



Original article



Evaluating the standards for solar PV installations in the Iberian Peninsula: Analysis of tilt angles and determination of solar climate zones

E. González-González^{*}, J. Martín-Jiménez, M. Sánchez-Aparicio, S. Del Pozo, S. Lagüela

Department of Cartographic and Land Engineering, University of Salamanca, Calle Hornos Caleros, 50, Ávila 05003, Spain

ARTICLE INFO

Keywords:

Photovoltaic energy
Solar potential
Roofs
Solar model
Tilt
Solar zoning

ABSTRACT

One of the main factors for the determination of the energy yield of photovoltaic (PV) systems is the incoming solar irradiation, which is a function of (i) the spatial configuration of the PV panels with respect to the Sun for (ii) each location. The aim of this work is to determine the PV potential in the Iberian Peninsula, attending to the two main criteria. Regarding (i), different methods for the estimation of the optimal PV tilt angle in the Iberian Peninsula, and how this parameter influences the PV production, are analysed. With respect to (ii), a climate zoning is proposed for the Iberian Peninsula, to be used as reference for the estimation of solar radiation for each location. The study is performed using experimental data from capital cities of the Iberian Peninsula (Spain and Portugal). In addition, the annual PV production was compared for several tilt angle configurations in order to estimate the energy losses per unit angle with respect to the energy produced with the optimal tilt angle. Results show that the tilt angle can be fixed as 34° for all the Iberian Peninsula, being the annual PV production losses lower than 1%. Differences lower than 1% were obtained between the different approaches existing in literature to calculate the optimal tilt angle, showing that although the tilt angle is a key parameter that influences the PV energy production, its variation must be significant in order to have an impact on production losses.

Introduction

Energy poverty is a manifestation of the economic scarcity and social exclusion concerns [1–4]. The increase in energy-poor citizens exacerbates the problem and thus awareness is raising among citizens globally [5,6]. Proof of this awareness is the inclusion of the energy availability problem in the Sustainable Development Goals of the United Nations Development Program [7]. According to this program, Goal number 7 refers to “Affordable and Clean Energy”, with the main aim of ensuring access to affordable, reliable, sustainable and modern energy as key to solve the energy poverty worldwide. However, there are more goals impacted by the energy issue, such as Goal number 11 (Sustainable Cities and Communities) and Goal number 12 (Responsible Consumption and Production).

Renewable energy resources have shown to be the alternative towards the reduction of the energy poverty and the sustainability of the energy supply [8,9]. One of the strengths of the renewable energy resources is their spatial availability [10], which enables their exploitation at large-scale, in energy farms [11], but also at small-scale, in such way that the consumers can supply their own energy demand [12]. Self-

consumption appears as the solution to energy poverty, since it can reduce the energy prices [13,14], and also to the lack of energy connection by isolated populations: in the Canary Islands (Spain) water and energy were supplied with water and hydrogen resources [15], while isolated rural areas search for the total energy supply with different combinations of renewable energy resources [16,17].

Among all renewable energy resources, the solar energy stands as the most adequate for its use at small-scale, thanks to the adaptability of the technology to be installed in different locations close to the user, such as building roofs [18]. Recent studies suggest that the EU rooftops could potentially produce up to 24.4% of electricity demand with PV [19]. Thus, this framework facilitates the inclusion of PV systems in urban buildings allowing self-consumption either individual or shared [20], reducing greenhouse gases emissions, and improving energy efficiency and sustainability.

Enabling residents of multi apartment buildings to commonly use electricity generated by a PV system (collective self-consumption) is a relatively new development [21]. In the Spanish context, Shared PV systems have been recently regulated [22], facilitating the integration of PV installations on shared rooftops in apartment buildings owned by different neighbours. The summation of energy demands from different

^{*} Corresponding author.

E-mail addresses: egonzalezgonzalez@usal.es (E. González-González), joseabula@usal.es (J. Martín-Jiménez), mar_sanchez1410@usal.es (M. Sánchez-Aparicio), s.paguilera@usal.es (S. Del Pozo), sulaguela@usal.es (S. Lagüela).

<https://doi.org/10.1016/j.seta.2021.101684>

Received 9 March 2021; Received in revised form 13 October 2021; Accepted 20 October 2021

Available online 2 November 2021

2213-1388/© 2021 The Author(s).

Published by Elsevier Ltd.

This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Nomenclature

Em	average monthly energy production [kWh]
Hm	average monthly sum of global irradiation per square meter [kWh/m ²]
N	north
W	west
<i>Greek letters</i>	
α	azimuth angle [°].
β	tilt angle [°].
β_{opt}	optimal tilt angle [°].
$\beta_{\text{opt-PVGIS}}$	optimal tilt angle [°] calculated by PvGIS.
ϕ	latitude [°].

users, within a radius of 500 m distance, as is the case of Spain, results in a maximization of the self-consumption of the energy generated, with very little over-production and almost no energy fed into the grid. According to [23], maximizing self-consumption from PV systems will be the most effective way to reduce energy poverty in households across most regions of the world, since self-consumption reduces the effect of the regulations and prices in the electricity market on the users. The aim of this paper is to analyse the performance of PV installations with different configurations (tilt angles), providing a range of tilt angles that optimize the production, especially thinking in those installations where the space available for solar panels is not enough to cover all the demand, as in shared PV systems.

Although PV systems have become much cheaper in recent years [24], it is important to know how much energy production is expected from the different possible PV configurations in order to consider all the aspects of influence in the decision of the design of the installation: economic advantages, energy efficiency and performance [25]. Regarding materials and efficiency, the coverage of PV modules has been improved based on plasmonics, which increase the absorption in PV modules due to the considerable reduction in the physical thickness of the absorber layers [26]. However, power ratings in PV modules are usually tested under standard conditions that involve perpendicular incident light, although the real angles of incidence differ from being perpendicular to the surface of the PV panel, which results in a decrease in the real performance of the panels due to the reflection effect mainly induced by the air-glass interface. This phenomenon has been studied in different works, such as [27,28].

Thus, depending on the spatial configuration of PV systems there will be a great variation in the generation of electricity. If the PV panels are coplanar to the roof surface, tilt and azimuth angles are not usually optimal. In this regard, the location is the basis for the determination of the annual PV energy production since it determines the angles of incidence of the Sun throughout the year.

In the case that supports are used to install the PV panels with the optimal tilt and azimuth angles, energy production can be generally maximized or optimized to the interest of the users so that production is maximum in the time frames where the user has the greatest demand or in the hours with higher prices for electricity. An example of optimization with azimuth angles in Spain is the South orientation for maximum annual production (maximum production rates at midday), while West-East orientation of the PV panels will have lower peak production but more extended during the day (earliest beginning and latest end of the production).

Estimating the losses of production due to the variation of the angles with respect to the optimal ones is essential to evaluate the economic feasibility and productive capacity of PV systems. This paper calculates the optimal PV tilt angles for the Iberian Peninsula and estimates the energy losses due to tilt angle variations with respect to the optimal.

In addition, this study leads to the determination of a map of solar climate zones, that can be used as a reference to know the maximum energy demand that can be supplied by solar PV panels in each point of the Iberian Peninsula, divided in provinces and districts in Spain and Portugal, respectively.

Some organizations have developed software tools to estimate the PV energy production [29], such as PvGIS [30] created by the European Commission, PvWatts [31] developed by the National Renewable Energy Laboratory (NREL) of the US, and RETScreen [32] from the Government of Canada. The works presented through this article have been performed using PvGIS estimation utility as it appears to be the most accurate for small variations in real data and for the chosen study area [33].

State of the art of the solar energy yield optimization

The solar energy production of PV panels depends on several parameters. Among them, their spatial configuration, defined by the latitude, azimuth and tilt angle, is the basis in the energy yield of the PV system [34–36]. In this regard, there are different studies that deal with energy PV production by means of the optimal tilt angle and the best PV configuration. For example, according to [37], the optimal PV tilt angle varies between 0° and 65° throughout the year in Turkey, being the optimal angle of 0° in June and 65° in December. Other researchers have done similar studies for each season of the year, as the works reported by [38] developed in Madinah, Saudi Arabia.

Regarding maximum energy PV production, some studies have quantified the increase of energy performance in about 30.79% for a PV panel with double axis sun-tracking system with respect to a fixed PV system [39,40]. When the use of tracking systems is not possible, the performance of the PV system can be optimized with respect to a fixed system as well. The analysis of the performance of tracking systems demonstrates that adjusting tilt angles six times per year could harvest 99.5% of the solar radiation compared to a PV system with daily tracking and panel adjustment in Saudi Arabia location [41].

Since the current framework of distributed energy generation with renewable sources impulses Building Integrated PhotoVoltaic (BIPV) installations in urban areas, the study of the energy yield of PV systems installed on building rooftops is essential. In this frame, the azimuth and the tilt angle of the roofs do not usually match the optimal for PV system. Thus, evaluating losses in production is necessary in order to determine the economic feasibility as well as the production capability of the PV installation [42,43]. However, an advantage of PV systems integrated in building roofs is the reduction of cooling energy demand in warm days thanks to the shadow produced by the panels covering the roof surface [44].

Finally, it should be noted that dusty environments could lead to PV energy losses. The decrease in PV production due to soiling could be up to 10% for a slightly dirty panel and up to 40% for a very dirty panel. In this sense, this production decrease would be reduced with slanted panels instead of horizontal panels [45–47].

Tilt angle-latitude relationship

If the focus is brought to the optimal PV spatial configuration in order to maximize the annual energy performance, the optimal azimuth angle depends on the Hemisphere in which the case study is located. For the North Hemisphere, southward orientation is the optimal, while for the South Hemisphere, optimization is obtained with northward orientations [48]. Once the azimuth angle is established, the optimal tilt angle to maximize annual PV energy production depends on the latitude of the case study.

Different investigations have been performed in order to determine the optimal tilt angle for a known latitude. Thus, considering the tilt angle equal to the latitude of the PV system location in order to validate the reliability of a BIPV (Eq. (1)), [49] demonstrated that the

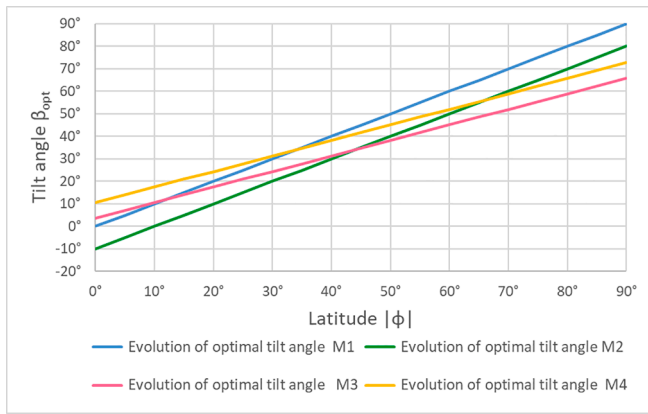


Fig. 1. Evolution of the optimal tilt angle with latitude, for the four methodologies analysed.

performance of PV systems is almost the same (98.5%) than that obtained with the estimated optimal angle for a range of latitudes from 0° to 85° in the North Hemisphere. Other studies stated that the optimal angle is the one obtained after subtracting 10° from the latitude (Eq. (2)) [50] for latitudes starting from 36° to 46°, while others added some constants to increase the accuracy in the relation between latitude and optimal tilt angle. In this way, [51] stated that the optimal tilt angle is the result of multiplying 0.69 to latitude and then adding 3.7° (Eq. (3)); where dust accumulation in the surfaces of the panels can be reduced increasing 10° for low latitudes ((Eq. (4)), being the losses less than 1% for deviations of the optimal tilt angle close to 10° [52]. More information about each equation can be found in the corresponding references. It should be noted that if the target is to maximize the PV production at a specific season instead of considering the entire year, the result is different. Thus, when maximizing the PV production for wintertime, the tilt angle should be higher than the angle obtained for maximizing PV production for the whole year. The opposite happens in the case of maximizing the PV production in summertime: the optimal tilt angle should be lower than the value obtained when maximizing production for the whole year. Some studies suggested a fixed value to vary the optimal annual tilt angle between ±15° [53], or ±20° [54], for the aim of maximizing the PV production in winter or summer.

In order to consider the different approaches existing in the literature, the following methodologies (M1-M4) have been analysed to obtain reliable conclusions about the optimum tilt angle of PV panels:

$$M1: \beta_{opt} = |\phi| \tag{1}$$

$$M2: \beta_{opt} = |\phi| - 10 \tag{2}$$

$$M3: \beta_{opt} = 3.7 + 0.69 \cdot |\phi| \tag{3}$$

$$M4: \beta_{opt} = 3.7 + 0.69 \cdot (|\phi| + 10) \tag{4}$$

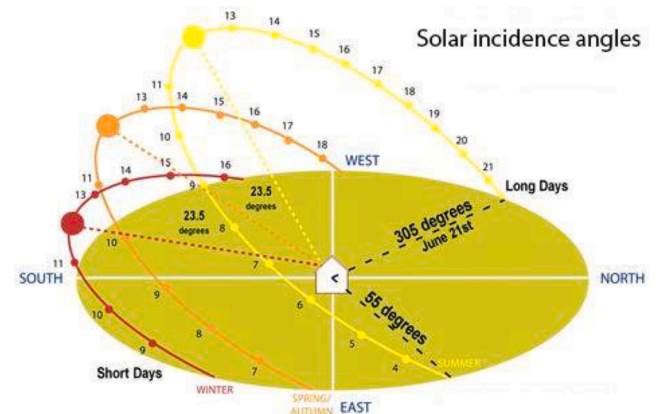


Fig. 3. Solar trajectories for 45° N latitude.

being ϕ the latitude in degrees and β_{opt} the optimal tilt angle in degrees.

All these methodologies focus on an optimal annual PV production for fixed PV systems. Fig. 1 shows how latitude variations affect the optimal PV tilt angle for the four methods analysed. Despite the different results obtained depending on the methodology applied, a common tendency is observed in which the optimal PV tilt angle has a direct correlation with latitude.

Climate zoning

Climate zoning is performed for several reasons, from providing guidelines for energy efficiency in buildings to performing Urban Heat Island analysis [55]. Regarding solar photovoltaic (PV) installations, the existence of climate zones can serve as a guide for the design of PV installations regarding the determination of both the best locations and the optimal tilt angle.

Climate maps are based on climatic parameters such as temperature, precipitation rate and solar irradiation. General climate maps are based on heating degree-days, temperature, and precipitation rate, while climate maps used for building sciences mainly use degree-days (heating and cooling) and moisture.

Regarding the computation of solar potential, the climate map required is based on the parameter of solar irradiation. In this case, the number of climate zones depends on the focus of the map: global irradiation or direct irradiation; and on the solar energy model used for the computation of the energy ratios. Thus, for example, global climate maps present Spain divided in two or three climate zones [56], while specific climate maps in the Iberian Peninsula classify the terrain in 5 or more zones [57] (Fig. 2).

Regarding solar energy models, their resolution also affects the map that can be generated. For example, comparing the two most common energy models, Pvgis [30] and PVWatts [31], the first tool is made by the European Commission and calculates solar irradiation from satellite

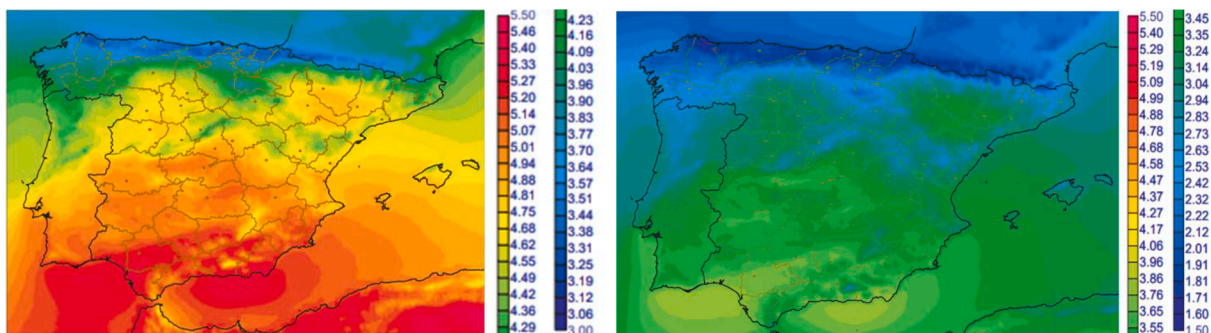


Fig. 2. Maps of solar climate zones in Spain: (a) annual global irradiation (kWh/m²day); (b) annual direct irradiation (kWh/m²day).

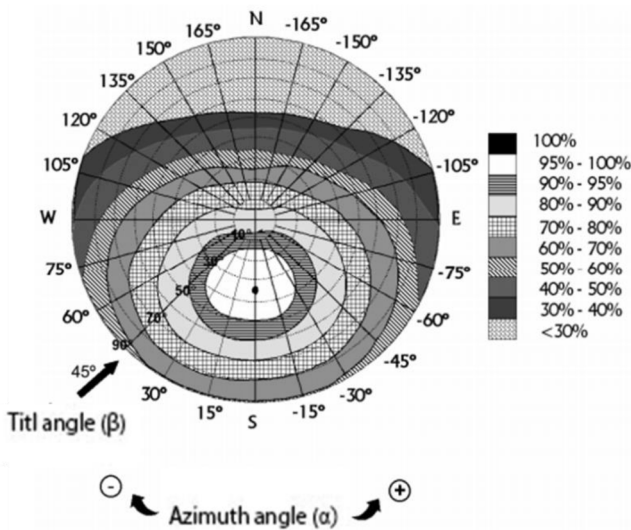


Fig. 4. PV production losses for a position 41° latitude.

data, climate reanalysis and historical data from 566 ground meteorological stations located in the European subcontinent [58]. However, PVWatts is developed by the USA National Renewable Energy Laboratory (NREL), and relies on a database covering the Americas, the Indian subcontinent and parts of Central Asia [59]. For this reason, when using PVWatts for studies in the European subcontinent, the irradiation value computed is the same for all the locations within a province.

Considerations

Solar trajectory

The maximum yield production of a PV system is obtained when the panel is facing the sunlight beams perpendicularly. During the day and along the year, the azimuth angle and the solar height vary periodically. The optimal tilt angle is not always the same neither through the year nor through the day. The longer the beams are perpendicular to the panel the better PV performance is achieved. Fig. 3 shows the different angles of the Sun trajectory over time for different times of the day and for different seasons for a latitude of 45° N. In order to receive the maximum irradiation, tracking systems could be used to adjust angle values through the day to optimize the panel position.

When the PV installation lacks a tracking system, optimal azimuth and tilt angles must be calculated for each location to compute the production with fixed PV panels. Regarding azimuth, South orientation is considered optimal for the North Hemisphere, and North orientation is the optimal for the South hemisphere. For both cases, the maximum energy production is obtained at the central time of the day.

In some cases, when the production is prioritized either at the beginning or the end of the day, the azimuth angle is variated to the East or to the West to maximize incoming radiation (and consequently, energy production) at the first or the last hours, respectively. The production curve is moved to the sunrise or sunset depending on the azimuth angle variation.

Maximum production losses due to PV orientation and tilt angle

In Spain, the Technical Edification Code (CTE) - HE section no. 5 [60] determines the methodology for the computation of production losses due to different PV spatial configurations. This methodology is based on the losses chart represented by Fig. 4, which is applicable for 41° latitude.

According to this regulation, South orientation (0°) is considered as reference and Eq. (5) is the mathematical statement for estimating the

Table 1

Maximum percentage of production losses allowed for photovoltaic panels in Spain according to the CTE [60].

TYPE OF SYSTEM	AZIMUTH AND TILT	SHADOWS	TOTAL
General	10%	10%	15%
Superposition	20%	15%	30%
Architectural Integration	40%	20%	50%

PV production losses.

$$PV \text{ production losses } (\%) = 100 \cdot [1.2 \cdot 10^{-4} \cdot (\beta - \beta_{opt})^2] \tag{5}$$

being β the tilt angle configured in degrees and β_{opt} the optimal tilt angle in degrees.

The CTE regulation in section no. 5 also establishes the maximum PV loss allowed (Table 1), that depends on the type of the PV system: general, superimposed or integrated. “Architectural integration” refers to the PV panels that have the double mission of being an architectural part of the building at the same time as an energy installation, substituting other construction elements such as cladding or envelope. “Superposition” refers to the PV panels that are placed parallel to the building envelope, not substituting the construction elements that form the envelope: for example, PV panels installed on the tiles of the roof. Last, “general” defines all PV installations that are neither integrated nor superposed, as can be PV panels supported by inclined structures.

Assuming the general case, the maximum percentage of PV production losses due to the PV azimuth and tilt angle with respect to the optimal production is 10%. This value has been considered as error threshold in this study for the Iberian Peninsula, because it is the most restrictive value.

Methodology

Analysis of optimal tilt for PV installations

The determination of the optimal tilt angle for PV installations in the Iberian Peninsula is performed through the computation of the optimal tilt angle for all the capital cities as representative locations of the provinces or districts, with a homogeneous spatial distribution. The computation of the energy production for each tilt angle, used to determine the tilt angle that results in the maximum production, is performed with PvGis [30]. The PV azimuth angle considered for all cases was 0° (South orientation).

The first step of the analysis was determining the optimal tilt angle of each location, according to the different methodologies under study. In addition to the optimal tilt angles defined with Eqs. (1)–(4) (also denoted as M1–M4), the optimal tilt angle (slope of the PV modules that gives the highest energy output for the whole year if the slope and azimuth angles stay fixed) provided by PvGis is considered as M6 (Eq. (7)) [58]. Since the average optimal tilt angle for all locations was 34°, this value was added to the analysis as fifth methodology, denoted as M5 (Eq. (6)). Thus:

$$M5: \beta_{opt} = 34^\circ \tag{6}$$

$$M6: \beta_{opt} = \beta_{opt-PVGIS} \tag{7}$$

Once all the methodologies involved were defined and the value of optimal tilt angle was calculated from each of them, the PV production for all locations (the capital cities) was computed.

The next analysis was to estimate the influence of the variation of the tilt angle in the PV energy production. With this aim, the PV production is estimated, for each location, for tilt angles from 0° to 90° with 5° steps.

The PV potential for all tilt angles was calculated with the proper query to the PvGis tool, as this tool is considered as reference in this study. These queries were performed through the PvGis Application

Table 2
Average monthly solar energy production for PVGIS optimal tilt angle per location.

Location	Latitude	Longitude	Optimal tilt angle (M6)	*Hm [kW·h/m ²]	Optimal tilt angle (M1)	Optimal tilt angle (M2)	Optimal tilt angle (M3)	Optimal tilt angle (M4)	Optimal tilt angle (M5)
Vitoria-Gasteiz	42.846	-2.668	35°	133	43°	33°	33°	40°	34°
Albacete	38.998	-1.860	34°	166	39°	29°	31°	38°	34°
Alicante	38.345	-0.481	35°	173	38°	28°	30°	37°	34°
Almería	36.840	-2.468	33°	188	37°	27°	29°	36°	34°
Ávila	40.656	-4.700	34°	158	41°	31°	32°	39°	34°
Badajoz	38.879	-6.970	33°	173	39°	29°	31°	37°	34°
Barcelona	41.388	2.170	38°	172	41°	31°	32°	39°	34°
Burgos	42.341	-3.700	33°	146	42°	32°	33°	40°	34°
Cáceres	39.476	-6.371	33°	171	39°	29°	31°	38°	34°
Cádiz	36.530	-6.293	32°	181	37°	27°	29°	36°	34°
Castellón de la Plana	39.986	-0.038	36°	171	40°	30°	31°	38°	34°
Ciudad Real	38.986	-3.927	33°	169	39°	29°	31°	38°	34°
Córdoba	37.885	-4.779	33°	174	38°	28°	30°	37°	34°
Coruña (A)	43.371	-8.396	34°	127	43°	33°	34°	41°	34°
Cuenca	40.072	-2.134	34°	161	40°	30°	31°	38°	34°
Girona	41.982	2.824	38°	160	42°	32°	33°	40°	34°
Granada	37.176	-3.598	33°	180	37°	27°	29°	36°	34°
Guadalajara	40.630	-3.166	35°	164	41°	31°	32°	39°	34°
Donostia-San Sebastián	43.321	-1.984	36°	126	43°	33°	34°	40°	34°
Huelva	37.257	-6.950	33°	188	37°	27°	29°	36°	34°
Huesca	42.140	-0.409	37°	167	42°	32°	33°	40°	34°
Jaén	37.766	-3.790	32°	174	38°	28°	30°	37°	34°
León	42.600	-5.572	36°	163	43°	33°	33°	40°	34°
Lleida	41.614	0.626	36°	165	42°	32°	32°	39°	34°
Logroño	42.466	-2.450	35°	143	42°	32°	33°	40°	34°
Lugo	43.012	-7.556	34°	137	43°	33°	33°	40°	34°
Madrid	40.417	-3.700	35°	170	40°	30°	32°	38°	34°
Málaga	36.720	-4.420	33°	181	37°	27°	29°	36°	34°
Murcia	37.983	-1.130	34°	173	38°	28°	30°	37°	34°
Pamplona	42.817	-1.647	35°	142	43°	33°	33°	40°	34°
Ourense	42.340	-7.865	34°	151	42°	32°	33°	40°	34°
Oviedo	43.360	-5.845	38°	135	43°	33°	34°	41°	34°
Palencia	42.012	-4.531	34°	157	42°	32°	33°	40°	34°
Pontevedra	42.434	-8.648	35°	152	42°	32°	33°	40°	34°
Salamanca	40.965	-5.663	33°	160	41°	31°	32°	39°	34°
Santander	43.461	-3.808	36°	126	43°	33°	34°	41°	34°
Segovia	40.949	-4.119	33°	153	41°	31°	32°	39°	34°
Sevilla	37.383	-5.996	32°	178	37°	27°	29°	36°	34°
Soria	41.764	-2.465	36°	160	42°	32°	33°	39°	34°
Tarragona	41.119	1.245	37°	171	41°	31°	32°	39°	34°
Teruel	40.344	-1.107	35°	159	40°	30°	32°	38°	34°
Toledo	39.857	-4.024	35°	169	40°	30°	31°	38°	34°
Valencia	39.470	-0.377	36°	172	39°	29°	31°	38°	34°
Valladolid	41.653	-4.728	33°	157	42°	32°	32°	39°	34°
Bilbao	43.257	-2.923	35°	124	43°	33°	34°	40°	34°
Zamora	41.504	-5.744	34°	161	42°	32°	32°	39°	34°
Zaragoza	41.656	-0.877	36°	164	42°	32°	32°	39°	34°
Lisboa	38.722	-9.139	32°	165	39°	29°	30°	37°	34°
Leiria	39.750	-8.808	34°	163	40°	30°	31°	38°	34°
Santarém	39.236	-8.685	33°	170	39°	29°	31°	38°	34°
Setúbal	38.525	-8.894	34°	182	39°	29°	30°	37°	34°
Beja	38.015	-7.863	33°	177	38°	28°	30°	37°	34°
Faro	37.019	-7.930	33°	193	37°	27°	29°	36°	34°
Évora	38.571	-7.914	33°	175	39°	29°	30°	37°	34°
Portalegre	39.297	-7.428	33°	169	39°	29°	31°	38°	34°
Castelo Branco	39.823	-7.497	33°	172	40°	30°	31°	38°	34°
Guarda	40.539	-7.265	33°	165	41°	31°	32°	39°	34°
Coimbra	40.203	-8.410	34°	160	40°	30°	31°	38°	34°
Aveiro	40.641	-8.654	35°	164	41°	31°	32°	39°	34°
Viseu	40.657	-7.912	34°	163	41°	31°	32°	39°	34°
Bragança	41.806	-6.757	34°	163	42°	32°	33°	39°	34°
Vila Real	41.301	-7.742	33°	158	41°	31°	32°	39°	34°
Porto	41.158	-8.629	35°	159	41°	31°	32°	39°	34°
Braga	41.545	-8.427	35°	155	42°	32°	32°	39°	34°
Viana do Castelo	41.692	-8.834	35°	158	42°	32°	32°	39°	34°

*Hm: Average monthly sum of global irradiation per square meter [kW·h/m²].

Table 3
Annual production losses for all locations respect to variations in tilt angle.

Location	Tilt Angle																			
	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°	
Albacete	13%	10%	7%	4%	2%	1%	1%	0%	1%	2%	4%	5%	8%	11%	16%	20%	25%	30%	36%	
Alicante	14%	10%	7%	5%	3%	1%	1%	0%	1%	2%	3%	5%	8%	12%	16%	20%	25%	30%	36%	
Almería	13%	10%	7%	4%	3%	1%	1%	0%	1%	2%	4%	6%	9%	12%	16%	21%	26%	31%	37%	
Aveiro	14%	10%	7%	5%	3%	1%	1%	0%	1%	1%	3%	5%	8%	11%	15%	19%	24%	29%	34%	
Ávila	13%	9%	6%	4%	3%	1%	0%	0%	1%	1%	3%	5%	8%	11%	15%	19%	24%	29%	35%	
Badajoz	12%	9%	6%	3%	2%	1%	0%	0%	1%	2%	3%	6%	9%	12%	16%	21%	25%	31%	37%	
Barcelona	16%	12%	9%	6%	3%	2%	1%	0%	1%	2%	3%	6%	9%	9%	13%	17%	22%	27%	32%	
Beja	12%	9%	6%	4%	2%	1%	0%	0%	1%	2%	4%	6%	9%	12%	16%	21%	25%	31%	37%	
Bilbao	13%	10%	6%	4%	2%	1%	0%	0%	0%	1%	2%	4%	6%	10%	13%	17%	22%	26%	32%	
Braga	14%	10%	7%	5%	3%	1%	0%	0%	0%	1%	3%	5%	7%	10%	14%	18%	23%	28%	34%	
Bragança	13%	10%	7%	5%	2%	1%	1%	0%	1%	1%	3%	5%	8%	11%	15%	19%	24%	29%	34%	
Burgos	12%	8%	5%	3%	2%	1%	0%	0%	1%	1%	3%	5%	8%	12%	15%	19%	24%	29%	35%	
Cáceres	13%	9%	6%	4%	2%	1%	1%	0%	1%	2%	4%	6%	9%	12%	16%	20%	25%	30%	36%	
Cádiz	12%	9%	6%	3%	2%	1%	0%	0%	1%	2%	4%	6%	9%	13%	17%	22%	27%	32%	38%	
Castellón de la Plana	15%	11%	8%	5%	3%	1%	1%	0%	0%	1%	2%	4%	7%	10%	14%	18%	23%	28%	33%	
Castelo Branco	13%	9%	6%	4%	2%	1%	0%	0%	0%	1%	3%	5%	8%	12%	16%	20%	25%	30%	36%	
Ciudad Real	12%	9%	7%	4%	2%	1%	0%	0%	1%	2%	4%	6%	9%	12%	16%	21%	25%	31%	36%	
Coimbra	13%	9%	7%	4%	3%	1%	0%	0%	0%	1%	3%	5%	8%	11%	15%	19%	24%	29%	34%	
Córdoba	12%	9%	6%	4%	2%	1%	0%	0%	1%	2%	3%	6%	9%	13%	16%	21%	26%	31%	37%	
Coruña (A)	11%	8%	6%	3%	2%	1%	0%	0%	0%	1%	2%	5%	7%	10%	13%	17%	22%	27%	32%	
Cuenca	14%	10%	7%	5%	2%	1%	1%	1%	1%	2%	3%	6%	8%	11%	15%	19%	24%	29%	35%	
Donostia-San Sebastián	13%	10%	7%	5%	3%	2%	1%	0%	1%	2%	2%	5%	7%	10%	13%	17%	21%	26%	31%	
Évora	13%	9%	6%	4%	2%	1%	0%	0%	1%	2%	3%	6%	9%	12%	16%	21%	25%	31%	36%	
Faro	13%	10%	7%	4%	3%	1%	1%	0%	1%	2%	4%	6%	9%	12%	17%	21%	26%	32%	37%	
Girona	16%	13%	9%	6%	4%	2%	1%	0%	0%	1%	2%	4%	6%	9%	13%	16%	21%	26%	31%	
Granada	13%	9%	6%	4%	2%	1%	0%	0%	1%	2%	4%	6%	9%	12%	17%	21%	26%	31%	37%	
Guadalajara	13%	10%	7%	5%	2%	1%	1%	0%	1%	1%	3%	5%	8%	11%	15%	19%	24%	29%	34%	
Guarda	13%	10%	7%	4%	2%	1%	0%	0%	1%	2%	4%	5%	8%	12%	16%	20%	25%	30%	36%	
Huelva	13%	10%	7%	4%	2%	1%	1%	0%	1%	2%	4%	6%	9%	12%	16%	21%	26%	31%	37%	
Huesca	16%	11%	8%	5%	4%	2%	1%	0%	0%	1%	2%	4%	7%	10%	13%	17%	22%	27%	32%	
Jaén	12%	9%	6%	3%	2%	1%	0%	0%	1%	2%	3%	6%	9%	12%	16%	21%	25%	31%	37%	
Leiria	13%	9%	7%	4%	2%	1%	0%	0%	0%	1%	3%	5%	8%	11%	15%	19%	24%	29%	34%	
León	15%	11%	8%	6%	3%	2%	1%	0%	1%	1%	2%	5%	7%	10%	14%	18%	23%	28%	34%	
Lisboa	12%	8%	5%	3%	2%	1%	0%	0%	1%	2%	4%	5%	8%	12%	16%	21%	25%	31%	36%	
Lleida	15%	11%	8%	5%	3%	1%	1%	0%	0%	1%	2%	4%	7%	10%	14%	18%	22%	28%	33%	
Lugo	13%	9%	6%	4%	2%	1%	0%	0%	0%	1%	3%	4%	7%	10%	14%	18%	22%	27%	33%	
Lugo	12%	9%	7%	4%	3%	1%	1%	1%	1%	2%	4%	6%	8%	12%	15%	19%	24%	29%	34%	
Madrid	14%	11%	7%	5%	3%	1%	0%	0%	1%	1%	3%	5%	8%	11%	15%	19%	24%	29%	35%	
Málaga	13%	9%	7%	4%	2%	1%	0%	0%	1%	2%	4%	6%	9%	13%	17%	21%	26%	31%	38%	
Murcia	13%	10%	7%	4%	2%	1%	0%	0%	1%	2%	3%	6%	8%	12%	16%	20%	25%	30%	36%	
Ourense	13%	9%	7%	4%	2%	1%	0%	0%	0%	1%	3%	5%	7%	11%	15%	19%	23%	28%	34%	
Oviedo	15%	11%	8%	5%	3%	1%	1%	0%	0%	1%	1%	4%	6%	8%	12%	16%	20%	24%	30%	
Palencia	13%	10%	7%	4%	3%	1%	0%	0%	1%	1%	3%	5%	8%	11%	15%	19%	24%	29%	34%	
Pamplona	13%	9%	6%	4%	2%	1%	0%	0%	0%	1%	3%	4%	7%	11%	14%	18%	23%	27%	33%	
Pontevedra	14%	10%	7%	5%	3%	1%	1%	0%	0%	1%	3%	5%	7%	11%	14%	18%	23%	28%	34%	
Portalegre	12%	9%	6%	4%	2%	1%	0%	0%	1%	1%	3%	5%	8%	12%	16%	20%	25%	30%	36%	
Porto	13%	10%	7%	4%	3%	1%	0%	0%	0%	1%	3%	4%	8%	11%	14%	19%	23%	28%	34%	
Salamanca	13%	9%	6%	4%	2%	1%	0%	0%	1%	1%	3%	6%	8%	11%	16%	19%	24%	29%	35%	
Santander	13%	10%	7%	5%	3%	2%	1%	0%	0%	1%	2%	4%	7%	10%	13%	17%	21%	26%	31%	
Santarém	12%	9%	6%	4%	2%	1%	0%	0%	1%	2%	4%	5%	8%	12%	16%	20%	25%	31%	36%	
Segovia	12%	9%	6%	4%	2%	1%	0%	0%	1%	1%	3%	5%	8%	12%	16%	20%	24%	29%	35%	
Setúbal	13%	9%	7%	4%	2%	1%	0%	0%	0%	1%	3%	5%	8%	12%	15%	20%	25%	30%	36%	
Sevilla	12%	9%	6%	4%	2%	1%	0%	0%	1%	2%	4%	6%	9%	12%	16%	21%	26%	31%	37%	
Soria	14%	11%	8%	5%	3%	1%	1%	0%	0%	1%	3%	4%	7%	10%	14%	18%	23%	28%	33%	
Tarragona	16%	12%	8%	5%	3%	2%	1%	0%	0%	1%	2%	4%	6%	9%	13%	17%	22%	27%	32%	
Teruel	14%	10%	8%	5%	3%	1%	1%	1%	1%	2%	3%	5%	8%	11%	14%	19%	24%	29%	34%	
Toledo	14%	10%	7%	4%	2%	1%	0%	0%	0%	1%	3%	5%	8%	11%	15%	19%	24%	30%	35%	
Valencia	14%	10%	8%	5%	2%	1%	0%	0%	0%	1%	2%	4%	7%	10%	14%	18%	23%	28%	34%	
Valladolid	13%	10%	6%	4%	3%	1%	0%	0%	1%	2%	3%	6%	8%	11%	15%	20%	24%	29%	35%	
Viana do Castelo	14%	10%	7%	4%	3%	1%	0%	0%	0%	1%	3%	4%	8%	11%	14%	18%	23%	28%	34%	
Vila Real	12%	9%	6%	4%	2%	1%	0%	0%	0%	1%	3%	5%	8%	11%	15%	20%	25%	30%	35%	
Viseu	13%	10%	7%	4%	2%	1%	0%	0%	1%	1%	3%	5%	8%	11%	15%	19%	24%	29%	34%	
Vitoria-Gasteiz	12%	9%	6%	4%	2%	1%	0%	0%	0%	2%	2%	5%	8%	11%	14%	18%	23%	28%	33%	
Zamora	12%	9%	6%	4%	2%	1%	0%	0%	1%	1%	3%	6%	8%	11%	16%	19%	24%	30%	35%	
Zaragoza	15%	11%	7%	5%	3%	1%	0%	0%	0%	1%	2%	4%	7%	10%	13%	18%	23%	27%	33%	

Program Interface (API). This API request uses as input data the location and azimuth and tilt angles desired. The web-based tool outputs the PV energy production (monthly data output, denoted as Hm) applying the solar model implemented in PvGIS [30]. The results, in comma-separated values (CSV) format, were collected in a macro programmed in Visual Basic for Applications (VBA) to be sorted in a spreadsheet. The

analysis and mapping of the result plots were performed within the framework of this spreadsheet.

Computation of total solar radiation

From the monthly PV potential computed for the optimal tilt angle

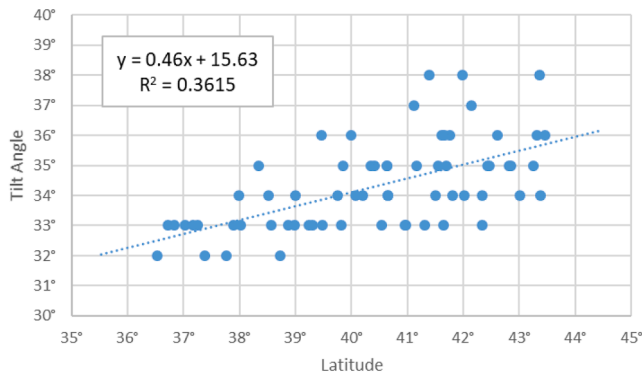


Fig. 5. Relationship between the latitude and the optimal PV tilt angle.

(M6) and South orientation, the Equivalent Sun Hours (ESH) are estimated, per representative location in the Iberian Peninsula. The location of reference for each administrative area is the capital city. That is, one request is made per capital city, regarding the monthly PV potential, and the values from the most favorable and least favorable months are considered for the classification of each area in the corresponding solar climate zone.

Results

With all the data computed, the optimal PV tilt angle was sorted for each location as well as its annual production that will be considered as reference value for further studies. Table 2 shows the production results for all locations under study, considering a PV installation with South orientation (0°) and the optimal tilt angle calculated by PvGIS (M6). The optimal tilt angles according to methodologies M1 to M5, are also shown in the table.

Latitude vs optimal tilt angle

Fig. 5 shows the optimal PV tilt angle value for all the locations under study obtained with PvGIS. Despite the existence of different tilt values for the same latitude, the tendency line shows that the more the latitude, the higher the tilt angle. The trend line equation has been calculated as Eq. (8):

$$\beta = 0.462 \cdot \phi + 15.639 \tag{8}$$

where β is the tilt angle and ϕ is the latitude, both in degrees.

The discrepancy observed between similar latitudes that present different values of optimal tilt angle could be caused by the fact that PvGIS considers more parameters to obtain the optimal tilt angle than the other methods, such as historical cloudy index and terrain shadows. This shows that, although the latitude is the most influential parameter regarding optimal tilt angle, the other parameters considered also play a role in its definition.

Determination of solar climate zones

As a result of the maximum and minimum solar radiation received monthly in each location of the Iberian Peninsula, the territory can be divided in six solar climate zones, according to the classification established in the Spanish CTE:

- Zone 1: from 1186.8 to 1319.0 kJ/m²
- Zone 2: from 1319.0 to 1451.3 kJ/m²
- Zone 3: from 1451.3 to 1583.5 kJ/m²
- Zone 4: from 1583.5 to 1715.8 kJ/m²
- Zone 5: from 1715.8 to 1848.0 kJ/m²
- Zone 6: minimum potential higher than 1848.0 kJ/m²

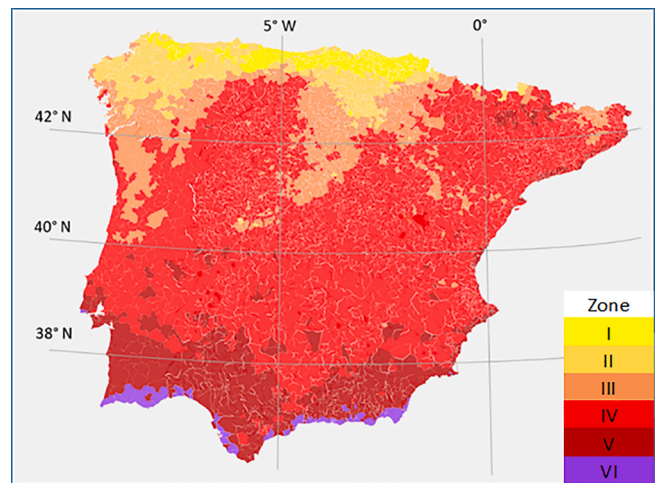


Fig. 6. Map of solar climate zones of the Iberian Peninsula.

According to these values and using the solar radiation values computed per location with PvGIS tool, a new proposal of map of solar climate zones of the Iberian Peninsula can be made, Fig. 6.

Discussion

Optimal tilt angle in the Iberian Peninsula

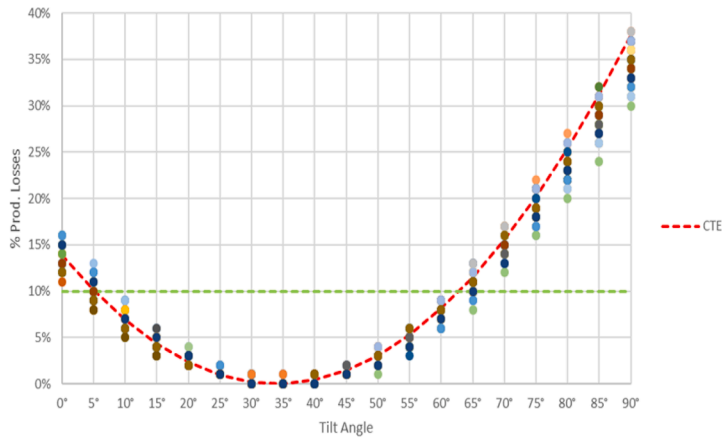
Figure shows the annual energy production losses for different tilt angles ranging from 0° to 90° with 5° steps, for all locations listed in Table 2. Results were compared to the curve of the CTE equation (Eq. (5)), considering 34° as optimal PV tilt angle and 0° as optimal azimuth angle.

Considering as threshold value the 10% (Fig. 7 – green dashed line) of maximum losses allowed in the “General case” of the CTE [60], the PV tilt angle can range between 10° and 60° in the Iberian Peninsula.

In the same way and taking into account that the optimal tilt angle varies if the maximum production is aimed for the whole year or only seasonally (maximum energy production in winter, or maximum energy production in summer). Fig. 8 shows the curves for the annual and seasonal losses for different tilt angles. The average PV production loss per city and that obtained from the CTE equation were represented, considering as optimal PV tilt angles 34° for maximizing production over a year. Winter seasonal production implies an increase in the optimal tilt angle of 21° (55°) and for the summer, the seasonal production tilt angle is decreased 14° (20°).

As a result of this comparison, it was observed that the CTE methodology (defined in Eq. (5)) results in a parabolic curve almost identical to the curve resulting from the mean of the values of energy production losses computed specifically from data of the cities; that is, considering 34° as the optimal tilt angle for annual production in the Iberian Peninsula.

Winter and summer seasonal optimal tilt angles have been obtained with the data extracted from the tilt analysis from 0° to 90° with 5° steps, considering as summer months: April, May, June, July, August and September, and as winter months: January, February, March, October, November and December. Thus, the optimal tilt angle is the average optimal tilt angle for all locations (maximum irradiation). If a maximum loss of 10% is allowed, the optimal tilt angle range is from 10° to 60° considering annual production; from 0° to 45° in summer; and from 30° to 80° in winter. Fig. 9 shows the optimal tilt angles computed for different locations, as representatives for the rest of the Iberian Peninsula.



- Albacete
- Alicante
- Almería
- Aveiro
- Ávila
- Badajoz
- Barcelona
- Beja
- Bilbao
- Braga
- Bragança
- Burgos
- Cáceres
- Cádiz
- Castellón de la Plana
- Castelo Branco
- Ciudad Real
- Coimbra
- Córdoba
- Coruña (A)
- Cuenca
- Donostia-San Sebastián
- Évora
- Faro
- Girona
- Granada
- Guadalajara
- Guarda
- Huelva
- Huesca
- Jaén
- Leiria
- León
- Lisboa
- Lleida
- Logroño
- Lugo
- Madrid
- Málaga
- Murcia
- Ourense
- Oviedo
- Palencia
- Pamplona
- Pontevedra
- Portalegre
- Porto
- Salamanca
- Santander
- Santarém
- Segovia
- Setúbal
- Sevilla
- Soria
- Tarragona
- Teruel
- Toledo
- Valencia
- Valladolid
- Viana do Castelo
- Vila Real
- Viseu
- Vitoria-Gasteiz
- Zamora
- Zaragoza

Fig. 7. Annual production losses with respect to variations in tilt angle. Although they cannot be seen, all tilt angles have been tested for all locations. In the following Table 3 all values are shown.

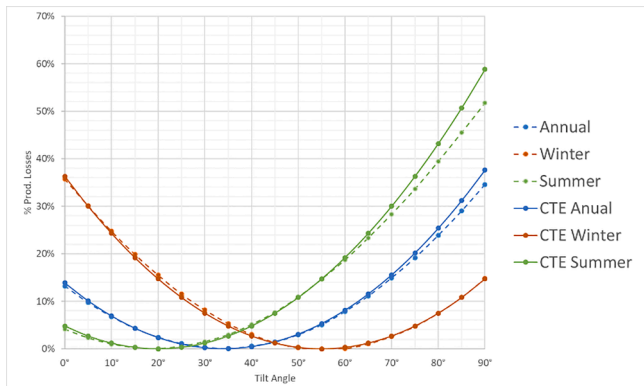


Fig. 8. Comparison of annual and seasonal production losses per tilt angle according to the computation of the PvGIS tool (dashed line) and the CTE Eq. (5) (continuous line).

Comparison of methodologies to estimate the optimal annual tilt angle

Comparing the production values obtained for each methodology and the production losses caused by the tilt angle with respect to the optimal production (Table 2), Fig. 9 shows the production losses for all locations in the Iberian Peninsula. Separated maps have been generated in order to classify which methodology is more accurate.

a) Fixed Optimal Tilt Angle (M5: $\beta = 34^\circ$)

Fig. 10(a) shows the energy losses with respect to the maximum annual performance for a fixed PV system with tilt angle (β) equal to the average of the optimal tilt angles calculated (34°). It is observed that the

Vitoria - Winter		Zaragoza - Summer	
Tilt	0° - Orien.	Tilt	0° - Orien.
0°	65.98	0°	197.50
5°	71.30	5°	202.00
10°	76.28	10°	205.00
15°	80.88	15°	207.00
20°	85.23	20°	208.17
25°	89.02	25°	207.50
30°	92.20	30°	205.67
35°	94.92	35°	203.00
40°	96.98	40°	199.33
45°	98.58	45°	194.33
50°	99.53	50°	188.17
55°	99.95	55°	180.67
60°	99.55	60°	172.50
65°	98.78	65°	163.17
70°	97.32	70°	153.00
75°	95.35	75°	141.83
80°	92.70	80°	129.83
85°	89.40	85°	117.33
90°	85.75	90°	104.32

Fig. 9. Seasonal solar radiation values for different tilt angles.

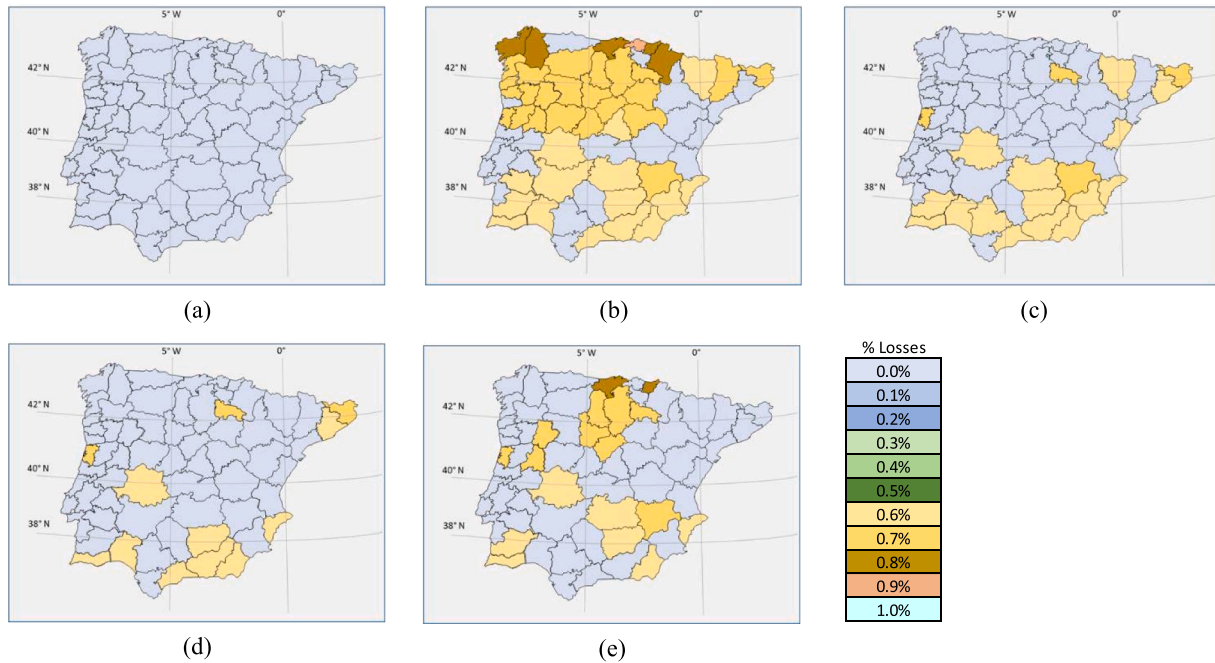


Fig. 10. Energy losses with respect to the reference production (M6), as computed with: (a) M5; (b) M1; (c) M2; (d) M3; (e) M4.

performance is almost 100% (0% losses) for all the locations of the Iberian Peninsula.

b) M1 (tilt angle $\beta = |\phi|$)

Fig. 10(b) shows the energy losses with respect to the maximum annual performance for a fixed PV system with tilt angle (β) equal to latitude (ϕ). It can be seen that the maximum losses are located in the north of Iberian Peninsula, reaching its maximum at 0.9% for the city of Bilbao.

c) M2 (tilt angle $\beta = |\phi| - 10$)

Fig. 10 (c) shows the energy losses regarding the maximum annual performance for a fixed PV system with tilt angle (β) equal to latitude ($\phi - 10$). It can be appreciated that the losses are lower than in M1, especially in the North locations, being the maximum loss value 0.7% for the cities of Girona, Logroño, Aveiro and Albacete.

d) M3 (tilt angle $\beta = 3.7 + 0.69 \cdot |\phi|$)

Fig. 10(d) presents the energy losses in reference to the maximum annual performance for a fixed PV system with tilt angle calculated as a result of methodology 3. The losses are a bit lower than in the methodology 2, being the maximum value 0.7% for the cities of Girona, Logroño and Aveiro.

e) M4 (tilt angle $\beta = 3.7 + 0.69 \cdot (|\phi| - 10)$)

Fig. 10(e) shows the energy losses with respect to the maximum annual performance for a fixed PV system with tilt angle calculated as a result of methodology 4. It can be appreciated that the losses are higher than in methodology 3, especially in the Northern locations, and similar to the results of methodology 2, being the maximum loss value 0.8% for the cities of Santander and San Sebastián.

Once the different expressions to calculate the optimal tilt angle are compared, the results show that the estimated annual production does not present great variations for each methodology, since the maximum production losses are always below 1% (the highest loss is 0.9% in M1),

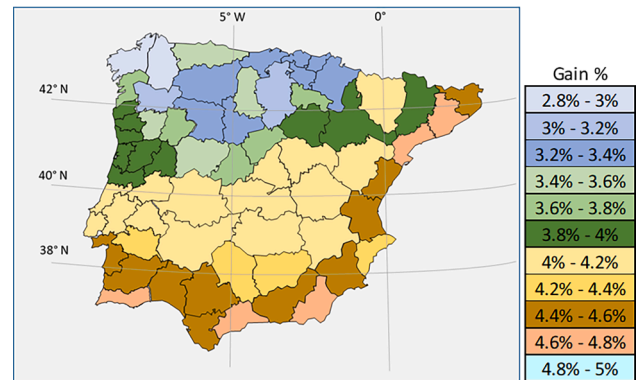


Fig. 11. Energy gain obtained with installations with two tilt angles (winter/summer) with respect to the annual reference production.

being the best methodology M5 ($\beta = 34^\circ$), followed by M3 ($\beta = 3.7 + 0.69 \cdot |\phi|$).

Comparison of production for seasonal optimal tilt angles with the production for annual optimal tilt angle

Considering the seasonal optimal tilt angles for winter (55°) and summer (20°) as mentioned in section above, the following Fig. 11 shows the energy gain for a two angles configuration PV system with respect to a fixed PV system with the same annual angle (34°).

The mean gains in energy production are 4%, with a clear division in the northeast-southwest direction.

Comparison of updated climate zones with the standard

Solar production values (H_m) computed per city with PvGIS have been used to calculate the mean monthly production (E_m) and the annual and seasonal (winter and summer) reference equivalent hours (Figs. 12–14, respectively). Reference equivalent hours are used to classify each province/district in 5 groups, the same number as in the CTE [60], with equitable production ranges, so that the difference

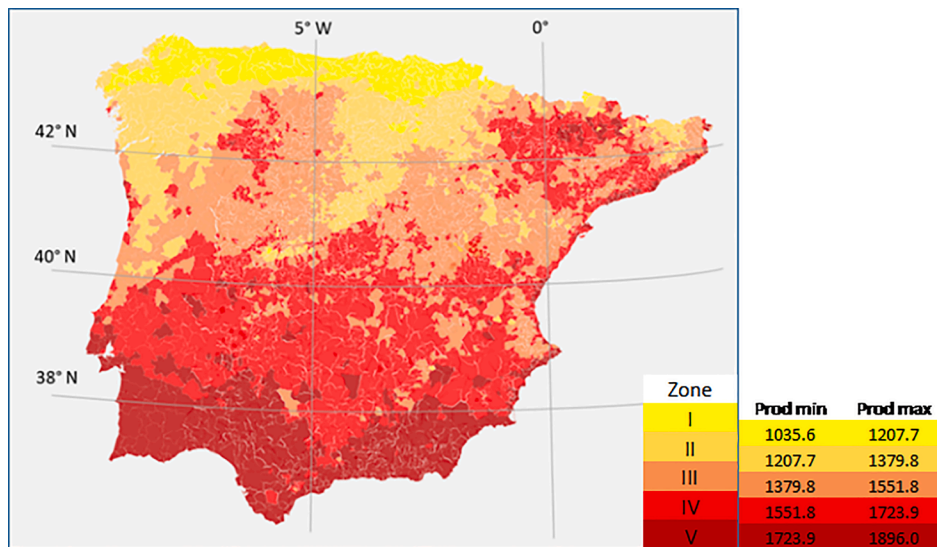


Fig. 12. Update climate zones in the Iberian Peninsula according to the annual solar energy production.

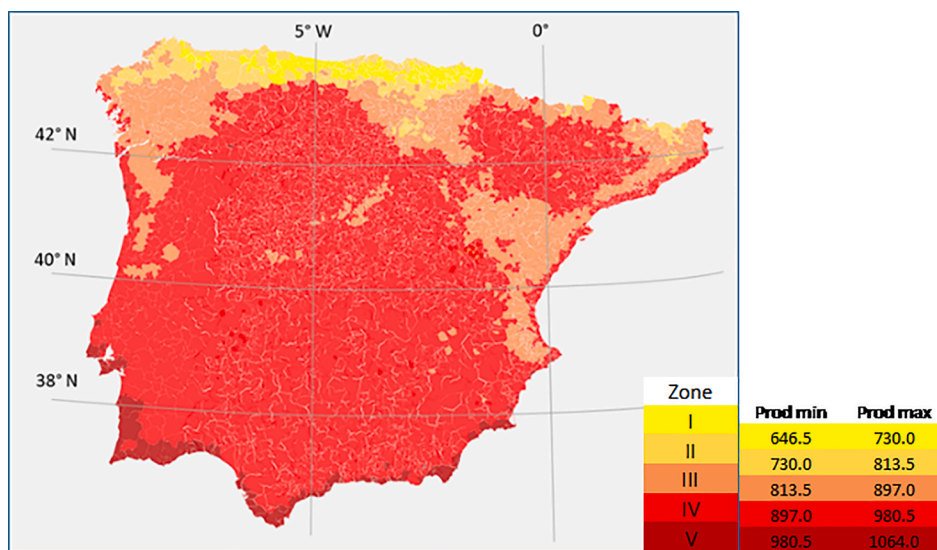


Fig. 13. Update climate zones in the Iberian Peninsula according to the seasonal (summer) solar energy production.

between maximum and minimum production values is equal for all groups.

Conclusions

After analysing the results, it can be concluded that for the Iberian Peninsula the optimal PV tilt angle can be established in 34° when maximizing the annual production is the target, since this is the tilt angle with lowest losses in the annual analysis. PV systems have annual production losses of less than 0.1% regarding that obtained for each optimal tilt angle. Considering that the Spanish national regulations for buildings set the maximum production loss due to tilt and azimuth angles allowed of 10%, the range for a yearly fixed tilt angle could be from 10° up to 60° in the Iberian Peninsula. However, when maximizing the seasonal PV production, the optimal tilt angles are 20° for summertime and 55° for wintertime, -14° and +21° regarding the optimal annual tilt angle, respectively, being both values within the range established by the CTE.

Comparing the different approaches existing in literature to calculate the optimal tilt angle, differences lower than 1% were obtained between

them. Thus, although the tilt angle is a key parameter that influences the PV energy production, its variation must be significant in order to have an impact on production losses.

When the PV systems are installed coplanar to the roof surfaces, tilt and orientation angles are not usually optimal. In these cases, the economic feasibility of the support installation depends on both the production losses and the support system installation costs. In this line, PV systems with not tilt angle fixed supports could be analysed, in order to modify this angle through the year, increasing the energy production from 2.8% up to 4.8% (two seasonal tilt angles configuration).

Finally, future works will deal with (i) the performance of an analysis of the azimuth angle similar to the present study about the tilt angle, (ii) the combination of the results of this study with those in [18] will make possible the classification of all the roofs of a city by their PV performance, and (iii) the energy gain considering four different seasonal tilt angles (Winter, Spring, Summer, Autumn).

CRedit authorship contribution statement

E. González-González: Formal analysis, Methodology, Writing –

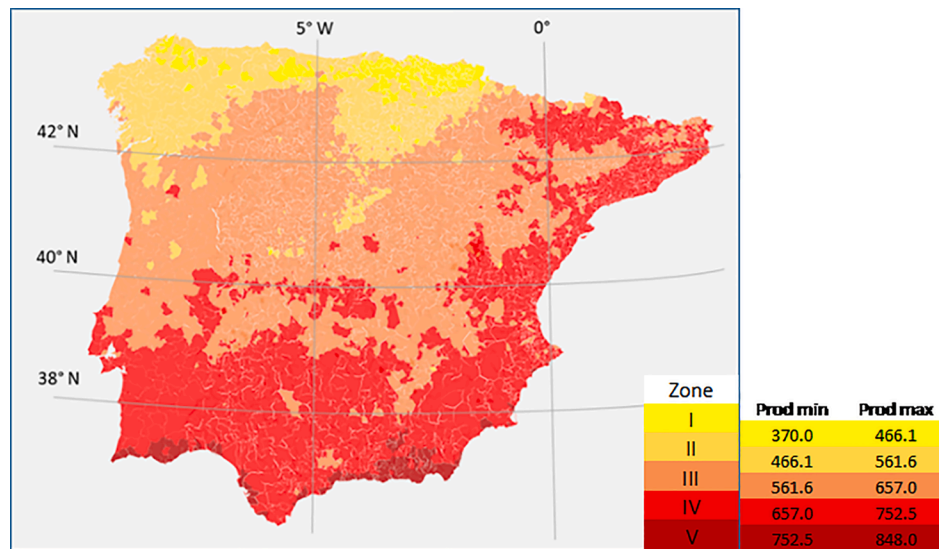


Fig. 14. Update climate zones in the Iberian Peninsula according to the seasonal (winter) solar energy production.

original draft. **J. Martín-Jiménez:** Data curation, Software. **M. Sánchez-Aparicio:** Resources, Validation. **S. Del Pozo:** Investigation. **S. Lagüela:** Conceptualization, Funding acquisition, Project administration, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors would like to thank Iberdrola S.L. and University of Salamanca for the funding provided through Cátedra Iberdrola VIII Centenary. We also express our gratitude to the Ministry of Science, Innovation and Universities for the funding given for the project RTC-2017-6291-3. Authors also want to thank to the Ministry of Education and the European Social Fund for the financial support given for pre-doctoral research staff (EDU/601/2020).

Funding

This work was supported by the Ministry of Science, Innovation and Universities of Spain [project RTC-2017-6291-3]; the Ministry of Education [EDU/601/2020]; and Cátedra Iberdrola-USAL VIII Centenary.

References

- Boemi S-N, Papadopoulos AM. Monitoring energy poverty in Northern Greece: the energy poverty phenomenon. *Int J Sustainable Energy* 2019;38(1):74–88.
- González-Eguino M. Energy poverty: an overview. *Renewable Sustainable Energy Rev* 2015;47:377–85.
- Mashhoodi B, Stead D, van Timmeren A. Spatial homogeneity and heterogeneity of energy poverty: a neglected dimension. *Ann Gis* 2019;25(1):19–31.
- Aristondo O, Onaindia E. Counting energy poverty in Spain between 2004 and 2015. *Energy Policy* 2018;113:420–9.
- Day R, Walker G, Simcock N. Conceptualising energy use and energy poverty using a capabilities framework. *Energy Policy* 2016;93:255–64.
- Okushima S. Gauging energy poverty: a multidimensional approach. *Energy* 2017; 137:1159–66.
- Jackson RB, Le Quéré C, Andrew RM, Canadell JG, Korsbakken JI, Liu Z, et al. Global energy growth is outpacing decarbonization. *Environ Res Lett* 2018;13(12): 120401. <https://doi.org/10.1088/1748-9326/aaf303>.
- Lee J, Shepley MM. Benefits of solar photovoltaic systems for low-income families in social housing in Korea: renewable energy applications as solutions to energy poverty. *J Build Eng* 2020;28:101016.
- Wang Z, Zhu Y. Do energy technology innovations contribute to CO2 emissions abatement? A spatial perspective. *Sci Total Environ* 2020;726:138574. <https://doi.org/10.1016/j.scitotenv.2020.138574>.
- Chu C-T, Hawkes AD. A Geographic Information System-based global variable renewable potential assessment using spatially resolved simulation. *Energy* 2020; 193:116630. <https://doi.org/10.1016/j.energy.2019.116630>.
- Laha P, Chakraborty B, Østergaard PA. Electricity system scenario development of India with import independence in 2030. *Renewable Energy* 2020;151:627–39.
- Huang P, Lovati M, Zhang X, Bales C, Hallbeck S, Becker A, et al. Transforming a residential building cluster into electricity prosumers in Sweden: optimal design of a coupled PV-heat pump-thermal storage-electric vehicle system. *Appl Energy* 2019;255:113864. <https://doi.org/10.1016/j.apenergy.2019.113864>.
- Mills AD, Levin T, Wiser R, Seel J, Botterud A. Impacts of variable renewable energy on wholesale markets and generating assets in the United States: a review of expectations and evidence. *Renewable Sustainable Energy Rev* 2020;120:109670. <https://doi.org/10.1016/j.rser.2019.109670>.
- Müsgens F. Equilibrium prices and investment in electricity systems with CO2-emission trading and high shares of renewable energies. *Energy Econ* 2020;86: 104107. <https://doi.org/10.1016/j.eneco.2018.07.028>.
- Prieto-Prado I, Del Río-Gamero B, Gómez-Gotor A, Pérez-Báez SO. Water and energy self-supply in isolated areas through renewable energies using hydrogen and water as a double storage system. *Desalination* 2018;430:1–14.
- Sokolnikova P, Lombardi P, Arendarski B, Suslov K, Pantaleo AM, Kranhold M, et al. Net-zero multi-energy systems for Siberian rural communities: a methodology to size thermal and electric storage units. *Renewable Energy* 2020;155:979–89.
- Huang J, Li W, Guo L, Hu Xi, Hall JW. Renewable energy and household economy in rural China. *Renewable Energy* 2020;155:669–76.
- Martín-Jiménez J, Del Pozo S, Sánchez-Aparicio M, Lagüela S. Multi-scale roof characterization from LiDAR data and aerial orthoimagery: automatic computation of building photovoltaic capacity. *Autom Constr* 2020;109:102965. <https://doi.org/10.1016/j.autcon.2019.102965>.
- Bódis K, Kougiás I, Jäger-Waldau A, Taylor N, Szabó S. A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union. *Renewable Sustainable Energy Rev* 2019;114:109309. <https://doi.org/10.1016/j.rser.2019.109309>.
- Fina B, Auer H, Friedl W. Cost-optimal economic potential of shared rooftop PV in energy communities: evidence from Austria. *Renewable Energy* 2020;152:217–28.
- Jäger-Waldau A, et al. Self-consumption of electricity produced with photovoltaic systems in apartment buildings - Update of the situation in various IEA PVPS countries. In: 2020 47th IEEE Photovoltaic Specialists Conference (PVSC); 2020. p. 0938–50. <https://doi.org/10.1109/PVSC45281.2020.9300442>.
- Ministerio para la Transición Ecológica, Real Decreto 244/2019, de 5 de abril, por el que se regulan las condiciones administrativas, técnicas y económicas del autoconsumo de energía eléctrica, vol. BOE-A-2019-5089. 2019, pp. 35674–35719. Accessed: Jul., 2021. [Online]. Available: <<https://www.boe.es/eli/es/rd/2019/04/05/244>>.
- Keiner D, Ram M, Barbosa LDSNS, Bogdanov D, Breyer C. Cost optimal self-consumption of PV prosumers with stationary batteries, heat pumps, thermal energy storage and electric vehicles across the world up to 2050. *Sol Energy* 2019; 185:406–23.
- Vartiainen E, Masson G, Breyer C, Moser D, Román-Medina E. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelized cost of electricity. *Progress Photovoltaics. Special Issue: EU PVSEC 2019*;28(6):439–53.
- Zhong Q, Tong D. Spatial layout optimization for solar photovoltaic (PV) panel installation. *Renewable Energy* 2020;150:1–11.

- [26] Harry A, Atwater and Albert Polman. Plasmonics for improved photovoltaic devices. *Mater Sustainable Energy* 2010;1–11. https://doi.org/10.1142/9789814317665_0001.
- [27] Sjerps-Koomen EA, Alsema EA, Turkenburg WC. A simple model for PV module reflection losses under field conditions. *Sol Energy* 1996;57(6):421–32.
- [28] Martín N, Ruiz JM. Annual angular reflection losses in PV modules. *Prog Photovoltaics: Res Appl* 2005;13(1):75–84. <https://doi.org/10.1002/ppp.585>.
- [29] Psomopoulos CS, Ioannidis GC, Kaminaris SD, et al. *Environ Process* 2015;2(Suppl 1):175. <https://doi.org/10.1007/s40710-015-0092-4>.
- [30] Joint Research Centre. Photovoltaic geographical information system. <https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html>.
- [31] NREL PVWatts Calculator. National Renewable Energy Laboratory. <<https://pvwatts.nrel.gov/>>. [last access: 10/November/2019].
- [32] Natural Resources Canada (NRCAN) CANMET Energy Technology Centre for renewable energy technologies analysis. <<http://www.nrel.gov/>>. [last access: 05/March/2021].
- [33] Sánchez-Aparicio M, Martín-Jiménez J, Del Pozo S, González-González E, Lagüela S. Ener3DMap-SolarWeb Roofs: a geospatial web-based platform to compute photovoltaic potential. *Renewable Sustainable Energy Rev* 2021;135:110203. <https://doi.org/10.1016/j.rser.2020.110203>.
- [34] Odeh S. Analysis of the performance indicators of the PV power system. *J Power Energy Eng* 2018;06(06):59–75.
- [35] Sharma S, Kurian CP, Paragond LS. Solar PV system design using PVsyst: a case study of an academic Institute. In: 2018 International Conference on Control, Power, Communication and Computing Technologies (ICCCCT). IEEE; 2018. p. 123–8.
- [36] Odeh S. The development of a performance indicator for PV power generators. In: *Transition Towards 100% Renewable Energy*. Cham: Springer; 2018. p. 295–309.
- [37] Bakirci K. General models for optimum tilt angles of solar panels: Turkey case study. *Renewable Sustainable Energy Rev* 2012;16(8):6149–59. <https://doi.org/10.1016/j.rser.2012.07.009>.
- [38] Benghanem M. Optimization of tilt angle for solar panel: case study for Madinah, Saudi Arabia. *Appl Energy* 2011;88(4):1427–33. <https://doi.org/10.1016/j.apenergy.2010.10.001>.
- [39] Sumathi V, Jayapragash R, Bakshi A, Kumar Akella P. Solar tracking methods to maximize PV system output—a review of the methods adopted in recent decade. *Renewable Sustainable Energy Rev* 2017;74:130–8.
- [40] Eke R, Senturk A. Performance comparison of a double-axis sun tracking versus fixed PV system. *Sol Energy* 2012;86(9):2665–72. <https://doi.org/10.1016/j.solener.2012.06.006>.
- [41] Kaddoura Tarek O, Ramli Makbul AM, Al-Turki Yusuf A. On the estimation of the optimum tilt angle of PV panel in Saudi Arabia. *Renewable Sustainable Energy Rev* 2016;65:626–34. <https://doi.org/10.1016/j.rser.2016.07.032>.
- [42] Al Garni HZ, Awasthi A, Wright D. Optimal orientation angles for maximizing energy yield for solar PV in Saudi Arabia. *Renewable Energy* 2019;133:538–50.
- [43] Hafez AZ, Soliman A, El-Metwally KA, Ismail IM. Tilt and azimuth angles in solar energy applications—a review. *Renewable Sustainable Energy Rev* 2017;77:147–68.
- [44] Liu S, Yan Y, Zhang Z, Bai J. Effect of distributed photovoltaic power station on cooling load induced by roof for sunny day in summer. *Therm Sci Eng Progress* 2019;10:36–41.
- [45] Ullah A, Imran H, Maqsood Z, Butt NZ. Investigation of optimal tilt angles and effects of soiling on PV energy production in Pakistan. *Renewable Energy* 2019;139:830–43.
- [46] Babatunde AA, Abbasoglu S, Senol M. Analysis of the impact of dust, tilt angle and orientation on performance of PV Plants. *Renewable Sustainable Energy Rev* 2018;90:1017–26.
- [47] Fountoukis C, Figgis B, Ackermann L, Ayoub MA. Effects of atmospheric dust deposition on solar PV energy production in a desert environment. *Sol Energy* 2018;164:94–100.
- [48] Guo M, Zang H, Gao S, Chen T, Xiao J, Cheng L, et al. Optimal tilt angle and orientation of photovoltaic modules using HS algorithm in different climates of China. *Appl Sci* 2017;7(10):1028. <https://doi.org/10.3390/app7101028>.
- [49] Cheng CL, Charles S, Jimenez Sanchez, Lee Meng-Chieh. Research of BIPV optimal tilted angle, use of latitude concept for south orientated plans. *Renewable Energy* 2009;34:1644–50. <https://doi.org/10.1016/j.renene.2008.10.025>. ISSN 0960-1481.
- [50] Gharakhani Siraki A, Pillay P. Study of optimum tilt angles for solar panels in different latitudes for urban applications. *Sol Energy* 2012;86(6):1920–8.
- [51] Lorenzo E. Radiación solar y dispositivos fotovoltaicos. Sevilla: Progensa; 2006.
- [52] Lamigueiro O P. Energía Solar Fotovoltaica. Available at: <<https://oscarperpinan.github.io/esf/ESF.pdf>>. (last access: March/2021).
- [53] Elminir HK, Ghitas AE, El-Hussainy F, Hamid R, Beheary MM, Abdel-Moneim KM. Optimum solar flat-plate collector slope: case study for Helwan, Egypt. *Energy Convers Manag* 2006;47(5):624–37. <https://doi.org/10.1016/j.enconman.2005.05.015>.
- [54] Yellott H. Utilization of sun and sky radiation for heating and cooling of buildings. *ASHRAE J* 1973;15.
- [55] Cardoso RS, Amorim MCCT. Urban heat island analysis using the 'local climate zone' scheme in Presidente Prudente, Brazil. *Investigaciones Geográficas* 2018;69:107–18. <https://doi.org/10.14198/INGEO2018.69.07>.
- [56] Global Solar Atlas. World Bank Group. Available at: <<https://globalsolaratlas.info/map>>. (last access: 05/March/2021).
- [57] Sancho JM, Riesco J, Jiménez C, Sánchez MC, Montero J, López M. Atlas de radiación solar en España utilizando datos del SAF de clima de EUMETSAT. Spain: Agencia Estatal de Meteorología; 2012.
- [58] PVGIS Meteorological Data. Institute for Energy and Transport, Joint Research Centre, European Commission. Available at: <https://www.pvsyst.com/help/met_eo_source.pvgis.htm>. (last access: 05/March/2021).
- [59] PVWatts Calculator. NREL. Available at: <https://pvwatts.nrel.gov/version_6.php>. (last access: 05/March/2021).
- [60] Spanish Building Technical Code. Available at: <https://www.coit.es/system/files/link_group/he_5_contribucion_fotovoltaica_minima_de_energia_electrica_77f479a7.pdf>. (last access: 05/March/2021).