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Simulation Based Productivity Forecast of 1 MW PV Power Plant in the Weather Conditions Typical for Belgrade Region

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Abstract

Having in mind that energy is being regarded as indispensable to the socioeconomic progress of developing and developed nations, where the main objective implies replacement and reduction of major portion of the fossil fuels utilization, implementation of renewable energy technologies where natural phenomena are transformed into beneficial types of energy are becoming more and more appreciated and needed. Among renewable energy resources we know today, solar energy is the most beneficial, relatively limitless, effective, and dependable. Given the aforementioned this paper provide an overview of 1 MW PV power plant forecast productivity generated by simulation, in the weather conditions typical for the Belgrade city region. The simulation is based on NREL (National Renewable Energy Laboratory) photovoltaic performance model which combines module and inverter sub models with supplementary code to calculate a photovoltaic power system's hourly AC output given a weather file and data describing the physical characteristics of the module, inverter, and array. Furthermore, the characteristic losses are calculated and presented for fixed array power plant and illustratively given in the form of Sankey diagram. Lastly, a variety of graphical data representations are available while the most important ones are given in the study.

Key words: *Simulation; photovoltaic power plant; typical losses*

1. INTRODUCTION

It is generally known that most modern societies depend on fossil fuels as sources of energy for development and growth. On the other hand, switching to renewable energy sources, such as photovoltaic (PV) systems, is necessary for sus-tainable development in the future. Currently, it is much more efficient to use fossil fuels to develop PV power plants than to combust the same amount of fossil fuels in conventional thermal power plants. Thus, the sooner PV systems are developed, the sooner society will reduce its reliance on fossil fuels [1].

Thanks to the massive price declines achieved in recent years and continued in 2014 [2], solar power is now broadly recognized as a cost-competitive, reliable and sustainable energy source. In fact, based on its technical characteristics, PV can and should be considered as a low risk investment for the financial community today. Its market uptake is strongly dependent on a stable and forward-looking regulatory framework that allows the realization of full competitive potential of solar.

2. PV PLANTS AND SYSTEMS STATUS IN SERBIA

Although on most of the Serbian territory the number of sunny days is significantly higher than in many European countries (over 2000h), high costs of solar irradiation modules and the accompanying equipment hinder more intensive use of this renewable energy source, which primarily depend on the social incentives for the establishment and implementation of the national RES (Renewable Energy Sources) Program [3]. According to the available data use of solar energy is currently almost negligible. However, production of solar energy, based on the sun potential in Serbia, can be considered as attractive for potential investors, but it requires significant initial investments as well as purchase of foreign equipment, which makes it much less attractive in compared to other RES [4].

In Serbia solar energy is considered more appealing mainly for the heating of water and rarely for the electricity generation. Either way, some significant PV ground-based power plants are given in the table 1.

Table 1. Some significant PV ground-based power plants in Serbia

PV power plant	Installed capacity	Date of commissioning
Solar Matarova	2 MWp	August 23, 2013
Solaris 1	1 MWp	December 27, 2013.
Solaris 2	1 MWp	October 24, 2014

In addition, more than 200 independent PV plants of 1 - 60 kWp have been installed in Serbia so far. These were mainly small rooftop PV systems connected to the grid while some of them are recognized in the table 2.

Table 2. Recognized independent PV systems (1-60 kWp) in Serbia [5]

PV system	Installed capacity (kWp)	Year of commissioning
Domit, Leskovac	34,32	2012
Technical School, Pirot	4,59	2013
Faculty of Sciences and Mathematics, Nis	2,08	2012
Faculty of Electronic Engineering, Nis	1,20	2011
Secondary School, Varvarin	5,00	2010
Electro -technical School Rade Koncar, Belgrade	5,00	2010
Technical School Mihajlo Pupin, Kula	5,00	2010
Technical school, Varvarin	5,00	2010
Daycare center, Belgrade	3,00	2012
Elektrovat Ltd., Cacak	54,72	2012
Mihajlo Pupin Institute, Belgrade	50,00	2013
Faculty of Technical Sciences, Cacak	1,05	2008
Faculty of Technical Sciences, Novi Sad FTS1	9,60	2011
Faculty of Technical Sciences, Novi Sad FTS2	15,90	2015
Elektromehanika Ltd., Nis	30,00	2014
Hemofrigo Ltd., Leskovac	60,00	2012
Primary School Dusan Jerkovic, Ruma	3,00	2004

PV solar plants in Varvarin, Belgrade and Kula were installed thanks to the donations of the Government of Spain and through the former Agency for the Energy Efficiency in Belgrade within the Project “Development of the installations for the promotion and use of solar energy in Serbia [6]. Recently, in Serbia there is an increased use of PV systems for traffic lights and other signalization [7].

3. PRELIMINARY DESIGN OF 1 MW PV POWER PLANT

In the following section a preliminary design and conceptual solution of 1 MW PV power plant has been given and analyzed.

At the begging, typical weather conditions for observed location were identified after which the conceptual PV system was suggested.

The predefined system was subjected to a simulation through NREL SAM (System Advisory Model), photovoltaic performance model which combines module and inverter sub models with supplementary code to calculate a photovoltaic power system’s hourly AC output given for the weather file and data, describing the physical characteristics of the module, inverter, and array. Lastly, obtained data are analyzed and correlated in order to generate forecasted, specific performance indicators of the PV system.

3.1 Weather conditions and location

Fundamental weather conditions at considered location of the PV plant are as follows: Latitude (44,82 °N), Longitude (20,28 °E), Elevation (99 m), Direct Normal irradiation (3,16 kWh/m2/day), Diffuse irradiation (1,79 kWh/m2/day), Average dry bulb temperature (11.5°C) and Average wind speed (3,1 m/s). Annual solar energy potential in terms of global, direct and diffuse irradiation is given in the figure 1.

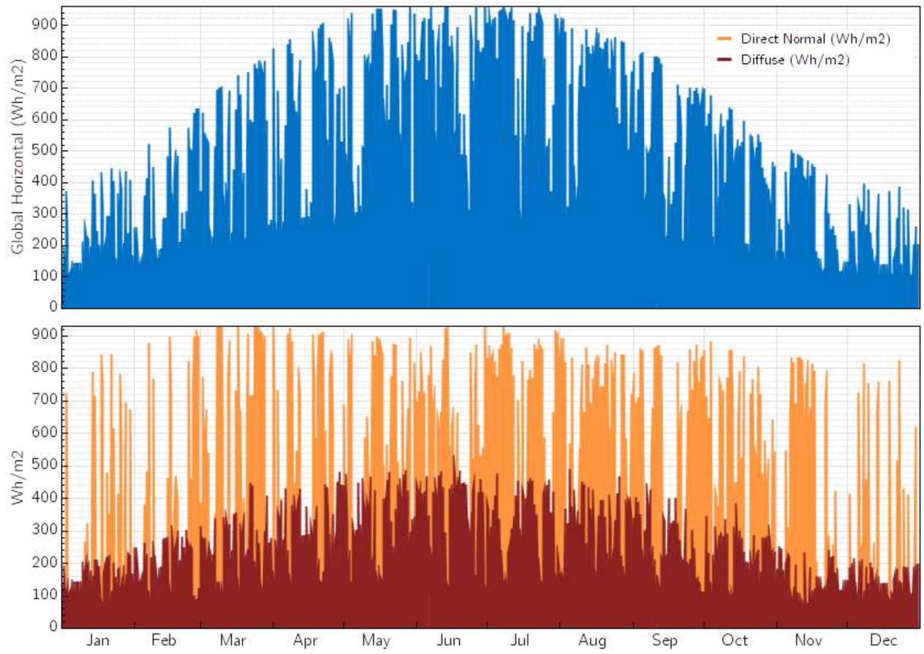

Figure 1. Global, direct and diffuse irradiation at analyzed location

3.2 **Module and Inverter specification**

The analysis was done for Yingli YL315P-35b solar modules which relevant characteristics at reference conditions (Total irradiance = 1000 w/m^2 and Cell temperature = 25°C) are given in the table 3, while the power diagram is shown in the figure 2 (left). Relevant physical characteristics of this module are module area (1,94 m^2), material (Multi C-Si) and number of cells per module (72).

Table 3. Yingli YL315P-35b solar module characteristics

Characteristics		Characteristics	
Nominal efficiency	16,23 %	Max power current (Imp)	8,60 A_{dc}
Max power (Pmp)	314,76 W_{dc}	Open circuit voltage (Voc)	45,80 V_{dc}
Max power voltage (Vmp)	36,60 V_{dc}	Short circuit voltage (Isc)	9,10 A_{dc}

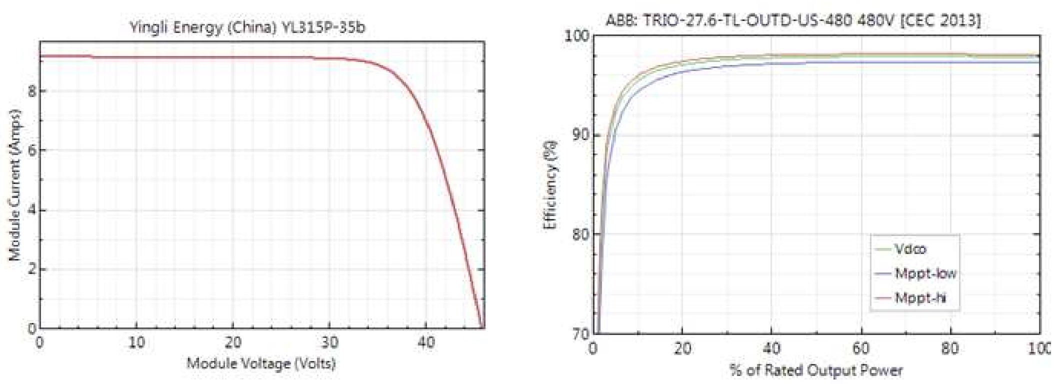

Figure 2. Yingli YL315P-35b solar module Current-Voltage diagram (left) and ABB Trio 27,6 TL-OUTD-US-480 efficiency curve diagram (right)

In addition, selected inverters are ABB Trio 27,6 TL-OUTD-US-480, which characteristics are given in the table 4. The inverter efficiency curve diagram is given in the figure 2 (right).

Table 4. ABB Trio 27,6 TL-OUTD-US-480 characteristics

Characteristics		Characteristics	
Weighted efficiency	97,73 %	Power consumption (operate)	95,31 W_{dc}
European weighted efficiency	97,43 %	Power consumption (night)	0,6 W_{ac}
Max AC power	27600 W_{ac}	Min MPPT DC voltage	520 V_{dc}
Max DC power	28205 W_{dc}	Max DC current	30,9 A_{dc}
Nominal AC voltage	480 V_{ac}	Nominal DC voltage	715,1 V_{dc}
Max DC voltage	950 V_{dc}	Max MPPT DC voltage	800 V_{dc}

3.3 **System design**

For the desired array size (1 MW_{dc}) with adopted DC to AC ratio 1,09, characteristics for configuration at reference conditions are given in the table 5.

Table 5. Module and Inverter characteristics for configuration at reference conditions

Module Characteristics		Inverter Characteristics	
Nameplate capacity	997,16 kWdc	Total capacity	910,8 kWac
Number of modules	3168	Total capacity	930,8 kWdc
Modules per string	18	Number of inverters	33
Strings in parallel	176	Max DC voltage	950 Adc
Total module area	6146 m2	Min MPPT voltage	520 Vdc
String Voc	824,4 V	Max MPPT voltage	800 Vdc
String Vmp	658,8 V		

Given the aforementioned, it was calculated that the number of strings in array amounts 176. Lastly, the exact location and PV plant layout are given in the figure 3.

Figure 3. Location and PV plant layout

It is generally known that wherever the energy is being transformed, losses are inevitable. The typical losses in a fixed PV plant occur mainly due to the module mismatch (2%), module soiling (5%), diodes and connection (0,5%), DC wiring (2%) and AC wiring (1%).

3.4 **Simulation of energy production**

As previously mentioned, simulation is based on SAM's photovoltaic performance model which combines specified modules and inverters with supplementary code to calculate a photovoltaic power system's hourly AC output for a given weather file and data, describing the physical characteristics of the module, inverter, and array [8].
The model calculates the system's AC electrical output over one year as an array of 8760 hourly AC power values. It reads hourly solar resource and temperature data from a weather file describing the resource at the system's location for the year, and uses them with inputs describing the system's design in equations to calculate module and inverter conversion efficiencies and energy losses.
The module model and inverter model calculate solar energy to DC electricity and DC to AC electricity conversion efficiencies, respectively, and account for losses associated with each component.

3.4.1 *Model Algorithm*

This section describes the basic algorithm of SAM's photovoltaic performance model. The details of each step listed below are briefly described in the following text. The hourly simulation model performs the following calculations for each of the 8760 hours in a year [8]:

1. For each of up to four sub-arrays:
    A. Calculate sun angles from date, time, and geographic position data from the weather file.
    B. Calculate the nominal beam and diffuse irradiance incident on the POA (plane of array irradiance). This depends on the solar irradiance data in the weather file, sun angle calculations, user-specified sub-array parameters such as tracking and orientation parameters, and backtracking option for one-axis trackers.
    C. Apply the user-specified beam and diffuse near-object shading factors to the nominal POA irradiance.
    D. For sub-arrays with one-axis tracking and self-shading enabled, calculate and apply the self-shading loss factors to the nominal POA beam and diffuse irradiance.
    E. Apply user-specified monthly soiling factors to calculate the effective POA irradiance on the sub-array.
2. If there is a single sub-array (Sub-array 1) with no tracking (fixed) and self-shading is enabled, calculate the reduced diffuse POA irradiance and self-shading DC loss factor.
3. Determine sub-array string voltage calculation method
4. For each of up to four sub-arrays, run the module model with the effective beam and diffuse POA irradiance and module parameters as input to calculate the DC output power, module efficiency, DC voltage, and cell temperature of a single module in the sub-array.
5. Calculate the sub-array string voltage using the method determined in Step 3.
6. Loop through the sub-arrays to calculate the array DC power:
    A. For Sub-array 1, apply the fixed self-shading DC loss to the module DC power if it applies.
    B. For each sub-array, calculate the sub-array gross DC power by multiplying the module DC power by the number of modules in the sub-array.
    C. For each sub-array, calculate sub-array net DC power by multiplying the gross sub-array power by the DC loss.
    D. For each sub-array, calculate the sub-array string voltage by multiplying the module voltage by the number of modules per string.
    E. Calculate the array net and gross DC power by adding up the sub-array values.
7. Run the inverter sub-model to calculate the gross AC power and inverter conversion efficiency.
8. Calculate the net AC power by applying the AC loss to the gross AC power.

4. SIMULATION RESULTS

According to the simulation results (for the year 1) annual energy production amounts 1279,84 MWh with capacity factor of 14,7%. In addition, characteristic energy yield is 1283 kWh/kW indicating the performance ratio amounts 0,83.
Furthermore, expected, monthly energy production is given in the figure 4.

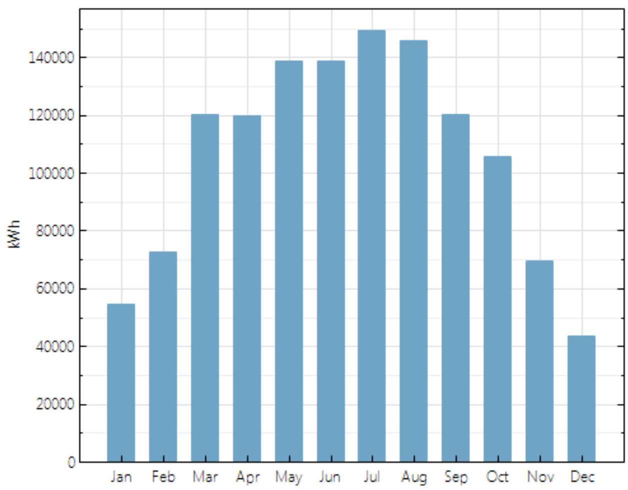

Figure 4. Expected monthly energy production

Previously mentioned losses are taken into account and illustratively given in the figure 5 in the form of Sankey diagram.

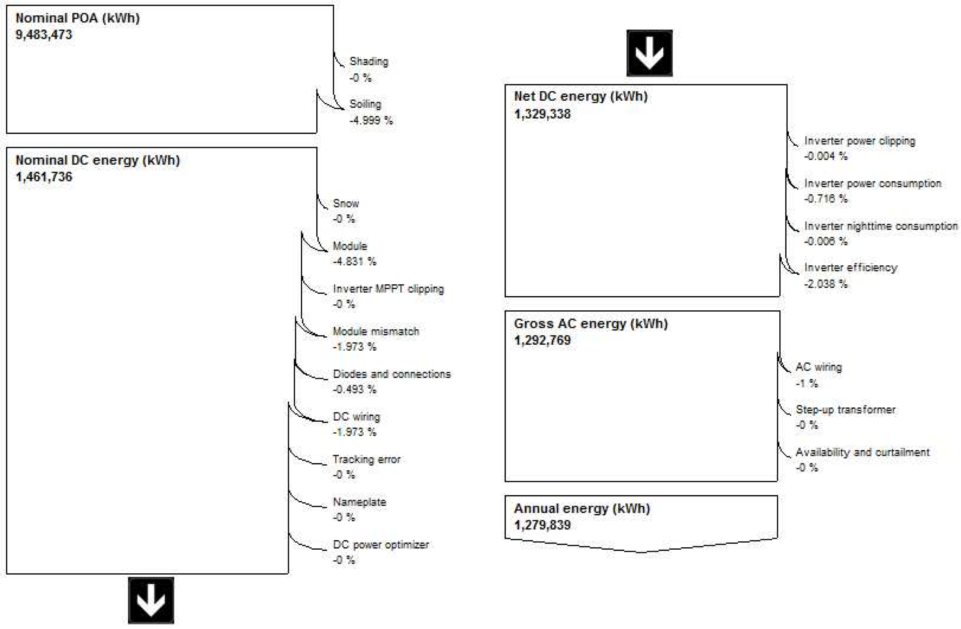

Figure 5. Typicall energy losses in the observed system

Lastly, array DC power histogram given in the figure 6 indicates the PV installation "pulse", providing a statistically verified forecast, valuable to stakeholders in order to monitor system behavior.

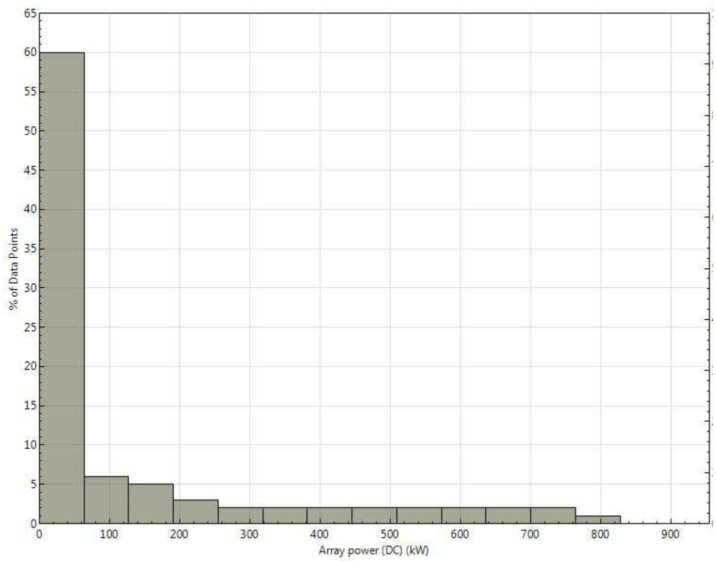

Figure 6. Array DC power histogram

5. CONCLUSION

From the obtained results it can be concluded that favorable conditions exist for the use of solar energy in Serbia, while according to the solar potential, Serbia is among the quite favorable locations in Europe.

In this paper key parameters for determining the energy efficiency of a conceptual, 1 MW nominal output power, PV power plant were observed. Simulation based analysis resulted in forecasted annual energy production of 1279,84 MWh with capacity factor of 14,7%. Characteristic energy yield was calculated to be 1283 kWh/kW indicating the performance ratio amounts 0,83.

Here, the temperature dependence of characteristics of PV panel is the main cause of lower performance ratio during the summer compared to the winter, which suggests consideration of hybrid versions of the panels (PV/Thermal) application.

In addition, typical losses characteristic for the fixed PV power plants were taken into account and presented in the form of Sankey diagram.

Lastly, array DC power histogram was generated in order to indicate the PV installation “pulse”. This histogram provides a statistically verified forecast, valuable to stakeholders in order to monitor system behavior.

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Simulacija produktivnosti solarne fotonaponske elektrane kapaciteta 1 MW u meteorološkim uslovima karakterističnim za područje Beograda

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Apstrakt

Imajući u vidu da se energija smatra neophodnom za socio-ekonomski napredak u razvujenim, ali i zemljam u razvoju, gde osnovni cilj podrazumeva supstituciju i smanjenje korišćenja velikog dela fosilnih goriva, primena obnovljivih energetskih tehnologija u kojima se prirodni fenomeni transformišu u korisnu energiju, postaju sve više i više cenjene i potrebne. Među obnovljivim izvorima energije poznatim današnjici, solarna energija se prepoznaje kao najkorisnija, relativno neograničena, efikasna, i povrh svega pouzdana. Imajući u vidu navedeno u ovom radu analizirana je solarna foronaponska elektrana kapaciteta 1 MW, čija je produktivnost utvrđena simulacijom za vremenske uslove tipične za regiju grada Beograda. Simulacija se zasniva na NREL (National Renewable Energy Laboratory) modelu za oderđivanje performanse fotonaponskog sistema, koji kombinuje module i invertere u pod modele sa dopunskim programskim kodom za izračunavanje izlazne naizmenične struje u vremenskom intervalu od jednog časa za prethodno definisane relevantne meteorološke karakteristike analizirane lokacije, kao i podatke koji opisuju fizičke karakteristike modula, invertera, i niza modula. Osim toga, proračunati karakteristični gubici su predstavljeni za fiksni fotonaponski sistem, što je ilustrativno prikazano u obliku Sankey dijagrama.

Ključne reči: *Simulacija; fotonaponska elektrana; karakteristični gubici.*