Köppen-Geiger-Photovoltaic Climate Classification

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Abstract — A new photovoltaic climate classification scheme that mixes the Köppen-Geiger climate classification with solar irradiation is proposed to give a simplified correlation between climate zones and performance of photovoltaic (PV) systems over large geographical areas. Temperature, precipitation and irradiation datasets have been combined using two classification levels to create 12 different climate zones. Additionally, the same datasets have been used in a comprehensive methodology to calculate the energy yield of PV systems. Numerical simulations have been run to compare different technologies over climates in the Contiguous U.S. and the continental territory of Chile. This paper opens the field for further analyses to be carried out across Europe and other regions worldwide.

Index Terms — climate classification, climate zones, energy yield, gridded data, performance, photovoltaic.

I. INTRODUCTION

Efforts to understand and accurately predict the performance and degradation of photovoltaic (PV) modules for a given location are a trend, since these studies can support and boost the optimal design, deployment and operation of projects depending mostly on the chosen location and PV technology. Many studies [1-5] have correlated climate conditions or climate zones with the performance of PV technologies, frequently using classification maps to identify macro- or micro-climates around the World.

Historically, climate classifications are mostly based on the Köppen-Geiger map (KG), which have been developed through the years since 1884, when Köppen draw the first classification worldwide map focused on the organic plants and based only on the ambient temperature as input climate data [6,7]. Later on, Köppen mixed his previous work with the precipitation data [8] to design the basis of the climatic classification which is still valid today. Even if several different versions of the initial KG scheme have been developed [7, 9, 10], the one made by Kottek et al. [11] has been a success and largely used in all scientific fields, as well as in the energy sector [12], providing a straightforward methodology which uses open-access global gridded datasets for ambient temperature (T_{amb}) and precipitation (P) to split the globe into 31 different climate zones. In the KG scheme, each zone is composed by the following three criteria: one letter for the “Main climates”

which gives a general understanding of the location; another due to the precipitation levels and the last letter indicating the temperature level. For instance, the “Cfa” zone means a warm temperate climate (C) fully humid (f) and hot summer (a).

However, the KG map takes into account only temperature and precipitation, while in PV technologies the most important climate factor regarding the performance and yield, is the solar irradiation. For this reason, we propose a new version of the KG map, called Köppen-Geiger-Photovoltaic map or abbreviated “KGPV”, which keeps some criteria from KG [11] to define the main climate zones, which are indicated as Temperature-Precipitation zones in this paper (TP-zones), but it also incorporates a new criterion for “Irradiation” (indicated as H-zones).

Additionally, the proposed climate classification will be correlated with the performance of different PV technologies over large geographical areas. Exploiting the same datasets than for KGPV, temperature and irradiation are combined into a PV modelling methodology to calculate the annual Energy Yield (Y) from monthly global gridded data. Furthermore, the accuracy of the irradiation data used is evaluated and compared with other data sources.

The datasets, methodologies and criteria to make the classification are explained in the following sections. Further on, numerical simulations are run to compare the performance of different technologies over the climates of the 48 states that form the Contiguous U.S. and the continental territory of Chile.

II. DATA AND METHODOLOGY

A. Datasets

Temperature and Precipitation global gridded datasets are provided by the Climatic Research Unit (CRU) of the University of East Anglia and the Global Precipitation Climatology Centre (GPCC) at the German Weather Service, respectively. Temperature data is taken precisely from the dataset CRU TS4.01 [13]. The dataset that contains the monthly land-surface precipitation data is called “GPCC Full Data Reanalysis Version 7” [14]. From both datasets, the monthly average ranging from 1900 to 2010 has been used in this paper,

which is consistent with previous climate classifications [9, 11] and allows us to assume a long-term analysis approach.

The solar irradiation has been taken from the project “ERA-CLIM model integration for the 20th Century” (ERA-20CM) by the European Centre for Medium-Range Weather Forecasts (ECMWF) [15]. This dataset complies with two requirements for our study, a global gridded data and historical data ranging from 1900 to 2010.

The variable called Surface Solar Radiation Downwards (SSDR) has been download in “monthly means of daily means” resolution. Moreover, the SSDR is defined as “a reasonable good approximation of a measure taken by a global pyranometer at the surface and it represents the flux passed through a square-meter of a flat horizontal plane” [16] and, then, it can be used as the typical Global Horizontal Irradiation (H_h). A validation and comments about this dataset are exposed below.

B. Temperature-Precipitation Zones

The first classification criterion has been taken from KG, allowing us to differentiate among Equatorial (A), Desert (B), Steppe (C), Temperate (D), Snow (E) and Polar (F) climates, and indicated as Temperature-Precipitation zones or TP-zones in this paper, because these variables are combined to classify the regions.

Table I indicates the classification criteria for these climate zones, where T_{min} is the monthly minimal temperature, T_{max} is the monthly maximal temperature, P_{ann} is the annual sum of precipitation and P_{th} is a dryness threshold, which depends on T_{ann} , the annual mean temperature, and the formula is given in (1) taken from [11]. Temperatures are given in °C and P_{ann} is given in mm/year. To calculate P_{th} , summer months range from July to September and winter months from January to March in the northern hemisphere.

$$P_{th} = \begin{cases} 2 \{T_{ann}\} & \text{if at least 2/3 of the } P_{ann} \text{ occurs in winter,} \\ 2 \{T_{ann}\} + 28 & \text{if at least 2/3 of } P_{ann} \text{ occurs in summer,} \\ 2 \{T_{ann}\} + 14 & \text{otherwise} \end{cases} \quad (1)$$

TABLE I

CRITERIA FOR TP-ZONES (TEMPERATURE-PRECIPITATION)

Legend	TP-zones	Criteria T_{min}, T_{max} : °C; P_{ann} : mm/year
A	Equatorial	$T_{min} \geq +18$ °C
B	Desert	$P_{ann} \leq 5 P_{th}$
C	Steppe	$5 P_{th} < P_{ann} < 10 P_{th}$
D	Temperate	-3 °C $< T_{min} < +18$ °C
E	Snow	$T_{min} \leq -3$ °C
F	Polar	$T_{max} \leq +10$ °C

C. Irradiation Zones

This second classification level considers the “Irradiation” (H-zones), where three thresholds allow to determine four different zones; Very High irradiation zone (noted as K) for locations with annual irradiation higher than 2250 kWh/m²/a, High irradiation zone (H) ranging from 1750 to 2250 kWh/m²/a, Medium irradiation zone (M) from 1200 to 1750 kWh/m²/a and Low irradiation (L) for locations with annual irradiation lower than 1200 kWh/m²/a.

D. Assumptions in Classification

The KGPV methodology provides a climate classification for a global scale and it does not differentiate among micro-climates, such as islands, small areas with complex topography or cities with extreme air pollution. For this reason, the following criterion is applied reducing the number of climate zones from 24 labels (all possible combinations between the 6 TP-zones with the 4 H-zones) to the 12 most relevant labels, depending on the zone surface ratio (S_r), which is expressed in (2), and defined as the division between the number of pixels for the zone “i-j” and the number of pixels for the whole zone “i”, where i = A, B, C, D, F or E and j = L, M, H or K.

$$S_r(i, j) = \frac{Pixels(i, j)}{Pixels(i)} * 100\% \quad (2)$$

This simplification will take into account only the areas with more than or equal to 10% of S_r , as shown in Table II. Even if the zone “AM” covers a 10.5% of surface, this label is excluded because it is representing only a slight portion of the whole Equatorial climate zone.

TABLE II
REDUCTION OF POSSIBLE KGPV ZONES

Surface Ratio [%]			H-zones (Irradiation)			
			L	M	H	K
			Low	Medium	High	Very High
TP-zones	A	Equatorial	0.0	10.5	88.6	0.9
	B	Desert	0.0	4.8	41.2	54.0
	C	Steppe	0.0	21.9	67.5	10.6
	D	Temperate	10.0	47.1	42.4	0.6
	E	Snow	63.4	32.8	3.7	0.1
	F	Polar	81.9	8.9	7.0	2.2

III. ENERGY YIELD CALCULATIONS USING GRIDDED DATA

Energy yield calculation methodology takes as input the monthly global gridded climate datasets for the minimal temperature, the maximal temperature and the GHI, and general parameters, such as the location, climate zone and PV technology parameters. Those will be employed in several mathematical models for the calculation of the representative day per month in hourly resolution. Module temperature and plane-of-array irradiation are calculated, since those variables have the highest impact in the PV performance over large

geographical regions, as reported by T.Huld et al. [17], but in this methodology we do not include other losses, such as, shading, spectral losses, low-irradiance losses or losses due to the angle of incidence. As final output, the energy yield for different technologies has been simulated. Fig. 1 summarizes this procedure and each step is described below.

A. Optimal Mounting

As PV modules are mounted generally in a fixed optimal position (tilt and azimuth) without shading, the incident irradiation or Plane-of-Array irradiation (H_{PoA}) has to be calculated from the horizontal values. The best azimuth angle (Az) is achieved when the modules are facing the equator line, while the tilt angle (β_{opt}) depends mostly on the Latitude of the site. Equations (3) and (4) show the empirical models to calculate an approximate optimal mounting position [18].

$$Az = \begin{cases} 180^\circ & \rightarrow \text{if modules are facing south} \\ 0^\circ & \rightarrow \text{if modules are facing north} \end{cases} \quad (3)$$

Fig. 1. Simplified scheme for PV performance modelling using gridded global climatic data.

B. Solar Times

The hourly solar position over a year is calculated using the “NREL SPA algorithm” [19] through the open-source library “PVLIB” [20], obtaining the Solar Zenith Angle (*Zenith*) and monthly average for Sunrise Time (*Sunrise*), Sunset Time (*Sunset*) and Local Noon Time (*Noon*).

C. Daylight Temperature

Mean ambient temperature is typically measured over the 24 hours/day, but as the PV modules operate only during the daylight, a recalculation of T_{amb} for this case is needed [21]. Using the solar times calculated before, additionally with T_{min} and T_{max} , a “sinusoidal model” [22] is applied to obtain the daylight mean ambient temperature ($T_{daylight}$). Explicit formulas are shown in (5) and (6).

$$T_{amb}(t_{1,2}) = \begin{cases} A_T \sin\left(2\pi t_1 + \frac{3\pi}{2}\right) + (T_{max} - A_T) & \rightarrow \text{from sunrise to noon} \\ & \text{(hourly time vector: } t_{sn}) \\ A_T \sin\left(2\pi t_2 + \frac{3\pi}{2}\right) + (T_{max} - A_T) & \rightarrow \text{from noon to sunset} \\ & \text{(hourly time vector: } t_{ns}) \end{cases} \quad (5)$$

$$T_{daylight} = \frac{\sum T_{amb}(t_{1,2})}{|t_{sn}| + |t_{ns}|} \quad (6)$$

where,

$$\begin{aligned} A_T &= \frac{T_{max} - T_{min}}{2} \\ t_1 &= \frac{n_1 - 1}{2|t_{sn}|}, n_1 = [1, 2, \dots, |t_{sn}| + 1] \\ t_2 &= \frac{n_2 - 1}{4|t_{ns}|} + 0.5, n_2 = [1, 2, \dots, |t_{ns}| + 1] \\ |t_{sn}|, |t_{ns}| &: \text{length of time vectors} \end{aligned}$$

D. Clear Sky and Transposition

To calculate the extra-terrestrial irradiation (DNI_{et}) we run PVLIB functions using the “Spencer model” and the Air Mass (AM) using the “Kasten and Young 1989 model” [23]. With these variables the Clear-sky Global Horizontal Irradiation (H_{h-CS}) is simulated using the “Ineichen model” [24].

Later on, H_{h-CS} , β_{opt} and Az are used in the “King model” [25] to obtain the Clear-Sky Global PoA Irradiation (H_{PoA-CS}).

The gain, noted as $Gain_h$, between the daily sum of H_{h-CS} and the daily sum of the global horizontal irradiation from ERA-20CM (H_h) is determined for each location using (7).

$$Gain_h = \frac{H_h}{\sum H_{h-CS}(t)} \quad (7)$$

E. Plane-of-Array Irradiation

H_{PoA} is calculated by multiplying the $Gain_h$ and H_{PoA-CS} from the dataset for each location, as shown in (8).

$$H_{PoA} = Gain_h * H_{PoA-CS} \quad (8)$$

F. PV Module Temperature

Using the “Nominal Operating Cell Temperature model (NOCT)” [26], the PV module Temperature (T_{Mod}) is determined from $T_{Daylight}$ and H_{PoA} as (9). An average value of the temperature at NOCT (44 °C) is considered for all the technologies.

$$T_{Mod}(t) = T_{Daylight}(t) + k_{NOCT} * G_{PoA}(t) \quad (9)$$

where,

$$k_{NOCT} = \frac{T_{NOCT} - 20^\circ\text{C}}{800 \frac{\text{W}}{\text{m}^2}} = 0.03 \left[\frac{^\circ\text{Cm}^2}{\text{W}} \right]$$

G. PV Performance Modelling

Energy yield (Y_f) is defined as the annual sum of the output power of the PV modules impacted by the irradiation and the module temperature, which depend on the used technology. This calculation is based on the “linear performance model” [27] shown in (10), where k_1 is considered equal to $1 [\text{m}^2/\text{kWp}]$, enabling us to get the “kWh/Wp” or “MWh/kWp” values, typically used to compare among PV technologies [28]. The power-temperature coefficients (γ) used in our study are shown in Table III.

$$Y_f = \sum_t [k_1 * G_{POA}(t) * (1 + \gamma * (T_{Mod}(t) - 25 \text{ }^{\circ}\text{C}))] \quad (10)$$

TABLE III

POWER-TEMPERATURE COEFFICIENTS FOR PV TECHNOLOGIES.

Technology	Power Temp Coef.
Mono c-Si	-0.40%/°C
Multi c-Si	-0.45%/°C
a-Si	-0.20%/°C
CIGS	-0.36%/°C
CdTe	-0.25%/°C

IV. COMPARISON OF SOLAR RESOURCE DATA

Solar irradiation from global atmospheric reanalyses models is currently getting the attention of the PV industry because of certain advantages, such as, the global or large spatial resolution, long term available time periods, generally free-cost, and besides the *GHI*, numerous other variables (temperatures, wind speeds, UV irradiation, etc.) can be also taken from these products. However, poor accuracy for certain locations has been exposed in the literature [29-31].

We have evaluated the ERA-20CM data (without horizon losses) between 2001 and 2010 with the NSRDB data (National Solar Radiation Database) provided by NREL, which is a satellite-based data source. To check validity, ten cities located in different climate conditions have been studied by their percentage error as (11). The results are shown in Table IV.

$$\varepsilon_{ERA20CM-X} = \frac{H_{ERA20CM} - H_X}{H_X} * 100\% \quad (11)$$

Additionally, taking data from the Global Solar Atlas website, *GHI* data provided by Solargis has been compared with the ERA-20CM data. However, due to the limited available data, we have taken into account different time period.

From our analysis, the discussion about the accuracy of the ERA-20CM database remains open, due to the large differences in some areas. As exposed in [30-31], the significant variation can be related with a poor prediction of clouds, or difficulty to estimate the surface irradiation in places, such as mountains or along the coastlines.

TABLE IV

ANNUAL GLOBAL HORIZONTAL IRRADIATION AND THE PERCENTAGE ERROR FOR ERA-20CM DATASET.

Irradiation [kWh/m ² /a]	KGPV-ERA-20CM 2001-2010	NSRDB 2001-2010	Global Solar Atlas 1999-2015
Atacama (Chile)	2665	-	2578 (+ 3.4%)
Santiago(Chile)	2299	-	2053 (+12.0%)
Albuquerque (US)	2122	2064 (+ 2.8%)	2062 (+ 2.9%)

Charlotte (US)	1634	1695 (- 3.7%)	1666 (- 1.9%)
Chicago (US)	1618	1480 (+ 9.3%)	1475 (+ 9.7%)
Denver (US)	1937	1736 (+11.6%)	1786 (+ 8.4%)
Miami (US)	1882	1904 (- 1.2%)	1910 (- 1.5%)
Los Angeles (US)	2206	1983 (+11.3%)	2016 (+ 9.5%)
Seattle (US)	1408	1245 (+13.0%)	1231 (+14.4%)
Yuma (US)	2163	2162 (+ 4.8%)	2144 (+ 5.7%)

V. CORRELATION OF CLIMATE ZONES AND ENERGY YIELD

A. Correlation for Contiguous U.S.

Excluding the states of Hawaii and Alaska, we have carried out the correlation between the KGPV zones and the PV Energy Yield over the other 48 states (Contiguous United States). The numerical division and illustrative representation of the land into the different climate zones is expressed in the Fig. 2.

Fig. 2. KGPV zones map for the Contiguous U.S.

By applying the Performance Modelling described above, the average expected annual energy yield of the contiguous U.S. per KGPV climate zones is illustrated as Fig. 3.

Fig. 3. Heat map of the annual energy yield for the main relevant KGPV zones and five PV technologies over the contiguous U.S.

From the results, as expected, the highest annual energy yield is observed in BH zones (Deserts with High Irradiation) installing amorphous silicon modules due to their low power-temperature coefficient. The lowest Y is detected in DM zones (Temperate climate with Medium Irradiation) using multi-c-Si PV modules, thereby compromising the relation between temperature and irradiation.

B. Correlation for Chile

Excluding the islands and the Antarctica territory, the same procedure as above is applied to continental Chile and shown in Fig. 4. This region is favoured for having a big desert in the north, classified as BK.

In Fig. 5, the simulated annual energy yield for the most relevant climate zones in Chile is presented. Crystalline technologies are strongly affected in the north, due to the very high temperatures. Amorphous silicon modules are still performing better than others because of its low power-temperature coefficient. Moving south along the country, the irradiation decreases and so the energy yield is also reduced.

Fig. 4. KGPV zones map for the continental territory of Chile.

Fig. 5. Heat map of the annual energy yield for the main relevant KGPV zones and five PV technologies over the Continental Chile.

VI. CONCLUSION

Besides the specific climate classification for PV projects, this paper proposes a new methodology based on the Köppen

classification scheme, by including the solar irradiation as an

additional variable. The KGPV scheme divides the Earth into 6 macro-climates (Equatorial, Steppe, Desert, Temperate, Snow and Polar climates), which are later divided into 12 zones, by applying the irradiation criteria: Very High, High, Medium and Low irradiation zones.

Therefore, as we want to reach the correlation between climate zones and PV performance, a new methodology to calculate energy yield for different technologies and climate dependence is proposed, mixing several mathematical models and computing tools.

The proposed climate classification and PV performance modelling have been calculated for the Contiguous U.S. and Chile. The results agree with the expectations, since the energy yield calculated is a compromise between the temperature and irradiation, where Desert Climates will produce more energy than the rest of the climate zones. However, temperate climates will produce the less energy regardless the PV technology because of the adverse climate conditions, not so high irradiation but still high ambient temperature.

This work is the basis for further correlations between climate zones and PV performance modelling over large geographical regions, but as discussed before, the input irradiation data should be studied carefully, since its accuracy can vary from one location to another.

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