WIND AND SOLAR IRRADIANCE GRIDDED DATA TO SUPPORT ASSESSMENT OF RENEWABLE ENERGY RESOURCES IN GREECE

A. PAPADOPOULOS¹, P. KATSAFADOS², S. KALOGIROU² and T. SOUKISSIAN³

¹Hellenic Centre for Marine Research, Institute of Marine Biological Resources and Inland Waters, 46.7 km Athens-Sounion Ave., 19013, Anavissos Attikis, Greece, ²Harokopion University of Athens, Department of Geography, 70 El. Venizelou Str., 17671, Athens, ³Hellenic Centre for Marine Research, Institute of Oceanography, 46.7 km Athens-Sounion Ave., 19013, Anavissos Attikis, Greece. tpapa@hcmr.gr

EXTENDED ABSTRACT

Common practice suggests that the assessment of wind and solar energy resources is based on data obtained from existing weather stations operated by the national meteorological services and other public services. Usually, these stations are placed at populated locations (for example airports, ports, urban, rural and protected areas) to support weather analysis, forecasts and warnings, local weather-dependent operations and research in meteorology, climatology and hydrology. Practically, the observed data collected from these stations are not suitable for wind farms and solar panel siting and installations. Moreover, time series of direct observations are not always available for sufficiently long periods; they have too sparse coverage and are generally not representative of specific areas. To overcome the shortcomings of the direct observations, alternative source of accurate data is required.

This paper addresses a particular example of considering numerical weather prediction models as alternative source of wind and solar irradiance data. The mesoscale meteorological model of the POSEIDON weather forecasting system has been appropriately configured to simulate historical records of the atmospheric conditions across the Mediterranean region at 10 km grid spacing and for a long period (1995-2004). The European Centre for Medium-Range Forecasts (ECMWF) ERA-40 reanalysis data and the ECMWF operational analyses were used to initialize the mesoscale model and to update its boundaries. Therefore, the mesoscale model downscapes the global data by producing fine-scale weather patterns consistent with the coarse-resolution features in the forcing data. Furthermore, a Geographical Information System (GIS) technique has been developed in order to allow for solar energy resource maps to be overlaid with other spatial datasets such as topographical and land use data. This will provide valuable and much needed information for the processing, analysis and mapping of possible scenarios for solar energy applications. Thus, the benefits of renewable energy across Greece could be highlighted.

KEYWORDS: Wind energy potential, solar energy potential, downscaling, POSEIDON system, GIS mapping

1. INTRODUCTION

Common practice suggests that the assessment of wind and solar energy resources is based on data obtained from existing weather stations that are operated by the national meteorological and other public services. The meteorological observations are made mainly to support the weather analysis, forecasts and warnings, the local weather-dependent operations as well as the research in meteorology, climatology and hydrology. To serve these applications the stations are placed at populated locations such as airports, ports, urban, rural and protected areas. Practically, wind farms have to be
installed at relatively high elevated remote areas which are experienced by relatively strong winds, but where there is no particular interest in routinely measuring the atmospheric conditions. In addition, the measurement of solar irradiance is costly and only few weather stations are equipped with the relevant measurement sensors. Therefore, the data collected from existing weather stations are not always suitable for solar panel and wind farms site selection and installation. Furthermore, if a new station is installed at area of particular interest, a minimum period of operation, at least one year (WMO, 1983), would require in order to utilize its measurements. However, even though the one-year measurements can be sufficient for studying the diurnal and sometimes the seasonal variability, definitely a longer period is required in order to obtain more reliable results and to better represent the long term variability. Taking these limitations into consideration, alternative source of accurate data is required.

Numerical Weather Prediction (NWP) model output can overcome, to a large extent, the limitations arising from using measurements obtained from weather stations. NWP models can simulate the atmospheric conditions and provide wind fields and solar radiation estimates over large regions timely and with much less cost than covering them with in situ measurements. Depending on the available computational power, several NWP with different horizontal resolution and vertical layers are in operational use. However, long term data sets obtained from operational NWP models may be inadequate because of the changes in the model configuration and the improvements in the numerical and data assimilation methods over time. The generation of global reanalysis data has made it possible to overcome such problems. Reanalysis data provide a reconstruction of consistent and high quality historical global atmospheric circulation patterns by using the same most recent assimilation method for the entire period of coverage (Kalnay et al., 1996) and the near latest, stable NWP model version. However, the rather coarse resolution of the current reanalysis data (commonly greater than 100 km grid size) provides limited representation of the mesoscale atmospheric processes and it precludes its direct application to assess wind and solar energy resources. Thus, an appropriate downscaling technique is required to resolve the desired fine-scale meteorological fields. Many studies have shown that dynamical downscaling has potential to effectively capture nonlinear mesoscale features that are absent in the global reanalysis (e.g., Mesinger et al. 2006).

To this end, Papadopoulos et al. (2011) developed a 10-year meteorological regional dataset with a horizontal resolution of 10 km through a dynamical downscaling procedure applied to global reanalysis data. In this study, basic parameters from this dataset were processed in order to derive valuable wind and solar energy parameters, to sort them into easily accessible subsets and to create maps of wind and solar power potential in different time scales. Furthermore, a Geographical Information System (GIS) technique has been developed to combine solar energy resources maps with other spatial datasets (e.g., topographical, land use data) and, to allow improved assessments of possible scenarios for solar energy utilization.

2. NUMERICAL WEATHER PREDICTION MODEL AND DATA

The mesoscale meteorological model of the POSEIDON weather forecasting system has been appropriately configured to simulate historical records of the atmospheric conditions across the Mediterranean basin and the surrounding countries at 10 km grid spacing and for a long period (1995-2004). The European Centre for Medium-Range Forecasts (ECMWF) ERA-40 reanalysis data (Uppala et al., 2005) and global operational analyses were used to initialize the mesoscale model and to update its boundaries. Consequently, the mesoscale model downscales the global reanalysis data by producing fine-scale weather patterns consistent with the coarse-resolution features in the forcing data. Selected upper air and surface parameters from the 10-year high-resolution model output were stored on the model grid points and on a regular 0.1° X 0.1° (about 10 km) grid. This
dataset, namely HDDM10 (the HCMR (Hellenic Centre for Marine Research) Dynamical Downscaling for the Mediterranean region at 10 km resolution) contains all the key parameters required for the assessment of wind and solar energy resources. More details about the sophisticated downscaling procedure and the comprehensive HDDM10 products are included in Papadopoulos et al. (2011).

2.1 Wind energy data

Wind energy is the kinetic energy of the moving air. Air particles with total mass \( m \) (kg) moving at height \( h \) with a velocity \( u_h \) (m s\(^{-1}\)) carry kinetic energy \( E \) (in Joule) which is given by the equation

\[
E = \frac{1}{2} \ m \ u_h^2
\]

(1)

The air mass \( m \) can be determined from the air density \( \rho \) (kg m\(^{-3}\)) and the air volume \( V \) (m\(^3\)) according to \( m=\rho V \). Considering that the air particles passing through an imagery area \( A \) (m\(^2\)) perpendicular to the direction of the wind at a given time interval \( t \) (s) travel a distance \( s \) (\( s=u \ t \)), then the volume \( V \) of the moving air particles is

\[
V = A \ s = A \ (u_h \ t)
\]

(2)

Hence, the wind energy during the time \( t \) can be expressed as

\[
E = \frac{1}{2} \ (\rho \ A \ u_h \ t)u_h^2 = \frac{1}{2} \ \rho \ A \ t \ u_h^3
\]

(3)

Then, the theoretical wind power \( WP \) (wind energy per unit time and is expressed in W), which does not take into account the energy losses in the wind turbine itself, is given as

\[
WP = \frac{1}{2} \ \rho \ A \ u_h^3
\]

(4)

Finally, by dividing the wind power \( WP \) by the cross-sectional area \( A \), the term \( WP/A \) is the theoretical wind power density, \( TWPD \), which depends only on the density of the air particles \( \rho \) and the wind speed \( u \) and has units of W m\(^{-2}\).

\[
TWPD = \frac{1}{2} \ \rho \ u_h^3
\]

(5)

The atmospheric air density is a diagnostic variable of the POSEIDON weather forecasting system and it is estimated considering all the phases of water. However, air density is not included directly into HDDM10 products, but according to Dalton’s law the density of moist air can be estimated as:

\[
\rho = \frac{p}{R_d T_{air} \left( 1 + \frac{R_v}{R_d} q \right)}
\]

(6)

where \( p \) (in Pa) is the air pressure, \( R_d \) is the gas constant for the dry air (equals to 287.04 J kg\(^{-1}\) K\(^{-1}\)), \( T_{air} \) is the air temperature in Kelvin, \( R_v \) is the gas constant for water vapor (461.50 J kg\(^{-1}\) K\(^{-1}\)) and \( q \) is the specific humidity (kg kg\(^{-1}\)).

The sufficient vertical resolution applied in the POSEIDON weather forecasting system permits the study of the wind speed fields at different elevations (i.e., the lower model levels were defined at 19.5, 61.7, 112.2 m above sea level). However, hub height varies
according to wind turbine models and in the larger models wind speed varies significant across the disc of the turbine rotor. For simplicity, in this work, the wind speed at a hub height of 80 m has been calculated from the wind speed at 10 m ($u_{10}$) above ground using the logarithmic law (Pielke, 2002):

$$u_{80} = u_{10} \frac{\ln(80/z_o)}{\ln(10/z_o)}$$

(7)

where, $z_o$ is the surface roughness length.

For all variables that appear in equations (6) and (7) hourly values for all days of the 10-year period are available through the HDDM10 dataset and substituting into the WPD equation (5), the wind power density for each grid point can be estimated on an hourly basis.

2.2 Radiative transfer scheme and solar energy data

The interaction of solar radiation with the earth-atmosphere system is responsible for maintaining the general circulation of the atmosphere as well as for the generation of various mesoscale circulations. The earth's surface primarily absorbs solar radiation and emits longwave radiation. Clouds and greenhouse gases both reflect and absorb incoming shortwave radiation, emitting longwave radiation both to earth and back to space. To compute the energy balance between shortwave and longwave radiation the POSEIDON weather forecasting system uses the radiation parameterization package which has been developed at the Geophysical Fluid Dynamics Laboratory (GFDL). The GFDL scheme includes the short wave parameterization of Lacis and Hanson (1974) and two-stream multi-band scheme with ozone from climatology and cloud effects; and the long wave parameterization of Fels and Schwarzkopf (1975) and Schwarzkopf and Fels (1991) and a multi-band scheme with carbon dioxide, ozone and microphysics effects. Taking into account the temperature distribution, the presence of clouds and the concentrations of water vapor, ozone, carbon dioxide, and aerosols the model calculates the temperature tendencies, longwave upward and downward fluxes and shortwave upward and downward fluxes.

The HDDM10 dataset provides the instantaneous incoming and outgoing shortwave radiation fluxes at hourly temporal resolution. Thus, the net solar radiation fluxes can be calculated at hourly temporal resolution. This instantaneous flux of the net solar radiation which is received per unit area on horizontal plane is called solar irradiance (W m$^{-2}$). Additionally, solar irradiation (or solar insolation) is the integral of the solar irradiance over a time period (e.g. 1 hour, day, month, year, etc.) and is expressed in Wh m$^{-2}$. The annual sum of solar irradiation as well the average annual daily solar irradiation at a specific location are of prime importance, as they are good indicators of the long-term performance and economics of solar energy systems at that location.

3. RESULTS

Wind power density (WPD) is a measure of the wind power potential at a particular location. For each hour from January 1999 to December 2004 at each 10x10 km$^2$ grid cell along the Mediterranean basin the wind power density at 10 m and at 80 m height above the surface has been calculated. Due to the cubic wind speed relationship the average daily wind power density has been computed by averaging the 24 hourly wind power density values per day. The maximum and minimum wind power density on a daily basis as well as the standard deviation for each grid cell are also calculated throughout the 10-year period. Similarly, average monthly wind power density has been estimated by averaging all wind power density values during the corresponding time period. Hence,
mean monthly, mean annual and the standard deviations of the monthly and annual means of the wind power density from the 10-year period have been calculated. Figure 1 shows the mean annual wind power density at 80 m height above the surface in the Greek territory. Additionally, the wind power density seasonal variability can be also investigated.

**Figure 1.** Mean annual wind power density at 80 m height above the surface in the Greek territory (W m⁻²)

Figure 2 shows the annual sum of the global solar radiation incident on a horizontal surface for the Greek mainland. Statistical properties including the average and the standard deviation of the daily solar radiation data for each grid point have been compiled. The solar radiation values are expressed also as monthly and yearly averages for the 10-year period. Minimum and maximum monthly and yearly averages are included to show the variability of a station's solar resource. The monthly mean data is calculated from daily estimates of solar radiation and the standard deviation of these daily values within each month are also provided.
Figure 2. Average annual sum (1/1995 – 12/2004) of global horizontal irradiation (in W m$^{-2}$) for Greek mainland.

Incorporating surface effects such as elevation and slope steepness with the solar data, results in a more accurate assessment of the local solar power potential and therefore more accurate solar resource assessment. In order to develop high resolution solar energy maps, the geographic information system (GIS) software ArcGIS is used to create a high resolution, i.e. 500x500 m$^2$ grid resolution, raster covering the entire study area of Greek mainland.

Generally, GIS is a technique to manipulate, manage, and analyze multidisciplinary geographic and related attribute data. In this work, a GIS-based modeling technique has been developed to process model generated gridded solar data and to produce the corresponding GIS layers. Then, the GIS topographical data layer was combined and analyzed with the solar raster data. Figures 3 and show examples of GIS maps of annual sum (1/1995 – 12/2004) of global horizontal irradiation (in W/m$^2$) for Greek mainland presenting regions with terrain slopes less than 1% and 5%, respectively.
Figure 3. The average annual sum (1/1995 – 12/2004) of global horizontal irradiation (in W m\(^{-2}\)) for Greek mainland. The coloured areas represent the regions with terrain slopes less than 1%.

Figure 4. The average annual sum (1/1995 – 12/2004) of global horizontal irradiation (in W m\(^{-2}\)) for Greek mainland. The coloured areas represent the regions with terrain slopes less than 5%.
4. SUMMARY

In this study, the ability of the HDDM10 dataset to provide useful information for the assessment of wind and solar energy resources is presented. Based on the products included in the HDDM10 basic parameters and statistical properties have been calculated. Furthermore, a methodology to map wind and solar energy resource at high resolution over a large territory is presented. The method introduces also GIS modeling techniques to resample the gridded data and to compute the solar energy resource at each grid point of a high resolution raster overlaid with other spatial datasets. The combination of the model gridded data and the GIS techniques represents a significant advancement in the assessment of renewable resources. As an application, the methodology was applied to develop a high resolution wind and solar energy atlas of the Greek territory.

REFERENCES