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Optimal Weighting of Parameters for Constructing Typical Meteorological Year Datasets for Photovoltaic Power Stations Operated under Hot Dry Maritime Climates

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Abstract

The objective of this study is to find an optimal set of the weights of different typical meteorological year (TMY) parameters for photovoltaic (PV) power plants operated under hot dry maritime climates. The TMY datasets are generated for a maximum period of six years, for which there are power output data available from a PV power station located in Abu Dhabi, United Arab Emirates and equipped with both polycrystalline silicon and cadmium telluride modules. After determining the typical yield year (TYY) i.e. the months with the plant yields closest to the long-term averages, the parameter weights that result in the closest month combination are found. In total, 19 TMY parameters are considered in the study. The TYY-based TMY parameter weighting approach proposed in this paper reduces the deviations of TMY-based yield estimates from the multiannual monthly averages as compared to the previously proposed TMY weighting sets. The resulting locally determined weight sets place approximately two third of the weight on irradiance variables and one third on parameters that are correlated with plant yield but not with irradiance. On an annual scale, no major benefit is derived from using the proposed TYY-based approach as compared to the previously proposed TMY weighting sets. In accordance with the objective, the weighting sets proposed in this study are expected to suit best the regions characterised by hot dry maritime climates such as the areas around the Persian Gulf and the Red Sea as well as the coastal regions of Egypt and Libya.

Keywords: *typical meteorological year, parameter weighting, photovoltaic power stations, hot dry maritime climate*

1. Introduction

Typical meteorological year (TMY) datasets are widely used to reduce the computation time and storage requirements when determining the optimal designs for photovoltaic (PV) power stations. In principle, the TMY datasets for PV plant projects should be constructed based on all the temporally variable parameters that have an impact on plant performance at the plant site. In addition, the parameters should be individually weighted based on their order of importance. As the relative differences in the importance of the parameters are highly location-specific, also the weights applied would ideally be adjusted based on the location.

Due to their abundant solar resource and proximity to major centres of electricity demand, the areas around the Persian Gulf and the Red Sea as well as the coastal regions of Egypt and Libya possess a large economic potential for PV power generation (Beták et al., 2012). These regions are characterised by a hot dry maritime climate and, therefore, significantly differ from the temperate climate regions that account for most of the world’s installed PV capacity. The most important differences are related to operating cell temperatures, atmospheric aerosol loading, and humidity levels. Due to the high ambient air temperature levels typical of hot dry climates, the output power-weighted average operating cell temperature is exceptionally high. The highly variable aerosol loading of desert conditions contributes to the variation in dust deposition as well as the variability of the incident solar spectrum together with atmospheric water vapour. Consequently, the commonly used PV performance modelling methodology may not appropriately address the regional conditions. This is the case with the TMY construction methods as well.

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In order to adjust the weights of different TMY parameters to suit the hot dry maritime climate type, the present study aims to determine an optimal set of weights based on five to six years of data on the power output of a 10 MWp PV power station located in Abu Dhabi, United Arab Emirates and equipped with polycrystalline silicon (pc-Si) wafer-based and cadmium telluride (CdTe) thin-film modules mounted at a fixed, roughly polar-aligned tilt. In addition, the weights previously proposed by Marion and Urban (1995), Stoffel et al. (2010), Kalogirou (2003), and Cebecauer and Šúri (2015) are evaluated with the same data. Abu Dhabi has a typical hot dry maritime climate, therefore, supporting the generalisation of the results to other regions characterised by the same climate type.

2. Methodology

2.1 Plant Yield Data Processing

A TMY dataset constructed for a PV power station should be designed to represent conditions under which the yield of the station is equal to the long-term average yield. Normally, TMY datasets are constructed based on the time series of those individual months whose statistics are in the best accordance with the long-term monthly statistics. That is why in this study, the first step is to find the individual months, during which the considered PV power station generated the yield closest to the long-term monthly average yield.

The power station's central inverters have measured output power since May 2009. The inverter-specific measurements are summed up for power blocks equipped with each module type resulting in two time series. At the beginning of a PV plant's operating life, down-time periods are frequent because the plant's operation and maintenance (O&M) plan is still under development and defective components are being detected and replaced. Hence, the plant output data recorded during this initial phase are not considered in the analysis. The included data cover a six-year period from October 2009 until September 2015 for the pc-Si module time series and a five-year period from October 2010 until September 2015 for the CdTe module time series.

The raw output data are corrected for outage losses in order not to bias the long-term average calculation. The outage losses have been quantified by the plant's operator and given in the annual plant performance reports. As TMY construction is only dependent on the ambient conditions at the plant's site, not on the plant's age, the data are also corrected for time-dependent degradation. In accordance with Jordan et al.'s (2012) findings, the time-dependent degradation rates are assumed to be one per cent per year for both sections of the plant. Finally, the long-term monthly average yields are calculated based on the five (CdTe) or six (pc-Si) monthly values corresponding to each year of the available power output data. The set of the individual months, during which the considered PV power station generated the yield closest to the long-term monthly average yield, can be considered as the typical yield year (TYY).

2.2 Ambient Data Processing

The dataset of ambient parameters is generated for the same period and scale as the TYY dataset. The considered ambient parameters are measured in the close vicinity of the power station and comprise global horizontal irradiance (GHI), beam normal irradiance (BNI), diffuse horizontal irradiance (DHI), ambient air i.e. dry-bulb temperature (T), wind speed (WS), wind direction (WD), and relative humidity (RH). The original data consist of average values over intervals of five and ten minutes. Dew point temperature (T_{dp}) values are estimated based on T and RH measurements using the August-Roche-Magnus approximation (Alduchov and Eskridge, 1996). The final dataset of ambient parameters consists of time series of 19 monthly statistics specified in Tab. 1.

Tab. 1: Monthly statistics used in TMY dataset construction.

Statistic	GHI	BNI	DHI	T	WS	WD	RH	T_{dp}
average	✓	✓	✓	✓	✓	✓	✓	✓
maximum				✓	✓		✓	✓
minimum				✓	✓		✓	✓
range				✓	✓		✓	

According to the best practice, a TMY dataset should be based on 15 years or more of source data (Cebecauer and Šúri, 2015). In this case however, the objective is not to generate a dataset that is a good representative of long-term climatic conditions but rather a test bed for different parameter weights. In order to assess how well different weight combinations predict the actual plant performance, the time frame of the TMY dataset needs to be the same as that of the plant output data.

2.3 Evaluation of Parameter Weight Sets

The method proposed by Cebecauer and Šúri (2015) is used to construct TMY datasets in the present study. Drawing on the past work on TMY dataset construction, Cebecauer and Šúri base their method on the concatenation of continuous multivariate time series spanning those individual months that are found to provide the best agreement with long-term monthly statistics. The different TMY parameter weight sets proposed by other authors or developed here are integrated in Cebecauer and Šúri's methodology. The previously proposed weight sets under consideration are presented in Tab. 2.

Tab. 2: Previously proposed TMY parameter weight sets under consideration.

Variable	**Statistic**	**TMY2**	**TMY3**	**Kalogirou**	**SGIS-PV**	**SGIS-CSP**
GHI	**average**	12/24	5/20	8/32	0.75	0.23
BNI	**average**		5/20	8/32		0.7
DHI	**average**				0.2	0.03
T	**average**	2/24	2/20	2/32	0.05	0.04
	maximum	1/24	1/20	1/32		
	minimum	1/24	1/20	1/32		
	range			1/32		
WS	**average**	2/24	1/20	2/32		
	maximum	2/24	1/20	1/32		
	minimum			1/32		
	range			1/32		
WD	**average**			1/32		
RH	**average**			2/32		
	maximum			1/32		
	minimum			1/32		
	range			1/32		
T_{dp}	**average**	2/24	2/20			
	maximum	1/24	1/20			
	minimum	1/24	1/20			
	CDF	0.2	0.2	0.2	0.2	0.2

TMY2 (Marion and Urban, 1995), TMY3 (Stoffel et al., 2010), Kalogirou (2003), SGIS-PV (Cebecauer and Šúri, 2015), SGIS-CSP (Cebecauer and Šúri, 2015)

In order to determine the TMY months, Cebecauer and Šúri (2015) deploy two approaches used in parallel: comparison of single monthly statistics with their long-term counterparts and comparison of monthly empirical cumulative distribution functions (CDF) with their long-term counterparts. In this study, the most appropriate weights also for these two TMY determination approaches (11 possible combinations with intervals of 0.1) are found based on the plant output data. When evaluating the previously proposed parameter weight sets however, the same TMY determination approach weights as used by Cebecauer and Šúri are adopted: 0.8 for single monthly statistics and 0.2 for monthly empirical CDFs.

3. Results and Discussion

The importance of correct weighting of TMY variables increases with the inter-annual variability of monthly plant yield levels. Fig. 1 presents this variability considering outage-corrected yield. It reaches its maximum in December with ranges of 17 and 21 per cent of the 5-year means with the pc-Si and CdTe modules, respectively. In the case of both module types, the months from May to October are characterised by a lower variability than the months from November to April. The variability of annual yield levels, in turn, is within a range of four per cent with the plant's pc-Si section and six per cent with the CdTe section.

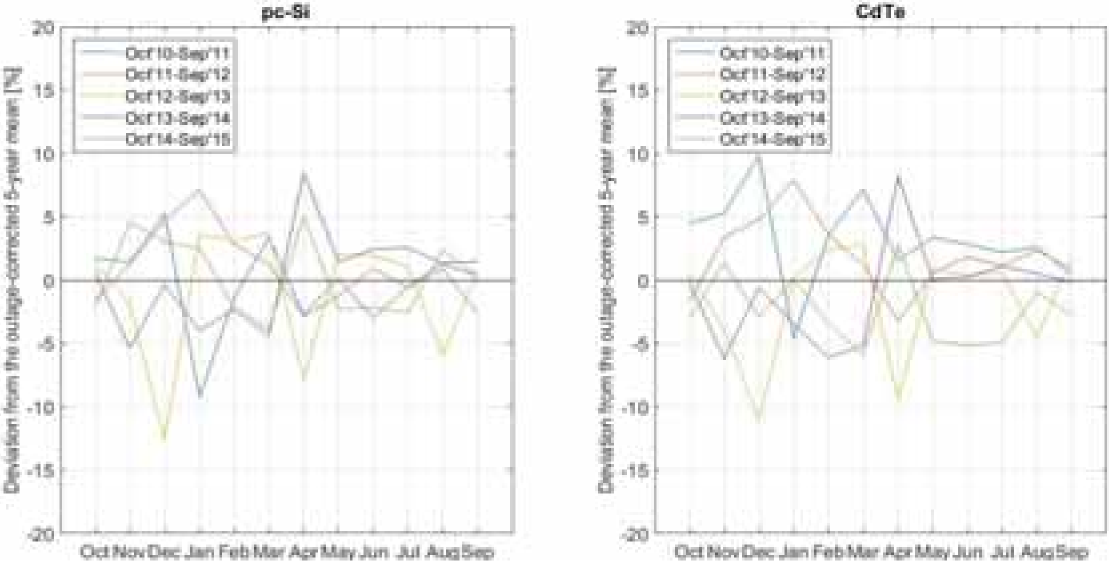

Fig. 1: Inter-annual variability of the outage-corrected monthly yields of the plant under consideration.

When determining the TYY months, outage-corrected plant yield data are further corrected for the assumed time-dependent degradation. The TYY months are found to be sensitive to the assumed rate of time-dependent degradation and therefore, a locally conducted degradation analysis is required to further improve the accuracy of the TYY month selection.

Fig. 2 compares the corrected TYY yields with the monthly mean yields. As can be seen from the figure, the monthly TYY yields are within a range from -2 to 2 per cent of the monthly means in all months apart from April and December in the case of the pc-Si modules and November in the case of CdTe modules. In both cases, the use of the TYY months results in the overestimation of the annual yield compared to the multiannual mean: by 0.9 per cent with the pc-Si modules and by 0.2 per cent with the CdTe modules.

The TMY dataset construction methods proposed by Marion and Urban (1995), Stoffel et al. (2010), and Kalogirou (2003) have not been designed for any specific solar energy technology. They consider a wide variety of different meteorological parameters and give half of the weight to irradiance variables. The two methods proposed by Cebecauer and Šúri (2015) for modelling the performance of PV and solar thermal power stations involve only three or four weighted TMY variables and place a 95 or 96 per cent weight on irradiance parameters, respectively.

After iterating through tens of thousands of different weighting sets for both sections of the power station, the sets resulting in TMY months with the greatest overlap with TYY are selected for further comparison. The respective weighting sets are presented in Tab. 3. With both module types, the combined weight of irradiance variables is 64 per cent. The remaining 36 per cent is placed on *T*'s monthly range in the case of the plant's pc-Si power blocks and on monthly average WS and minimum RH in the case of the CdTe blocks. It is not clear why the use of these meteorological statistics resulted in the best agreement between the TMY and TYY months. The monthly average *T* was initially expected to exist in the optimal weighting sets together with irradiance parameters due to the significant impact of *T* on solar cell temperature. One reason for the somewhat surprising outcome may be the strong positive correlation between *T* and irradiance variables and the consequent positive correlation between *T* and plant yield. *T* range and average WS are also positively correlated with plant yield but exhibit low correlation with irradiance parameters. Thus, they may better capture the actual negative impact of *T* on plant yield. The TMY determination approach through CDFs is emphasised over individual statistics with a weight of 0.7 in both cases.

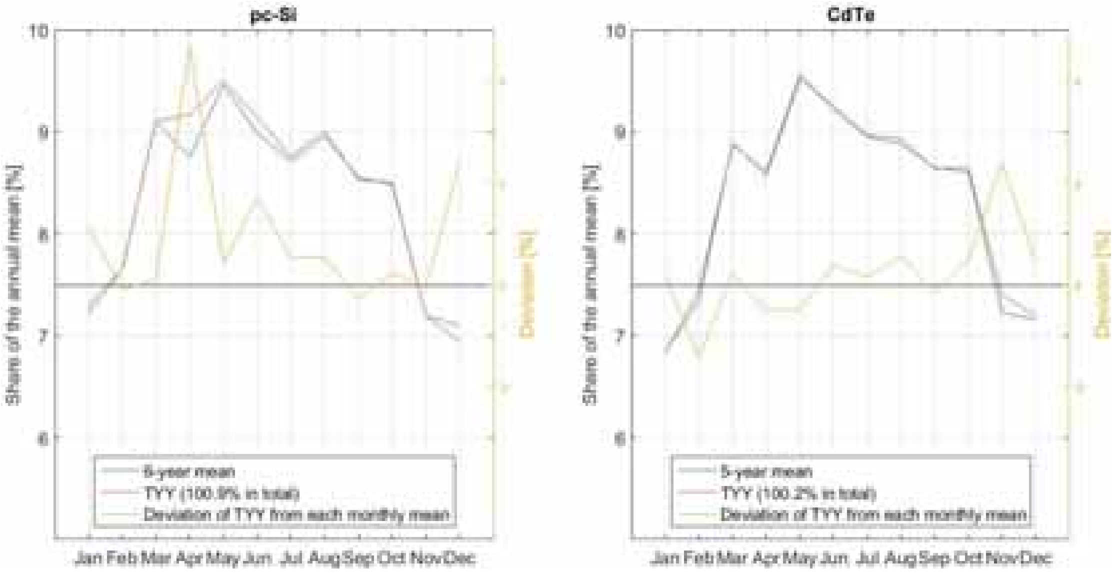

Fig. 2: Deviation of outage and time-dependent degradation-corrected TYY yields from monthly means.

Tab. 3: Weighting sets resulting in TMY months with the greatest overlap with TYY for both module types

Module type	GHI average	BNI average	DHI average	*T* range	WS average	RH minimum	CDF
pc-Si	0.11	0.23	0.30	0.36			0.7
CdTe	0.45	0.19			0.35	0.01	0.7

Fig. 3 compares the monthly yields estimated based on the different TMY weighting sets to the multiannual monthly mean yields. As can be seen from the figure, the monthly deviations are reduced in most cases when using the TYY-based weighting set (AD) as compared to the previously proposed sets. Fig. 4 shows the performance of the different sets in terms of root mean square error (RMSE) and bias. The improvement in RMSE is more significant with the CdTe section due to the better agreement of its TYY months with the multiannual monthly means. In both cases, RMSE is reduced, however. While RMSE measures the monthly average deviation, bias can be considered as the annually aggregated error. As implied by the bias bar graph of Fig. 4, the AD sets do not perform better than the previously proposed sets on an annual scale. In fact, the AD set for the pc-Si section results in the highest bias amongst all the sets. As this is due to the overestimating TYY yields, the bias can be reduced by using longer time series as the basis for TYY determination. The findings presented in Fig. 4 imply, however, that on an annual scale, the choice of the TMY parameter weighting set does not have a major impact on the estimated yield levels if the set is selected amongst the previously proposed sets.

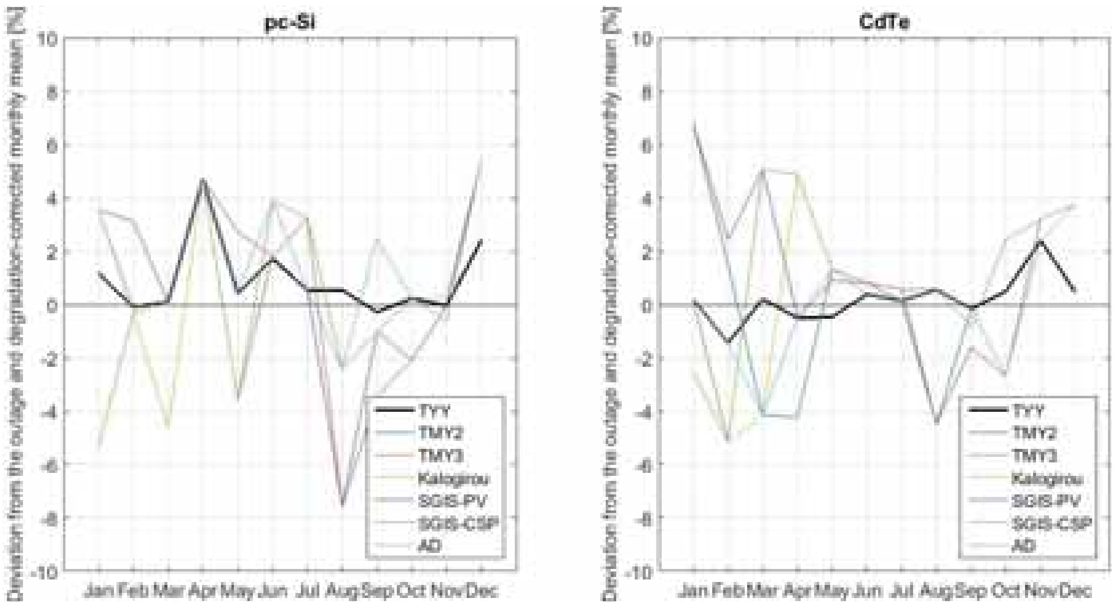

Fig. 3: Deviation of yield estimates based on different TMY variable weighting sets from the multiannual monthly mean yields (AD = weighting set optimised for the power station of interest)

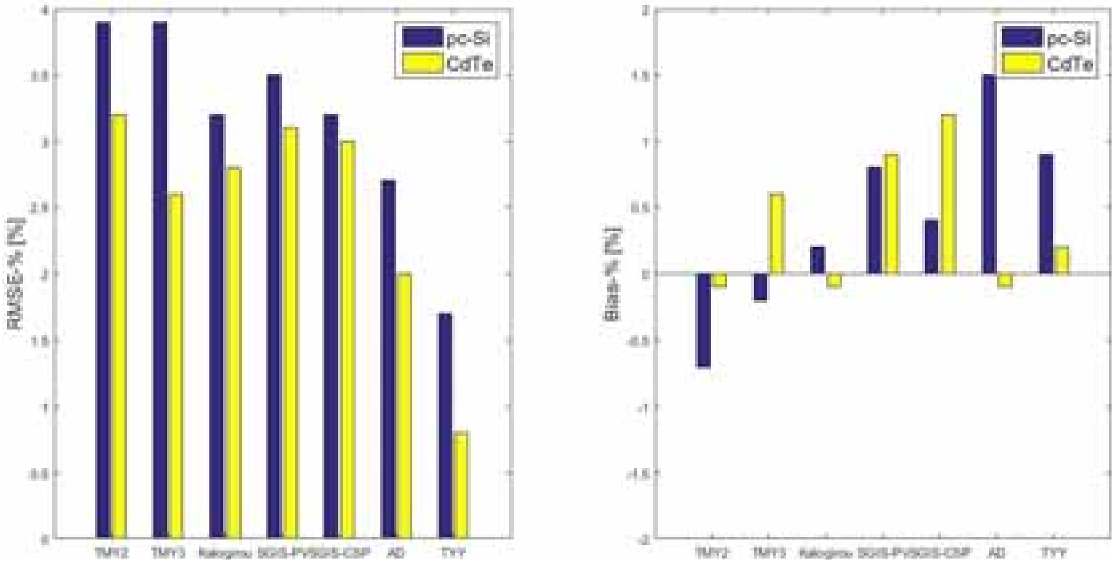

Fig. 4: Performance of different TMY variable weighting sets when compared to the multiannual monthly mean yields

4. Conclusion

In this study, weights of different TMY parameters are adjusted to suit PV plant performance assessment under the hot dry maritime climate type of Abu Dhabi. The results are expected to be generalizable to other regions characterised by the same climate type. The use of an appropriate weight set is the more important, the higher is the inter-annual variability of monthly yield levels. The variability is found to exhibit both seasonal dependence characterised by higher levels during winter months and technological dependence with higher levels for the CdTe module-equipped power blocks. In December, which is the month with the highest inter-annual yield variability, the difference in yield between the best and worst years can be more than 20 per cent of the multiannual mean yield.

The TYY-based TMY parameter weighting approach proposed in this paper reduces the deviations of TMY-based yield estimates from the multiannual monthly means as compared to the previously proposed TMY weighting sets. The resulting locally determined weight sets place approximately two third of the weight on irradiance variables and one third on parameters that are correlated with plant yield but not with irradiance, *T* range and WS in specific. The performance of the proposed approach is highly dependent on the accuracy of TYY on a yearly scale and therefore, further improvement can be achieved by using longer yield time series and deploying locally identified rates of time-dependent degradation. On an annual scale, no major benefit is derived from using the TYY-based approach as compared to the previously proposed TMY weighting sets.

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