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Solar energy prediction and verification using operational model forecasts and ground-based solar measurements

P.G. Kosmopoulos [a, b, *], S. Kazadzis [a, c], K. Lagouvardos [a], V. Kotroni [a], A. Bais [b]

[a] Institute for Environmental Research & Sustainable Development, National Observatory of Athens, Greece
[b] Laboratory of Atmospheric Physics, Physics Department, Aristotle University of Thessaloniki, Greece
[c] Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Davos, Switzerland

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ABSTRACT

The present study focuses on the predictions and verification of these predictions of solar energy using ground-based solar measurements from the Hellenic Network for Solar Energy and the National Observatory of Athens network, as well as solar radiation operational forecasts provided by the MM5 mesoscale model. The evaluation was carried out independently for the different networks, for two forecast horizons (1 and 2 days ahead), for the seasons of the year, for varying solar elevation, for the indicative energy potential of the area, and for four classes of cloud cover based on the calculated clearness index (k_t): CS (clear sky), SC (scattered clouds), BC (broken clouds) and OC (overcast). The seasonal dependence presented relative rRMSE (Root Mean Square Error) values ranging from 15% (summer) to 60% (winter), while the solar elevation dependence revealed a high effectiveness and reliability near local noon (rRMSE ~30%). An increment of the errors with cloudiness was also observed. For CS with mean GHI (global horizontal irradiance) ~ 650 W/m^2 the errors are 8%, for SC 20% and for BC and OC the errors were greater (>40%) but correspond to much lower radiation levels (<120 W/m^2) of consequently lower energy potential impact. The total energy potential for each ground station ranges from 1.5 to 1.9 MWh/m^2, while the mean monthly forecast error was found to be consistently below 10%.

1. Introduction

The fifth assessment report of the Intergovernmental Panel for Climate Change [1] concluded that the evidence for climate change is now incontrovertible and that a large part of this ongoing change is attributable to human activities, particularly the increased release of GHG (greenhouse gases) into the atmosphere. Several actions point to the fact that a more climate-resilient economy and society must be built in each country, such as measures aimed at reducing fuel consumption for energy production, emphasis on energy efficiency and conservation, as well as on power generation from renewable sources such as the Sun.

Solar energy is the most abundant renewable resource and therefore much of the focus on sustainable energy is targeting optimum solar energy exploitation [2]. By 2050, the EU (European Union) Energy Policy Plan aims to limit climate change by capping the global temperature rise to no more than 2 °C [3]. For this reason, the EU provided the possibility for a reduction of GHG emissions in the member countries by 80–95% and hence established a goal of 20% of primary energy from renewable origin by 2020 [4]. In order to achieve this goal, the EU has laid out specific technology-roadmaps that will lead to the integration of low carbon energy technologies and in particular the deployment of CSPP (Concentrated Solar Power Plants) and CP (Concentrated Photovoltaic) installations in the energy economy.

The energy source for any stand-alone PV (photovoltaic) system is the solar insolation available at the location of the installation. The performance of such a stand-alone PV system is directly affected by the amount of insolation available to the system [5]. PV systems enable direct conversion of GHI (global horizontal irradiance) into electricity through semi-conductor devices. Electricity from PV systems is expected to have a potential infrastructure of more than 200 GW by 2020 [6]. For the design, implementation and efficient operation of these systems, the weather-dependent production plays a key role and determines the balance between production and demand. To enhance their efficient control and improve the accuracy of information on the availability of solar radiation, higher quality solar radiation data and validated forecasts

* Corresponding author.
E-mail address: pkosmo@meteo.noa.gr (P.G. Kosmopoulos).

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are essential for planning and for deployment purposes. A major challenge is that forecasting the available insolation is not an easy task since it depends strongly on localized site-specific and complex weather conditions.

Greece is one of the few EU countries endowed with potential for electricity production from renewable sources because of its climate, and with short-term objectives to increase the production from renewable energy sources to at least 20% of the total national energy production. Management of the electricity grid with a large volume of solar energy will require high-quality information on every aspect of solar power generation, and in particular, solar radiation forecasting. However, solar yield forecast is still at an early stage and few studies have dealt with the forecasting of solar resources and its application to management of solar-based electricity power plants and grid integration strategies. One interesting solar forecasting implementation is taking place in Germany since 2008, where two German transmission system operators mandated different forecast providers to implement and test PV forecasts for their balancing areas. These transmission system operators manage 2.9 GW of installed PV corresponding to over 200,000 systems across their balancing areas [7].

Many studies have focused on the benchmarking of different approaches to forecast solar irradiance in different study areas such as Germany, Switzerland, Austria and Southern Spain [8–11]. The aim behind all these studies was to predict operational solar energy. The Energy Managing Authority for Greece is the IPTO (Independent Power Transmission Operator, http://www.admie.gr) to which the NOA (National Observatory of Athens) provides solar energy forecasts for the next 48 h based on numerical weather prediction outputs. In this work, we present a comprehensive evaluation study of the reliability of GHI forecasts provided by the NOA operational weather forecasting chain based on the MM5 mesoscale model. The validation is carried out over Greece, and uses 48 h forecasts of GHI at 2-h temporal resolution. The aim is to investigate the current performance of the model for solar yield forecasting in the study region which is among the areas with the largest solar capacity in the EU. The work is organized as follows: in Section 2 the experimental design is presented. The evaluation of the model forecasts based on the observations is presented in Section 3. Finally, a summary of the results and some conclusions are provided in Sections 4 and 5.

2. Location, data and methods

2.1. Study area

The study area (Fig. 1) covers the region of Greece, in the southern part of the Balkan Peninsula. The whole region is located in the transition zone from temperate to subtropical climates, presenting a Mediterranean climate. For the needs of this study, 8 surface meteorological and solar radiation stations were selected from the network of stations operated by NOA, and also 3 stations from the HNSE (Hellenic Network for Solar Energy), with the aim to include a representative sample describing the climate variability within the study area.

The location of the stations is given in Fig. 1 and their coordinates and heights in Table 1. More precisely, Florina, Drama and Thessaloniki stations are located in the north of the study region and present a continental climate with low temperatures in winter, mean CF (cloud fraction) of about 0.7. The mean cloud fraction is based on a 10 year climatology study [12] in which satellite sensor MODIS is used. In summer months, the northern Greece presents CF of about 0.2–0.3. Amfiklia station is located in one of the highest plateaus of Greece, bounded at the west by the Pindos mountain. The area presents a relatively dry continental climate and high variability of the cloudiness during spring and autumn (CF ~0.4–0.5). The station Chania is located in the south of the study region, at the western part of the Crete island. As a consequence, presents a mild Mediterranean climate with CF ~0.6 in winter, ~0.1 in summer. Stations labeled as Kranidi, Argos and Paralia Achaias present similar climate conditions to the station Chania with mean CF ~0.6 in winter and ~0.1–0.2 in summer months. Spata and Athens stations are located on the Attica peninsula, which projects into the Aegean Sea. Athens station is sited into the Attica basin and is bounded by mountains. Spata station corresponds to the airport of Athens situated 35 km outside the city. This station is in the east part of Attica, at the middle of the study region, and similarly with Athens station presents an annual precipitation of about 380 mm. The last station is Arta, which is located in the western part of the study region and is influenced by frontal systems (annual precipitation is about 1100 mm and CF ~0.6 to 0.7 in winter and ~0.3 in summer). The climatological mean local noon values of GHI in the north of the study region range from ~700 W/m^2 at the surface to more than 800 W/m^2 at 3 km height. The mean local noon radiation values (mean maximum instant values) are based on a 5 year climatology study using data from the satellite sensor CALIOP [12]. At the same local noon time, the mean values in the southern Greece are about 830–850 W/m^2 (from t he surface to 3 km height).

2.2. Solar measurements and models

2.2.1. Solar radiation measurements and quality control

The automated surface meteorological stations deployed by NOA are of type Davis Wireless Vantage Pro2 Plus. As part of the NOA's automated surface meteorological station network, total solar radiation is also measured at a number of stations uniformly distributed across Greece. In this study, we make use of the solar irradiance measurements. Solar irradiance is measured with pyranometers with silicone photodiode detectors having an irradiance resolution of 1 Wm^{-2} and a sampling rate of 50 s [13]. The instrument calibration has been validated and corrections were applied using simulated observations with the radiative transfer model LibRadtran, as described later. Maximum absolute differences found were 5% for daily GHI integrals. We also used the HNSE (Hellenic Network for Solar Energy), which is a system for supporting applications of solar energy. Currently GHI pyranometers have been installed in different locations in Greece. For our verification study, we used the instrumentation from Athens, Thessaloniki and Argos stations. All stations are equipped with Kipp & Zonen pyranometers (types CM21, CM11 and CM10), which were calibrated before installation by comparison to a secondary standard pyranometer. Measurements for both networks are recorded automatically and are available on the internet (http://www.meteo.gr and http://www.helionet.gr for NOA's network and HNSE respectively).

To ensure the quality of measurements for both networks, we used the radiative transfer model LibRadtran [14] in order to verify and correct when needed the absolute calibration and the angular response errors of NOA and HNSE stations, under clear sky conditions. Basic input parameters to the radiative transfer simulations were the oblique angle of sunlight reaching the surface, ozone, reflectivity of the earth's surface, aerosol optical depth (at 550 nm) and water vapor. Outputs were the high resolution GHI spectral irradiance values that spectrally match the corresponding integrated values of Davis solar energy instruments and Kipp & Zonen pyranometers. GHI measurements were collected every 10 min from NOA network and every 1 min from HNSE. For our study, we picked out the temporal matching data to 2-h resolution in order to match the numerical weather prediction model temporal resolution. For input data to our radiative transfer model simulations, we