CONCEPTUAL DESIGN AND ECONOMIC FEASIBILITY OF BUILDING OF ROOF TOP PHOTOVOLTAIC POWER PLANT ON THE LABORATORY OF TECHNICAL FACULTY IN PODGORICA

Vladan Durković,Željko Đurišić***

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Abstract: This paper analyses the conceptual design of a photovoltaic electric power plant on the roof of the laboratory of the technical faculty in Podgorica. It gives estimation of the solar capacity of this microlocation, as well as the presentation of the capacities of the technical realization and economic feasibility of building of this power plant.

1. INTRODUCTION

The building of photovoltaic (PV) power plants has constantly risen recently. Note that 40 GW PV power plants in total were installed in the world in 2015, therefore the total installed power of PV power plants currently is 177 GW. China has the biggest rise in the installed power in 2015 with 10.4 GW, followed by Japan with 9.6 GW. However, Germany has still been the leader in the total installed power of PV power plants with approximately 40 GW [1].

The roof power plants are popular in urban areas. These plants have less installed power and relatively easily satisfy the provisions for the connection to a grid, not occupying an additional space.

Given that the bigger part of the Montenegrin territory has more than 2000 sunny days in a year, the authors considered that it was interesting to carry out an analysis of the development of the PV plant on the top roof of the laboratory of the technical faculty in Podgorica. Also, there are similar ideas in the region [2], [3]. This paper, after the description of the micro-location and the estimation of its solar potential gives an analysis

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* Vladan Durković working at the Faculty of Electrical Engineering, University of Montenegro, Montenegro and PHD student at the Faculty of Electrical Engineering in Belgrade, Serbia. (phone: 382-68-893973; e-mail: vladan.d@ac.me).

** Željko Đurišić, is now with Faculty of Electrical Engineering, University of Belgrade, Serbia (e-mail: djurisic@etf.rs).

of the production of this PV power plant. The analysis of the economic feasibility of the building of the PV plant is given at the end of the paper.

2. DESCRIPTION OF MICROLOCATION

The flat top roof of the laboratory of the Technical faculties, whose base is oriented 20^{o} westward in relation to the south , and that is partly in the shadow of the technical faculty's building ,was chosen as the site of building, Fig. 1. The detailed analysis of the estimation of the production of the PV plant that takes into account the shadow is possible by the use of professional software programs [4].

Due to the lack of the professional software, the estimation of the impact of shadow was carried out in the following manner. Three reference points were taken for the calculation of shadow and these are designated with 1,2, and 3 at Fig. 1.

Fig. 1. View on the roof of the laboratory of the technical faculties at Podgorica

The shadow impact on the production of the photovoltaic solar plant was determined using the diagram of The sun's trajectory and the shadow model that was formed on the basis of the constructional design of this building. For reference point 2, Fig. 1, the diagrams of The sun's trajectory for individual months (for a mean day in each month) and the model of shadow are given at Fig. 2.

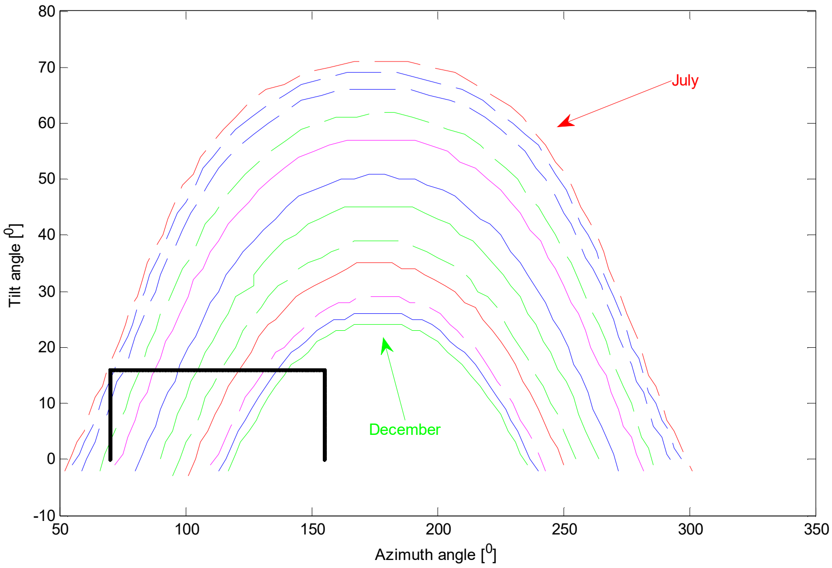

Fig. 2. Diagrams of the sun's trajectory for certain months and the shadow model

From Fig. 2 it can be observed that the PV plant is in a shadow during the morning times when it actually will not produce electrical energy. Additionally, it should be noted that the duration of shadow is different for each month in a year. The shadow will be the longest in December and it will not exist in July.

3. ESTIMATION OF SOLAR POTENTIAL OF THE MICROLOCATION

The measurements of irradiation were the starting data for the estimation of the solar potential of given location. However, today there are many databases of irradiation obtained on the basis of earth and satellite measurements, as in [5],[6]. This paper uses the measurements from the PVGIS database [5]. This database comprises the perennial 15-min measurements of horizontal irradiation, therefore the error due to the variations of annual values of insolation is reduced. For the more precise observation of the production, it is advisable that the measurement equipment be installed at the very target location, that , besides a pyranometer, should have a thermometer in order to observe the real efficiency of FN panel as precisely as possible.

Regarding the shadow effect, it is necessary that the irradiation in the database be equalized with zero when there is a shadow. After the update of the horizontal irradiation, using Liu-Jordan's equation (1) [7], it is necessary to divide the total horizontal irradiation into a direct and diffusion component.

$$\frac{I_{DH}}{I_H} = 1.390 - 4.027 \cdot K_T + 5.531 \cdot K_T^{\ 2} - 3.108 \cdot K_T^{\ 3} \qquad (1)$$

where K_T is clearness index, I_{DH} is diffusional horizontal irradiation [kW/m^2], I_H is total horizontal irradiation [kW/m^2].

Clearness index is calculated with:

$$K_T = \frac{I_H}{I_o} \qquad (2)$$

where I_o is horizontal irradiation of extra-terrestrial radiation [kW/m^2].

Irradiation I_0 is calculated with:

$$I_0 = \left(\frac{24}{\pi}\right) \cdot SC \cdot \left[1 + 0.034 \cdot \left(\frac{360 \cdot n}{365}\right)\right] \left(\cos L \cdot \cos\delta \cdot \sin H_{sr} + H_{sr} \cdot \sin L \cdot \sin\delta\right) \qquad (3)$$

where SC is solar constant 1377 W/m^2, n isordinal number of observed day in a year, L is latitude [^{0}], δ is solar declination [^{0}], calculated according to (4).

$$\delta = 23.45 \cdot \sin\left(\left(n - 81\right) \cdot \frac{360}{365}\right). \qquad (4)$$

where H_{SR} is hour angle of the sunset calculated with (5).

$$H_{sr} = \cos^{-1}\left(-\tan(L) \cdot \tan(\delta)\right) \qquad (5)$$

Having in mind that the total horizontal irradiation is a sum of the direct and diffusion horizontal irradiation, the following equation is obtained:

$$I_{BH} = I_H - I_{DH} \qquad (6)$$

where I_{BH} is direct horizontal irradiation [kW/m^2]

The total diffusion and reflected radiation falling onto the PV module, set under the slope angle Σ[^{0}] in relation to the horizontal axis, can be calculated with the following equations:

$$I_{DC} = I_{DH} \cdot \left(\frac{1 + \cos\Sigma}{2}\right) \qquad (7)$$

$$I_{RC} = \rho \cdot I_H \cdot \left(\frac{1 - \cos \Sigma}{2} \right) \tag{8}$$

where I_{DC} is diffusion irradiation falling on a PV module [kW/m^2], I_{RC} is reflected irradiation falling on a PV module [kW/m^2], ρ is reflection coefficient (0.2-0.8).

Direct component of the sun's radiation, I_{BC} [kW/m^2] falling on a PV panel is calculated with:

$$I_{BC} = I_{BH} \cdot \left(\frac{\cos \theta}{\sin \beta} \right) \tag{9}$$

where θ is altitude angle [^{0}], β is incidental angle [^{0}].

After the calculation of the sun's radiation components, the total irradiation falling onto a PV panel I_C [kW/m^2] is a sum of direct, diffusion and reflected components, (10).

$$I_C = I_{BC} + I_{DC} + I_{RC} \tag{10}$$

Due to the architectural design of the roof , the active area of PV module is yawed for 20^0 in relation to the south towards the west.

Based on the equations (1)-(10), it is possible to determine an optimal slope and azimuth angle, for which a PV power plant has the biggest production. However, due to the limitations of the azimuth angle, the optimal value of slope angles was determined with the architectural design of the roof. Table I gives an optimal slope angle of the PV, determined for points 1,2 and 3. Also, Table I presents an optimal slope of the PV plant if there was no shadow. The optimal azimuth angle for this power plant is 0^0. Table I shows that the more shadow the smaller optimal PV slope angle is.

The reflection degree depends on the facility's environment where the PV plant is situated and it can be increased if the roof area is smeared with white coating (for example, with asfaltol).

Table I. Optimal slope angle of individual modules

	PV plant without shadow	PV plant 1	PV plant 2	PV plant 3
Slope angle [^{0}],	35	27	31	33

The standard value of the reflection coefficient is 0.2 for grey concrete areas, while this coefficient would be 0.65 if the roof was covered with asfaltol.

Smearing of the laboratory's roof in case of PV plant 3, almost entirely compensates the losses due to the impact of shadow and azimuth angle for panel of 20^0. Besides the positive effects in sense of the rise of irradiation on the roof surface, asfaltol would decrease temperatures of concrete roof areas what would also contribute to the bigger efficacy of the panel. Given that the investment for painting of the roof is relatively small in comparison to the effects that would be obtained through the production of the PV plant, this paper thereafter assumes that the roof is painted by asfaltol.

Table II. Estimated value of insolation [kWh/m^2/day] at the surface of a PV module for different reflection coefficients

	PV power plant without shadow (ρ=0.2)	PV power plant 1 (ρ=0.2)	PV power plant 1 (ρ=0.65)	PV power plant 2 (ρ=0.2)	PV power plant 2 (ρ=0.65)	PV power plant 3 (ρ=0.2)	PV power plant 3 (ρ=0.65)
January	2.7477	1.80	1.8468	2.3853	2.4521	2.5381	2.6092
February	3.5496	2.617	2.6850	3.1338	3.2278	3.2754	3.3737
March	4.7700	4.2594	4.3914	4.6626	4.8165	4.8573	5.0176
April	5.6841	4.815	4.9619	5.3174	5.4876	5.4595	5.6342
Maj	6.5586	5.803	5.9771	6.0971	6.3410	6.3381	6.5916
June	7.2396	6.7001	6.9546	6.9521	7.2419	7.100	7.3982
July	7.6861	6.9612	7.2314	7.6398	7.9454	7.5502	7.8522
August	7.1253	6.2538	6.4791	6.7019	6.9567	6.8875	7.1492
September	5.6441	4.8767	5.0376	5.3461	5.5332	5.4916	5.6838
October	4.2642	3.5081	3.6097	3.9769	4.0962	4.2363	4.3634
November	2.8747	1.7739	1.8200	2.7844	2.8624	2.874	2.9545
December	2.3181	1.0195	1.0450	1.7168	1.7623	1.7756	1.8235
Annually	5.0385	4.1989	4.3367	4.7259	4.8936	4.8653	5.0376

4. ANALYSIS OF PRODUCTION PHOTOVOLTAIC POWER PLANT

The conceptual solution of the PV plant consists of 348 PV modules in total , with total installed power of 104.4kW$_p$, (PV plant 1- 162 modules (48.6 kW$_p$), PV plant 2 - 84 modules (25.2 kW$_p$), PV plant 3 - 102 modules (30.6 kW$_p$)), Fig. 3. The spacing between the rows is determined according to the position of the Sun on 21. December at 12h and is 4m.

Fig. 3. Roof PV power plant (PV power plant 1- orange PV modules FN modules; PV power plant 2 – red PV modules; PV plant 3 – blue PV modules)

The rise of temperature of PV modules above the standard value (25^0C) causes a drop of module efficacy for about 0.5%/^{0}C. The temperature of a PV module can be estimated on the basis of an ambient temperature according to the following equation :

$$T_{pv} = T_{amb} + \left(\frac{NOCT - 20}{0.8}\right) \cdot I_c \tag{11}$$

where T_{pv} is temperature of a PV module [ºC], T_{amb} is ambient temperature [ºC], I_c is solar irradiation on the surface of a module [kW/m^2], *NOCT* – (*Normal Operation Cell Temperature*) temperature of solar cells under the normal exploitation conditions. The normal exploitation conditions are for the ambient temperature of 25^0C, wind speed of 1m/s and solar irradiation of 0.8 kW/m^2. For the majority of PV modules, the value of NOCT is 47^0C.

Besides the temperature, the efficacy of conversion is significantly affected by: degree of invertor efficienc , module dirtiness and non-compatibility of modules. In order to obtain as good system efficacy as possible, it is necessary that the modules forming the panel have as similar characteristics as possible. The rated power at AC side is calculated according to equation (12).

$$P_{AC} = P_{DC,STC} \cdot \eta_Z \cdot \eta_N \cdot \eta_T \cdot \eta_{inv} \tag{12}$$

where $P_{DC,STC}$ is rated power of PV plant under standard conditions, η_z is average loses due to dirt (adopted 4%), η_n is average loses due to incompatibility of modules (adopted 3%), η_{inv} is declared euro-efficiency of an invertor (adopted 97.7%), η_t is loses due to over-temperature. The losses due to over-temperature are calculated on the basis of the mean maximum month values of temperature in [8] and equation (11).

A simple way for the presentation of the efficiency of the production in PV power plant is through its annual AC energy and capacity factor (CF – Capacity Factor), equation (13).

$$W(kWh/god) = P_{AC}(kW) \cdot CF \cdot 8760(h/god) \tag{13}$$

The expected annual productions of PV panels and their capacity factors are given in Table III. The total estimated annual produced electrical energy of the PV power plant is 130,80 MWh/year.

Table III. Expected annual production of the power plant and capacity factor

	Expected production [MWh/year]	CF [%]
PV plant 1	56.364	14.56
PV plant 2	33.074	16.47
PV plant 3	41.367	16.97

5. ANALYSIS OF PRODUCTION OF PHOTOVOLTAIC POWER PLANT

The possibilities that electrical energy be purchased by the Feed-In tariff and market prices are considered within the economic analysis. According to the decision by the Montenegrin Government [9] , the purchase price of electrical energy produced in PV systems on buildings or construction structures is 150 €/MWh. The average annual market price for a daytime , according to the EEX stock market 64 €/MWh.

The production costs can be calculated according to the following equation:

$$c = \frac{\left(\frac{i \cdot (1+i)^n}{(1+i)^n - 1}\right) \cdot I_{tot}}{A \cdot E} + m \tag{14}$$

where i is interest rate, n is exploitation period of PV plant (adopted 25 god), I_{tot} is total investment (adopted 1.1 €/W_p), A is availability of PV (this factor includes the degradation of a PV panel and availability of distribution grid; adopted value 95%), E is annual produced electrical energy (adopted 130.8 MWh), m is operative costs (adopted 0.01 €/kWh).

At Fig. 4, yellow colour presents the price of electrical energy according to the Feed-In tariff, while light green colour presents the market price, and magenta, red, blue and black colour present the production costs of power plants 1,2,3, PV a power plant 1,2,3 and entire PV plant, respectively.

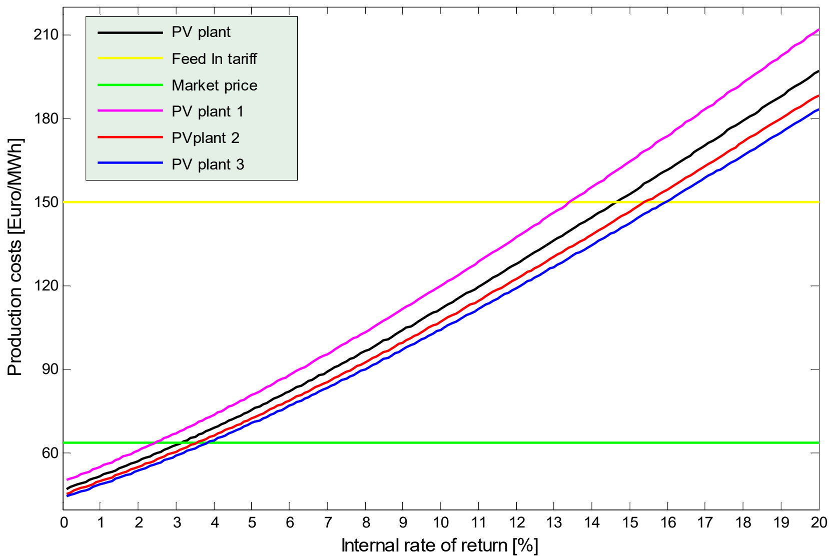

Fig. 4. Estimated production costs in the PV power plant in case of purchasing of electrical energy by the Feed-In tariff and market prices.

Based on Fig. 4, it can be concluded that, in case of purchasing of electrical energy by the Feed-In tariff, PV plants 1,2 and 3 are economically feasible because their internal return rates are (IRR) 13.4%, 15.3% and 16%, respectively. The IRR factor for the entire PV power plant 14.6%. In case of purchasing of electrical energy by market prices , PV power plants 1,2 and 3 and entire PV plant will make a profit in its life cycle if the investment costs are provided with an interest rate less than 2.5%, 3.6%, 3.85% and 3.1% respectively.

6.CONCLUSION

This paper analyses an opportunity and feasibility of the building of the PV power plant on the roof of the laboratory of The technical faculty in Podgorica. The PV power plant consists of three units with total installed power of 104.4 kW_p. This project is financially payable because it proved a relatively high internal return rate of 14.6% for the case of purchasing of electrical energy by the Feed-In tariff, while this investment would not be payable if the energy is purchased in market prices because it shows a relatively low return rate of 3.1% for this case.

Apart from the distributed production of electrical energy and profit that would be attained in this power plant, it can be an accompanying part of the laboratory. All measurements of electrical and non-electrical parameters, given the location of the power plant, would be easily incorporated into the laboratory area and included into the teaching.

The electric schemes of connecting of panels and the choice of invertors were not analysed in this paper because they should be adjusted to the needs of the laboratory and connector point for the distribution grid.

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