A brief overview about models and methods to calculate the tilt angle and orientation of photovoltaic panels to maximize power generation

Mirelys Torres-Pérez[1], Rafael Rodríguez-Puente[2,3]*

[1]Informatics Department, Faculty of Technical Sciences, University of Las Tunas

[2]Computer Science Department, Faculty of Science, University of Namibia

[3]Programming Department, Faculty 3, University of Informatics Science, Cuba

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Abstract

Photovoltaic systems are presented as an alternative energy for a sustainable development that can satisfy global energy requirements and provide electricity in remote locations, usually inaccessible and away from the electrical network. An essential step in the installation of a photovoltaic solar module is to determine the tilt angle and orientation with respect to the horizontal plane, because an incorrect orientation and inclination can decrease the production capacity and lifetime of a photovoltaic module. The optimum angle for collector's surfaces of a solar system is determined by many factors such as the incident radiation on the place of the installation and the solar sky, where the shadow of objects that cannot be eliminated like buildings, mountains and others must be taking into account. Based on a literature review of the models and methods more employees worldwide, we provide a brief overview of models and methods to calculate the angle and orientation of a panel in order to maximize power generation.

Keywords: *photovoltaic panels; power generation; tilt angle; orientation.*

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*Corresponding author: E-mail: rafaelrp@uci.cu (R. Rodríguez-Puente)

1 Introduction

Photovoltaic systems are presented as an alternative energy for a sustainable development that can satisfy global energy requirements and provide electricity in remote locations, usually inaccessible and away from the electrical network. To maximize the capture of the incident solar radiation energy, a solar absorber unit must be positioned at the right orientation, which can be described in tilt and azimuth angles, an incorrect orientation and inclination can decrease the production capacity and lifetime of a photovoltaic module.

In this paper we mention the theoretical aspects of choosing a tilt angle for solar collectors and provide a brief overview of models and methods to calculate the angle and orientation of a solar panel used at different locations in the world, in order to increase the electric power generation.

1.1 Tilt angle by latitude

The tilt angle calculations described in the literature may be widely classified into two categories: calculation by latitude angle and calculation by maximizing the global radiation falling onto the solar panel surface.

Table 1: Tilt angle by latitude

Author	**Recommended tilt angle**
Duffie and Beckmann (2013b)	$\varphi \pm 15°$
Heywood (Asowata et al. 2012)	$\varphi - 10°$
Lunde (Lunde 1980)	$\varphi \pm 15°$
Chinnery (Asowata et al. 2012)	$\varphi + 10°$
Lof and Tybout (Lof and Tybout 1973)	$\varphi \pm 10° \rightarrow 30°$
Garg (Garg 1982)	$\varphi + 15°$
	$\varphi - 15°$
	$0.9\ \varphi$

‡The minus sign refers to the summer season and the positive sign is for the winter

There are clearly wide discrepancies for the proposed optimum tilt angle when the latitude angle is solely used and no definitive value is given. To calculate a yearly optimum tilt angle based primarily on the latitude angle φ, a brief review of the various schemes is summarized in Table 1. These methods are simple and straightforward but are approximate nevertheless (Armstrong and Hurley 2010). This means, they do not account the topography of the terrain or the effects of the atmosphere and the Earth, for that reason are recommended for latitudes that not experience significant seasonal variations and for terrains with no complex orography. Table 1. Tilt angle by latitude.

1.2 Tilt angle and orientation by maximizing the solar radiatione

A common approach for choosing the tilt and orientation angle is to maximize the amount of global radiation falling on the surface of the solar panel. This could be achieved performing solar radiation measurement at the site of the installation or employing a solar radiation model. The former practice is the most accurate; however, lack of complete meteorological information and the constraint of having expensive measuring instruments at every location and orientation are the common issues related to solar process analysis. As a resolution, a number of techniques have been developed and improved to provide a satisfactory approximation for determining the behavior of solar radiation energy (Ng Adam et al. 2014).

In the literature, we found models whose results are obtained by calculations based in geometric, physical, atmospheric and astrophysics considerations, models based in databases of terrestrial measures of radiation or derivatives of satellite observation, as well as mixed models that use calculation and historic measurements of radiation (Díaz 2013). In this paper will focus in the models that take into account the tilt angle of the receiving surface; thus, varying its value in the model we can obtain the optimum tilt angle corresponding to maximum insolation.

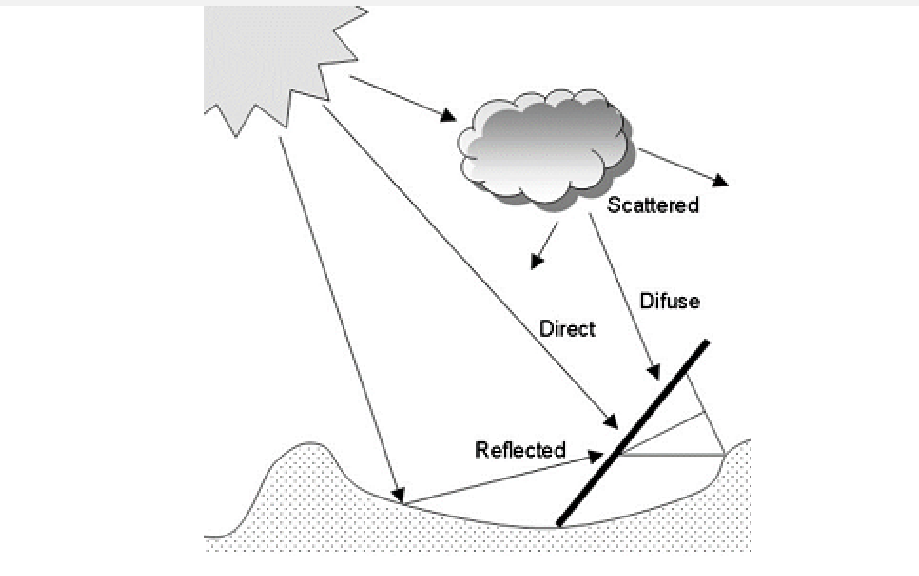

Figure 1: Components of the solar radiation(Keller and Costa 2011).(**1**)

The calculation of the solar radiation that strikes a surface on the Earth is not simple, because depends of many factors. As can be seen from Figure 1, a part of the incident energy is scattered and absorbed by air molecules, clouds and other particles in the atmosphere, the scattered radiation that reaches the ground is called diffuse irradiation G_d. Some of the radiation is reflected from the ground onto the receiver; this is named reflected (or albedo) irradiation G_r. The radiation that is not reflected or scattered and reaches the surface directly is called direct irradiation G_D. Then, the summation of these three components is the total (or global) irradiation G_t that strikes the absorber unit (Keller and Costa 2011).

The amount of radiation is also strongly dependent on the lengths of the path of the rays through the atmosphere (air mass). The air mass that the sunrays have to pass for striking a surface is in the morning or evening much more, for that reason the irradiation is much less than at noontime. Therefore, the influence of the air mass is also in coherency with location of the sun in the sky (Keller and Costa 2011).

If the absorber surface is not a horizontal surface, can produce shadows when the sun is behind the absorber. Similarly, objects around the absorber can cause shadows on it. The influencing factors of total radiation are (Keller and Costa 2011):

1. The effects of the Atmosphere and the Earth.
2. The location of the sun in the sky.
3. The nature and the orientation of the absorber.

In these sense, Dubayah and Rich (1995) recognize the topography as a major factor in determining the amount of solar energy incident at a location on the Earth's surface. "Variability in elevation, slope, slope orientation (azimuth or aspect), and shadowing, can create strong local gradients in solar radiation that directly and indirectly affect such biophysical processes as air and soil heating, energy and water balances, and primary production" (Dubayah and Rich 1995). These influencing factors are complex and some of them (e.g., the effect of clouds) are calculated only by approximation.

The distribution of the radiation varies extensively across the globe, in the northern hemisphere; the greatest amount of radiation is received by locations situated between latitudes 15° N and 35° N. The next favorable belt lies between 15° N and the equator, which includes Central America. Countries situated between the latitudes 35° N and 45° N experience significant seasonal variations resulting in less radiation received, such as Spain or Turkey. The least favorable locations are situated beyond 45° N; many countries in Northern Europe are located in this belt such as Ireland, England, Norway and Sweden. Almost half of the radiation arrives at the surface as diffuse radiation, due to frequent heavy cloud cover (Armstrong et al. 2010). For this reason, methods are unsuitable, as they do not consider atmospheric conditions.

Due to the different treatment of sky diffuse component, the solar radiation models can be categorized into two groups known as isotropic and anisotropic models (Duffie and Beckman

2013b). The isotropic diffuse model, created by Liu and Jordan (1963) is the most employed between the isotropic models. On the other hand, for the anisotropic models stands the Hay and Davies (1980), Reindl et al. (1988), a model referred as the HDKR (Hay, Davies, Klucher, Reindl) providing by Klucher (1979) and Perez et al. (1990). These methods does not account the topography of the terrain, the shadows or the effects of the atmosphere and the Earth, for that reason are recommended for latitudes that not experience significant seasonal variations and for terrains with no complex orography.

The Klein and Theilacker (KT) method is frequently used to show the effects of slope and azimuth angle on total energy received on a surface for a monthly, seasonal, or annual basis. Is appropriate for an interest location when $\bar{H}$, where H is the monthly average daily radiation on a horizontal surface, is the only available solar radiation data at the site and for regions with significant seasonal variations. It is a bit more cumbersome and requires some year historical data of $\bar{H}$ for it use, but shows improved results over the isotropic method when compared with hourly calculations based on many years of radiation data. It has been employed in urban and rural areas as show the investigations of Ng et al. (2014) and Jafarkazemi and Saadabadi (2013).

A new method for choosing the optimum tilt angle for a solar panel, that takes into account the frequency of cloud has been presented by Armstrong and Hurley (2010), which is particularly suitable, but not limited to climates susceptible to frequently overcast skies. This method can be applied to any location with knowledge of the monthly sunshine duration and hourly cloud observations. However, the topography and shadows are not taking in account.

Modelling solar radiation flux on complex surfaces become practical because of advances in computer technology, both software and hardware (Hetrick et al. 1993). In this sense, GIS has been spread internationally like the appropriate modelling platform for formulating and running sophisticated solar radiation models.

The first model based on GIS was SOLARFLUX implemented under ArcGIS, it uses as input a topographic surface, specified as a grid of elevation values, as well as latitude, time interval for calculation, and atmospheric conditions (transmittivity) (Dubayah and Rich 1995). Solar Spatial Analyst tool implemented under the commercial ArcGIS 10 (ESRI 2011) and r.sun (Šúri and Hofierka 2004) implemented under GRASS GIS environment (Neteler et al. 2012) calculate the clear-sky global irradiation maps considering the shadowing of the local terrain, i.e. produced by the Digital Elevation Model (DEM) itself. These models consider only the heights, tilts and aspects of the points of the land surface, i.e., the data provided by the DEM. However, they do not consider placing the collecting surface at a different or even variable heights, tilts and orientations. Recall that any modification of these parameters may change considerably the received radiation (Tabiket al. 2013).

Tabik et al. (2013) presented a GIS's tool to compute the optimal solar panel positioning maps on large high-resolution DEM. It is able to find out the maximum solar energy input that can be captured on a surface located at a specific height on each point of the DEM and the optimal angles (i.e., slope and orientation) that allow capturing this maximum energy. It generates the maps of maximum solar energy, optimum tilt and optimum orientation by a multi-algorithm especially appropriate for heterogeneous multicore-GPU architectures.

For Building-integrated Photovoltaics (BIPV), the orientation and tilt angles of the PV generator acquires specific nuances. Mainly because, the best tilt and orientation angles are not always possible in buildings, as there are many other factors architects and engineers have to harmonize a lot of conditions, urban regulations, form and function of the building, constructive systems or materials available (Cronemberger et al. 2012).

Few related works have addressed applications affine to this problem but only on fix surfaces. Hofierka and Kaňuk (2009), developed a tool called PVGIS based on r.sun (Šúri and Hofierka 2004) for estimating the photovoltaic potential on specific building surfaces, generally roofs with a predefined tilt and azimuth. A similar tool called PV was proposed in (Choi et al. 2011) to be implemented under ArcGIS. Both tools are limited to small urban areas, the used sequential baseline model per se is costly from a computational point of view, and building new tools on the top of it makes it even more expensive (Tabik et al. 2013).

Besides the conventional solar modelling methods, the optimization exercise can be done using other techniques such as genetic algorithm (GA), simulated annealing (SA), particle swarm optimization (PSO) and artificial neural network (ANN), in which the methods are proper for the estimation dealing with complex non-linear variables. Chen et al. (2005) presented the optimal angle of the fixed solar panels situated in Taiwan using GA and SA optimization techniques. Talebizadeh et al. (2011) used GA and KT methods to determine the optimum orientation of a solar absorber. They noted that the optimum tilt angles were more sensitive to direct solar radiation.

Khatib et al. (2012) compared linear, non-linear and ANN models to predict the diffuse radiation in Malaysia and indicated that the ANN could generate better estimate. Celik and Muneer (2013) used the generalized regression type of neural network to determine the solar irradiation on a tilted surface, which had presented a good accuracy with 0.987 as coefficient of determination.

2 Discussion

As a "rule of thumb", the south-facing surface offers better solar irradiance energy collection for the regions placed in the Northern Hemisphere and vice-versa (Panchal and Shah 2012;

Pardhi and Bhagoria 2013; Sharma and Harinarayana 2013). At the medium and high latitudes, the sun tends to the south or north sky of the site for a longer period.

In the region of low latitude, however, the scenario may be dissimilar. The sun tilts to both southern and northern skies of the site with a more uniform period in one year. Therefore, for the low-latitude region, despite of its location at the Northern Hemisphere, the north-oriented surface can potentially intercept a prominent amount of solar irradiance. It leads to a rational assumption that the north-facing components can receive a reasonable amount of radiation energy. The optimum tilt angle is expected to be positioned facing the north for seasonal optimum energy collection (Ng et al. 2014).

Because the distribution of the solar radiation varies all over the year, for a better use of this resource it is advisable to correct the tilt angle of the panels in different periods of the year, Elminir et al. (2006) proposed two times in a year: in winter and summer. Ahmad and Tiwari (2009) suggest correct the angle four times in a year: in spring, summer, autumn and winter. Nevertheless, the regimen of use and consumption that it works mainly in winter, summer or all year round will determine the different inclination for the collector surface in each case. "Optimization of collector orientation for any solar process that meets seasonally varying energy demands, such as space heating, must ultimately be done taking into account the time dependence of these demands" (Duffie and Beckman, 2013a).

Bérriz and Álvarez (2008) express that, the most favourable position for the collector surface of solar radiation will be the one that: in terms of the application of the system, perceives the greater quantity possible of energy, i.e. unique or hybrid, autonomous or matched to the network; because the objective of the installation defines the regimen of use and consumption. Considering this, it is necessary that the objectives of the application be one of the input variables in determination of the angles of inclination and orientation for a collector surface.

Additionally, for determining the quantity of times on a year that must be corrected the tilt angle of solar panels, is necessary to consider the cost of correct the angle versus the gain of energy. Because in some cases like the autonomous solar panels displayed in rural areas of Cuba, a specialist is the responsible of going to the place and corrects the angle manually. Many models and methods studied are suitable for some region and do not contemplate the entire influencing factor. Table 2 summarize those aspects.

3 Conclusion

Estimate the radiation incident on the earth is not a simple matter, because their divergent features (irregularity and fluctuation of solar radiation) which make it impossible to deter-

Table 2: Tilt angle by latitude

Method or Model	**Recommended region**	**Influencing factors does not account and/or requirements**
Tilt angle by latitude	For latitudes that not experience significant seasonal variations and for terrains with no complex orography	The topography, the effects of the atmosphere and the Earth, shadows, the seasonal variations and the objective of the application.
Isotropic and anisotropic models	For latitudes that not experience significant seasonal variations and for terrains with no complex orography.	The topography, shadows, significant seasonal variations and the objective of the application.
Klein and Theilacker (KT) method	For interested locations where $\bar{H}$ is the only available solar radiation data at the site and for regions with significant seasonal variations.	It is a bit more cumbersome to use and require some year historical data of $\bar{H}$ for its use. Does not account the objective of the application.
Armstrong and Hurley	For regions with significant seasonal variations.	The topography, shadows and the objective of the application.
SOLARFLUX, Solar Spatial Analyst and r. sun	Modelling solar radiation on complex surfaces, with small DEMs.	Do not consider placing the collecting surface at a different or variable heights, tilts and orientations. Costly from a computational point of view.
PVGIS and PV	For urban environment	Costly from a computational point of view.
GIS tool proposed for Tabik	For modelling solar radiation on large areas.	Require large high-resolution DEMs for it use. Does not account the objective of the application.

mine exactly the values in different parts of the world, involving physical, chemicals and geographical process.

Calculate the tilt angle by latitude is very simple but does not account many of the influencing factors. On the other hand, by maximizing the global radiation falling onto the solar panel surface require that the user make multiples executions of the model modifying the angle and orientation until get the right value.

The evolution of this kind of models will become more complex. These models will be based in informatics technologies, bringing the possibility of combine then with techniques such as genetic algorithm, particle swarm optimization and artificial neural network, among others.

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