Physical potential of the photovoltaic system

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Abstract. This paper aims to determine the physical potential of the photovoltaic system in two locations in Montenegro. The focus is on urban areas suitable for PV systems on buildings' rooftops. The determination is performed with meteorological datasets of the Institute of Hydrometeorology and Seismology of Montenegro and analyzed using Matlab. The methodology presented in this paper includes detailed hourly data of global solar radiation on the horizontal surface for 2017. The results show the highest monthly average solar radiation for different inclination and orientation angles of the observed locations, Podgorica (7255.724 Wh/m^2) and Bar (8428.876 Wh/m^2), in June. For a more precise determination of the potential of PV systems is crucial to know not only the physical potential but also geographic, technical and economic potential. The presented results are the basis and the first step toward a deeper analysis of photovoltaic potential. It implies the inclusion of a significantly longer dataset, more locations and comparing results with those from the region and the EU.

1 Introduction

Solar radiation is a key factor determining electricity produced by photovoltaic (PV) systems [1]. By their properties, PV systems are considered as energy sources of the future. Many researchers have addressed the PV systems as the most dominant source of renewable energy technologies. By Dincer [2], the most important reason is that it is unlimited and clean energy of the solar systems. Many studies show that PV systems will have a significant share in the electricity of the future.

By Makrides et al. [3], the enormous potential of PV technology is evident and favorable in countries with high irradiation, such as the Mediterranean region. By Pedraza [4], solar energy is a clean energy source useful for electricity generation and heating in sunny countries. Solar power is costly and cannot be considered as efficient as other renewable energy sources.

By Bajat et al. [5], Montenegro is one of the European countries with the highest potential for the development, production, and consumption of solar energy, with an average annual

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potential insolation of 1800 kWh/m² and solar duration of over 2000 h per year for most of its territory.

By Babic [6], solar energy and PV power plants are the most modern power sources. The criteria used to evaluate the modernity of an energy source are a renewable primary energy source, the potential for its use, environmental acceptability, availability, reliability, distribution, type of technology, aesthetics, modularity, stability, demanding maintenance, mode of operation and competitiveness in price.

By Sikic [7], there are two primary groups for the direct use of solar energy. The first is active utilization, in which solar energy is converted into heat or electricity with specially designed devices (collectors, cells). In another passive way, solar energy can be used without intermediate devices. This is mainly related to the construction and orientation of buildings. The most important penetration of renewable energy sources, including solar energy, is in connection with active buildings that combine energy efficiency measures and auto-production [8].

By Seder [9], when analytically determining the potential of solar radiation, it is vital to collect data on the intensity of solar radiation, and the suitability of a specific climate for installing PV systems can be assessed. Namely, less global radiation also means less electricity production for installed PV or solar power plants of the same installed capacity. The integration of PV systems mainly depends on the location of the installation place and the type of installation. Zambrano-Asanza [10] describes the PV solar potential in an urban sector. If such a sector is in locations suitable from the point of view of PV systems, it means they have perfect conditions for installing PV systems on the rooftop of buildings, particularly.

By Xu et al. [11], solar potential in the urban environment is becoming a topic of great importance due to actual environmental and energy crises. They calculated PV output for roofs and facades and showed differences between the three types of urban blocks. Thus commercial blocks received the total solar irradiation, followed by residential and industrial blocks. There is a similarity in PV potential within similar urban block types. Determining the influence of urban form on solar potential is an area of increasing interest. It is necessary to explore the land use and determine the PV potential of each block by estimating the solar radiation available per square meter of the site area. This will help urban planners to optimize PV installation methods for different building types. Many researchers describe the relationship between urban space and solar potential. Izquierdo et al. [12] identify different levels of PV potential: physical potential, geographical potential, technical potential, and economic and social potential.

For efficient and effective integration of PV systems into networks, it is crucial to determine the availability of PV potential for electricity generation. By Mavsar [13], the basic methodology has four levels of calculation of PV potential: physical potential (PP), geographical potential (GP), technical potential (TP), and economic potential (EP). Several studies describe the correlation among PV potentials and include different names (e.g., physical, geographical, technical, spatial, economic, urban, social, etc.). By Sredensek et al. [14], while the PP means the total amount of solar energy coming to a specific area, the GP means the spatial availability of a certain area where the PP was calculated. For urban areas, GP of the PV systems depends mainly on the mutual position of nearby buildings, more precisely, shadows of nearby buildings and other obstacles. It also affects the other two potentials, TP and EP.

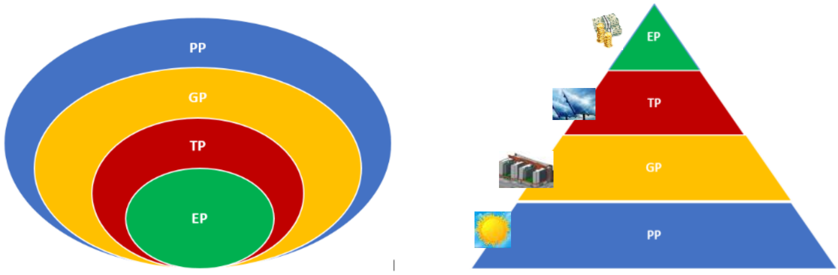


Fig.1. Four levels of PV potentials: PP - total solar radiation on rooftops; GP - available solar radiation on rooftops: TP - electricity generation by the efficiency of PV system; EP - electricity generation by the electricity price [14].

For a convincing estimation of PP, it is advised as suitable to use long-term databases. Such databases from trusted sources reduce calculation unreliability to a minimum. By Buffat et al. [15], estimating the solar radiation potential of roofs in large regions considering long-term databases (22 years) reduces the uncertainties. Less populated areas are often more suitable for installing PV systems than urban areas with large buildings.

This paper assesses and analyzes the availability of the physical potential of PV systems in two selected locations, Podgorica and Bar, in Montenegro. Several studies [13][14], [16] describe that analysis of all four potentials, and preferably simultaneously, is necessary for further understanding of sustainable and safe investment in PV systems. Such analyses are planned for further work on the doctoral dissertation. In addition, the calculation of CO_2 emission equivalents would also be conducted to explore the contribution of rooftop PV to urban energy security [17].

2 Problem background

The PV work, the historical background, various devices and concepts, and the physical limitations of conversion efficiency are well described by Lincot [18]. The PV effect was discovered by Edmond Becquerel in 1839. Then it took 115 years to make the first efficient solar cell, with a few Watts produced, about 50 years to deploy 3 GW of production capacity worldwide, and only 13 years to reach 300 GW in 2016.

The essential in PV systems is to know the amount of sunlight available at a particular location at a given time. By Seme [19][19], the electricity produced by a solar power plant depends primarily on the available solar radiation that reaches the solar modules, the quality and type of solar modules, their temperature, the DC/DC converter and the DC/AC inverter. Solar radiation that reaches the earth's surface depends mainly on the conditions in the atmosphere and the geographic location. Solar radiation is higher for PV modules when the rays fall directly on the module surface. By Dubey et al. [20], PV modules with less temperature sensitivity are preferable for the high-temperature regions and more responsive to temperature will be more effective in the low-temperature regions. The geographical distribution of PV energy potential considers the effect of irradiation and air temperature on PV system performance.

2.1. Calculation of the incidence angle of the Sun

The Sun's angle depends on latitude, time of year, and time of day. During the day, to any given location, it decreases from sunrise until noon and increases until sunset. At greater angles (morning and evening) solar radiation has to pass through a deeper layer of the atmosphere, which reduces its irradiance. So sunlight feels less intense in the evening than at noon. Clouds and aerosols in the atmosphere scatter/absorb radiation and so reduce the amount of radiation that reaches the Earth's surface. As cloud cover increases, the Sun's angle becomes less significant when measuring irradiance. A few main parameters determine the Sun's relative position to the Earth. Solar hour angle $\omega(t)$ turns the local solar time (LST) into degrees (^{0}) that the Sun has passed according to (1):

$$\omega(t) = (LST - 12) \cdot 15^{0} \quad (1)$$

Solar altitude angle $\alpha_s(t)$ is an angle between the Sun and the horizontal surface by (2):

$$\sin \alpha_s(t) = \sin \delta \sin L + \cos \delta \cos L \cos \omega(t) = \cos z(t) \quad (2)$$

The elevation angle is the angular height of the Sun in the sky measured from the horizontal. Confusingly, altitude and elevation are also used to describe the height in meters above sea level. The elevation is 0 ° at sunrise and 90 ° when the Sun is directly overhead (e.g., the equator on the spring and fall equinoxes). Zenith angle $z(t)$ s the angle between the Sun and the vertical, by (3):

$$z(t) = 90^{0} - \alpha_s(t) \quad (3)$$

Declination angle δ is the angle between the equator and a line drawn from the center of the Earth to the center of the Sun. Inclination angle β (or tilt) is the angle of the surface above the horizon. Solar azimuth angle γ shows the direction from which the sunlight is coming. Latitude L of the location of interest is positive for the northern hemisphere and negative for the southern hemisphere.

The incidence angle of the Sun $i(t)$ is the angle between sunbeams and the normal to the surface with any azimuth angle (an inclined surface) by (4):

$$i(t) = \cos^{-1}[\sin \delta \sin L \cos\delta - \sin \delta \cos L \sin \beta \cos \gamma + \cos \delta \cos L \cos \beta \cos \omega(t) + \cos \delta \sin L \sin \beta \cos \omega(t) \cos \gamma + \cos \delta \sin \beta \sin \omega(t) \sin \gamma] \quad (4)$$

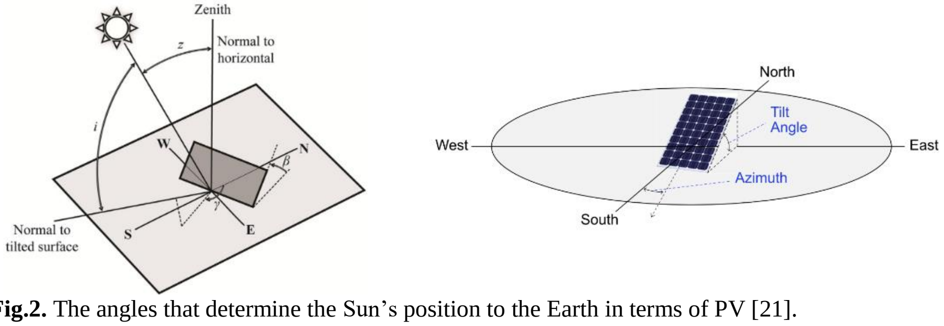


Fig.2. The angles that determine the Sun's position to the Earth in terms of PV [21].

2.2. Calculation of the physical potential of the PV system

Solar radiation is characterized by measuring solar irradiance and solar insolation. Solar irradiance (radiation) represents power per area at a given moment, while solar insolation is the energy per area delivered over a specified time.

The PP determines the solar radiation energy received by the entire considered surface during a certain period by (5):

$$PP = A_T \cdot \int_{Sunrise}^{Sunset} G_h(t)dt \quad (5)$$

where A_T is the entire roof surface in the area under consideration (m^2), while $G_h(t)$ is the global solar radiation on a horizontal surface (W/m^2).

3 Methodology

This paper covers more than 20 scientific articles published last two decades, in which authors deal with PV properties. This section presents meteorological data of the observed areas in Montenegro for further determination of PV potential. The collected data, results and associated analyses of the obtained results are provided, and the relevant method for determining the PV potential is present.

This paper aims to determine the PP in the considered area based on the available meteorological data. Data from the IHMS are hourly values of the air temperature (T), which will be used in the next phases of PV potential determination, and global solar radiation on the horizontal surface (G_h), which is important and used for PP. The year 2017 is a typical meteorological year with high-quality data sets for two locations in Montenegro, Podgorica (Central region) and Bar (Southern region). By Huld et al. [22], hourly resolution of data allows for more detailed estimates of PV performance. Meteorological and climatological studies rely on knowledge of the solar radiation field over large areas in both the short and long term. The points of interest of this paper are two areas located in the central and southern regions of the country. Planning solar energy systems requires data on solar irradiation at the site where the system will be installed. Determining the PP on the roofs of buildings represents a sustainable and safe investment and a means of self-sustainability in the energy sector. Correct assessment of the efficiency of PV systems is also of importance. At this stage of the research, there was no data on the available roof area due to the lack of official geospatial data for the considered locations. Those data will be obtained in the second phase of research while the GP, TP and EP determining. For this reason, the PP is considered when A_T is one square meter of some rooftop. So, the PP has to calculate using the hourly solar radiation data on a horizontal surface for Podgorica and Bar. The results are in section 4.1.

4 Results

Using two locations helps determine how much solar energy they have. In addition, they show that using a large amount of data is fundamental for accurately assessing the PV potential. The results achieved by this research depend on different local variables related to weather and climate conditions, PV module characteristics, and, mainly, the user's behavior [8]. The hourly meteorological data for one year are outlined for two locations (Podgorica and Bar) under the analysis of the PP.

4.1. Evaluation of the physical potential

The PP calculation was described in subsection 2.2. The edited meteorological data provided by IHMS of Montenegro were imported into Matlab software, and PP determination procedure was performed. PV system will collect solar radiation most efficiently when the Sun's rays are perpendicular to the panel's surface. Figures 4 and 5 show the PP for each month and the expected values, where: the highest values are achieved in the summer months. In June, the monthly average solar radiation is 8428.876 Wh/m^2 of the considered area of Bar. The lowest values are in the winter months. In December, the monthly average solar radiation is 3272.75 Wh/m^2 of the considered area of Podgorica.

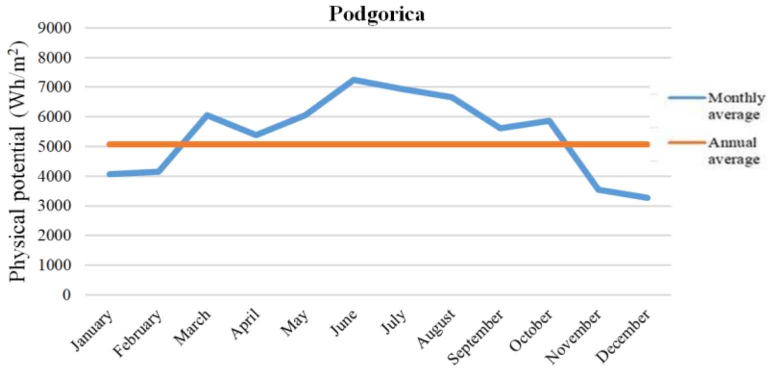


Fig.4. PP (Wh) expressed per unit area (1 m^2) of rooftops in Podgorica based on hourly measurements for 2017.

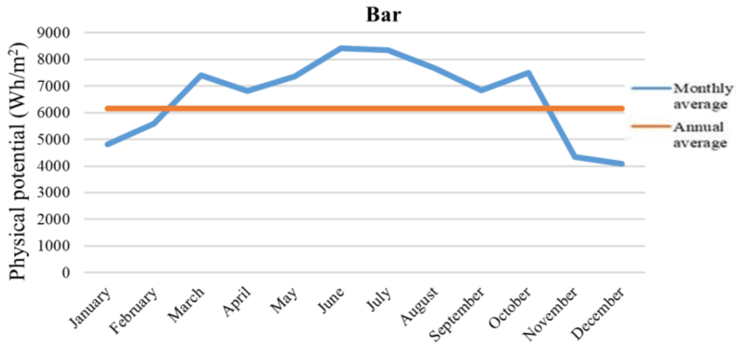


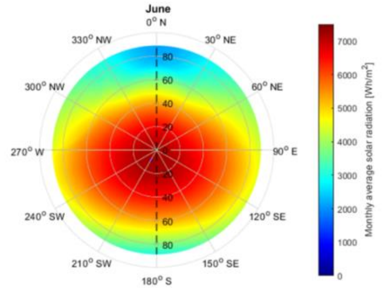
Fig.5. PP expressed per unit area (m^2) of rooftops in Bar based on hourly measurements for 2017.

Table1. Values derived from Matlab for Podgorica (PG) and Bar (AA-Annual average).

	Azimuth (°)		Tilt (°)		Monthly average solar radiation(Wh/m^2)	
	PG	Bar	PG	Bar	PG	Bar
Jan	187	180	72	69	4067.86615821031	4810.18140750250
Feb	187	189	66	66	4151.42549449889	5597.42266158885
Mar	188	195	53	54	6054.21539786678	7401.82016759437
Apr	191	204	35	36	5386.07227184055	6823.05149022643
May	186	225	18	24	6065.02122598906	7369.66552982281
June	207	249	10	20	7255.72425859810	8428.87608658488
Jul	208	232	14	21	6933.82783113296	8356.47002970134
Aug	194	213	29	32	6655.85001330436	7658.90838748198
Sep	176	195	46	47	5620.46878639211	6829.17640208357
Oct	179	184	61	62	5865.56893865277	7491.09367279674
Nov	177	181	70	66	3552.22518949724	4332.59097071825
Dec	182	165	74	74	3272.75958350278	4092.83645424464
AA	187	194	43	42	5071.81139076168	6150.27720730271

This is due to the declination of the Sun, which means that the northern hemisphere of the Earth is tilted towards the Sun during the summer months. As a result, in the summer months, the Sun's rays reach the northern hemisphere at sharper angles, and the Sun stays in the sky longer and reaches a higher angular height compared to the same time of day in the winter months. So, for Podgorica, the azimuth angle is 207° and the tilt angle was 10° in December 2017. Similarly, for Bar the azimuth angle is 249° and the tilt angle was 20° in June 2017, as described in subsection 4.1.

The results derived by integration of datasets into Matlab show that the highest monthly average solar radiation for different inclination and orientation angles of the observed location Podgorica is 7255.724Wh/m^2 and Bar is 8428.876Wh/m^2. For both locations, the highest levels are in June. As shown in Fig.6 and 7, the results are presented as polar contour plots. The maximum value of solar irradiation is a blue dot.



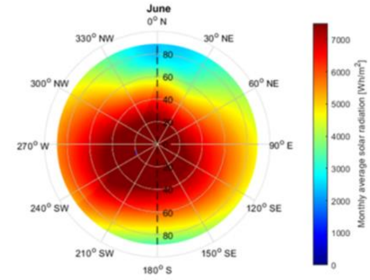
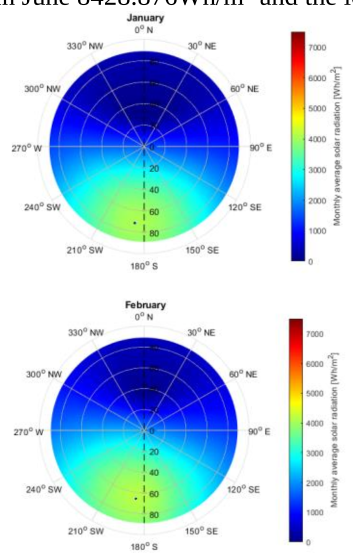


Fig. 6. Polar contour plot of monthly average solar radiation for different inclination and orientation angles of the observed area of Podgorica. A surface facing 207^0 SW with an inclination angle of 10^0 received the highest monthly average solar radiation of 7255.724Wh/m^2 in June 2017.

Fig. 7. Polar contour plot of monthly average solar radiation for different inclination and orientation angles of the observed area of Bar. A surface facing 249^0 SW with an inclination angle of 20^0 received the highest monthly average solar radiation of 8428.876Wh/m^2 in June 2017.

4.2. Comparison of results from two locations

As shown in Fig. 10 and 12, for Podgorica, the monthly average solar radiation presents the highest values in June at 7255.724 Wh/m^2 and the lowest in December at 3272.759 Wh/m^2. As shown in Fig. 11 and 13, for Bar, the monthly average solar radiation presents the highest values in June 8428.876Wh/m^2 and the lowest in December at 4092.836 Wh/m^2.



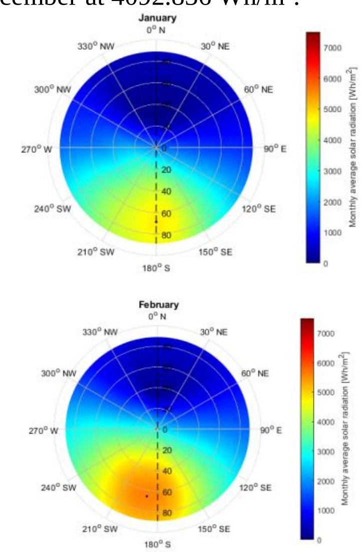


Fig.8. Polar contour plots of monthly average solar radiation for different inclination and orientation angles of the observed area of Podgorica (January - February).

Fig.9. Polar contour plots of monthly average solar radiation for different inclination and orientation angles of the observed area of Bar (January and February).

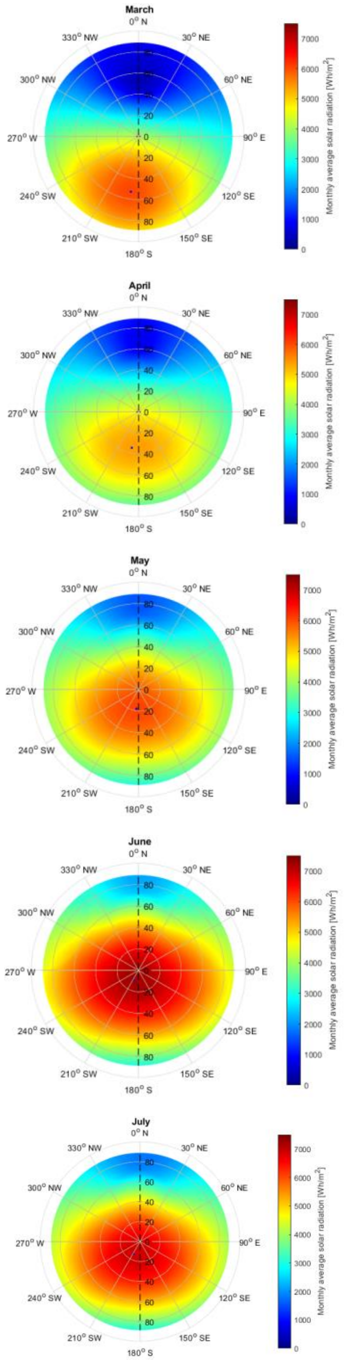


Fig.10. Polar contour plots of monthly average solar radiation for different inclination and orientation angles of the observed area of Podgorica (March - July).

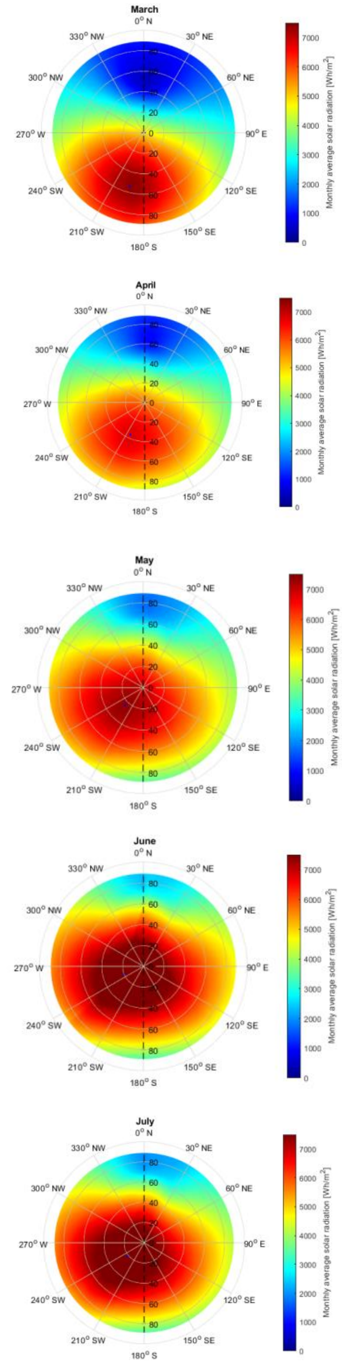


Fig.11. Polar contour plots of monthly average solar radiation for different inclination and orientation angles of the observed area of Bar (March - July).

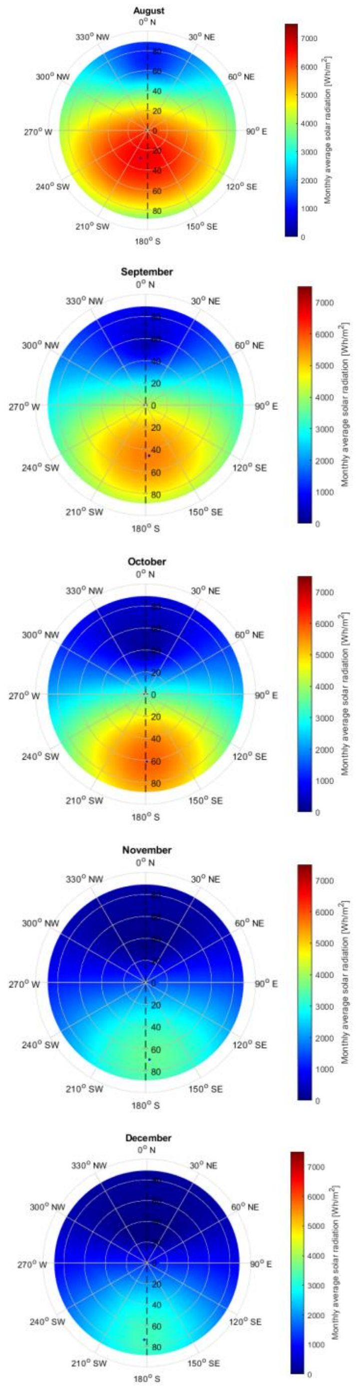


Fig.12. Polar contour plots of monthly average solar radiation for different inclination and orientation angles of the observed area of Podgorica (August - December).

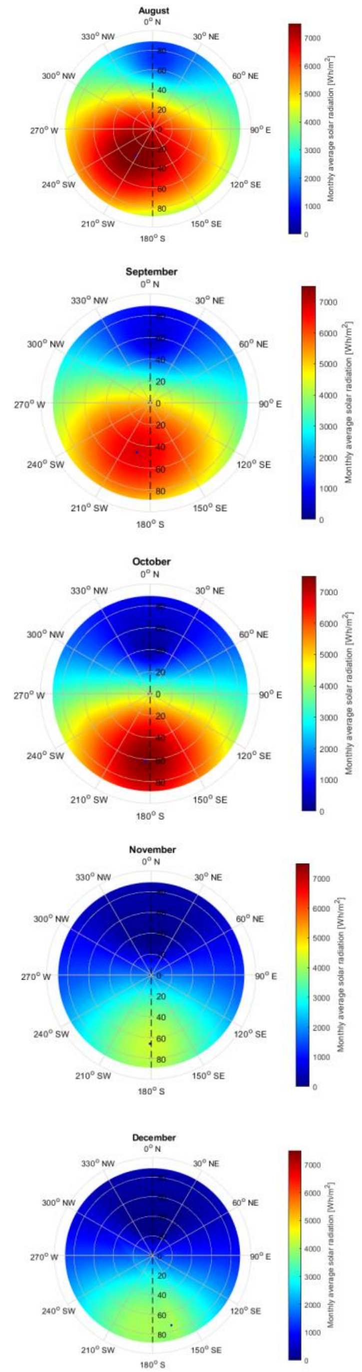


Fig.13. Polar contour plots of monthly average solar radiation for different inclination and orientation angles of the observed area of Bar (August - December).

5 Further work

This paper presents the determination of total solar radiation on rooftops, known as PP. This paper represents the first part of the doctoral thesis in progress, which will also include the determination of the other three levels of PV potential (geographical, technical and economic) and the calculation of carbon dioxide emissions. This approach is vital to explore the contribution of rooftop PV potential as a significant space for clean energy. Detailed analysis of all four potentials is necessary to further understand sustainable and safe investment in PV systems. In line with [14], determining maximum PV potential based on several potentials simultaneously will be in special focus of my research.

Also, in further work to determine all four PV potentials, the approach of substituting geospatial technologies and software will be considered if no available ones are used in the existing open literature. This is because, for example, until the completion of this work, it is not known that there were official LIDAR data for Montenegro. Such data, but for other countries, were used when determining the geographic potential in most research studies on this topic.

Conclusion

This research paper brought the determination of the PP for two locations in Montenegro for the first time. It is unknown that this has been done so far for any location in Montenegro. It is mainly known that the most suitable months in Montenegro in terms of PP are the months from April to September. This paper has confirmed this and shown that the highest PP values are in June for both locations, placed in different regions of the country. PV potential depends mostly on the intensity of solar radiation on the horizontal surface (G_h), which means that the higher the value of G_h, the higher the potential. But, PV system efficiency and efficacy depend on many other vital factors like the position of the building, then the movement of energy prices, and the level of investments in renewable energy sources. Therefore, it is also essential to determine GP, TP and. For the determination of GP, geospatial technology needs to detect and count a number of objects and available rooftop surfaces. For determination of TP and EP it is important to have data about seasonal electricity generation variations. It will be a great challenge to get all the necessary data for comprehensively determining the potential of PV systems in the near future.

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Senior Advisor, Sector of Meteorology, IHMS, 2010 - 2013

Senior Advisor - Climate Change & ENV, Ministry of Environment and Tourism, 2007 - 2010

Physicist, Nuclear Medicine Diagnostic Department, Clinical Center of Montenegro, 2007

Professor of Physics, High and Elementary Schools (Podgorica, Cetinje, Nikšić), 1998 – 2007

Certificates/Award:

Certificate of successful completion the EUMETrain course „Synoptic and Mesoscale Analysis of Satellite Images ", 2016

Certificate of successful completion „Using Scatterometer Wind and Altimeter Wave estimates in Marine Forecasting ", EUMETSAT, 2016

Certificate of Excellence, International Summer School on Applications with the Newest Multi Spectral Environmental Satellites, EUMETSAT, EUMETrain, 2015

Certificate: UNIDO National Cleaner Production Expert, 2014

Certificate: "Beyond Response: Better Preparedness for Environmental Emergencies", 2013

Certificate: 2nd International Conference Protection Ecology Security, 2013

Certificates: "Floods, the Most Frequent Natural Disaster in the Mediterranean ", 2011, Drought risk assessment, 2010, Disaster Risk Reduction/BCPR/UNDP, 2010

Certificate: Clean Development Mechanisms - Kyoto protocol, National Strategy for Sustainable Development, 2008

Certificate of Academic Committee the 38th International Physics Olympiad, Isfahan, Iran, 2007

Gold Medal in biology, Youth Science Movement (Pokret - Nauku mladima) - Competition of Elementary Schools of the Socialists Federative Republic of Yugoslavia, Cetinje, SFRY, 1986

Languages

English - B2.1 CEFR

French - A2 CEFR

Montenegrin, Serbian, Bosnian, Croatian - Native