Evaluation of Incoming Solar Radiation at titled surfaces at various European Cities

Moustaka A.[1], Raptis I.P.[2], Giannakaki E.[1], Kazadzis S.[3,2]

1 National and Kapodistrian University of Athens, Department of Physics, Athens, Greece

2 Institute for Environmental Research and Sustainable Development, National Observatory of Athens (IERSD/NOA), Greece

3 Physikalisch Meteorologisches Observatorium Davos, World Radiation Center (PMOD/WRC), Switzerland

*corresponding author e-mail: annamou@phys.uoa.gr

Abstract: Solar energy is one of the most sustainable, safe and abundant renewable energy sources. Inclined Photovoltaic panels are used aiming to maximize received energy. Inclination of installation most popular choice is a tilt angle equal to location latitude, which under clear sky conditions is the most effective. Cloud coverage changes the solar radiation field by limiting the direct and enhancing the diffuse radiation and affects the optimum tilt angle. In order to study this impact, hourly data extracted from Copernicus Atmosphere Monitoring Service for 21 European cities, (2005-2019) were used. Hay model for diffuse irradiance and Isotropic constant albedo model for reflected irradiance were used to simulate the incoming radiation on surfaces with various inclination angles and constant azimuth angle (southwise). Finally, regression equations are proposed for the simple and practical estimation of the optimum angle as a function of latitude and CMF in annual and seasonal basis. Also, in order to evaluate different suggestions of changing tilt angle, three scenarios are investigated and the energy potential of annual results is compared. Results showed that with increasing cloudiness the difference of the optimum to the theoretical (equal with the location latitude) angle is increasing.

1 Introduction

The performance of Photovoltaic (PV) panels is highly influenced by tilt angle (the vertical angle with respect to the ground) and the orientation (an azimuth or horizontal angle with respect to a reference) and the orientation (an azimuth or horizontal angle with respect to a reference) for a given location (Nicolás-Martín et al. 2020). The maximum energy output, can be achieved when a PV panel is positioned in a way that the sun rays arrive at the panel vertically. In order to collect the maximum possible daily energy, one approach is to use tracking systems (Sungur, 2009). A solar tracker is a mechanical device that follows the movement of the sun on its daily path across the sky. However, trackers are expensive and are not always applicable (Nann, 1990). Thus, in most of the cases, PV panels are installed to fixed tilt and azimuth angles, that are manually adjusted. For solar energy application in the northern hemisphere, optimum orientation for the azimuth angle is considered southwise (Mehleri et al., 2010). An empirical practice used for fixed-tilt installations is to use the location's latitude, which theoretically can provide the maximum energy, year round, for clear sky conditions. In real sky conditions, the main contributor to the variability of solar radiation and hence to the optimum tilt angle is the presence of clouds. In specific, cloud coverage always leads to slopes closer to the horizontal to be more efficient energywise, which indicates anisotropy of the diffuse light with higher diffuse contribution coming from angles closer to the zenith (Raptis et al., 2017). One parameter that takes into account the effect of cloud is the Cloud Modification Factor (CMF), which is defoned as the ratio of the actual solar radiation divided by the clear sky radiation. To estimate the global irradiance on a tilted PV panel, in order to calculate the optimum tilt angle (β_{opt}) at a given location, the following variables are needed to be calculated; the beam irradiance (BI_β), the reflected irradiance (RI_β) and the diffuse irradiance (DI_β). In this study, he have used data of these variables on horizontal plane at ground and top of the atmosphere level from Copernicus Atmosphere Monitoring Service (CAMS), in addition to empirical models for diffuse radiation (DI_β) like Isotropic (Liu and Jordan 1961), Hay (Hay 1979), Reindl (Reindl et al. 1990) and Perez (Perez et al. 1990). These models are similar in estimating the isotropic background and deviate by whether they consider the circumsolar and horizon band regions of diffuse irradiance (Gracia and Huld 2013). In most of the cases a standard model for reflected irradiance (RI_β) is used with constant albedo value (Liu and Jordan 1963) (0.2). For the computation of the beam irradiance (BI_β) reaching the inclined surface, a purely geometric relation can be used which depends on the surface's inclination angle and the sun's coordinates. Additionally, more than one change of the optimum tilt angle of PV panels through the year can lead to a higher energy benefit, depending on the conditions prevailing on the site of interest.

In this study, we rely on hourly data from CAMS in order to calculate the optimum annual and seasonal angles for 21

European cities for the period 2005-2019. The results are used in order to propose regression models for the practical and simple calculation of optimum angle as a function of latitude and CMF. Also, three scenarios of changing the tilt angle through the year are investigated by comparing the annual energy outcome.

2 Data and Methodology

Hourly data for the years 2005-2019 for 21 European cities (as shown in Figure 1), available from CAMS were used. This service can provide global (GHI), beam (BHI), diffuse (DHI) irradiance on horizontal plane at ground level for clear and real sky conditions and the irradiation on horizontal plane at the top of the atmosphere ($I_{0,h}$). The following quality control criteria were applied to hourly values and those outside the limits were rejected(De Miguel et al. 2001) (i) GHI≥0.19Whr/m^2; (ii) GHI≤1.12·I_{sc}; (iii) DHI≤1.1·GHI; (iv) DHI≤0.8·I_{sc}, and (v) BHI≤I_{sc} where Isc is the solar constant equal to 1366.1 W/m^2 (Zheng 2017). CMF was calculated from the hourly ratio GHI divided by Clear sky GHI. Solar geometry parameters, like azimuth angle (Az), zenith angle (Sza) and elevation (El) were estimated for all cities

using astronomical calculations.

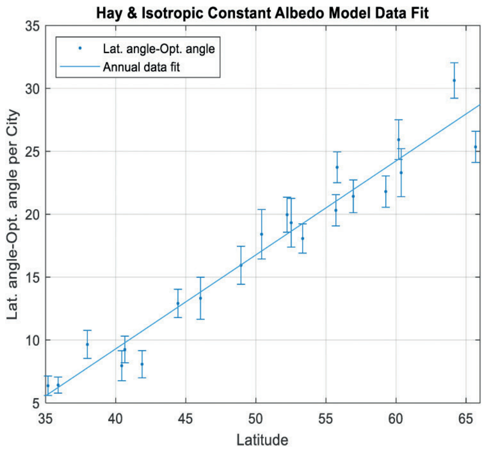
Fig. 1. 21 European cities of interest.

In addition, global irradiance on the tilted surface was calculated using data for real sky conditions. BI_β is calculated from hourly values of GHI, DHI, incidence angle and solar zenith angle (Psiloglou et al. 1996). For the RI_β, the constant albedo value of 0.2 is used. With the use of albedo, the tilt angle and hourly data for GHI the computation of RI_β is straightforward (Psiloglou et al. 1996). Hay's model is very popular among engineers (Raptis et al. 2017), so it was selected in order to estimate the DI_β reaching the tilted surface.

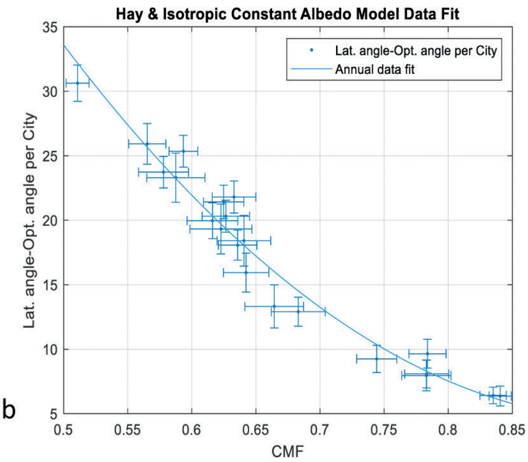
3 Results

Hourly data for the period 2005-2019, were used, as described in the data and methodology section, in order to calculate the optimum annual and seasonal angles for 21 European cities. Meanwhile, for the consideration of the influence of clouds, hourly CMF values were calculated. Thus, optimum annual and seasonal angles were represented in relation with latitude and CMF and corresponding polynomial fits were provided.

Latitude has a clear effect on the difference between latitude angle and annual optimum angle, leading to important increase of the difference for higher latitudes (Figure 2a). The reason is that for higher latitudes the present of clouds becomes more significant and in general cloud coverage leads to optimum tilt angles closer to the horizontal. This effect leads to higher divergence between latitude and annual optimum angle for regions in higher latitudes. The linear function has a RMSE=1.72 ° with R^2=0.95, which indicates the difference of optimum angle could be estimated by this fit. In addition Figure 2b, shows the dependence of the difference from CMF. As CMF decreases, indicating higher cloud coverage, the difference between latitude and annual optimum angle increases. On the contrary, difference becomes more significant for higher values of CMF. As stated before, the main contributor for this result is cloud coverage. The 2nd order polynomial function has a RMSE=1.52° with R^2=0.96, which indicates that CMF could be alternatively used as a proxy for estimating the difference.



a



b

Fig. 2.. Mean annual values as calculated from Hay model and Isotropic constant albedo model are shown in addition with 1**σ**, for the years 2005-2019(a) as a function of latitude and (b) as a function of CMF, alongside with the corresponding fits.

Table 1. Annual regression coefficients and goodness of fitting for the difference between latitude angle and annual optimum angle as a function of Latitude and CMF, respectively.

	Latitude	CMF
P_0	-20.56	136.3
P_1	0.7466	-279.6
P_2	0	148.3
R^2	0.9453	0.9590
RMSE	1.7159	1.5253

Following the idea, that 4 changes per year of the fixed tilt angle could provide an energy benefit, without much work (Raptis et al., 2017), we have repeated the same calculations for four seasons. For the estimation of seasonal optimum angle regression models are proposed and presented in Table 2. The spring's and autumn's regression models for the difference between latitude angle and seasonal optimum angle as a function of latitude shows similar behavior as annual's regression model. Autumn's and annual's results are alike because of the similar CMF and same cloud coverage conditions lead to regression models that are closely convergent. Spring's model is close to annual's results too, but the cloud coverage conditions, which are a bit more different from annual's (a bit lower values of CMF) leads to a more significant difference. Summer and winter are two seasons characterized by different cloud coverage conditions, than the annual results. These two seasonal models as a function of latitude and CMF have the biggest divergent from annual model. It appears that winter's regression model has the worst RMSE and R^2 and the biggest discrepancy from annual model. This result is caused by the extreme values and variations for clouds coverage leading to high deviations in optimum seasonal angle especially in higher latitudes.

Table 2. Seasonal regression coefficients and goodness of fitting for the difference between latitude angle and annual optimum angle as a function of (i) Latitude and (ii) CMF.

(i)Latitude	Spring	Summer	Autumn	Winter	(ii)CMF	Spring	Summer	Autumn	Winter
P_0	-15.16	34.96	-15.91	-35.25	P_0	108.5	94.84	149.9	210.5
P_1	0.5061	-0.3708	0.5081	-0.1879	P_1	-235.6	-135.6	-351.8	-643.9
P_2	0	0.006845	0	0.0136	P_2	129.8	71.4	211.2	444.4
R^2	0.8709	0.9203	0.8911	0.7395	R^2	0.9635	0.9035	0.9510	0.7402
RMSE	1.8614	0.9157	1.6969	6.9291	RMSE	1.0173	1.0076	1.1699	6.8953

In order to evaluate different suggestions of changing tilt angle, three scenarios are investigated and the energy annual results ($kWhr/m^2$) are shown in Figure 3. For the first scenario, a fixed angle equal to the latitude angle for every city is used. The second scenario is based on the fixed angle equal to the annual optimum as computed for every city with Hay model and Isotropic constant albedo model. The third and last scenario considers four changes of the angle, at the median dates among the solstices and equinoxes. It is obvious that for every city the third scenario provides the better energy annual results. The energy results between the two first scenarios, shows that for lower latitudes the difference among them is not significant. At these latitudes the difference between latitude and annual optimum angle is low cause of the smaller cloud coverage (Figure 2a, Figure 2b), which leads to smaller energy differences. As latitude and cloud coverage become higher, the difference between the two first scenarios becomes more significant, as a result of higher differences between latitude and annual optimum angle (Figure 2a, Figure 2b). The most important result between three scenarios is the small benefit using the third scenario in comparison with the second scenario for cities in higher latitudes. The difference among them is very small and the energy advantage of four seasonal changes, in contrast with cities in lower latitudes is nearly cancelled.

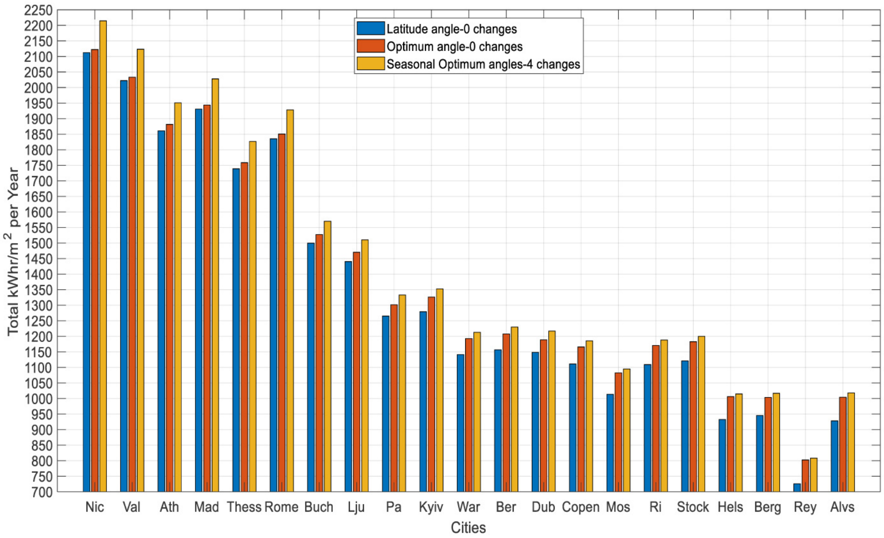


Fig. 3. Annual energy (kWhr/m^2) reaching a surface with tilt angle (a) constant through the year and equal to latitude angle, (b) constant through the year and equal to annual optimum angle and (c) seasonal optimum under four changes in the median dates among solstices and equinoxes.

4 Conclusions

Hourly data have been used alongside with models for diffuse irradiance in order to estimate optimum tilt angle and expressed it as a function of latitude and CMF. First and second order polynomial fits have been used for the relation of the difference of the optimum tilt angle to the latitude in respect to latitude and CMF, accordingly. As cloud coverage becomes more significant for higher latitudes, optimum tilt angles closer to horizontal tend to be preferable, which indicates higher diffuse contribution coming from angles closer to zenith. This leads to higher difference between optimum and latitude angle for cities in higher latitudes and lower CMFs. These areas are the ones with less good agreement in the estimation of tilt angle by the provided polyonomial fits. In addition, seasonal regression models were proposed for the estimation of seasonal optimum angle, where winter data showed the less accurate showing the less accurate fitting. The regression fits provided for the seasons can be widely used to estimate the tilt angle in other locations, with respect to either latitude or CMF. Finally, from the three investigated scenarios, the four changes of optimum angle gave the best results for annual energy outcome. However, for higher latitudes the four changes of tilt angle through the year didn't display a significant impact on the annual energy in comparison with the fixed annual optimum angle. Thus, even it is preferable for lower latitudes to change more than one time through the year the tilt angle, for higher latitudes a fixed annual optimum angle can lead to comparable energy output. Use of such data and methods can be used for any city and results for specific months and seasons based on their (local) cloudiness. Combined with their contribution to the annual solar radiation can be used. In this case hybrid scenarios (for example calculating seasonal optimum angles and make 4 changes during the year) can be used in order to improve the total annual or seasonal solar energy potential, depending on the user needs.

Acknowledgments The research work was supported by the Hellenic Foundation for Research and Innovation (HFRI) under the HFRI PhD Fellowship grant (Fellowship Number: 2544) and partly funded by the European Commission project EuroGEO e-shape (grant agreement No 820852).

References

De Miguel, A., Bilbao, J., Aguiar, R., Kambezidis, H., & Negro, E. (2001). Diffuse solar irradiation model evaluation in the north Mediterranean belt area. Solar energy, 70(2), 143-153.

Gueymard, C. (1993). Mathermatically integrable parameterization of clear-sky beam and global irradiances and its use in daily irradiation applications. Solar Energy, 50(5), 385-397.

Gracia, A. M., & Huld, T. (2013). Performance comparison of different models for the estimation of global irradiance on inclined surfaces. EUR--Scientific and Technical Research series.

Hay, J. E. (1979). Calculation of monthly mean solar radiation for horizontal and inclined surfaces. Solar energy, 23(4), 301-307.

Liu, B., & Jordan, R. (1961). Daily insolation on surfaces tilted towards equator. ASHRAE J.;(United States), 10.

Liu, B. Y., & Jordan, R. C. (1963). The long-term average performance of flat-plate solar-energy collectors: with design data for the US, its outlying possessions and Canada. Solar energy, 7(2), 53-74.

Mehleri, E. D., Zervas, P. L., Sarimveis, H., Palyvos, J. A., & Markatos, N. C. (2010). Determination of the optimal tilt angle and orientation for solar photovoltaic arrays. Renewable energy, 35(11), 2468-2475.

Nann, S. (1990). Potentials for tracking photovoltaic systems and V-troughs in moderate climates. Solar Energy, 45(6), 385-393.

Nicolás-Martín, C., Santos-Martín, D., Chinchilla-Sánchez, M., & Lemon, S. (2020). A global annual optimum tilt angle model for photovoltaic generation to use in the absence of local meteorological data. Renewable Energy, 161, 722-735.

Perez, R., Ineichen, P., Seals, R., Michalsky, J., & Stewart, R. (1990). Modeling daylight availability and irradiance components from direct and global irradiance. Solar energy, 44(5), 271-289.

Psiloglou, B. E., Balaras, C. A., Santamouris, M., & Asimakopoulos, D. N. (1996). Evaluation of different radiation and albedo models for the prediction of solar radiation incident on tilted surfaces, for four European locations.

Raptis, P. I., Kazadzis, S., Psiloglou, B., Kouremeti, N., Kosmopoulos, P., & Kazantzidis, A. (2017). Measurements and model simulations of solar radiation at tilted planes, towards the maximization of energy capture. energy, 130, 570-580.

Reindl, D. T., Beckman, W. A., & Duffie, J. A. (1990). Evaluation of hourly tilted surface radiation models. Solar energy, 45(1), 9-17.

Sungur, C. (2009). Multi-axes sun-tracking system with PLC control for photovoltaic panels in Turkey. Renewable energy, 34(4), 1119-1125.

Zheng, H. (2017). Chapter 2—Solar Energy Utilization and Its Collection Devices. Solar Energy Desalination Technology; Elservier: Amsterdam, The Netherland, 47-171.Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA, Eds. (2001) Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA