ESTIMATION OF PHOTOVOLTAIC POWER GENERATION POTENTIAL IN SERBIA BASED ON IRRADIANCE, AIR TEMPERATURE, AND WIND SPEED DATA

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This study is devoted to the research of spatial-temporal variation of electricity generation from the kilowatt-peak photovoltaic system made of crystalline silicon solar cells. The research was conducted in the territory of Serbia using the model for estimation photovoltaic performances as a function of incident irradiance and module temperature. Preparation of input data and calculation of the final results was done within the geographical information system. Some of the required raster data, like solar irradiance and wind speed, were already available, while air temperature raster was created from discrete set of observed data using the regression-kriging model. Obtained results were presented in the form of raster maps that enabled further analysis and discussion about new findings. The analysis of seasonal variations reveals that during spring and summer months photovoltaic systems are producing up to 70% of total annual electricity yield. In terms of the spatial distribution, the most promising areas for electricity generation are located in the south part of Serbia and along main river valleys. In addition, discussion part addresses the issue of data imperfection caused by the accuracy of the selected model, as well as quality and availability of data series.

Key words*: Serbia, solar energy, photovoltaic performance, module temperature*

1. Introduction

The power produced by photovoltaic (PV) system depends on a wide range of factors, among which are those that can be altered in planning, installation and operation phase to minimize losses. King *et al*. [1] identified seven factors that influence the performances of PV module: cumulative solar irradiance, module power rating, operating temperature, maximum power voltage dependence on irradiance level, soiling, variation in the solar spectrum, and angle of incident (AOI) effect.

Various authors use some of these factors to evaluate the performance of PV modules in their studies. For example, Pavlović *et al*. [2] investigated how much energy a different type of PV plants of 1 MW generates in the same place, using the coordinates of Sokobanja in Photovoltaic Geographical

Information System (PVGIS). The influence on reducing the energy efficiency of solar modules by soiling was researched by Radonjić *et al.* [3] and Radivojević *et al.* [4]. Pantić *et al*. [5] made a practical field study of three identical solar modules with different inclinations in order to analyze changes in their efficiency, performance ratio, and fill factor during the year 2013.

Unlike previous, there are numerous studies that explored power output of the same module mounted in a different place. An early and well-known research was done by Šúri *et al*. [6]. The aim of that paper was to express the national and regional differences of PV power generation potential among the member states and candidate countries of the European Union. Huld *et al*. [7] developed a model that provides good estimation of PV module power output as a function of in-plane irradiance and module temperature, and with empirical coefficients obtained by series of power measurements performed indoors. The model was implemented into the web application PVGIS [8] which offers users the ability to evaluate the performance of a PV system at any location in the geographic area covered. Huld and Amillo [9] upgraded the model by adding into account AOI effect, spectral sensitivity, and wind speed data to estimate performance variations of crystalline silicon (c-Si) and cadmium telluride (CdTe) PV module over large geographical areas.

According to Djurdjevic [10] Serbia has some areas with favorable, but mostly good conditions for solar PV electricity production. Taking that into consideration, in this study, we explored spatial and intra-annual variability of PV power generation potential using the mathematical model described in papers [7, 9, 11]. Global irradiance on an optimally inclined surface, air temperature, and wind speed data were prepared and applied to the selected model. Rather than mapping the incoming solar radiation, like it was done by Luković *et al*. [12], we presented monthly and annual solar potential in terms of generated kilowatt-hour per kilowatt-peak (kWhkWp^{-1}) of c-Si PV system. This kind of information will contribute to more precise estimations of PV potential compared to some previous studies [13-15] and it will enable to the formulation of effective policies for PV expansion.

2. Study area

The study area refers to the territory of Serbia, located in south-eastern Europe on the Balkan Peninsula with mathematical coordinates 41.53°N-46.11°N and 18.49°E-23.00°E (Fig. 1). The total area of Serbia is 88361 km^2 with a population of 7186862 inhabitants (without Autonomous Province Kosovo and Metohija) in 2011 [16]. The northern part of the country is flatland with an altitude less than 200 m above sea level (a.s.l.), while the area south of the Sava and the Danube is mountainous and it reaches the heights more than 2000 m a.s.l.

Serbia has a higher number of sunshine hours (between 1500 and 2200 hours per year) than the most of the European countries [17]. The average energy of global solar radiation has tendency to increase from the north-west (~1200

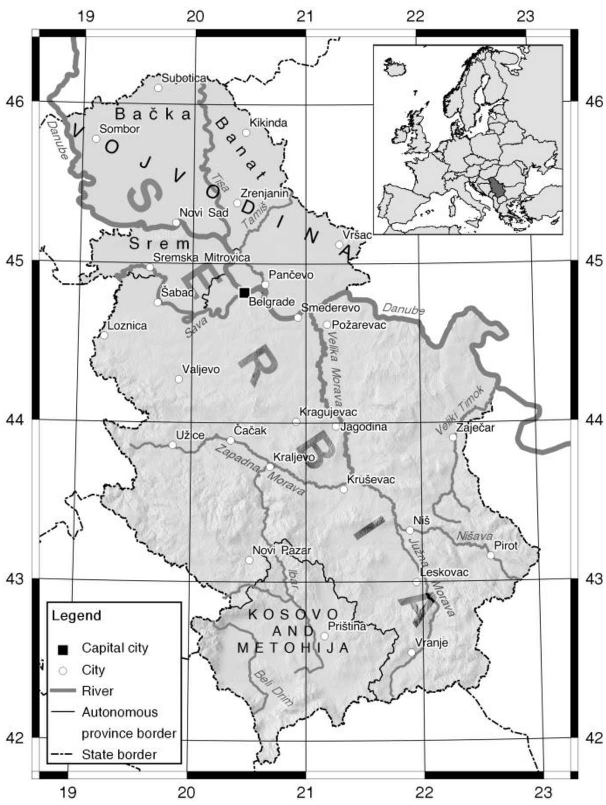

Figure 1. Study area

kWhm^{-2}) to the southeast (~1550 kWhm^{-2}) of the country [18]. Total annual solar energy for the whole territory of Serbia is estimated at 1.2 × 10^5 TWh [19].

3. Material and Method

3.1. Input data set

The analysis of PV module performance in the territory of Serbia is based on the model that uses three input data: solar irradiance, air temperature and wind speed. Generally speaking, the higher the intensity of solar radiation, the greater the energy yield per kilowatt-peak (kWp) installed [20]. Higher air temperature reduces the efficiency of PV module. According to Ranganathan *et al.* [21] every increase in temperature by one degree of Celsius drops the electrical efficiency of crystalline and amorphous silicon cells for 0.45% and 0.25% respectively. Areas with lower or moderate air temperature followed by high radiation enhance the performances and production of PV system. Wind also plays an important role in energy production. Findings of Kaldellis *et al.* [22] clearly indicate that the difference between the cell and ambient temperature is much smaller during the calm (usually between 10 °C and 20 °C) compared to the high wind speed cases.

Differences between databases and irregularities in a single database have influenced the selection of the most appropriate solution for input data in the proposed model. Photovoltaic Geographical Information System (PVGIS © European Communities, 2001-2017), develop by Huld et al. [23], was the source of solar irradiance data. Monthly and yearly average global irradiance on an optimally inclined surface over the period 2005-2015, with spatial resolution 0.025° × 0.025° (~ 3 km at Equator), were taken from PVGIS-CMSAF database as input data for the model. A 10-year period is usually considered desirable for the evaluation of PV project, due to the importance of inter-annual variability of solar irradiance [20]. Considering geographic position of Serbia, optimally inclined surface is 33°-35°, with a degree or two less for the eastern part and a degree or two greater for the western part of Serbia [10]. Wind speed data were obtained from the Wind Atlas Balkan [24] dataset. Monthly mean and the annual mean values of a 32 years period, from 1981 to 2012, were presented in the form of raster maps with a spatial resolution of 3 km × 3 km. The maps are refined onto finer rasters with resolution 100 m × 100 m using two-dimensional spline interpolation. This spatial resolution was capped for the final model results. Since the mean air temperature in Wind Atlas Balkan dataset was recorded at 10 m above the ground, we decided to model the spatial distribution of temperature based on values collected from 63 stations [25] in Serbia for the same period as wind speed data. The available sources of measured air temperature data were incomplete, especially for stations located on the territory of the Autonomous Province of Kosovo and Metohija. The problem was solved by interpolating the missing data from the nearest station.

3.2. Mathematical model for PV performance

3.2.1 Wind speed

For the planning of ground mounted photovoltaic systems, it is useful to know wind speed at 2 m above the ground. The influence of adhesion in the ground layer of the atmosphere requires the inclusion of terrain roughness in wind speed calculation. Input data of wind speed were given at 50 m above the ground. Wind speed at height of anemograph $V_{(r)}$, usually 10 m above the ground, can be estimated using the following equation [26]:

$$\frac{V_{(z)}}{V_{(r)}} = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_r}{z_0}\right)} \tag{1}$$

where $V_{(z)}$ is the wind speed at certain height z, in our study 50 m above the ground. Values for terrain roughness z_0 were given for each type of Corine Land Cover Classes [27], according to Silva, *et al*. [28] (see Tab. 1).

Table 1.Roughness values for different types of CLC classes [28]

Description of Corine Land Cover Classes	Roughness [m]
Continuous urban fabric	1.2
Broad-leaved forest; Coniferous forest; Mixed forest	0.75
Green urban areas; Transitional woodland/shrub; Burnt areas	0.6
Discontinuous urban fabric; Construction sites; Industrial or commercial units; Sport and leisure facilities; Port areas	0.5
Agro-forestry areas; Complex cultivation patterns; Land principally occupied by agriculture, with significant areas of natural vegetation	0.3
Annual crops associated with permanent crops; Fruit trees and berry plantations; Vineyard; Olive groves	0.1
Road and rail networks and associated land	0.075
Non-irrigated arable land; Permanently irrigated land; Rice fields; Salt marshes	0.05
Sclerophyllous vegetation; Moors and heathland; Natural grassland; Pastures	0.03
Dump sites; Mineral extraction sites; Airports; Bare rock; Sparsely vegetated areas	0.005
Glaciers and perpetual snow	0.001
Peat bogs; Salines; Intertidal flats	0.0005
Beaches, dunes, and sand plains	0.0003
Water courses; Water bodies; Coastal lagoons; Estuaries; Sea and ocean	0.001

The wind speed at 10 m above the ground was calculated based on Eq. (1). Because the PV modules are usually placed on support structure approx. 2 m above the ground, Eq. (2) was used to estimate wind speed at modules' height [29]:

$$\frac{V_{(z)}}{V_{(r)}} = \left(\frac{z}{z_r}\right)^n \tag{2}$$

where n represents a degree of exponential dependence between wind speed and height. For similar research Huld and Amillo [9] used 1/5 degree of exponential dependence. Therefore, the same value was used in our research.

3.2.2 Air temperature

Monthly mean and the annual mean air temperature raster maps of Serbia were created using the Regression kriging module implemented in System for Automated Geoscientific Analyses (SAGA)

4.1.0 software package [30]. Auxiliary raster maps of elevation, longitude, and latitude were added in order to improve prediction capabilities of interpolation model. The Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global [31] was used as source for elevation data. It is shown that more than 70% of the variation in temperature measured at 63 stations can be explained by elevation. The high percentage of explained variation (*i. e.* R-squared) allows further spatial extrapolation of values measured at sampling locations [32].

The predictions started with multiple linear regression of temperature versus elevation, longitude, and latitude in order to obtain coefficients and derived residuals at all sample locations. After that, covariance structure of residuals was modeled as a variogram. The spherical mathematical model was used in variogram analysis, except in the case of December temperature where the quadratic model showed better fitting with experimental semi-variogram. Based on modeled variogram, residuals are then interpolated using ordinary kriging and added to estimated trend. Results of prediction are in the form of 30 m × 30 m grid, same as digital elevation model that was used as auxiliary predictor. Resampling of originally data enables compatibility with other input data.

3.2.3 Module temperature

Module temperature (T_{mod}) can be expressed as a function of the air temperature (T_{amb}), incident irradiance (G), and wind speed (v) using Eq. (3), given by Faiman [33]:

$$T_{\mathrm{mod}} = T_{amb} + \frac{G}{U_0 + U_1 v} \tag{3}$$

where U_0 is a coefficient describing the effect of the radiation on the module temperature (Wm^{-2}K^{-1}), and U_1 describes wind cooling effect (Wm^{-3}sK^{-1}). Values of coefficients for crystal silicon modules U_0 = 26.9 and U_1 = 6.20 were taken from a paper published by Kohel *et al*. [34]. It should be noted that estimated T_{mod} represents the temperature at the back of the PV module. This value can be refined to reflect the true cell temperature through a simple relationship given by King *et al.* [35]. In order to stay in line with the original formula and empirical coefficient (U_0 and U_1), we retain the values obtained by the Eq. (3).

3.2.4 PV module performance

Output power of PV module is assumed to depend on incident irradiance and module temperature. There are numerous of energy prediction methods that give similar results at least when it comes to crystalline silicon (c-Si) modules [36]. Although none of these methods are preferred among the others, in this study, we chose the one based on King's model [35], modified by Huld *et al*. [7] in the form of Eq. (4):

$$P(G',T') = G' P_{\mathrm{STC}} (1 + k_1 \ln(G') + k_2 (\ln(G'))^2 + k_3 T' + k_4 T' \ln(G') + k_5 T' (\ln(G'))^2 + k_6 T'^2) \tag{4}$$

where $G' = G/G_{\mathrm{STC}}$, $T' = T_{\mathrm{mod}} - T_{\mathrm{STC}}$, and P_{STC} is module power at standard test condition (STC). There are three standard test conditions: T_{STC} = 25 °C, G_{STC} = 1000 Wm^{-2}, and air mass is 1.5. The coefficients k_1 to k_6 are found for each type of PV module by last-squares fit to measurements performed at European Solar Test Installation (ESTI) laboratory [37]. For the present study, we used coefficients for c-Si modules that were taken from Tab. 2, founded by Huld *et al.* [7]. The estimated PV module performance uses P_{STC} = 1 kW_p.

Table 2. Coefficients k_1-k_6 for the calculation c-Si PV module performance in Eq. (4) [37]

Coefficient	c-Si
k_1	–0.017237
k_2	–0.040465
k_3	–0.004702
k_4	0.000149
k_5	0.000170
k_6	0.000005

4. Results and discussion

Based on the available dataset and mathematical model described in Section 3, seventeen maps of estimated PV power generation potential (one map with average annual values, four maps with average season values, and twelve maps with average monthly values) were created.

According to the map of average annual PV power generation potential (Fig. 2(a)) values range from 1175 to 1739 kWhkWp^{-1}. Areas with values over national average (1497 kWhkWp^{-1}) are located in the southern parts of Serbia and along river valleys of the Danube, Sava, Timok, Nišava, Ibar, Zapadna Morava, Velika Morava, and Južna Morava. These areas cover around 63% of low mountain zone (500-1000 m a.s.l.), and around 57% of hilly terrain zone (200-500 m a.s.l.). The highest potential has the Metohija valley, areas north from Priština, lower terrain of Lepenac watershed, and terrain around headwaters of Južna Morava. Spatial distribution of the areas with the highest potential is related to Mediterranean influences in this part of the country. Areas with values under national average are predominantly located within high mountain zone (over 2000 m a.s.l.) and in the Northern part of Serbia. Minimum value is registered in the far south of the country (National park Šar-planina).

Seasonal and monthly analyses of PV performance were conducted in order to examine the changes in electrical output over the time. Related maps (Fig. 2) show that higher electrical output of PV system is expected during the summer months. The obtained values are in the range between 459 kWhkWp^{-1} and 633 kWhkWp^{-1}. Only the western parts of the country and high mountains have values below 500 kWhkWp^{-1}. During the summer months, the cloudiness is more pronounced over the Dinaric mountains. Therefore, the intensity of solar irradiation is slightly lower in this part than in the rest of the country, which affects the output of PV system. The results for the three most productive months (June, July, and August) support the claim that Serbia has favorable climate conditions for the PV power generation. Despite increased air temperature and lower wind speed followed by high irradiance, July is the best scored month of the year, with average value of 190 kWhkWp^{-1} for the whole territory of Serbia. During August, PV performances are also good, since the average value for Serbia is 185 kWhkWp^{-1}. The third ranked month acording to the PV power generation potential is June, with average value of 168 kWhkWp^{-1}. Spring period also corresponds to a good performance of PV systems, especially for the geographic region Timočka Krajina, located in the Eastern Serbia, around the Timok River. In contrast, this region has lower PV power generation potential during the autumn, especially in November, considering it has lower number of sunshine hours compare to the rest of the country.

In April, PV performances are slightly better than in May, considering their national average, 166 kWhkWp^{-1} *vs*. 160 kWhkWp^{-1}, respectively. Gburčik *et al.* [18] concluded that during the April PV panels oriented to south with slope of 30°, have greater monthly energy income than otherwise, while in May this applies to panels with slope of 10°.

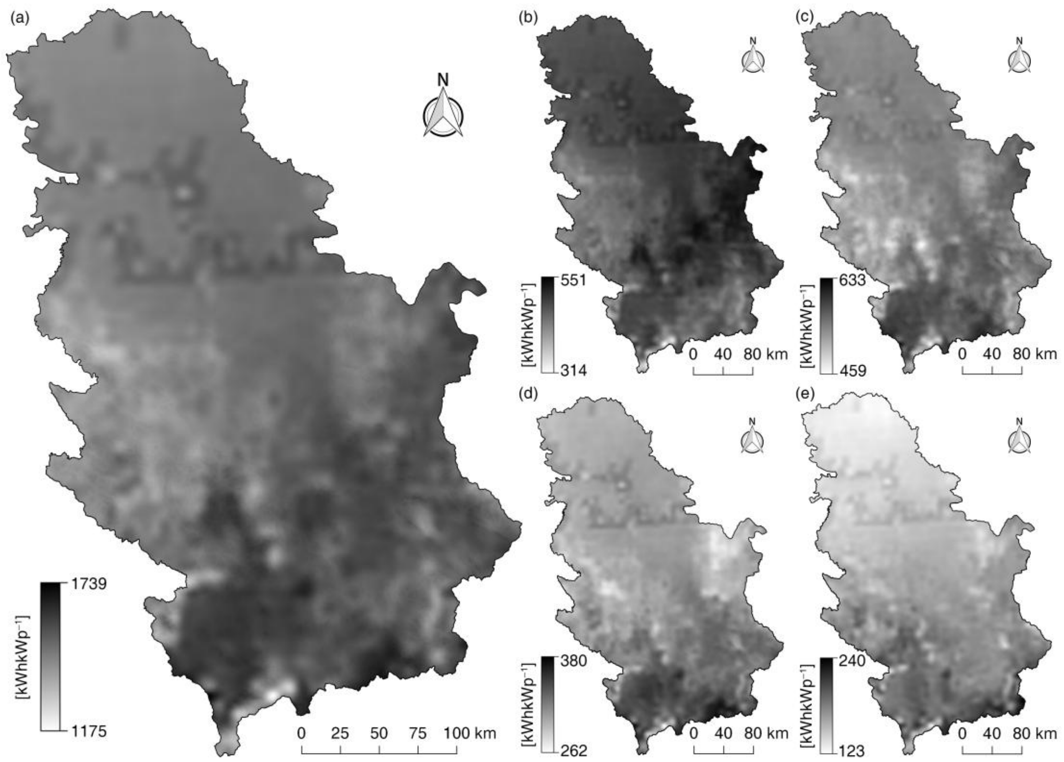

Figure 2. Electricity generation from a 1 kWp PV system: (a) the average annual values [kWhkWp^{-1}], (b) the average spring values [kWhkWp^{-1}], (c) the average summer values [kWhkWp^{-1}], (d) the average autumn values [kWhkWp^{-1}], (e) the average winter values [kWhkWp^{-1}]

Considering that the cloudiness is especially pronounced during the winter months and has fairly even distribution throughout the territory of Serbia, solar irradiance values are very low (68-117 Wm^{-2}). Despite the fact that other parameters (temperature and wind) allow smooth operation of the PV system, electric output during the winter does not exceed 240 kWhkWp^{-1}. January and December are months with the lowest PV potential, with mean values 48 kWhkWp^{-1}. The seasonal comparison indicates a higher potential in autumn than in winter, but lower than in spring. During the autumn, mean cloudiness in the Pannonian plain is 53% [38], while sunshine duration in Kikinda reaches the values of ~480 hours [39]. Nevertheless, northern part of Vojvodina has value ~300 kWhkWp^{-1}, while at the far south of Serbia it reaches ~380 kWhkWp^{-1}. The solar irradiance increases with decreasing geographic latitude, so the southern regions are more suitable for the exploitation of solar energy.

Solar irradiation is an intermittent source of energy that causes the daily-seasonal and geographical variation of PV performances. Fig. 3(a) shows that June, July, and August are the most productive months, which corresponds to higher electric consumption, mainly due to home air conditioning [40]. In general, PV power generation follows seasonal distributions according to prevalent climate conditions. Some variations are notable under regional and local climate characteristics which are especially evident in eastern part (see fig. 3(b)). During the winter months, average electricity generation drops below yearly average in a range between 58% (Southern Serbia, *i.*

e. Vranje) and 72% (Northern part of Vojvodina, *i. e*. Kikinda), while during the summer months it rises above yearly average around 55% for all three meteorological stations (see fig. 3(a)).

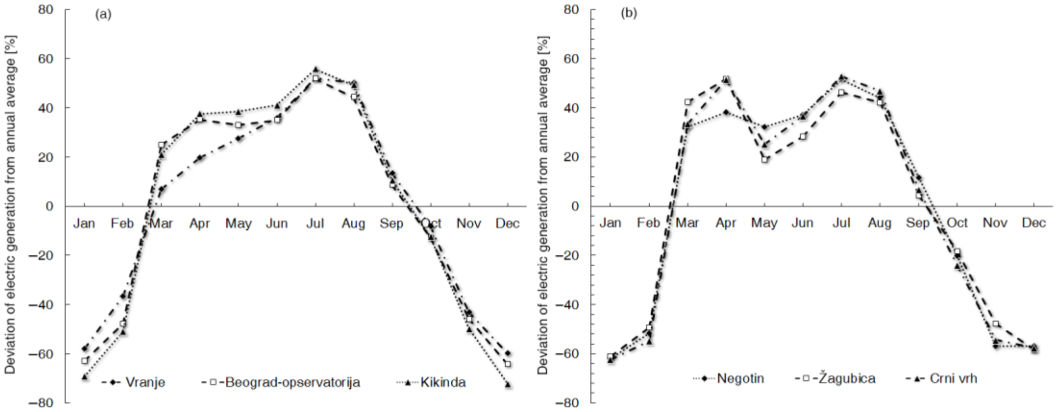

Figure 3. Monthly deviations of electric generation from annual average [%] for meteorological station: (a) Vranje, Beograd, and Kikinda, (b) Negotin, Žagubica, and Crni vrh

Fig. 4 shows disparities of electricity generation from 1 kWp system among municipalities in Serbia. Comparison is enabled by calculating the difference between the municipal average and the average for the whole country. The results indicate that 86% of municipalities in the Region of Kosovo and Metohija have values above the national average, while 71% of municipalities in the Region of Šumadija and Western Serbia have the values below the national average. In Vojvodina, only 11% of municipalities have values above the national average, and they are mainly located in South Banat District. The Region of Southern and Eastern Serbia has good PV potential, especially municipalities located in the great river valleys.

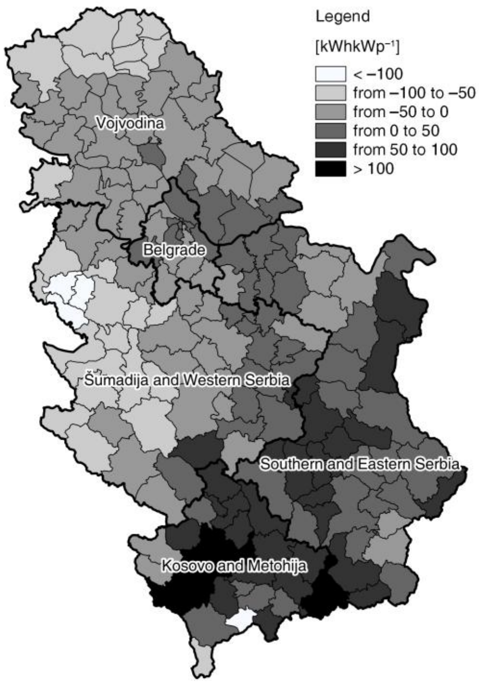

Figure 4. Differences between municipal averages and national average in electricity generation of 1 kWp PV system

Comparing the map of average annual PV power generation potential (Fig. 2(a)) and similar maps published by the World Bank Group [41], certain matches in spatial distributions were noticed – both are showing the highest potential in the south part of Serbia. Geographic region of Timočka Krajina and great river valleys are areas with good potential on both maps. Nevertheless, a range of values is different since we used the different set of data. An important issue is related to the uncertainty of temperature data in places where there is no meteorological observations. Computer programs and spatial interpolation methods offer a solution to overcome this problem. Many authors [42-44] demonstrated practical application of regression-kriging method to calculate air temperature values at locations of interest. The accuracy of modeled temperature values depends on selected auxiliary information and quality of field observation data. For the purpose of the selected model it was necessary to supplement certain series of data since there is a discontinuity in observation and recording of data at the selected stations.

In addition, the coordinates of meteorological stations are given with accuracy of one minute, which in our latitudes means that each station is positioned somewhere in the area of about 3.24 km^2 [45].

The presented spatial distribution of PV potential should be taken with reservation when it comes to applied technology and climate changes. Widely applied c-Si PV modules were selected for modeling power output with respect to the module temperature. As it was noted in Section 3.2.3, the result of Eq. (3) represents the temperature at the back of the module, which can be distinctly different (based on the type and mount of PV module) than the temperature of the cells inside the module. On one hand, the increase in temperature causes lowers efficiency of PV modules, but on the other hand, this heat can be used as an advantage to improve their efficiency of the hybrid photovoltaic/thermal systems [46]. Some regions can become unfavorable for the PV power generation, especially during the summer months, due to climate changes that cause the increase in air temperature, as it was noted in the paper of Prokić [47] for the Nišava river valley.

5. Conclusions

In this paper, spatial and temporal variations of PV power output were analyzed in order to estimate the potential of the solar energy use in Serbia. Power generation from 1kWp PV system was calculated based on solar irradiance, air temperature, and wind speed. A set of high resolution maps was created to present final results, as well as to support the discussion about new findings. Based on the obtained results following conclusions were derived:

- Areas with the above-average PV power output overlapped with most populated and infrastructural equipped zones, while those with the highest potential are located in the climate zone under Mediterranean influences;
- During spring and summer months, PV systems produce from 64% (in south) to 70% (in north) of the annual electricity yield; and
- The seasonal variability of the PV output coincides with seasonal changes in electricity demand.

Finally, the results of this study will be of great importance for the development of a national strategy for decentralized model of energy generation based on renewable energy sources. In the future we plan to use average daily data for the most productive period of the year in order to predict electricity output for most suitable sites in Serbia. The results of such research will serve as a basis for the introduction of a *system of expected exchange* as part of a comprehensive incentive scheme.

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