Experimental investigation of the optimum photovoltaic panels’ tilt angle during the summer period

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ABSTRACT

The photovoltaic (PV) technology has made considerable progress during the recent years in both grid connected and stand-alone applications, especially in areas of high local solar potential. In this context, the interest recently demonstrated in the Greek region concerning PVs encourages the investigation of optimum operation conditions for such systems. At the same time, summer-only applications, being rather common in Greece, require maximum exploitation of the local solar potential during the specific period of the year. For this purpose, an experimental study is currently carried out in the area of Athens, in order to evaluate the performance of different PV panel tilt angles during the summer period. According to the experimental results obtained, the angle of 15° (±2.5°) is designated as optimum for almost the entire summer period, while conclusions drawn are accordingly theoretically validated by means of established solar geometry equations.

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1. Introduction

Remarkable increase of installed capacity worldwide [1] and constantly decreasing costs [2] of the photovoltaic (PV) technology have turned PV applications into one of the most interesting energy alternatives, especially in areas of high quality solar potential. In this context, analogous interest is noted during the recent years in the Greek region as well [3,4], where the favorable local solar potential (annual solar energy at horizontal plane even exceeding 1650 kWh/m² [5], Fig. 1) encourages operation of such systems. Installed capacity of PVs in Greece (Fig. 2) exceeds 200 MW (end of 2010) [6], i.e. almost four times the respective of the previous year (55 MW), while at the same time a promising local PV industry seems to emerge (Fig. 3).

Furthermore, considerable remuneration of energy produced by grid connected rooftop PV systems under a feed-in-tariff of 550 €/MWh [7] has attracted numerous applicants in the category of <10 kWp (Fig. 4). At the same time, experience gained in the field [8] (7% of installed capacity corresponds to systems below 10 kWp and 17% to systems below 20 kWp) largely applies to the sector of small scale stand-alone systems as well. Actually, owed to the fact that there are numerous remote consumers across the Greek region [9,10] that cannot appreciate connection to a solid electricity grid, PV stand-alone applications gradually gain interest on the basis of experience obtained by the operation of small to medium scale grid connected systems.

What should be noted is that a large share of these remote consumers concern summer use only (e.g. summer houses, summer hotel units), while in many of these cases, extreme water needs (especially in semi arid areas of the Aegean islands) should also be stressed. As a result, use of PV systems in such summer-only applications (when the local available solar potential maximizes) is thought to be an interesting solution that needs to be examined for the satisfaction of both electrification and irrigation needs [11–14].

At the same time, efficient operation of PV installations depends on many factors, among which is also the tilt angle of panels. Acknowledging the need to ensure maximization of energy production during the summer months of the year for the applications previously discussed, a systematic effort is currently undertaken to obtain the optimum summer tilt angle of a PV installation located in the area of Athens, central Greece. For this purpose, conduction of experimental measurements during the entire summer season is carried out in the specific study, so as to designate the optimum panels’ tilt angle during the specific period of the year.

At this point, it should be noted that investigation on the optimum panel installation angle started in the early 80’s. At that time, Felske [15] investigated the optimum tilt angle in relation to
the off-south angle, concluding that for a given azimuth angle, the optimum collector tilt should be expected at an angle between $3^\circ$ and $10^\circ$ less than the given location latitude. Furthermore, according to Tsalides and Thanailakis [16], the year-round optimum tilt angle for the area of Athens ($37^\circ58'\ N$) and for north-facing panels serving constant loads was determined at $57^\circ$, which is 50% higher than the local latitude. Following, Balouktsis et al. [17] presented a similar calculation algorithm for the case of variable loads, estimating the optimum tilt angle of PV panels for the island of Kythnos ($37^\circ25'\ N$) during the entire year. According to their results, the optimum angle per month was found to vary from 0° (June, July) to 60° (December), while the optimum PV tilt angle for the entire year was $26^\circ$.

Moreover, based on experimental measurements, Kacira et al. [18] investigated the optimum tilt angle of PV panels in Sanliurfa Turkey ($37^\circ N$), by using two PV panels, with the first one kept at a fixed tilt angle and the second one mounted on a two-axis solar tracking system. According to their results, the monthly optimum tilt angle ranges between 13° in June and 61° in December. Based on experimental measurements as well, Gaglia et al. [19] reported that the optimum PV tilt angle for the area of Athens ($36^\circ57'\ N$) ranges between 23° and 33°. Finally, Mehleri et al. [20] presented a computational methodology for the determination of the optimum tilt angle and the orientation of PV panels, based on solar radiation measurements recorded at the National Technical University of Athens ($37^\circ58'\ N$). Their conclusion was that the optimum tilt angle for the entire year is $30^\circ$.

At the same time Koronakis [21] investigated the optimum angle for PV panels operating in Athens for each month of the year, designating that optimum summer angles range from 5° to 17°. Similar were also the results of Benghanem [22] concerning somewhat lower latitudes (angle of 12° for a latitude of 24.5° N), while Skeiker [23] estimated optimum angles for the month of

Fig. 1. Wind and solar potential in the Greek territory (based on data from [5]).

Fig. 2. Recent progress of PV installations in Greece (based on data from [6]).

Fig. 3. Characteristics of Greek PV manufacturers (based on data from [6]).
August in the order of 12.5°–17°, for latitudes between 35°N and 40°N.

According to the above research results, the optimum angle of PV panels varies considerably between different studies, mainly due to the calculation models used and the atmospheric environment of the location at which the experiment takes place. Besides that, what may also be concluded is that emphasis is usually given on the determination of the year-round optimum tilt angle. Considering the above, an attempt is carried out in the present study so as to determine the summer period optimum angle for PV panels operating in the area of Athens. For this purpose, experimental investigation of the subject examined is currently undertaken for the entire summer period. In this context, emphasis is given on examining the effect of varying the panel tilt angle from the expected optimum one, while accordingly, an effort is made by the authors so as to interpret results obtained through theoretical validation on the basis of established solar geometry equations.

2. Experimental setup and procedure of the experiment

2.1. Description of the experimental setup

The PV configuration used for the experimental measurements is installed on the roof of the S.E.A.&ENVI.PRO. Laboratory, i.e. on the top of one of the buildings comprising the TEI of Piraeus Campus [11]. The exact location is determined by the geographical coordinates of 37°58’ N and 23°40’ E and a high quality local solar potential (see also Fig. 5). The installation consists of two PV arrays, six panels each (Fig. 6), with each of the arrays being mounted on a metal frame, properly designed so that the tilt angle can be adjusted from 0° to 90°, at a 5° step.

Furthermore, the twelve panels of the installation are connected in six parallel strings of two. Six ammeters and voltmeters placed on the control panel of the installation (Fig. 6), are used to provide the necessary measurements of current and voltage from each of the strings. The orientation of the PV panels is fixed with the azimuth angle set equal to zero, while their type is multi-crystalline (LA361-KS1S-manufactured by Kyocera) with the respective technical characteristics given in Table 1.

Moreover, for the measurement of solar radiation, two pyranometers of Li-Cor type are used. The first pyranometer measures the global radiation on the horizontal plane and the second is mounted on the PV base so that it can measure the global radiation upon the PV surface, at the tilt angle each time selected (Fig. 6). Finally, what should also be mentioned is that all measurements taken are also collected in a data logger (STYLLITIS-41) (see also Fig. 6) that is able to store data for up to 30 days through the use of a computer.

2.2. Description of the experimental procedure

The basic concept of the experimental procedure is to compare, on a real time basis, the performance of four identical PV panels during the summer months of the year. The two of them (PV pair I) are kept at a fixed tilt angle of 15° (which is according to the results of previous studies expected to be the optimum tilt angle during the summer months for the specific area) and the other two are set to periodically vary their tilt angle (PV pair II).

Measurements were taken every 10 min during daylight, while the panel tilt angles examined correspond to 0°, 15°, 30°, 45°, 60° and 75°. Besides that, as already mentioned, measurements were taken at the hot period of the year (from mid-May to mid-September) with the above mentioned panel tilt angles being examined consecutively, for a 20-day period each (see also Table 2). At the same time, the global solar irradiance at both the horizontal and the tilted plane, as well as the current and voltage output for each of the PV pairs, were all recorded.

After the collection of measurements for the time period of study (e.g. \( t_0 - t_0 + \Delta t \)), performance of the two pairs of PV panels investigated is based on the assessment of their energy yield. More specifically, the hourly energy output of each pair is calculated as [24]:

\[
E_{PV} = \int_{t - t_0}^{t - t_0 + \Delta t} I_i(t) \cdot U_i(t) \, dt
\]

where “\( I_i \)” is the current output and “\( U_i \)” is the output voltage of each pair of PV panels.

However, to obtain a more straightforward comparison between the performance of different tilt angles, estimation of the mean capacity factor “\( C_{FPV} \)” for the respective period of measurements is also undertaken (see also Eq. (2))

\[
C_{FPV} = \frac{E_{PV}}{N_p \cdot \Delta t}
\]

with “\( N_p \)” being the peak power of the PV panels (i.e. 51 Wp each panel).

Prior to the conduction of measurements however, to increase reliability of results obtained, statistical similarity of both the pyranometers and the pairs of PV panels used was examined through the application of the h-test method [25,26].
Similarity of both pyranometers and PV pairs may be reflected from the measurements presented in Figs. 7 and 8 respectively, as well as from the data of Table 3. On top of that, what should also be noted is that to avoid influence of factors such as dust [27,28], all four PV panels were kept clean from any external pollutant throughout the experimental period, thus ensuring similar performance which is validated by the h-test.

3. Experimental results

Experimental results obtained appear first in Fig. 9, where one presents representative daily performance comparisons between the fixed and the variable PV panels’ tilt angles. More precisely, in Fig. 9 the 10 min average electrical current production “I_i” of each PV pair along with the respective 10 min distribution of solar radiation at the horizontal plane are included. In this context, current production “I_i” is as expected analogous to the distribution of solar radiation, while the effect of the panels’ tilt angle becomes evident.

In fact, by observing the results obtained, there is a minor difference in the produced electrical current between the 15° (fixed angle PV pair) and the 0° (variable angle PV pair) case, which is then however found to increase considerably, up to the point of 60°. At the same time, statistical similarity of the two PV pairs is also reflected from the results of the 15° case, where difference of current production is negligible. On the other hand, the increasing trend of “I_i” difference noted between the fixed and the variable angle PV pair seems to fade out in the case of 15°—75°, with measurements concerning the specific case taken in the period between late August and mid-September.

At this point it is important to note that the hour on the x-axis in the respective set of figures is set at local standard time (LST) and

![Image](image_url)

**Fig. 6.** Aspects of the experimental setup.

**Table 1**

Technical characteristics of the PV panels employed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power</td>
<td>51.0 W</td>
</tr>
<tr>
<td>Voltage at maximum power</td>
<td>16.9 V</td>
</tr>
<tr>
<td>Current at maximum power</td>
<td>3.02 A</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>21.2 V</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>3.25 A</td>
</tr>
<tr>
<td>Length</td>
<td>988 mm</td>
</tr>
<tr>
<td>Width</td>
<td>448 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>36 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>5.9 kg</td>
</tr>
<tr>
<td>Maximum efficiency</td>
<td>14%</td>
</tr>
</tbody>
</table>

**Table 2**

Experimental measurements’ plan.

<table>
<thead>
<tr>
<th>Variable angle PV pair</th>
<th>Period of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>15/5/10 to 3/6/10</td>
</tr>
<tr>
<td>15°</td>
<td>4/6/10 to 23/6/10</td>
</tr>
<tr>
<td>30°</td>
<td>24/6/10 to 13/7/10</td>
</tr>
<tr>
<td>45°</td>
<td>14/7/10 to 2/8/10</td>
</tr>
<tr>
<td>60°</td>
<td>3/8/10 to 22/8/10</td>
</tr>
<tr>
<td>75°</td>
<td>23/8/10 to 11/9/10</td>
</tr>
</tbody>
</table>
therefore the solar noon is not at 12:00 LST, which may also derive from the daily profile of the solar radiation measurements presented in some of the cases of Fig. 9 (e.g. 15°—45° and 15°—60°).

Accordingly, based on the use of Eqs. (1) and (2), typical weekly distribution of “CFPV” for all comparison sets examined is given in Fig. 10. More precisely, according to the results obtained, better performance of the 15° panel tilt angle is illustrated in all cases examined, with the greatest difference between the fixed and the variable angle PV pairs appearing in the case of 15°—60° (e.g. difference of the daily “CFPV” even above 6% in absolute values).

On the other hand, the 15° “CFPV” value is found to mostly vary between 15% and 22%, i.e. an expected result for the area and period of investigation, while difference between the fixed and the variable angle PV pairs is minimum in the case of 15°—0° (e.g. even dropping below 0.15% in absolute values). Overall, the 20-day long term average relative difference between the fixed and the variable angle PV pairs’ “CFPV” is given in Table 4, where maximum deviation noted in the case of 15°—60° is found to decrease in the case of 75°, owed mainly to the time period of experimental measurements (see also Table 2).

In this context, what should also be stressed is that given the peak power of the PV panels (i.e. 102 W for each of the pairs), difference noted in the “CFPV” values may be used to estimate the respective reduction in energy production. For example, in the extreme case of 15°—60°, the 20-day energy output of the fixed PV pair (i.e. 9.75 kWh) drops to 7.08 kWh for the 60° PV pair, which is equal to a relative difference of 27.3% (see also Table 4) that underlines the importance of selecting the optimum tilt angle.

4. Theoretical investigation of experimental results

After the experimental investigation of the optimum tilt angle for the summer period, an effort is currently undertaken in order to interpret the results obtained through the theoretical investigation of the problem examined.

Theoretical determination of the optimum summer tilt angle is based on the established equations of solar geometry [24,29] and more precisely on the minimization of the solar radiation incidence angle. Note that zero incidence angle implies vertical incidence of the solar radiation upon the surface under study and thus maximum absorbance of solar radiation (see also Fig. 11).

In this context, incidence angle “θ” is provided by Eq. (3), where parameters involved also include the panel tilt angle “β”, the latitude of the location examined “ϕ”, the azimuth angle “γ”, the solar hour angle “ω” and the solar declination “δ”.

$$
\cos \theta = \sin \delta \sin \varphi \cos \beta - \sin \delta \cos \varphi \sin \beta \cos \gamma 
+ \cos \delta \cos \varphi \cos \beta \cos \omega 
+ \cos \delta \sin \varphi \sin \beta \cos \gamma \cos \omega 
+ \cos \delta \sin \sin \beta \sin \gamma \sin \omega
$$

(3)

Next, solar declination “δ” is given by Eq. (4), where “D” is the Julian day of the year.

$$
\delta = 23.45 \times \sin \left( \frac{360}{24} \times \left( D + 284 \right) \right) / 365
$$

(4)

Furthermore, solar hour angle “ω” is a function of solar time “ST” and is provided by the following equation, where “ST” is used in decimal form.

$$
\omega = 15^\circ \times (ST - 12)
$$

(5)

Subsequently, in order to estimate the solar time “ST”, local standard time “LST” along with the standard and the local meridian of the area (“LST” and “L” respectively) are required,

$$
ST = LST \pm 4 \times (LST - L) + E_t - c
$$

(6)

with (+) applying for the west hemisphere and (−) for the east. On top of that, “c” corresponds to the 1 h correction (i.e. 60 min) applying only during the period from the last Sunday of March to the last Sunday of October so as to raise the daylight saving time (otherwise c = 0). Furthermore, “E_t” corresponds to the time correction function, given by the Watt equation below

$$
E_t = 9.87 \times \sin (2B) - 7.53 \times \cos B - 1.5 \times \sin B
$$

(7)

with “B” being also a function of the Julian day of the year “D”.

$$
B = 360 \times (D - 81) / 364
$$

(8)
In this context, using the information of Table 5 concerning assigned values of input parameters, variation of the incidence angle \(\theta\) in relation to the selected panel tilt angle \(\beta\) for the entire summer period is given in Figs. 12 and 13. More precisely, in Fig. 12 one may obtain an example for the 15th of May, which comprises the typical solar day of the specific month [30]. As one may see, there are six different curves of incidence angle \(\theta\), covering the entire range of tilt angles examined, i.e. from 0° to 75°, while distribution of the solar irradiance at horizontal level is also included. In this context, distribution of the incidence angle is found to present minimum values for the mid-day period (i.e. when the available solar radiation maximizes) in the case of panel tilt angle equal to 15°. On the other hand, the situation is inverted during the early morning and late afternoon hours, when the panel tilt angle of 0° presents the lower incidence angle value.

Nevertheless, as one may obtain from the figure, the 15° tilt angle remains optimum for almost the entire day (from 10:00 to 17:00), which also corresponds to the period of maximum solar irradiance kept above 500 W/m². As a result, it becomes clear that for this typical day of May, 15° is the optimum tilt angle since it ensures the most vertical incidence of the solar irradiance upon the surface of PV panels for the period of the day that solar irradiance maximizes.

Similar to Fig. 12, in Fig. 13 one may obtain the respective results for the entire period investigated, on the basis of a one-month time interval, again using the typical solar days of each month investigated [30]. As one may obtain from the figure, the angle of 15° is maintained as optimum until late July–early August, although it
should be noted that the respective period of the day, during which 15° produce the lower incidence angle, is found to gradually narrow (in comparison with the respective of May, i.e. from 10:00 to 17:00).

On the other hand, the 30° panel tilt angle seems to produce the

Fig. 10. The impact of the tilt angle variation on the daily capacity factor of the PV panels set at the tilt angle of 15°

Table 4
Relative deviation of the “CFPV” between the fixed and the variable angle PV pairs.

<table>
<thead>
<tr>
<th>Variable angle PV pair</th>
<th>Relative deviation of CFPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>2.8%</td>
</tr>
<tr>
<td>15°</td>
<td>-0.3%</td>
</tr>
<tr>
<td>30°</td>
<td>8.5%</td>
</tr>
<tr>
<td>45°</td>
<td>17.0%</td>
</tr>
<tr>
<td>60°</td>
<td>27.3%</td>
</tr>
<tr>
<td>75°</td>
<td>23.6%</td>
</tr>
</tbody>
</table>

Fig. 11. Incidence angle “θ” and tilt angle “β” of a given surface.
minimum incidence angle for the following period between mid-August and mid-September. Acknowledging the results obtained for the period of examination, it becomes evident that among the different angles currently examined, 15° comprises the most efficient in terms of local solar potential exploitation.

Accordingly, if matching the time periods of investigation (see also Table 2) with the theoretical distributions of the incidence angle, the "CFPV" deviations previously obtained from the experimental results may be explained. More precisely, as one may see, in the early period of the summer, i.e. when the 0° tilt angle was tested, difference between the "CFPV" of the fixed and the variable angle PV pairs should be minimum, validating the theoretical distributions of the respective angles appearing in Fig. 12. Besides, as already mentioned, although 15° appears to be more efficient during mid-day, the opposite is noted during the morning and afternoon hours, when 0° produce the minimum incidence angle.

Furthermore, not considering the month of June (i.e. when the 15°—15° pair was tested) and proceeding to the period of early July, greater difference between the 15°—30° relative deviation of the "CFPV" in comparison with the 15°—0° case, see also Table 4, is justified on the basis of distributions presented, with the 15° distribution demonstrating a clear advantage over the respective of 30°. Subsequently, similar is also the conclusion for the 15°—45° case (mid-July to end of July—early August), with the greater relative deviation of the "CFPV" in comparison with the former—illustrated by the comparison of theoretical distributions.

Fig. 13. Theoretical daily distributions of the incidence angle for various panel tilt angles vs local solar potential (May 15).
5. Conclusions

Based on an experimental setup, installed at the area of Athens-Greece (37°58’ N and 23°40’ E) and comprising of a fixed and a variable angle PV array, systematic series of measurements concerning the performance of two PV pairs were carried out during the summer period. More specifically, consecutive, 20-day sets of measurements were taken for each different angle of the variable angle PV pair (i.e. 0°, 15°, 30°, 45°, 60° and 75°), while keeping the fixed angle PV pair at 15°. More precisely, extensive, 10 min measurements of solar irradiance and PV current and voltage output were conducted throughout the summer period, allowing for the estimation of the respective energy production by each of the two PV pairs. In this context, emphasis was given on the evaluation of performance of the two PV pairs through estimation of the relative “\(C_{PV}\)” deviation (of the variable tilt angle PV pair in comparison with the fixed -optimum angle PV pair) during the consecutive time periods of measurements. According to the results obtained, performance deviation is as expected largely depending on the selected tilt angle and the period of examination, with the greatest deviation (i.e. 27.3%) between the fixed and the variable tilt angle PV pairs -for the current set of measurements- noted in the case of 15°-60°. On the other hand, the respective minimum difference was noted in the case of 15°-0°, with the corresponding deviation not exceeding 3%.

Subsequently, through the use of solar geometry equations, experimental results were investigated under the view of diurnal incidence angle distributions, considering that maximum energy production is ensured by the minimization of the solar incidence angle. Diurnal distribution of the solar incidence angle was examined for the typical days of the months under examination, covering the entire range of tilt angles investigated. Furthermore, by also taking into account the respective distribution of solar irradiance, theoretical designation of the optimum tilt angle was possible. More precisely, by examining the patterns of solar incidence angle and solar irradiance distributions, the expected optimum tilt angle was decided by considering the extent at which minimization of the solar incidence angle was obtained during the day. Through this theoretical investigation of the problem, experimental results obtained were validated, reflecting at the same time the clear advantage of the 15° (±2.5°) angle in the area of Athens and central Greece in general, for almost the entire summer season.

Appendix A

According to the h-test method, measurements provided by two different measuring instruments of the same type (e.g. two pyranometers) may differ by a predefined value of “\(d_0\)” (currently taken equal to zero) –at a reliability level of 95%– only if the following condition is validated,

\[-\theta_C < \theta_0 < \theta_C\]  

(A.1)

with “\(\theta_0\)” being calculated on the basis of the Student distribution, using the following equation

\[\theta_0 = \left(\frac{\bar{x}_1 - \bar{x}_2}{s_1^2/N_1 - s_2^2/N_2}\right)^{1/2}\]  

(A.2)

where “\(\bar{x}_1\)”,” “\(s_1\)” and “\(N_1\)” are the average, standard deviation and number of measurements respectively.

Furthermore, by using the necessary input values (e.g. see also Table 3) and Eq. (A.3) following, the value of freedom degrees “\(\xi\)” may be estimated.

\[\xi = \frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}\]  

(A.3)

Using “\(\xi\)” and the value of “\(\theta_0\)” -determined by the Student distribution table for a reliability of 95%– similarity or dissimilarity of the two measuring instruments is eventually designated through validation -or not- of Eq. (A.1).

References
