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SPACE-TIME HIGH-RESOLUTION DATA OF THE POTENTIAL INSOLATION AND SOLAR DURATION FOR MONTENEGRO

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The assessment of the potential use of renewable energy resources requires reliable and precise data inputs for sustainable energy planning on a regional, national and local scale. In this study, we examine high spatial resolution grids of potential insolation and solar duration in order to determine the location of potential solar power plants in Montenegro. Grids with a 25-m spatial resolution of potential solar radiation and duration were produced based on observational records and publicly available high-resolution digital elevation model provided by the European Environment Agency. These results could be further used for the estimation and selection of a specific location for solar panels. With an average annual potential insolation of 1800 kWh/m^2 and solar duration of over 2000 h per year for most of its territory, Montenegro is one of the European countries with the highest potential for the development, production, and consumption of solar energy.

***Key words*: potential insolation, solar duration, Montenegro.**

INTRODUCTION

As a result of increasing energy demand and related environmental concerns, renewable energy sources (RES) have been receiving increasing attention over recent decades. Among the different RES, the sun is an abundant, free, and clean source of renewable energy that can be used to generate heat and electricity (Mekhilef *et al*., 2011; Hosenuzzaman *et al*., 2015; Rustemli *et al.*, 2013). Solar thermal systems are now widely used for heating water, heating and cooling space, food refrigeration, desalination, drying, cooking, power generation (concentrating solar power system), etc. (Mekhilef *et al.*, 2011; Kannan and Vakeesan, 2016). Despite its numerous advantages, solar energy plays a negligible part in the global energy supply, although certain solar technologies, i.e., photovoltaic (PV) systems, have rapidly developed over recent decades, with system prices falling by about 80% between 2008 and 2016 (Waldau-Jäger, 2016). Moreover, the levelized costs of electricity generated from utility-scale PV systems were competitive with fossil fuels in 2018 (International Renewable Energy Agency [IRENA], 2019).

The European Union aims to increase the share of RES in the gross final energy consumption from 20% in 2020, to 32% by 2030 and 55% by 2050 (European Parliament, Council of the European Union 2009, 2018; European Union 2012). According to the Energy Community Treaty, to achieve this goal, all EU countries—including non-EU countries that follow EU regulations on RES—should adopt National

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Action Plans (NAPs), and other regulations to further increase the exploitation of RES. For instance, in Germany, the share of RES in the gross final energy consumption in 2018 was 16.6%. However, the contribution of RES to the gross electricity production was 37.8%, mainly from wind (18.5%) and solar PV (7.7%) (Federal Ministry for Economic Affairs and Energy, 2019). Over 1.6 million subsidized PV power plants, with a total nominal capacity of approximately 45.9 GW, were installed by 2018 in Germany (Fraunhofer ISE, 2019).

Concerning solar energy systems, the spatial and temporal distribution of solar radiation is a key component for the selection of their location, planning and performance simulation. The estimation of solar radiation is very important for remote areas where data obtained by ground station measurements are unavailable. Interpolation techniques are appropriate for lowland areas with a weather station density of one station per 1000 km^2 or more (Ruiz-Arias *et al*., 2009). Empirical models have been developed to overcome limited ground-level measurements of solar radiation based on other observational records, i.e., air temperature (Almorox *et al*., 2011; Yacef *et al*., 2014; Hassan *et al*., 2016), cloudiness (Ehnberg and Bollen, 2005; Badescu and Dumitrescu, 2013; Kostić and Mikulović, 2017), precipitation (Matsuda *et al*., 2017), humidity (Yang and Koike, 2002), air pollution (Zhao *et al*., 2013), sunshine duration, (Ångström, 1924; Prescott, 1940; Wang and Zhang, 2010; Chen, *et al*. 2013; Suehrcke, *et al*. 2013; Yao *et al*., 2018), etc. For example, Adeala *et al*. (2015) used multiple weather parameters to estimate the monthly average daily global solar radiation for the nine provinces of South Africa. Although satellite measurements provide a less accurate solar radiation value compared with ground-level measurements, they provide better spatial-temporal coverage. Several studies have indicated the advantages of combining satellite and ground-level measurements of solar radiation (D'Agostino and Zelenka, 1992; Journée and Bertrand, 2010; Lu *et al*., 2011).

Šúri and Hofierka (2004) determined three groups of factors that affect the interaction between solar radiation, the Earth's atmosphere and its surface: (1) Earth-Sun geometry (declination, latitude, solar hour angle); (2) topography (elevation, slope, aspect, and shadows); and (3) atmospheric attenuation (gases, clouds, solid and liquid particles). The first two groups can be modelled using trigonometry with a high level of accuracy (Liu *et al*., 2012). Topographic solar radiation models use information derived from Digital Elevation Models (DEMs) within a geographical information system (GIS) to provide rapid and accurate estimation over a wide geographic area (Tovar-Pescador *et al*., 2006; Hofierka, 2013). Modelling the third group of factors is possible with a certain level of accuracy because of the dynamic nature and complex interactions in the Earth's atmosphere (Šúri and Hofierka, 2004). Nevertheless, several software packages offer different methodologies for estimating solar radiation, such as Solei in IDRISI (Miklánek, 1993), SRAD as part of TAPES-G (Terrain Analysis Programs for the Environmental Sciences – Grid version) (Gallant and Wilson, 1996), Solar Analyst in ArcView and ArcGIS of ESRI (Fu and Rich, 2002), and the r.sun module of GRASS GIS (Geographic Resources Analysis Support System) (Šúri and Hofierka, 2004). Luković *et al*. (2015) used a DEM with a 90 m × 90 m resolution in the SAGA GIS (System for Automated Geoscientific Analyses) environment to map solar radiation in Serbia.

The main aim of this study was to create an open access solar radiation database for Montenegro and to analyze spatial-temporal variations. For this purpose, we applied a methodology proposed by Luković *et al*. (2015), adding improvements regarding the spatial resolution of input data layers, resulting in higher modelled outputs, and calibrating outputs based on observed measurements at eight weather stations. Such accurate and high spatial resolution solar radiation data are useful, not only for energy generation purposes, but also in various fields of applications in climatology, ecology, engineering, land management, and environmental science (Dubayah and Rich, 1995; Šúri and Hofierka, 2004; Tovar-Pescador *et al*., 2006).

THE PRESENT SITUATION OF ENERGY PRODUCTION AND CONSUMPTION IN MONTENEGRO

Montenegro ratified the Paris Agreement in 2016, thereby taking responsibility to limit the rise in global temperature by 1.5 °C in the second half of the 21st century. Efforts towards achieving this goal include reducing CO_2 emissions by 30% by 2030 compared to 1990 (Djurovic *et al*., 2018), and increasing the portion of energy produced from renewable sources, among which solar energy should be a priority.

In 2017, RES in Montenegro achieved a 32.3% share of the gross final energy consumption, i.e., 50.1% in the electricity sector, 36.1% in the heating and cooling sector, and 0.8% in transport (Energy Community, 2020). The target regarding the share of RES in the gross final energy consumption for 2020 was set to 33%, while the sectoral targets were set to RES having a 51.4 % share of the gross final electricity consumption, 38.2 % of the gross final consumption of energy for heating and cooling, and 10.2 % of the final consumption of energy in transport (Energy Community, 2014). Thermal power plants generate 53.9% of the total electricity, the rest comes from hydropower plants (42.1%) and wind turbines (4%) (Regulatorna agencija za energetiku Crne Gore, 2018). The contribution of solar energy to the gross electricity generation from RES in 2017 is negligible (0.1%) (Energy Community, 2020) and it is below the expected 0.7% for 2020 (Energy Community, 2014). During the period 2012 to 2017, within the project "Solar Katuns", 243 PV systems were installed in summer pasture settlements in the mountain areas of Montenegro (Government of Montenegro, Ministry of European Affairs, 2017; Regulatorna agencija za energetiku Crne Gore, 2018). According to the Energy development strategy of Montenegro (Ministarstvo ekonomije Crne Gore, 2014), expected PV power generation in 2030 is 52 GWh, which is ~1.4% of the national target for RES electricity production for 2030. The solar thermal energy will contribute to energy saving in the building sector, since it will substitute a great part of the electricity used for domestic water heating. Considering the absence of observational records for solar radiation in Montenegro, globally available solar radiation maps for the territory of Montenegro are generated based on satellite data (Ministarstvo za zaštitu životne sredine, kopna i mora Republike Italije, 2007).

PHYSICAL GEOGRAPHIC CHARACTERISTICS OF MONTENEGRO

The study area of Montenegro comprises almost 3% of the Balkan Peninsula, covering an area of 13812 km^2 (Burić *et al*., 2015), of which 210 km^2 are occupied by internal waters. Montenegro is characterized by complex orography that consists of a narrow Adriatic coastline (300-km long) stretching in the southern parts of the country, a limestone region in its central parts and the mountains of Montenegro, averaging more than 2000 m above sea level in the northern parts of the country (Figure 1).

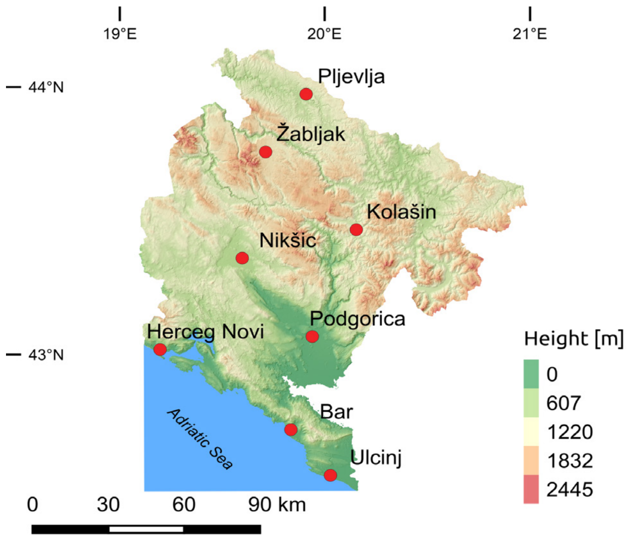

Figure 1. The geographical map of Montenegro, with the locations of weather stations

According to Koppen's classification of climate, most of Montenegro exhibits characteristics of a Mediterranean climate, characterized by hot and dry summers and mild and rainy winters in the south and coastal area, whereas the central parts of the country exhibit characteristics of a moderate-continental climate. In the higher mountainous areas in the north, which are over 1000–1200 m above sea level, there is a continental climate with cold winters and hot, humid summers with well distributed rainfall (Burić *et al*., 2013; Burić *et al*., 2014). The average amount of annual rainfall ranges from about 800 mm in the northeast to above 4000 mm in its southern parts, where one of the wettest areas of the Mediterranean region is located (Ducić *et al*., 2012). The average annual temperature ranges from 4.6 °C in Žabljak (1450 m a.s.l.) to 15.8 °C in Budva (2 m a.s.l.). The highest temperature of 44.8 °C was recorded in Podgorica (49 m a.s.l.). The coastal area receives up to 2600 h of sunshine per year. In the central plain areas, there are also a large number of sunshine hours: during winter it is similar to the amount of solar radiation of the coast, but relatively less in summer. Based on calculated averages for the period 1971–2000 the annual sunshine hours range from 2560 h/year for Ulcinj, 2479 h/year for Podgorica, 2239 h/year for Nikšić to 1589 h/year for Pljevlja (Italian Ministry for the Environment, Land and Sea, 2007).

METHODOLOGY AND DATA

Grids of potential insolation (INcoming SOLar radiATION), which represent the amount of solar radiation received at the Earth's surface (Petersen *et al*., 2016) and the duration of solar insolation (Li *et al*., 2011), were produced for Montenegro for 2018 in the SAGA GIS (Böhner *et al*., 2006) open-source software environment using the "Potential Incoming Solar Radiation" tool (Conrad, 2010). This tool calculates diffuse, direct, and total insolation, together with the duration of insolation for a certain period, aggregated to a specified time resolution. The latest version of SAGA GIS offers the r.*sun* algorithm (Šúri and Hofierka, 2004) for the calculation of insolation indices. Since the algorithm does not take cloudiness into consideration when calculating insolation parameters, the daily outputs require correction. Therefore, the outputs were multiplied by the daily Insolation Clearness Index (ICI) grid that characterizes the sky clearness (Beyer *et al.* 1997; Šúri and Hofierka 2004).

Despite the fact that SAGA offers a different combination of input parameters, our focus was on the most prevailing factors of the spatial variability of the radiation/insolation: topographic indices derived from digital surface models (DSM), geographical coordinates and ICI. Moreover, data on the observed duration of insolation from weather stations were also used for calibrating the duration of the insolation grids.

The European Digital Elevation Model (EU-DEM), implemented under the Copernicus program and provided by the European Environment Agency (2016), was used in this study as a digital surface model. It is a new hybrid product, primarily based on SRTM DEM and ASTER GDEM data with a 25-m grid cell resolution.

The daily Insolation Clearness Index data were obtained from the NASA Langley Research Center (LaRC) POWER Project (Stackhouse *et al*., 2020). These data were provided in vector format as points spread over a 0.5 × 0.5 degree (approx. 55.5 × 55.5 km at the Montenegro average geographical latitude) grid for a specified time period and region of interest. In this manuscript, we use daily data for 2018. Daily measurements were rasterized and downscaled to a resolution of 25 m using cubic spline interpolation (Figure 2).

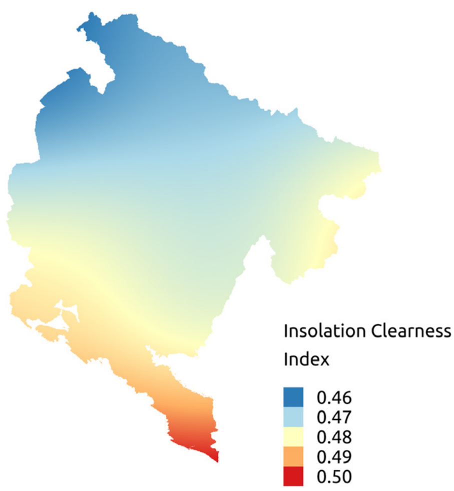

Figure 2. Insolation Clearness Index (ICI) map for Montenegro in 2018 (lower index values indicate more cloudiness)

Monthly data on the observed duration of sunshine in hours were collected for eight weather stations in Montenegro: Bar, Herceg Novi, Nikšić, Podgorica, Kolašin, Žabljak, Pljevlja, and Ulcinj (Figure 1). The grid of solar duration obtained by the SAGA Potential Incoming Solar Radiation module was calibrated with observational data in order to obtain more reliable outputs.

RESULTS

The grids of potential insolation and solar duration with 25-m spatial resolution were calculated for each day of 2018. The grids obtained were aggregated at monthly and annual levels. The monthly and annual values for potential insolation and solar duration are given in Table 1. Based on statistics for the overall grid cells values, median values (Md) and interquartile ranges (IQR) between the 75th and 25th percentiles were also calculated.

Table 1. Monthly and annual potential insolation (PI) [kW/m²] and solar duration (SD) [hours] with respective medians (Md) and interquartile ranges (IQR) for 2018. Statistical measures are based on all pixels over the territory of Montenegro for the corresponding time period

Month	PI	PI_Md	PI_IQR	SD	SD_Md	SD_IQR
Jan	74	74.6	44.3	74.7	81.4	29.1
Feb	73.6	74.8	31.4	60.8	65.1	22.7
March	107.9	110.4	27.1	108.5	113.6	26.7
April	186.7	191.9	21.1	194.4	198.7	33.1
May	211.2	215.4	12.1	227.4	233.8	41.5
June	211.2	213.5	21.7	229	230.9	38
July	238.8	241.7	19.7	249.4	250.7	45.2
Aug	230.8	236.4	18.5	274.3	280.5	35.3
Sep	197.7	203.2	36.3	219.4	224.9	35.3
Oct	129.7	133.5	44.4	154.9	162	33
Nov	81.2	82.7	43	70.6	75.8	28.4
Dec	67.3	67.9	45.8	73.9	79.7	36.3
Annual	1810.2	1854.3	323.2	1976.5	1980.2	364.9

The highest potential insolation is recorded in July (238.8 kW/m²), whereas the greatest number of sunshine hours is in August (274.3 h). December is the month with the lowest potential insolation (67.3 kW/m²), whereas solar duration is the lowest in February (60.8 h).

In order to check the sensitivity of the results regarding the spatial resolution of DEM, the same procedure was repeated with an SRTM DEM with a spatial resolution of 90 m. The results obtained for both potential insolation and solar duration were similar, suggesting that the algorithms provided in *r.sun* module are invariant to spatial resolution.

Solar duration (SD) was also used as a measure of incoming solar radiation. The maps showing the duration of insolation were calibrated with *in situ* measurements from eight weather stations. Monthly summaries from SAGA GIS were paired with monthly in situ measurements, and simple linear regression was performed. The output model parameters for calibration are given in equation (1):

$$S_{CAL} = 1.5436 \cdot S_{SAGA} - 72.3342 \qquad (1)$$

where S_{CAL} is a calibrated grid value of SD and S_{SAGA} is a grid value of SD generated using the SAGA Potential Incoming Solar Radiation module.

In order to validate the model, 10-fold cross validation was performed at a monthly level. The resulting Root Mean Square Error (RMSE) was 23.9 h/month and the Mean Absolute Error (MAE) was 19.9 h/month with a coefficient of determination R^2 = 0.93. A Scatterplot of the SAGA *calculated* and *in situ* measurements with a regression line is shown in Figure 3.

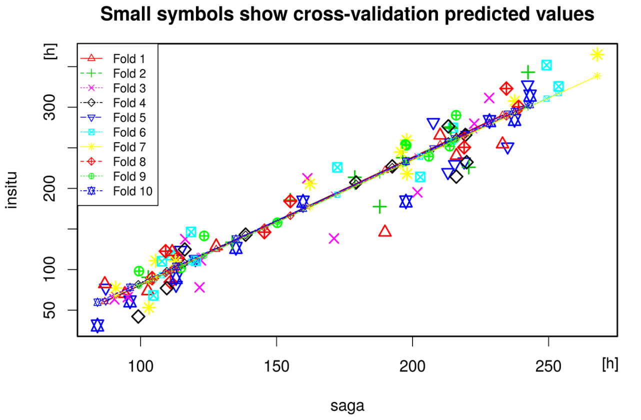

Figure 3. The scatterplot of SAGA calculated and in situ measurements of solar duration in 2018

DISCUSSION

Almost identical values for the average/mean and median for both PI and SD in Table 1, indicate their symmetrical distribution over the area of Montenegro.

The spatial pattern of the annual potential solar radiation (Figure 4) shows lowland areas and the southern slopes of the mountains in Montenegro receiving generally the highest amount of solar radiation. On the other hand, the western parts of Montenegro receive the lowest portions of potential solar radiation.

Higher IQR values (higher than 30 kW/m²) for potential insolation are characteristic for autumn and winter months, which means that during that time of year, differences in PI values are pronounced, depending on the spatial location.

Figure 5 shows that the greatest annual solar duration in Montenegro is in the coastal and central parts of the country (over 2000 h). The lowest annual number of sunshine hours (below 600 h) is mainly over the western slopes in the mountainous areas of Montenegro.

In contrast to potential insolation, higher IQR values (higher than 30 h) for solar duration are characteristic for spring and summer months, which means that during that time of year, differences in PI values over the area of Montenegro are more pronounced, depending on the spatial location.

The maps (grids) of monthly and annual aggregations of potential insolation and solar duration for Montenegro in 2018 are publicly available and freely accessible at URL: http://osgl.grf.bg.ac.rs/en/materials/insolation_mne/.

Furthermore, data and corresponding metadata are published through Geoserver and Geonetwork, which are standard services for data and metadata dissemination, supported by the Open Geospatial Consortium (OGC) and Open Source Geospatial Foundation (OSGEO). As per OSGEO:

> "GeoServer is a web server that allows you to serve maps and data from a variety of formats to standard clients such as web browsers and desktop GIS programs. Data is published via OGC standards based interfaces, such as WMS, WFS, WCS, WPS" (OSGeo, 2020).

Data can be sought or downloaded in various standard formats for a specific location of interest. These platforms have a long and proven history of successful applications in various domains (Yu *et al.*, 2013; Cignetti *et al.*, 2019; JeeHee *et al.*, 2019).

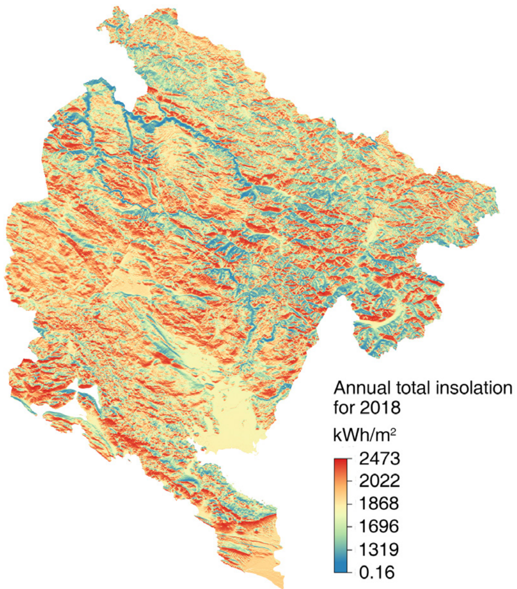

Figure 4. The grid of annual potential solar insolation in 2018

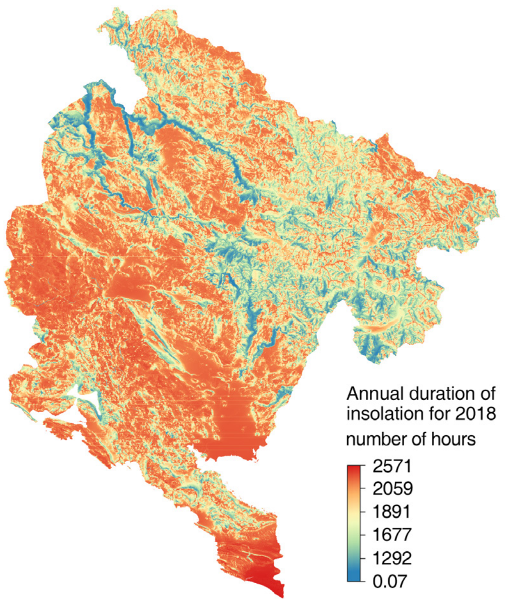

Figure 5. The grid of annual duration of insolation in 2018

All maps (grids) are open access, freely available to download in raster GeoTIFF format with a resolution of 25 m. They are georeferenced in the UTM (Universal Transversal Mercator) projection, which enables their usage for planning and designing the future production and consumption of solar energy for the whole of Montenegro. The high spatial resolution of the grids produced makes them suitable for both regional and sub-regional studies. Please refer to this paper when using these data.

CONCLUSIONS

This paper presents the first database of potential insolation and solar duration at a high spatial resolution (25 × 25 m) for the entire area of Montenegro. The resulting solar duration database was additionally calibrated with a regression model with a high coefficient of determination ($R^2 = 0.93$).

Considering the relatively small area of the territory of Montenegro, large differences in the annual values of solar radiation cannot be observed. Montenegro shows great potential for solar energy systems, as the number of sunshine hours is over 2000 h per year over most of the territory of Montenegro and more than 2500 h per year along the coastal areas. The amount of solar radiation in Montenegro, especially in the coastal and central areas, is comparable to the amount of solar radiation in European Mediterranean countries. Since the results obtained show very high solar radiation in the coastal and central areas of Montenegro, the use of solar thermal energy in Montenegro is strongly recommended. As in other Mediterranean countries, the solar power systems do not require high levels of performance, because of the generally high solar radiation and mild characteristics of the climate. Since tourism is one of the national priority sectors in Montenegro, the highest economic benefits might be achieved through the implementation of passive as well as active solar architecture (solar collectors for heating in households and tourist facilities) (Ministarstvo za zaštitu životne sredine, kopna i mora Republike Italije, 2007). The methodology presented in this work is applicable for the calculation of solar irradiation on the scale of higher resolution (i.e., roofs of buildings). However, to obtain such precise and detailed results for solar radiation, a good quality digital surface model, based on a stereophotogrammetry or Light Detection and Ranging (LiDAR) technology survey is required (Protić *et al.*, 2018). Supported by systems for spatial visualization, decision modelling and spatial decision support, these results are powerful tools that can be used in urban planning (Marić *et al.*, 2016).

Considering the potential of Montenegro in solar energy, solar architecture should be subsidized through different national projects and initiatives.

Acknowledgments

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