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Comparative analysis of energy yield of photovoltaic module mounting systems without solar tracker with tilt update for urban applications

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***Abstract*—This paper presents a comparative analysis of energy yield of different mounting systems of PV modules without solar tracker with tilt update for urban applications. Three tilt update frequencies have been considered: daily, monthly, and yearly, in ten cities around the world, in the Northern Hemisphere, with a Mathematica© code. The optimum tilts angles for each day, month and year have been calculated. The energy gain with respect to the annual optimum tilt angle have been calculated. Daily tilt updates is the most energy productive, but it more expensive to implement. Updating the tilt angle daily is slightly better than doing so monthly. The use of a manual system for monthly tilt updates is beneficial, due to the reduced number of PV module position changes and the energy gain.**

***Index Terms*—Photovoltaic systems, Mounting systems without solar tracker, Tilt update frequency.**

I. Introduction

In recent years, urban environments are considered to be important points for the installation of solar photovoltaics technologies, due to their high density of population [1], their high density of energy consumption [2], their air pollution, etc.

Solar Photovoltaic (PV) energy is a clean and practical technology, because the characteristics of its components allow freedom of installation. Its potential is demonstrated by the exponential increase in installed capacity worldwide. The cumulative solar photovoltaic power generation capacity from 23 (GW) in 2009 to 754 (GW) in 2020 [2].

The installation of this technology on roofs is growing rapidly. Thus, it is estimated that by 2050 the electricity generated on rooftops will exceed that generated by PV plants [3]. Specifically, the percentages of electricity generated by photovoltaic systems are estimated to be as follows: 21.40% in solar PV plant, 14.90% in residential roof PV and 11.60% in commercial/goverment roof PV. It is estimated that 36 billion (m^2) of the global roof area will be potentially suitable for the installation of PV systems [4].

The mounting systems for PV modules used in large-scale PV plants can be classified into two types: with, and without solar tracker. The number of movements classifies the solar trackers into:

(i) Two rotation movements (named dual-axis trackers). The control algorithm minimises in real time the angle of incidence of the Sun's rays reaching its surface.
(ii) A single rotation movement. The axis of this system can have different slopes and orientations. The control algorithm also minimises in real time the angle of incidence of the Sun's rays reaching its surface.

In mounting systems lacking solar tracking, ground-mounted photovoltaic, the PV modules have an tilt angle that remains fixed all year round. Dual-axis trackers increase power generation by $12 - 28\%$ compared to a ground-mounted PV system [5]. And compared to single-axis trackers, they increase power generation from 3 to 16% [5]. The range of variation of these results is strongly influenced by the site latitude of the PV plant.

Dual axis tracker systems are more expensive to procure and install: they generally add a premium of 40–50% to the average deployment costs with respect to a system of the same size without solar tracker, and 20 - 25% with respect to a similarly-sized single-axis tracker system

A dual-axis tracker usually represents a 40–50% increase in the average installation costs over a system of the same size with fixed tilt angle and a over a system of similar size with a single axis tracker.

The drive system of the solar tracker used in large-scale PV plants is implemented by means of motors. Solar trackers greatly increase the cost of a PV plant.

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The initial investment cost of PV plants using dual-axis solar trackers and single-axis solar trackers is higher compared to PV plants without solar tracking. The increase is between $40-50\%$ for the first type of PV plants and between $20-25\%$ for the second type [6]. Due to the high cost of active tracking, they are not used for urban applications [7].

On the other hand, mounting systems that lack solar tracking may have different tilt update frequencies. For example, 3 different tilt update frequencies can be considered: daily, monthly, and yearly (constant tilt). In urban applications, mounting systems with a fixed tilt angle throughout the year are the most commonly used. From this reality, some questions arise: can tilt updates improve this arrangement?, how much energy gain would be obtained?, and would cost be a constraint on the use of tilt updates?. The specific contributions of this study can be summarized in the following proposals: (i) A detailed analysis of the energy gain for 2 different tilt update frequencies: daily and monthly, with respect to a fixed annual tilt angle; (ii) A study of the effect of daily and monthly tilt update frequency on the total irradiance received by a surface.

Another aspect related to the update frequency is the cleaning cycle of the PV modules. Dust accumulation on PV modules is one of the most important factors affecting their efficiency [8].Therefore, matching the two operations can reduce the cost of system operation.

II. Governing equations

The solar irradiance incident on a PV module has a strong dependence on the angle between the PV module and the incident solar rays. Therefore, the this solar irradiance on a surface depends on the Sun's position. The solar angles used to describe the apparent motion of the Sun with respect to the PV modules are the zenith angle of the Sun (θ_z) and the azimuth of the Sun (γ_S).

The position of a PV module is defined by tilt angle (β) of PV module with respect to horizontal surface and surface azimuth angle (γ), which represents the orientation of the PV module with respect to due South. The optimum orientation depends on the hemisphere (southoriented in the Northern Hemisphere and northoriented in the Southern Hemisphere [9]). Fig. 1 shows the solar geometry used in the current study.

A. Estimation of the amount of total irradiation on a tilted surface

The total irradiation on a tilted surface for each day of the year, and each tilt angle can be compute [10]:

$$\begin{aligned}\mathbb{H}_t(n,\beta) = \int_{T_R(n)}^{T_S(n)} \Bigg[\mathbb{I}_{bh}(n,T) \cdot \frac{\cos\theta_i}{\cos\theta_z} + \\ + \mathbb{I}_{dh}(n,T) \cdot \left(\frac{1+\cos\beta}{2}\right) + \\ + \left(\mathbb{I}_{bh}(n,T) + \mathbb{I}_{dh}(n,T)\right) \cdot \rho_g \cdot \left(\frac{1-\cos\beta}{2}\right) \Bigg] \cdot\ dT \quad (1)\end{aligned}$$

where $\mathbb{H}_t$ is the adjusted total irradiation on a tilted surface (W/m^2), $\mathbb{I}_{bh}$ is the adjusted beam horizontal irradiance (W/m^2), $\mathbb{I}_{dh}$ is the adjusted diffuse horizontal irradiance, n is the day of the year (day), β is the tilt angle (rad), θ_z is the zenith angle of the Sun (rad), θ_i is the incident angle (rad), ρ_g is the ground reflectance (dimensionless), T is the solar time (h), T_R is the sunrise solar time (h), and T_S is the sunset solar time (h).

The following considerations have been made in equation (1):

(i) The total irradiation depends strongly on the weather conditions of the site. The term "adjusted" refers to the fact that weather conditions have been taken into account in the determination of the horizontal irradiances.

(ii) The adjusted horizontal irradiances, I_{bh} and I_{dh}, have been calculated using the method proposed by [11]. This method uses 3 steps to determine the adjusted horizontal irradiances: (1) Hottel's model [12] to estimate the beam solar irradiance transmitted through clear atmosphere; (2) Liu's and Jordan's model [13] to estimate the diffuse solar irradiance though a clear-sky, and (3) Fourier series approximation to correct the clear-sky models and to adapt them to the weather conditions of a particular site.

(iii) The isotropic model of Liu and Jordan [14] for the diffuse solar irradiance on a tilted surface has been used. This model has also been used by several researchers [15], [16], [17].

(iv) The isotropic model of Liu and Jordan [14] for the ground reflected solar irradiance on a tilted surface has been used. This model has also been used by several researchers [15], [16], [17]. Typical ρ_g values for different ground surfaces has been computed by [18] A value of 0.2 is commonly adopted if no information is available about ground surface [18].

The angle of incidence is calculated according to the equation and conditions proposed by [10]:

$$\begin{aligned}\cos\theta_i = \sin\delta\cdot\sin\lambda\cdot\cos\beta - \\ - \sin\delta\cdot\cos\lambda\cdot\sin\beta\cdot\cos\gamma + \cos\delta\cdot\cos\lambda\cdot\cos\beta\cdot\cos\omega \\ + \cos\delta\cdot\sin\lambda\cdot\sin\beta\cdot\cos\gamma\cdot\cos\omega + \\ + \cos\delta\cdot\sin\beta\cdot\sin\gamma\cdot\sin\omega \quad (2)\end{aligned}$$

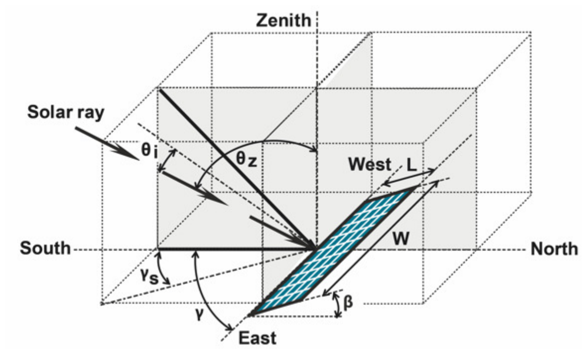

Fig. 1. Solar geometry used in the current study.

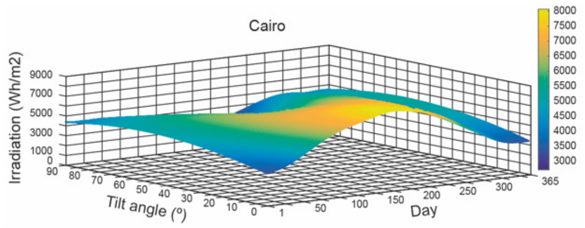

Fig. 2. Adjusted total solar irradiation on a tilted surface $\mathbb{H}_t\,(n,\beta)$.

where δ is the solar declination (rad), λ is the latitude (rad), β is the tilt angle (rad), γ is the azimuth angle (rad), and ω is the hour angle (rad).

B. Determination of the optimum tilt angle for mounting systems without solar tracker with tilt update frequency.

The equation (1) has a strong dependence on the tilt angle. And it varies with the update frequency. In the following, the value of the optimum tilt angle will be determined for three update frequencies: daily, monthly and yearly. Only in systems with a fixed yearly angle are equations available to determine the optimum tilt angle [19], [20]. For the other two time periods, procedures that maximise the total irradiation falling onto the tilted surface are used [5].

Fig. 2 shows the representation of equation (1) for the case of Cairo (Egypt) (Latitude: $30°29'24''N$, Longitude: $31°14'38''W$, Altitude: 41 m). In this figure, 900 intervals have been used to discretise the tilt angle which can vary $[0^o, 90^o]$.

1) Daily tilt updates: The analytical procedure requires, by means of equation (1), to calculate the optimum tilt angle, $\beta^d_{opt}(n)$, for each day n of the year (see Fig. 2). The tilt angle $\beta^d_{opt}(n)$ such that irradiation for that day [5]:

$$H^n_t(\beta^d_{opt}(n)) = \max_{\beta}\; H^n_t\,(\beta) \tag{3}$$

2) Monthly tilt updates: The analytical procedure requires, by means of equation (1), to calculate the optimum tilt angle, $\beta^m_{opt}(m)$, for the period into the 12 months. In this case, it is a matter of solving as many optimisation problems of the form [5]:

$$H^{\beta,m}_t = \int_{f(m)}^{l(m)} H_t\,(n,\beta)\,dn; \quad \max_{\beta}\; H^{\beta,m}_t \tag{4}$$

where $m = 1,\ldots,12$ and $f(m)$ and $l(m)$ are the first and last days of each month, respectively.

3) Annual optimum tilt angle: The analytical procedure is based on the application of Cavaleri's principle [5]. For this, it requires, by means of equation (1), to calculate the optimum tilt angle, β^y_{opt}, for the year (see Fig. 2). In this case, it is a matter of solving as many optimisation problems of the form [5]:

$$H^{\beta}_t = \int_{1}^{365} H_t\,(n,\beta)\,dn; \quad H^{\beta^y_{opt}}_t = \max_{\beta}\; H^{\beta}_t \tag{5}$$

C. Energy gain

The concept of energy gain (EG) is commonly used to assess the optimum tilt angle for a period of time [21]. In this context, the following equation is introduced to facilitate the study:

$$EG = \frac{\mathbb{H}(*) - \mathbb{H}(\beta^y_{opt})}{\mathbb{H}(\beta^y_{opt})} \times 100 \tag{6}$$

Where the index $*$ stands the corresponding tilt updates (daily (β^d_{opt}) and monthly (β^m_{opt}) tilt updates).

III. Results and Discussion

This section will estimate the effect of the tilt updates of the PV modules on the annual energy. For this purpose, a code has been developed in Mathematica software to calculate the optimum tilt angle for three update frequencies: daily, monthly and yearly. To generalise the study, ten locations in the Northern Hemisphere were analysed.

Based on the methodology presented by [11], the real weather conditions of the ten locations studied have been taken into account for the determination of solar irradiance. The PVGIS database [22] has been used for the satellite estimations of monthly-averaged global and diffuse solar irradiations received on a horizontal surface.

A. Case study

To generalise the study on the effect of PV module tilt updates on annual energy worldwide, this study concentrates on ten distinct climatic zones. This work analyses sites ranging from 6° to 60° North latitude, with a step of about 6°. Tables I and II show the geographical characteristics of the sites studied.

Table I. Locations under study.

	Locations		Locations
1	Medellin (Colombia)	6	Almeria (Spain)
2	Bangkok (Thailand)	7	Toronto (Canada)
3	Morelia (Mexico)	8	Wien (Austria)
4	Karachi (Pakistan)	9	Hamburg (Germany)
5	Cairo (Egypt)	10	Helsinki (Finland)

Table II. Data of locations under study.

Loc.	Latitude	Longitude	Altitude (m)
1	$06°14'38''N$	$75°34'04''W$	1469
2	$13°45'14''N$	$100°29'34''E$	9
3	$19°42'10''N$	$101°11'24''W$	1921
4	$24°52'01''N$	$67°01'51''E$	14
5	$30°29'24''N$	$31°14'38''W$	41
6	$36°50'07''N$	$02°24'08''W$	22
7	$43°39'14''N$	$79°23'13''W$	106
8	$48^o15'00''N$	$16°21'00''E$	20
9	$53^o33'00''N$	$10°00'03''E$	19
10	$60°10'10''N$	$24°56'07''E$	23

Table III. Optimum tilt angles (^{o}).

Loc.	β^y_{opt}	β^m_{opt}					
		Jan	Feb	Mar	Apr	May	Jun
1	4.5	29.4	20.2	7.0	5.0	13.9	17.9
2	13.2	36.8	27.8	14.4	0.7	0.1	0.1
3	19.9	45.2	36.5	22.1	5.9	0.1	0.1
4	23.6	48.5	39.9	26.4	11.1	0.1	0.1
5	24.2	52.3	43.3	30.5	15.8	3.4	0.1
6	30.3	59.6	50.7	37.0	21.9	9.5	3.4
7	30.6	61.0	52.4	40.9	25.8	13.8	8.0
8	32.9	64.1	55.3	43.9	29.8	17.3	11.0
9	36.8	69.2	61.2	49.5	35.9	22.5	15.5
10	38.6	78.2	65.3	54.6	39.4	27.5	20.4

Loc.	β^y_{opt}	β^m_{opt}					
		Jul	Aug	Sep	Oct	Nov	Dec
1	4.5	16.9	10.3	3.1	13.7	24.9	31.1
2	13.2	0.1	0.1	6.9	18.9	31.8	38.7
3	19.9	0.1	0.1	13.1	29.9	42.6	48.1
4	23.6	0.1	4.6	18.5	34.1	45.7	50.6
5	24.2	0.1	10.5	24.8	39.2	49.9	54.8
6	30.3	6.1	16.7	30.7	44.9	56.2	61.7
7	30.6	10.5	20.8	34.7	47.3	59.1	63.2
8	32.9	13.9	24.1	38.2	51.9	60.4	66.2
9	36.8	18.4	29.1	42.9	56.8	67.1	71.4
10	38.6	23.4	34.1	47.4	63.2	73.9	80.7

B. Optimum tilt angles

Based on the equations (5) and (4) previously described, the optimum tilt angles are calculated considering the effects of the different weather conditions. Table III shows, for the 10 locations under study, the optimum tilt angles.

C. Estimated annual irradiation

Based on the equation (1), the annual energy is calculated considering the effects of the tilt updates of the PV modules. Table IV shows, for the 10 locations under study, the estimated total annual solar irradiation.

Table IV. Annual solar irradiation (MWh/m^2).

Location	$\mathbb{H}(\beta^d_{opt})$	$\mathbb{H}(\beta^m_{opt})$	$\mathbb{H}(\beta^y_{opt})$
Medellin (Colombia)	1.8953	1.8940	1.8299
Bangkok (Thailand)	1.9558	1.9543	1.8852
Morelia (Mexico)	2.2931	2.2906	2.1772
Karachi (Pakistan)	2.3477	2.3453	2.2398
Cairo (Egypt)	2.3939	2.3913	2.2779
Almeria (Spain)	2.2214	2.2188	2.1084
Toronto (Canada)	1.5018	1.5002	1.4450
Wien (Austria)	1.3886	1.3871	1.3408
Hamburg (Germany)	1.2115	1.2102	1.1701
Helsinki (Finland)	1.0899	1.0885	1.0562

Obviously, daily tilt updates is the most energy productive. However, the annual solar irradiation obtained with daily tilt updates and monthly tilt updates are very similar. The deviations are not greater than 0.13%. This is very important. Fig. 3 shows the daily differences in solar irradiation between the daily and the monthly update for Cairo. This differences is less than 45 (Wh/m^2) of daily solar irradiation.

D. Energy gain

Fig. 4 shows of annual energy gain in the locations under study.

It is seen from Fig. 4 that:

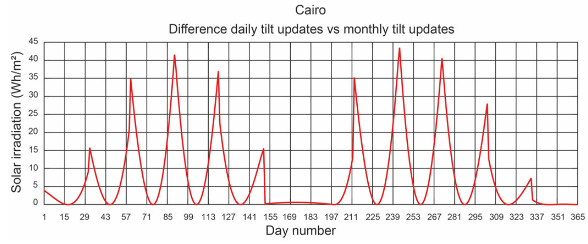

Fig. 3. Difference in irradiation between daily and monthly tilt updates in Cairo.

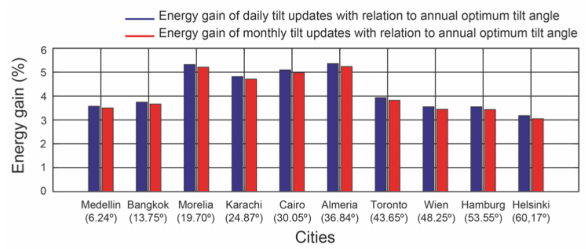

Fig. 4. Comparison annual energy gain.

(i) The percentage of the energy gains associated with daily tilt updates, referenced to constant tilt ranges from 3.18% (high latitude) to 5.36% (middle latitude).

(ii) The percentage of the energy gains associated with monthly tilt updates, referenced to constant tilt ranges from 3.05% (high latitude) to 5.24% (middle latitude).

Therefore, the implementation of a manual system for monthly tilt updates is beneficial, due to: (i) The reduced number of PV module position changes, (ii) The energy gain. Although the daily update generates more energy, the daily change of module position makes it more expensive to implement.

IV. Conclusions

In this paper a comparative analysis of energy yield of different mounting systems of PV modules without solar tracker with tilt update for urban applications in 10 cities in the North Hemisphere is presented. Three tilt update frequencies have been considered: daily, monthly, and yearly. Using a Mathematica© code, the optimum tilts angles for each day, month and year have been calculated. The proposed evaluation indicator is the energy gain with respect to the annual optimum tilt angle. In summary, our analysis yields the following conclusions: (i) Daily tilt updates is the most energy productive; (ii) Updating the tilt angle daily is slightly better than doing so monthly; (iii) The percentage of the energy gains associated with daily tilt updates, referenced to constant tilt ranges from 3.18% (high latitude) to 5.36% (middle latitude); (iv)The percentage of the energy gains associated with monthly tilt updates, referenced to constant tilt ranges from 3.05% (high latitude) to 5.24% (middle latitude).

The use of a manual system for monthly tilt updates is beneficial, due to: (i) The reduced number of PV module position changes, (ii) The energy gain. In addition, the change of the PV module position can coincide with its cleaning cycle.

The extension of this work would be the implementation of a manual system for monthly tilt updates.

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