Development of a Greek solar map based on solar model estimations

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Abstract: The realization of Renewable Energy Sources (RES) for power generation as the only environmentally friendly solution, moved solar systems to the forefront of the energy market in the last decade. The capacity of the solar power doubles almost every two years in many European countries, including Greece. This rise has brought the need for reliable predictions of meteorological data that can easily be utilized for proper RES-site allocation. The absence of solar measurements has, therefore, raised the demand for deploying a suitable model in order to create a solar map. The generation of a solar map for Greece, could provide solid foundations on the prediction of the energy production of a solar power plant that is installed in the area, by providing an estimation of the solar energy acquired at each longitude and latitude of the map. In the present work, the well-known Meteorological Radiation Model (MRM), a broadband solar radiation model, is engaged. This model utilizes common meteorological data, such as air temperature, relative humidity, barometric pressure and sunshine duration, in order to calculate solar radiation through MRM for areas where such data are not available. Hourly values of the above meteorological parameters are acquired from 39 meteorological stations, evenly dispersed around Greece; hourly values of solar radiation are calculated from MRM. Then, by using an integrated spatial interpolation method, a Greek solar energy map is generated, providing annual solar energy values all over Greece.

Keywords: MRM, Meteorological Radiation Model, Greek solar map, solar radiation

INTRODUCTION

Solar power systems have been at the forefront of the global energy market for at least one decade. In the meantime, the world realized that the only environmentally friendly solution concerning power generation is the implementation of RES. In this context, following the rapid development of wind energy, solar power systems also presented remarkable market increment. At the same time, rapid increase of photovoltaic systems' installations has been recorded in many European countries, including Greece, where during the recent period installed photovoltaic capacity almost doubles every two years with total installations in 2013 exceeding 2.5 GW_e. It is obvious that there is an increased interest in the possession of up-to-date and accurate solar radiation data which are playing a key role in energy resource assessment of solar power systems.

In recent years, solar radiation modelling utilizing existing climatic-parameters, such as sunshine duration, cloud cover, relative humidity, air temperature etc., has shown remarkable progress. It is generally accepted that the use of models for solar radiation prediction, instead of using scattered ground-based measurements, is essential during solar energy systems design, because in most cases the low density and the limited number of solar radiation measuring stations cannot describe the required variability of the climatic parameters involved (Muneer, Younes and Munawwar, 2007).

Several solar radiation models have appeared globally since the middle of the 20th century in order to generate solar radiation on horizontal plane, mostly under clear sky conditions (Gueymard, 2012). For example, the US National Solar Radiation Data Base provides hourly radiation data and Typical Meteorological Years (TMYs) for 239 US regions, with more than 90% of these data deriving from appropriate modelling (Maxwell, 1998). Also, the European Solar Radiation Atlas (ESRA) model is used for providing topography-based maps of solar irradiance in Europe and bordering countries (Page, Albuisson and Wald, 2001).

In the context of the above, a broadband model, which has been developed in Greece in the late 80's by the Atmospheric Research Team at the National Observatory of Athens for estimating solar radiation on horizontal surface, is the Meteorological Radiation

Model (MRM). Since then, consecutive versions (latest version 5) of the model have been released with their full description given in a series of publications (Kambezidis, Adamopoulos and Sakellariou, 1999; Psiloglou and Kambezidis 2007; Kambezidis, 2008). Application of MRM may be found in a variety of solar resource assessment studies as well as in solar irradiance forecasting (Museruka and Mutabazi, 2007; González, Serrano and Wiesenberg, 2010). The main advantage of MRM is its simplicity in acquiring and using the necessary input data (i.e. four measured variables namely, air temperature, relative humidity, barometric pressure and sunshine duration).

On top of theoretical models' application, solar irradiance maps, created by spatial interpolation of estimated solar radiation data, can provide a first insight of solar potential of a candidate location. Several spatial interpolation methods can be found in the literature such as natural neighbour interpolation (Dinis, Jorge and Belinha, 2009), inverse functions of distance (Pons and Ninyerola, 2008), multiple linear regression (Daly, Neilson and Phillips, 1994), splines (McKenney et al. 2008) or kriging (Ruiz-Arias et al. 2011). The results of different studies, which compare deterministic and stochastic methods for the interpolation of environmental variables, show that kriging methods present considerable advantages against deterministic interpolation procedures (Luo, Taylor and Parker, 2008). Such methods are based on the analysis of statistical properties, such as the data distribution and spatial correlation between the measured points among sites, providing reliable estimates for homogeneous terrains with similar climate characteristics.

In the framework of the above, the present study utilizes geostatistics combined with model estimated solar radiation data for several meteorological stations across the Greek territory for the estimation of global solar energy in large-scale. More precisely, the present work relies on collected synoptic data values from 39 meteorological stations of the Hellenic National Meteorological Service (HNMS) during a fifteen-year period. The meteorological data include 3-hour values of air temperature, relative humidity, barometric pressure and daily values of sunshine duration. By using linear interpolation on the 3-hour values, an hourly database was generated. The corresponding database was filled with hourly values of global solar radiation on horizontal plane calculated by MRM. Finally, a solar map was developed by using spatial interpolated kriged data derived from solar radiation values in 39 different areas across the country. The solar energy map created, aims to serve basic solar resource information and to provide a general view of the distribution of the solar radiation over the country.

METHODOLOGY

Fifteen (15) years of synoptic meteorological data were used, covering the period between 1985 and 1999. Measurements were obtained from 39 meteorological stations of the HNMS evenly dispersed around Greece (see Figure 1).

The meteorological data include 3-hour values of air temperature, relative humidity and barometric pressure along with daily values of sunshine duration. It should be noted that the data underwent a further quality control procedure through cleaning and gap filling in order to remove unwanted or false values and fill in potential corrupted or erroneous data points. More specifically, in order to detect and exclude erroneous data, a routine quality control procedure was applied, which was based on the physical range of the parameters and the maximum time-step variation (Psiloglou and Kambezidis, 2007). By using linear interpolation on the 3-hour values, an hourly database was generated.

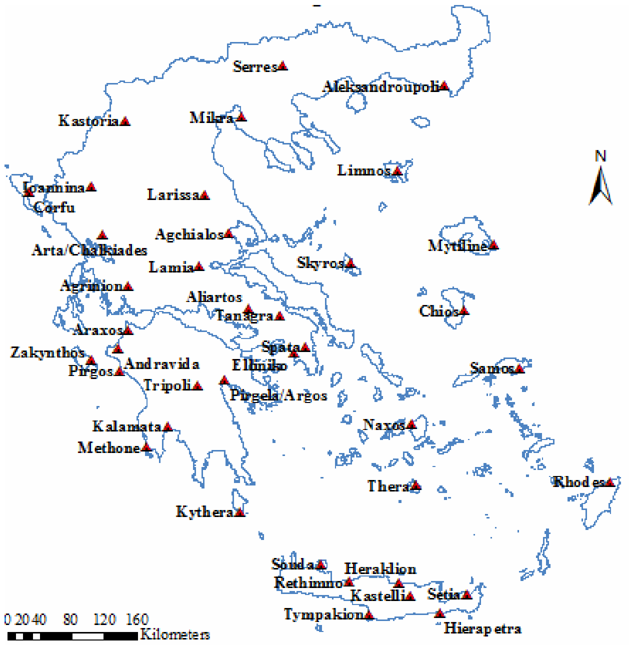


Figure 1: Location of the 39 meteorological stations used in the study

The MRM model, version 5, was engaged in order to generate solar radiation values for the 39 meteorological stations. According to the model, the direct beam component of solar radiation normal to a horizontal plane at the earth's surface, under clear sky and natural atmosphere, is the extra-terrestrial radiation at the top of the atmosphere modified by the absorption and scattering from its various constituents. Thus, during cloudless periods, the direct beam radiation I_b, received on a horizontal surface can be expressed as:

$$I_b = I_{ex} \cdot cos\theta_z \cdot T_w \cdot T_r \cdot T_o \cdot T_{mg} \cdot T_a \qquad (1)$$

where θ_z is the solar zenith angle, I_{ex} is the normal incidence extra-terrestrial solar radiation on the n_i-th day of the year; the T terms are the broadband transmission functions for water vapor (T_r), uniformly mixed gases $(CO_2, CO, N_2O, CH_4 \ and \ O_2)$ absorption (T_{mg}), ozone absorption (T_υ) and aerosol total extinction (scattering and absorption) (T_a).

The diffuse sky radiation under clear sky conditions, is assumed to be made up of a portion of singly scattered by the atmospheric constituents (molecules and aerosol particles) direct beam radiation, I_{ds}, plus a multiple scattering component I_{dm} (Psiloglou, Santamouris and Asimakopoulos, 2000):

$$I_{ds}=I_{ex}cos\theta_z T_w T_{mg} T_o T_{aa} 0.5(1 - T_{as} T_r) \quad (2)$$

where T_{aa} is the aerosol transmittance function due to absorption only and T_{as} the aerosol transmittance due to scattering alone.

The total solar radiation received under clear sky conditions on horizontal plane at the earth surface, is the sum of the beam and diffuse components, i.e.:

$$I_t = I_b + I_d \quad (3)$$

The corresponding direct beam solar radiation under cloudy skies I_{cb}, can be obtained by:

$$I_{cb} = I_b \cdot T_c \quad (4)$$

where T_c is the cloud transmittance.

Accordingly, the diffuse radiation at ground level under cloudy skies I_{cd}, is the sum of the I_{cds} and I_{cdm} components. The single scattered portion of the diffuse radiation in the presence of clouds, I_{cds}, is computed by Barbaro et al. (1979):

$$I_{cds} = I_{ds} \cdot T_c + k^* \cdot (1 - T_c) \cdot (I_b + I_{ds}) \quad (5)$$

where k^* is an empirical transmission coefficient, whose value is a function of latitude and is obtained from Berland and Danilchenko (1961). The ground reflected, atmospheric and cloud backscattered diffuse term I_{cdm} is modeled as in clear sky conditions:

$$I_{cdm} = (I_{cb} + I_{cds}) \frac{a_g \cdot a_{cs}}{1 - a_g . a_{cs}} \quad (6)$$

where a_g is the surface albedo and a_{cs} is the albedo of the cloudy sky.

Finally, the total solar radiation received under cloudy sky conditions (partly or overcast) on horizontal surface is the sum of the horizontal direct beam and diffuse components, i.e.:

$$I_{ct} = I_{cb} + I_{cd} \quad (7)$$

The obtained 15-year hourly solar radiation database was used to develop a TMY for each one of the meteorological station. A TMY is a dataset of hourly values of solar radiation and meteorological parameters which is composed of months selected from individual years concatenated to form a complete year. The TMY is defined as a year representing climatic conditions considered to be typical over a long period of time. For the generation of the 39 TMYs, the Sandia method was used (Hall et al. 1978) as modified by Pissimanis et al. (1988) and Argiriou et al. (1999). Sandia method is an established empirical methodology for selecting individual months from different years over the available period, based on Filkestein-Schafer (FS) statistics of fourteen daily indices, namely maximum, minimum, mean and range of air temperature, relative humidity and barometric pressure and daily direct and global solar energy. The weighted sum of FS statistics is calculated by using weighting factors for each daily index (Table 1).

Table 1: Weighting factors used for the FS statistics

Parameter	Daily index	Weighting factor
Air temperature	*Maximum*	3
	Minimum	3
	Mean	9
	Range	3
Relative humidity	*Maximum*	3
	Minimum	3
	Mean	9
	Range	3
Barometric pressure	*Maximum*	5
	Minimum	3
	Mean	3
	Range	3
Global radiation	*Daily sum*	25
Direct radiation	*Daily sum*	25
Sum		100

The hourly solar radiation data of the 39 TMYs were used in order to calculate the annual global solar energy obtained on horizontal plane. After testing several spatial interpolation methods, the Empirical Bayesian Kriging (EBK) was proved the most accurate for creating the Greek solar map. Figure 2 presents a scatter plot of the estimated annual solar energy by EBK at the location of the 39 meteorological stations versus the real values as they were calculated by the TMY's. As indicated by the graph, the correlation between estimated and real values is very good as the coefficient of determination (R^2) exceeds 87%.

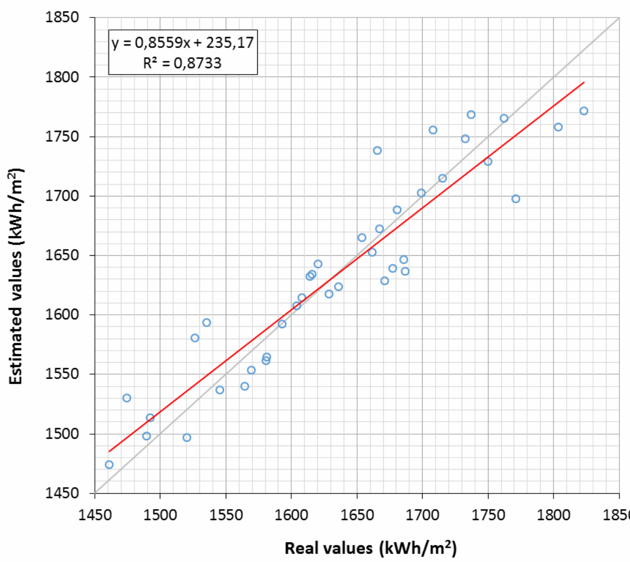


Figure 2: Comparison of estimated and real annual energy values for the 39 locations under investigation in Greece

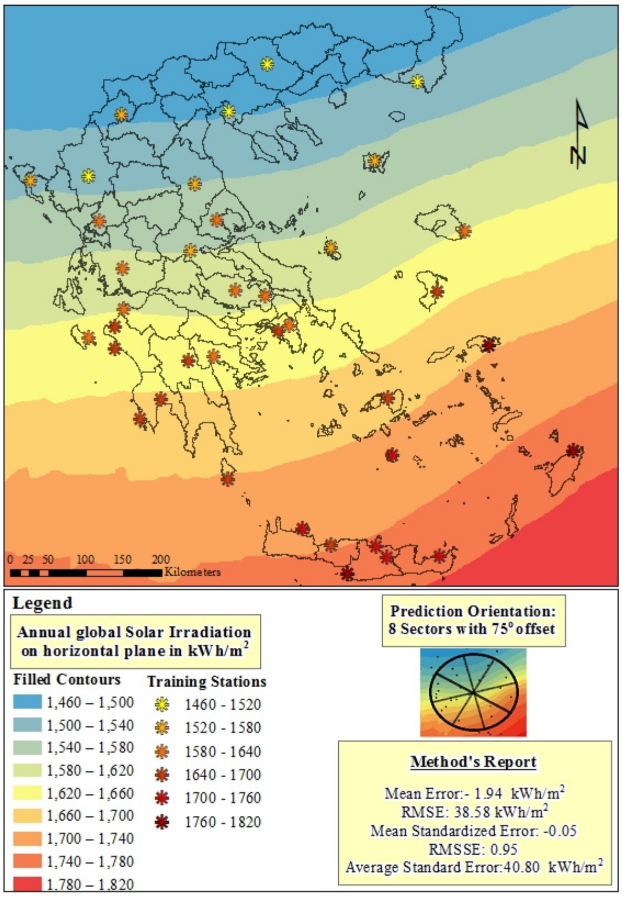
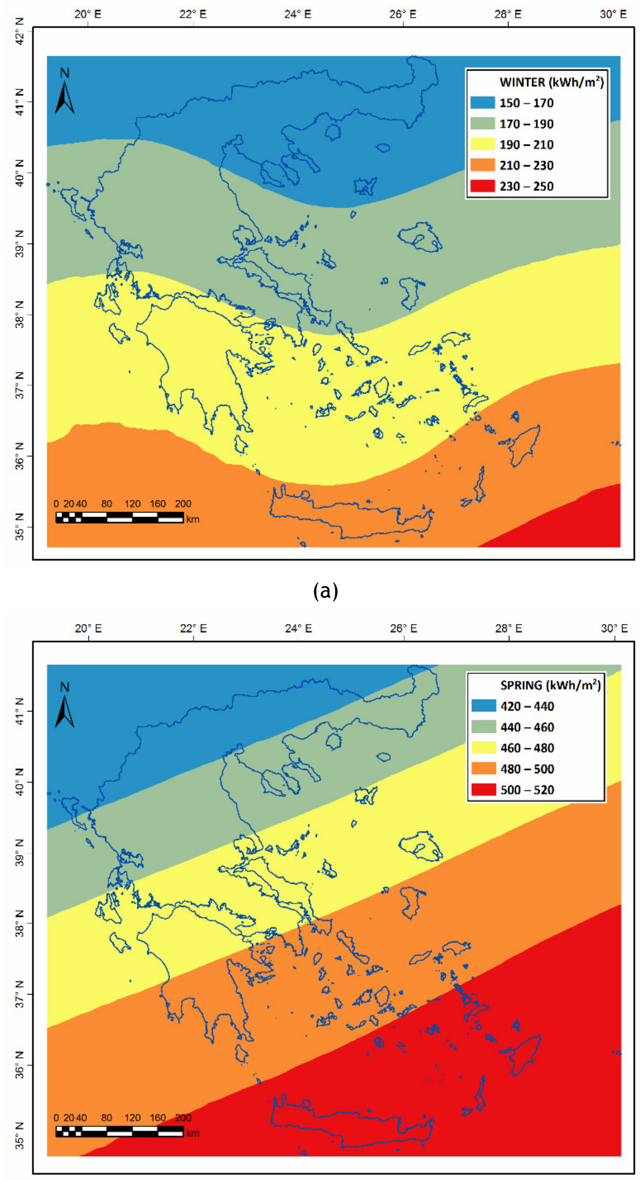


Figure 3: Solar map of Greece based on EBK method

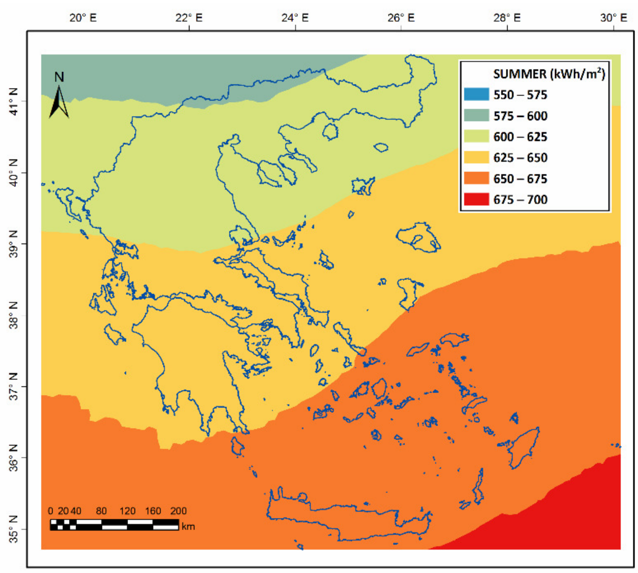
Based on the above methodology, an updated solar energy map was developed along with the corresponding predicted errors (Figure 3). Figure 3 presents the global solar energy variation throughout the Greek region divided in 9 solar zones. The signs on the meteorological stations' locations are colored based on their real annual solar energy value. According to the results, the annual solar energy in Greece ranges between 1450 and 1820 kWh/m^2, with northern areas possessing higher values of solar energy. The mean error of the estimated vs the real values is 1.94 kWh/m^2 which is relatively low if considered that it is applied to annual solar energy values.

Regarding the seasonal variation of solar energy in Greece (Figures 4 and 5) it is clear that during the winter the east coastal areas of the mainland process the local minimum values of solar energy. The reduce solar energy values are attributed to the NE winds that prevail at the cold period of the year increasing the orographic cloud and carrying wet air masses enriched in humidity by passing over the Aegean Sea. During the summer period the NE end of Greece possesses the maximum annual solar energy values which is in accordance with the cloud distribution presented by Lolis, Bartzokas and Metaxas (1999) for the same period of the year.

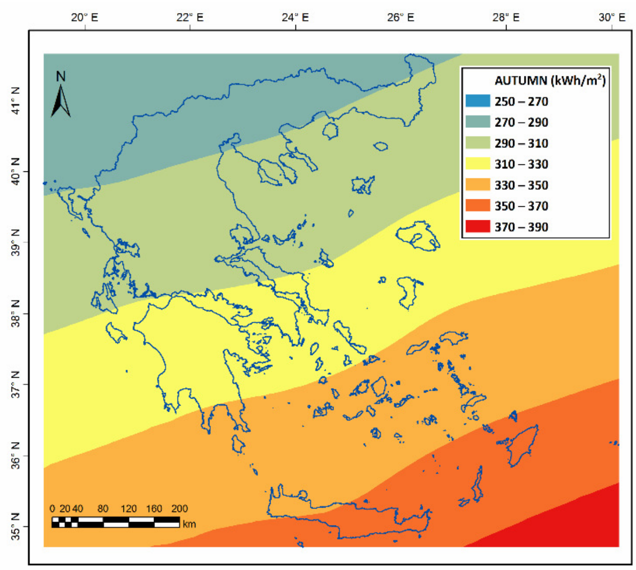


(b)

Figure 4: Solar energy spatial distribution in Greece during a) winter and b) spring period



(a)



(b)

Figure 5: Solar energy spatial distribution in Greece during a) summer and b) autumnal period

CONCLUSIONS

The possession of up-to-date and accurate solar radiation data play a key role in energy resource assessment of solar power systems. Given the low density and limited number of solar radiation measuring stations the use of solar radiation models is imperative. The present research work presented an integrated procedure which was used in order to develop an updated Greek solar map based on the solar radiation data estimated by the Meteorological Radiation Model for 39 meteorological stations of the Hellenic National Meteorological Service. The solar energy map created, provides solar resource information for any location over the country along with the general view of the distribution of the solar radiation.

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