison of their performance. The modules for comparison are installed with the same approximate nameplate capacity in three different configurations viz. Roof-top, floating on water and ground. Their performance is monitored and analyzed over a 3 month period. Thin-film CdTe demonstrated substantial advantage under all three conditions over crystalline Si in Thailand's tropical climate which is characterized by high temperatures and humidity throughout the year. Advantage demonstrated by thin-film CdTe is further supported by greater economic, environmental, reliability and life-cycle advantages that are summarized in the later part of the study.

1. Introduction

About 174,000 terawatts (TW) of energy from sun is received by the upper atmosphere of earth and after losses 94,800 TW is available on earth's surface that can be consumed for energy generation. World energy demand is currently estimated at about 18 TW which is a small fraction of the energy received on earth's surface. By 2030, world energy demand is expected to grow by about 30% to maintain the current living standards. However, the growth in photovoltaic development and installations is much faster than the growth of energy demand (Haegel et al., 2017). Due to the steep increase in production and installation of photovoltaics as well as improvement in conversion efficiency the cost of photovoltaics is seeing a sharp decline (Haegel et al., 2017; Branker et al., 2011; Lazard, 2014). These among other factors contribute to making photovoltaic electricity a major source of energy generation.

Crystalline silicon photovoltaics is the dominant photovoltaic technology globally for solar installations (Fraunhofer, 2018). Apart from crystalline silicon, there are two thin-film technologies that are prominent in the photovoltaics market – cadmium telluride (CdTe) and copper indium gallium di-selenide (CIGS). Over 17 GW of CdTe photovoltaics has been installed globally (First Solar, 2017) and CIGS annual manufacturing capacity currently is estimated at about 1.5 GWp (Fraunhofer, 2018). Thin-film CdTe being one of the prominent photovoltaic technologies, it is important to understand scope and impact of CdTe photovoltaics for large scale energy generation. To evaluate the performance of CdTe photovoltaics against crystalline silicon photovoltaics under different installation conditions, same approximate nameplate capacity (~3 kW) were installed and monitored. The three installation conditions investigated were roof-top, floating on water (Trapani et al., 2015; Miguel Redón Santafé et al., 2013) and ground. Based on the collected data their performance was compared. The collected results were also used to generate a prediction model for thin-film CdTe and the predictability of thin-film CdTe module was evaluated. Other researchers have performed similar studies to understand the performance of solar modules in the field (Kichou et al., 2018;

* Corresponding author.
E-mail address: Amit.Munshi@colostate.edu (A.H. Munshi).

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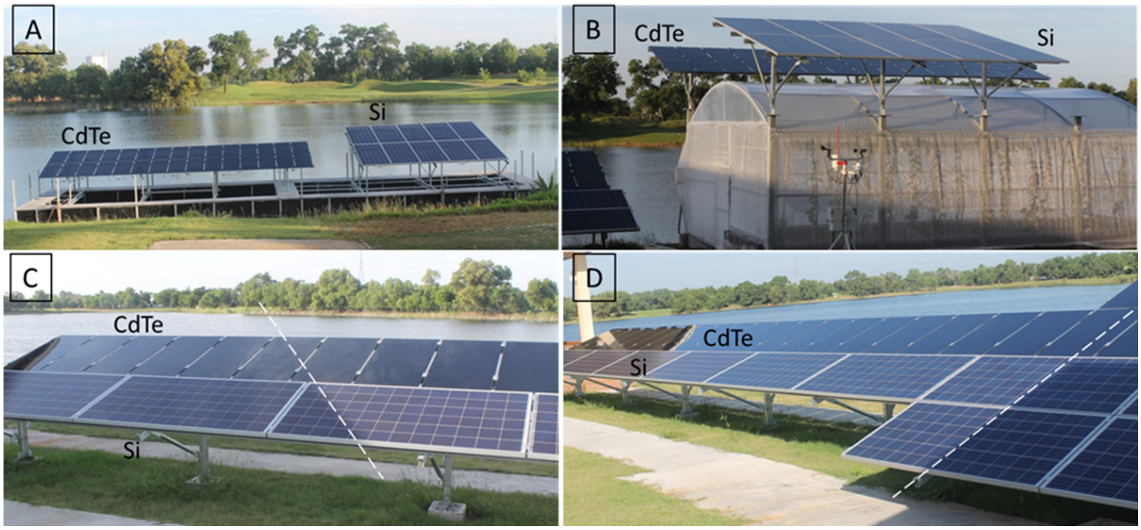

Fig. 1. Equal capacity (~3 kW) of ground installation of CdTe and c-Si for performance evaluation. (A) Floating (B) Greenhouse rooftop (C) Ground installation morning shadow (D) Ground installation evening shadow.

Rajput et al., 2018). The comparison of c-Si and thin-film CdTe performance is presented here in terms of performance over 3 month study, performance per day over one month period and performance over an entire day of operation. The study presented here also addresses various questions such as effects of humidity and temperature, power generation advantage, reliability, environmental impact and toxicity.

2. Performance and reliability of thin-film CdTe modules

To evaluate the performance of the two most prominent photovoltaic technologies under field operating conditions, about 3 kW of CdTe and c-Si modules were installed under different conditions. These installations included ground installations, roof-top and floating type on a lake. These installations were constructed at a golf course in Thailand. The goal of this study was to compare the performance of CdTe against c-Si under exactly same operating conditions. In addition, the modules on ground were so installed that both CdTe and c-Si modules had similar shadowing from nearby construction in the morning as well as the evening. Fig. 1 shows the shadowing of these installed arrays. These structures help to accommodate different types of panel and differentiate their temperature dependencies.

The installed capacity of CdTe thin-film panels at each installation was about 3150 W and poly crystalline is about 3050 W details for which are given in Table 1.

A temperature data logger is used to record the ambient and module temperature using thermocouples which are attached to the rear side of the panels (Sreewirote et al., 2017). The duration between consecutive readings was 10 min. DC and AC electrical parameters were monitored by respective sensors which measured voltage, current and power output of the installed solar panels. Solar radiation was measured using pyrometers which were placed at the same tilt angle as panels. Recording of the data was continued for 2 months.

Table 1
Different installations.

Type of installations	Type of panel	Max rating of panel (W)	No of panels	Total (W)
Green house roof-top	Crystalline	305	10	3050
	Thin-film	105	30	3150
Floating on water	Crystalline	305	10	3050
	Thin-film	105	30	3150
Ground installation	Crystalline	305	10	3050
	Thin-film	105	30	3150

Fig. 2 shows the normalized power output for all 3 conditions over an entire day. In all three cases, CdTe thin-film produced considerably higher power than polycrystalline Si. This higher performance is primarily due to better temperature coefficient of CdTe thin-film photovoltaics as compared to c-Si. More details regarding this will be discussed in the discussion section.

For the arrays that were installed on ground with the same amount of shading for CdTe thin-film and c-Si, CdTe thin-film demonstrated a much greater advantage over polycrystalline silicon as can be seen in Fig. 2. As mentioned earlier, the arrays of ground mounted panels are so installed as to allow partial shading of the arrays in the morning and evening.

Though equal shading occurred in both CdTe thin-film and polycrystalline panels, CdTe thin-film panels showed much better output. The maximum difference in the performance was predominantly in the morning hours. The normalized power difference is shown in Fig. 3. At its peak, CdTe thin-film demonstrated about 1.6 kW advantage over the polycrystalline Si panels. Effect of shading during evening hours was observed to have less effect on the arrays. Performance output of CdTe thin-film arrays on ground installation was also compared to same capacity CdTe thin-film rooftop mounted panels. The maximum difference between these was observed to be only 310 W. This further provides evidence that CdTe thin-film modules are substantially less sensitive to environmental conditions than polycrystalline silicon panels.

The energy production during shading hours for these arrays is shown in Table 2. It is evident from these results that polycrystalline silicon panels show a greater loss in power generation when compared to CdTe thin-film panels. While performance of thin-film CdTe panels was seen to be better under various field operating conditions over an entire day, it was important to analyze the performance of these arrays over a longer period of time. For this purpose using the data logger described earlier, performance of these arrays was monitored over a period of one month. Thin-film CdTe modules substantially outperformed the performance of c-Si as well. A comparison of the peak power output of thin-film CdTe panels against polycrystalline Si panels is shown in Fig. 4. The output here is plotted in terms of percentage of installed capacity of both arrays.

The analysis period was further extended to a period of 3 months. The ratio for output in terms of installed capacity to actual peak power generation was monitored for these arrays and performance for each over this 3 month period is shown in Table 3.

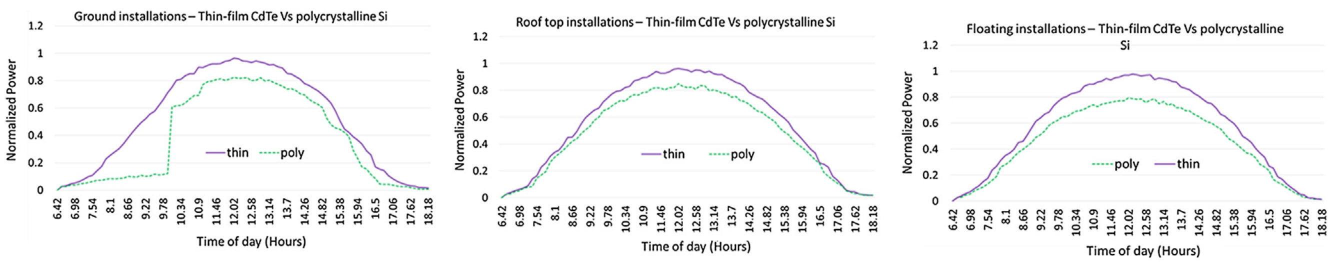

Fig. 2. Normalized power generation comparison of CdTe thin-film against polycrystalline Si under 3 different operating conditions.

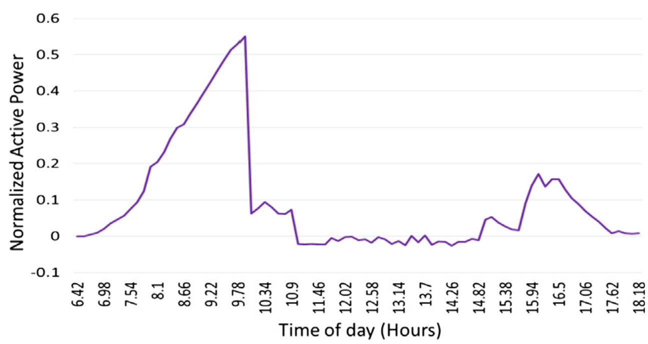

Fig. 3. Normalized power generation difference between ground mounted thin-film CdTe and polycrystalline Si arrays that are partially covered in shadow during the morning and the evening.

Table 2
Comparison of energy generation in one day.

Installation condition	Panel type	Power generation
Greenhouse rooftop	Polycrystalline Si	17.1 kWh
	Thin-film CdTe	20.4 kWh
Ground installation	Polycrystalline Si	14.1 kWh
	Thin-film CdTe	19.4 kWh
Floating	Polycrystalline Si	17.5 kWh
	Thin-film CdTe	20.8 kWh

Table 3
Ratio of installed capacity to actual output over a 3 month period.

	Polycrystalline silicon			Thin-film CdTe		
	Rooftop	Ground	Floating	Rooftop	Ground	Floating
Dec	82.23	80.06	83.93	96.44	95.87	97.37
Jan	79	81	82	93.46	95.61	96.65
Feb	81.50	82.30	82.56	94.44	96.32	97.30

Under all operating conditions, the performance of thin-film CdTe was observed to be about 20% better than polycrystalline silicon. Based on the performance data collected over this period of 3 months and temperature for these modules monitored for the same period. Based on the collected data, temperature dependency of the thin-film CdTe modules was calculated. The voltage reduced with increase in temperature while current increased. Meaning the voltage had negative coefficient and current had a positive coefficient which is found to be in agreement with literature. The voltage coefficient of the thin-film CdTe modules was calculated to be −1.8 and current coefficient was calculated to be 0.24. Thus the power coefficient for these modules was found to be −0.432. Data from this study, radiation in W/m^2 and ambient temperature from weather prediction were used as an input for Artificial Neural Networks (ANN) toolbox (Elobaid et al., 2015) to generate a model to predict behavior of CdTe thin-film modules. Fig. 5 shows the comparison predicted power output against actual power

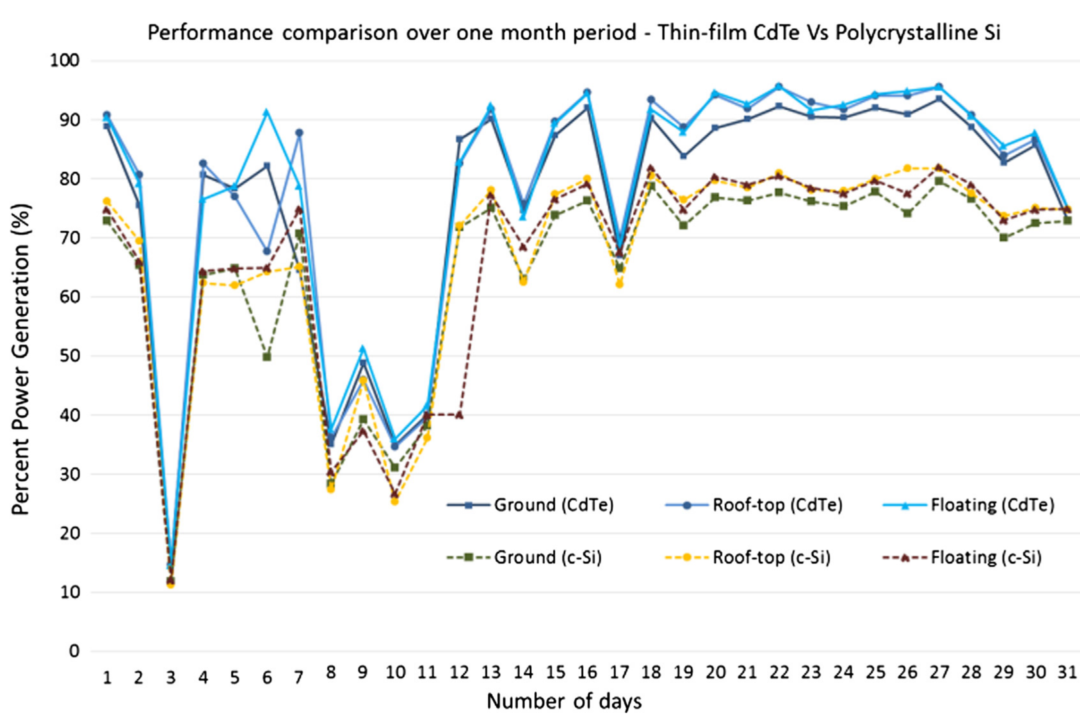

Fig. 4. The power output of each type of installation analyzed with respect to its installed capacity.

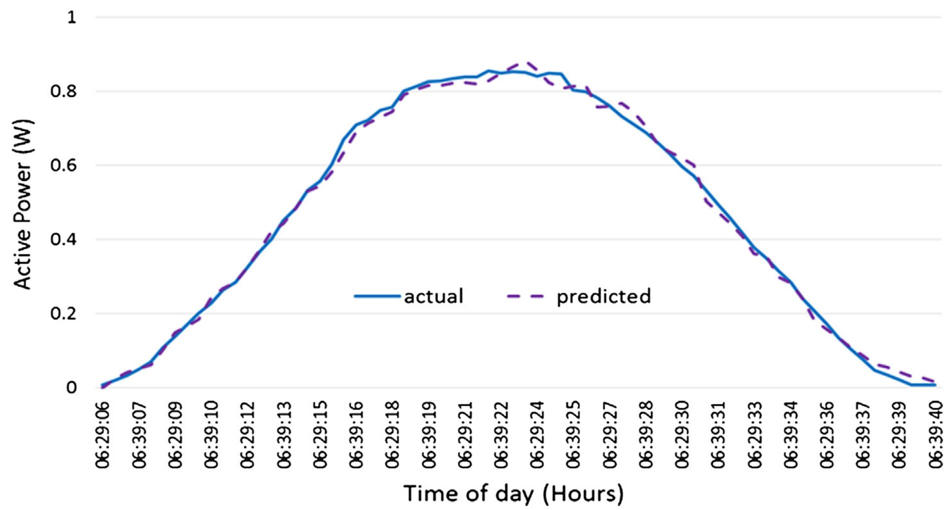

Fig. 5. The predicted power output compared to predicted output for CdTe array.

output. These are observed to be in excellent agreement suggesting good reliability and predictability of thin-film CdTe modules under field operating conditions. This is in good agreement with the data published by First Solar Inc. for their commercially commissioned CdTe modules (Report: INFORME). Difference in performance seen in this study is much larger than published by First Solar INC. The difference is attributed to higher diffused component of light and higher response of CdTe thin-film modules to diffused component of light within this study. This is also inferred from higher response of CdTe modules shown in Fig. 2 and shading condition shown in Fig. 1c and d.

3. Degradation rate of thin-film CdTe

As important it is to understand the performance and predictability of photovoltaic modules for commercial application, it is necessary to understand the degradation of modules under field operating conditions. An extensive survey was conducted by NCPRE (National Center for Photovoltaic Research and Education) at Indian Institute of Technology, Bombay and National Institute of Solar Energy, Haryana in India to understand the degradation rate of commercial photovoltaic installations all over India (Dubey et al., 2014, 2017). India has a wide variety of climatic conditions. A study of degradations rates for photovoltaic installations all over India may be considered as a reliable source of information for photovoltaic performance.

Under this study, installations for several photovoltaic technologies such as monocrystalline silicon, polycrystalline silicon, amorphous silicon, copper indium gallium selenide (CIGS), CdTe and silicon HIT modules were studied for their performance degradation. This study showed that degradation in CdTe installation was the lowest with exclusion of HIT (Dubey et al., 2014, 2017). However, it was clarified that not enough data for HIT technology was available due to very few installations and therefore the data for HIT technology was not conclusive. The P_{max} degradation rate for thin-film CdTe modules was reported to be between 0.8% and 1.02% per year while various silicon technologies exhibited degradation rate between 1.31% and 2.57% (Dubey et al., 2014, 2017). This suggests that thin-film CdTe modules exhibit higher reliability not only under short-term test conditions but also long-term large-scale commercial installations.

4. Price learning curve of thin-film CdTe

The actual cumulative photovoltaic capacity has consistently exceeded the projected capacity. This is complemented by the improvement in conversion efficiency of photovoltaic devices beyond the most optimistic estimates (Haegel et al., 2017). However, as explained by Haegel et al., the ultimate test of a technology is the market (Haegel et al., 2017). The current module average price for thin-film CdTe are at par with polycrystalline Si (Lazard, 2014). Moreover, as per photovoltaics report published by Fraunhofer Institute of Solar Energy Systems, Germany; it has been shown that by the end of 2015 the cumulative production of thin-film photovoltaics was 24 GW while that of crystalline silicon was 235 GW (Fraunhofer Institute, 2016). In spite of such a large difference in production, the inflation adjusted module prices for both technologies were approximately the same (Lazard, 2014). This is a substantially less installation volume to achieve competitive module average selling prices. This a lays strong evidence that price learning curve for thin-film technology is far more suited for large scale energy generation. Low module average selling prices for CdTe have led to very low power purchase agreements (PPA). While PPA prices below \$0.05/kWh are fairly common in United States, the lowest PPA price recorded in United States is ~\$0.038/kWh using First Solar's thin-film CdTe modules (Kenning, 2015; Ian et al., 2015). This by many estimates is the cheapest PPA for any energy technology.

5. Environmental impact and life-cycle analysis of thin-film CdTe

It is evident from the study presented here that thin-film CdTe photovoltaics provide an economic advantage as well as greater reliability under field operating conditions. To further establish thin-film CdTe as a technology for large scale energy generation, it is important to understand its environmental impact. Similar studies have been performed by other researchers to understand the lifecycle impact of CdTe photovoltaics (Kim, 2014). Cadmium is a group 2B carcinogen and cadmium is availed as byproduct of smelting metals such as zinc and lead. If cadmium was not consumed for a useful purpose at its produced rate, it would be stockpiled, cemented and buried or disposed of in landfills (Fthenakis, 2004). These are not sustainable and desirable means of cadmium disposal. Use of cadmium for production of CdTe-based photovoltaics is accepted as a more environmentally friendly means since CdTe is more stable than elemental cadmium. It has also been established that in case of a fire the cadmium released from CdTe panel would be absorbed and trapped within the encapsulating glass and would thus be prevented from flowing into the environment.

Emissions from Cd production are another important consideration and a fundamental question. Based on ISO (International Standard Organization) directives, emissions from cadmium are only 0.58% of the total emissions from zinc refining to achieve cadmium as a byproduct (Fthenakis, 2004; Raugei et al., 2007). Moreover, atmospheric cadmium emissions from the life-cycle of CdTe photovoltaics are estimated at 15.0–17.0 g Cd/ton Cd produced (Fthenakis, 2004). Thin-film

CdTe also has the lowest life-cycle cadmium and greenhouse gas (GHG) emissions amongst all energy technologies (Alsema et al., 2006). More than 90% of these cadmium emissions are estimated to be caused by use of fossil fuels electricity in the photovoltaic manufacturing process. These cadmium emissions from CdTe photovoltaics are estimated to be the lowest amongst all energy technologies with exceptions of natural gas and hydroelectricity. The global warming potential for CdTe photovoltaics is the lowest amongst all photovoltaic technologies at 17 g (CO_2-eq)/kWh (Report: INFORME; Raugei et al., 2007). These can further be reduced by utilizing photovoltaic electricity for production of CdTe modules. These environmental advantages are further extended to use of water for production. CdTe photovoltaics utilize about 0.27 kg/kWh of water while between 0.53 kg/kWh and 1.23 kg/kWh is required for c-Si photovoltaics (Raugei et al., 2007). 0.06 kg/kWh abiotic material input is required for CdTe which is also the lowest amongst all commercial photovoltaic technologies (Raugei et al., 2007). Gross energy requirement estimates for CdTe is also substantially lower than other photovoltaic technologies which imply lower energy payback time (Fraunhofer Institute, 2016; Raugei et al., 2007; Alsema et al., 2006; Munshi and Sampath, 2016). Energy payback time for CdTe photovoltaic systems is estimated at being between 0.5 and 0.6 year while all other photovoltaic technologies are estimated between ~0.8 and 4.9 years (Raugei et al., 2007). This advantage for CdTe is expected to be greater in warm and humid climates where the power generation advantage is greater. The acidification potential and freshwater ecotoxicity potential are also estimated to be the lowest for CdTe photovoltaic systems (Raugei et al., 2007).

6. Discussion

Commercial photovoltaic modules are rated at Standard Test Conditions (1000 W/m^2, AM1.5, 25 °C) but the actual operating conditions are significantly different. The true nature of module performance is important to be evaluated under actual field conditions. Warm and humid climate is understood to be the most testing conditions for long-term application of photovoltaic modules (Dubey et al., 2014). This study was aimed at developing an in-depth understanding of performance of the two most significant commercial photovoltaic technologies under such testing conditions. The results of this study show good agreement with the study published by Virtuani et al. (2010) as well as report by First Solar Inc (Report: INFORME) where CdTe demonstrated much lower temperature coefficient. This suggests that thin-film CdTe modules have a significant power generation advantage over the largest commercial photovoltaic technology i.e. crystalline silicon.

Conversion efficiencies of photovoltaic devices generally are observed to decrease with increase in operating temperatures. This is fundamentally due to increase in internal carrier recombination rate that is caused by increase in carrier concentration. For all photovoltaic technologies the open-circuit voltage experiences a sharp decrease while short-circuit current generally tends to improve with increasing temperature (Virtuani et al., 2010). It is observed that the reduction in open-circuit voltage is significantly less than silicon and CIGS photovoltaics while there is a modest increase in short-circuit current. These effects combined with very low loss in fill-factor with increase in temperature leads to power generation advantage for thin-film CdTe photovoltaics when compared to polycrystalline silicon. The P_{max} temperature coefficient was measured at −0.21%/°C for laboratory test conditions by Virtuani et al. while it is measured between −0.34%/°C and −0.28%/°C by First Solar Inc. for commercial modules (Report: INFORME; Virtuani et al., 2010). Typical field operating temperatures for photovoltaic modules is 40 °C to 60 °C and literature references as well as study presented here show evidence that CdTe photovoltaic arrays have a substantial power generation advantage over polycrystalline Si within this temperature range.

This observation is also supported by physical calculations as explained by Green (2003). Larger band-gap materials have a greater absolute sensitivity to voltage, but on normalizing these with actual voltage values the condition reverses. Therefore, higher band-gap material i.e. CdTe has a lower sensitivity to temperature when compared to a lower band-gap material i.e. silicon. The short-circuit current generally increases with increase in temperature. This is due to decreasing band-gap increase in band-to-band absorption coefficient. The effect of temperature on short-circuit current is also related to the indirect band-gap of crystalline Si (Green, 2003). It is more important to achieve high absorption in indirect band-gap materials with increasing temperature and collect more carriers. Therefore, direct band-gap thin-film CdTe photovoltaics show greater improvement in short-circuit current with increasing operating temperature. Fill-factor is the ratio of maximum power point to the product of open-circuit voltage and short-circuit current. Due to the dependencies of open-circuit voltage and short-circuit current on temperature as explained earlier, this ratio at any given temperature will be larger for thin-film CdTe when compared to c-Si at that temperature. This explains the lower loss in fill-factor with increasing temperature for thin-film CdTe (Virtuani et al., 2010; Green, 2003).

Light absorption in photovoltaic devices is also affected by humidity to a large extent. When the spectral responses of thin-film CdTe are compared to crystalline Si, it becomes evident that humidity does not affect the performance of CdTe while it has a substantial effect on absorption of silicon (Report: INFORME). External quantum efficiency results show that the loss in response for crystalline silicon at 950 nm is the highest (Report: INFORME). This is also the region for crystalline Si where the quantum efficiency is the highest. The second absorption band at about 1150 nm sees a similar loss (Report: INFORME). Such loss in absorption is not observed with thin-film CdTe. Instead, most areas under CdTe quantum efficiency show a mild gain (Report: INFORME). This explains the reason for better performance of thin-film CdTe under higher humidity.

7. Conclusions

Several advantages of thin-film photovoltaics have been demonstrated and summarized in this study. Thin-film CdTe shows several advantages over crystalline silicon including field performance under extreme climatic conditions, techno-economic aspects and environmental as well as life-cycle impact. The presented experiments are conducted in Thailand that has a warm and humid climate that is considered to be the most extreme conditions for photovoltaic operation. Under these conditions, thin-film photovoltaic arrays demonstrate up to 20% power generation advantage over c-Si arrays. Incorporating shadowing conditions for installed test fields makes it evident that thin-film CdTe would perform more reliably under cloudy conditions. This makes thin-film CdTe more suitable for large range of climatic conditions. Greater reliability of field performance is also demonstrated within this study that leads to excellent predictability of field performance through computational modeling. This provides a basis for thin-film CdTe to be extensively utilized for utility scale electricity generation.

In addition to analysis of the thin-film CdTe arrays in extreme climatic conditions, several other advantages of thin-film CdTe are also summarized. Although, cadmium is a primary ingredient in CdTe photovoltaics, Cd emissions over its manufacturing and life-cycle is observed to be one of the lowest amongst all energy technologies. Lowest energy payback time makes thin-film CdTe suitable for very large scale applications. Low cost of manufacturing establishes it as a suitable technology to meet the growing energy demand. Low CO_2 emissions and low global warming potential makes thin-film CdTe more attractive for environmentally sustainable energy generation. Moreover, low utilization of water for manufacturing and per kWh electricity generation compliments the necessity to reduce clean water utilization for industrial processes. Thus, thin-film CdTe photovoltaics provide an opportunity to be utilized as an excellent alternate to conventional energy sources as well as more expensive c-Si photovoltaics.

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