

Impact of consumption profile on costs of electricity in low-power grid-connected photovoltaic systems

Aleksandar Panić, Igor Jovanović, Dragan Mančić

Abstract – This paper analyses impact of consumption profile on costs of electricity for households which use low-power grid-connected photovoltaic (PV) systems in Republic of Serbia. Analysis was done by simulating the work of two different low-power grid-connected PV systems designed for two different consumption profiles. First PV system, with installed DC power of 5.55 kW, was designed for a consumption profile which aims to minimize the amount of energy taken from the grid by concentrating most of the consumption in part of the day around the noon. Second PV system, with installed DC power of 4.07 kW, was designed for a consumption profile which offsets significant part of grid consumption from the period around the noon to the lower tariff. Results of the simulation show that the PV system designed for the consumption profile which doesn't include significant consumption in the lower tariff generates slightly higher savings in every month of the year than the PV system designed for the load profile which includes significant consumption in lower tariff.

Keywords - Renewable energy sources, Low-power PV systems, Grid-connected PV systems.

I. INTRODUCTION

Photovoltaic (PV) systems are used to convert solar energy into electrical energy. Each PV system consists of PV panels and an inverter. According to their connection to the power grid, PV systems can be classified as autonomous, grid-connected, or hybrid systems [1].

In the Republic of Serbia, grid-connected PV systems are the most widely adopted due to relatively low initial investment costs and reliable electricity supply during periods of low solar irradiance. For households with low-power grid-connected PV systems of up to 10.8 kW, electricity billing is based on the net-metering method. This method calculates electricity costs using the balance between imported and exported energy in both higher and lower tariffs during the current month, as well as any accumulated surplus energy from previous months. Energy surplus occurs when exported energy exceeds imported energy. However, net-metering does not account for electricity that is generated by the PV system and consumed directly within the household without passing through the meter. This direct consumption is the most economically favorable, as it does not influence the electricity bill calculation.

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Exported energy and accumulated surplus reduce the cost of imported energy at discounted tariff rates, which are 5.906 RSD/kWh for the higher tariff and 1.476 RSD/kWh for the lower tariff [2]. If the imported energy exceeds the available surplus, the remaining portion is charged at standard electricity prices, as presented in Table I.

TABLE I
Prices of kWh of electrical energy for different zones and tariffs in the Republic of Serbia, expressed in RSD

	Higher tariff	Lower tariff
Green zone	13.454	4.153
Blue zone	19.655	5.703
Red zone	38.257	10.354

In order to maximize savings, households that use grid-connected PV systems usually consume most of the energy in the period of the day around the noon to maximize direct consumption and minimize energy import from the grid. An example of a consumption profile in which the goal is to achieve savings by maximizing the direct consumption, denoted as Consumption Profile 1 (CP1), is shown in Fig. 1. During cloudy days, the energy produced in the PV system in the part of the day around the noon can't supply the entire consumption in the household, which leads to a certain part of the energy in this period being imported from the grid and later paid at a price of 5.906 RSD/kWh, or more. Given that the price of a kilowatt-hour supplied from the grid in the green zone in the lower tariff is 4.153 RSD, consumption profile that can potentially generate higher savings moves part of the grid consumption from the period around the noon to a lower tariff. Example of such consumption profile is shown in the Fig. 2 and denoted as Consumption Profile 2 (CP2).

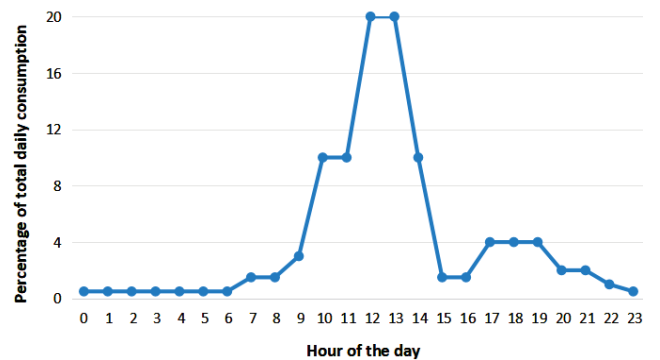


Fig. 1. Consumption Profile 1

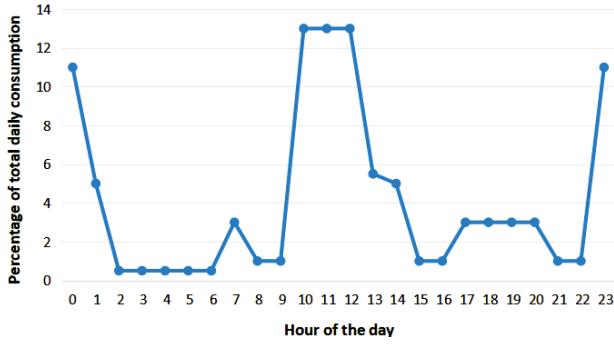


Fig. 2. Consumption Profile 2

This paper presents an analysis of the impact of the consumption profiles on costs of electricity for a low-power grid-connected PV system. After covering the design process of the PV systems used for previously shown consumption profiles in chapter two, the analysis was done by comparing results of simulation of both PV systems. Results of the simulation carried out using PV*SOL¹ are presented in chapter three.

II. PV SYSTEM DESIGN

The household for which the PV systems were designed in this paper is located in Pirot, Serbia (location N43.15°, E22.58°). It has excellent potential for installing the system, because part of the roof of 54 m² is oriented southeast, with an azimuth angle of -10° and a slope of 29°. Also, the surrounding objects do not cast a shadow on the observed side of the roof. The installed DC power of the PV system can be calculated using the expression [3]:

$$P_{dc} = \frac{P_{ac}}{\eta_m \cdot \eta_s \cdot \eta_{inv} \cdot \eta_T} \cdot 1.1. \quad (1)$$

In expression (1), P_{dc} represents the installed DC power and P_{ac} represents the AC power of the PV system, while η_m , η_s , η_{inv} , and η_T , represent coefficients which define losses due to mismatch of the characteristics of the PV panels, soiling of the PV panels, losses in the inverter and losses due to increased temperature of the PV panels in the real operating conditions, respectively. Multiplication with factor 1.1 represents the correction due to the cable losses and PV panel ageing losses [4]. AC power of the PV system can be determined using expression [3]:

$$P_{ac} = \frac{W_y}{365 \cdot h_{1-sun}}. \quad (2)$$

In expression (2), P_{ac} represents the AC power of the PV system, W_y represents the total energy consumption in the household for a one-year period, while h_{1-sun} represents the equivalent number of sun hours for the location where PV system is going to be installed. Total energy consumption

in the household for which the PV systems were designed was 7186 kWh in year 2023. Fig. 3 shows the energy consumption in the household in higher and lower tariff in each month of 2023, with total consumption in higher tariff of 5066 kWh and total consumption in lower tariff of 2120 kWh.

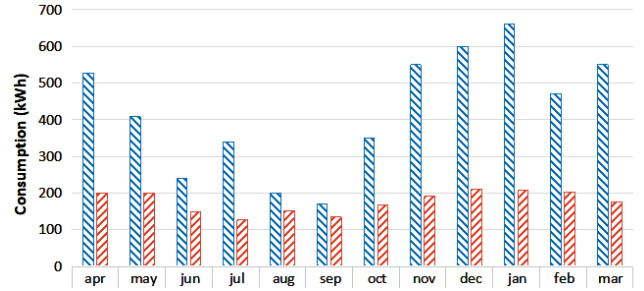


Fig. 3. Consumption in higher (HT – blue bars) and lower tariff (LT – red bars) in household in each month of 2023

For the calculation of the AC power of the PV system (PV1) designed for the CP1, the total energy consumption of 7186 kWh was taken into account, because of the goal of maximizing the energy supply from the PV system and minimizing the energy supply from the grid. In the calculation of the AC power of the PV system (PV2) designed for the CP2, only the consumption in the higher tariff with value of 5066 kWh was used. The goal in this case is to supply larger part of the energy consumption using PV system, while supplying part of the consumption using the low-price energy from the grid in the lower tariff.

According to data from the meteorological database used by PV*SOL, the equivalent number of sun hours h_{1-sun} for the surface with a slope of 29° and an azimuth angle of -10° in Pirot is 4.31 h/day. Based on the previously mentioned data, using the expression (2), the AC power of the PV system for the consumption profile that does not include consumption in the lower tariff is $P_{ac1} = 4.57$ kW, while the AC power of the PV system for the consumption profile that includes consumption in the lower tariff is $P_{ac2} = 3.22$ kW.

The mismatch of the characteristics of the PV panels during the PV system operation is ignored in this paper, so the value η_m is 1. The soiling of the panels can also be ignored, due to the frequent occurrence of wind, roof tilt and precipitation. The efficiency of commercially available inverters with power of up to 10 kW which are used in low-power grid-connected PV systems ranges between 96% and 98%, so the value in the middle of this range, 97%, was taken for the calculation in this case. The coefficient of efficiency reduction due to the increased temperature of the PV panel in real operating conditions compared to standard test conditions, η_T , can be determined using the expression [5]:

$$\eta_T = 1 + \alpha_p \cdot \frac{(T_{pa} - 25)}{100}, \quad (3)$$

¹ <https://pvsol.software/>

where α_p is the power reduction temperature coefficient and T_{pa} is the average value of the maximum operating temperatures of the PV panel for each month of the year. This temperature value is calculated in this way because of the large difference between the maximum operating temperature of the PV panels in the summer and winter months. The maximum operating temperature for each month of the year is calculated using the expression [5]:

$$T_p = T_{amb} + I_c \cdot \frac{NOCT - 20}{0.8}, \quad (4)$$

in which T_p is the temperature of the PV panel, T_{amb} is the ambient temperature, I_c is the irradiance expressed in kW/m^2 and $NOCT$ is the nominal temperature of the PV panel. Expression (4) is used to calculate the temperature of the PV panel under operating conditions different than the standard test conditions. For the design of the PV system in this paper, the monocrystalline PV panel CS3L-370M² manufactured by Canadian Solar was used, whose nominal temperature is 42°C. Based on the values of the ambient temperature and irradiance for each hour in one year period from PV*SOL database, arithmetic mean value of calculated maximum temperatures of PV panels for each month using expression (4) is 46.23°C and represents the average value of the maximum operating temperatures of the PV panels, T_{pa} . The value of the power reduction temperature coefficient of the PV panel CS3L-370M, α_p , is 0.35%/K. Based on the previously mentioned values of T_{pa} and α_p , η_T coefficient can be determined using the expression (3) and its value in this case is 0.926.

Based on the previously calculated AC power and expression (1), the DC installed power of the PV system PV1 is determined as $P_{dc1} = 5.56 \text{ kW}$ using the expression (2). The DC installed power of the PV2 is determined as $P_{dc2} = 3.94 \text{ kW}$. The number of required PV panels for the realization of a PV system is determined by dividing the calculated DC installed power by the power of the used PV panels at standard test conditions and rounding the obtained value to the nearest whole number. The power of the CS3L-370M PV panel at the standard test conditions is 370 W, so the number of required PV panels for the realization of PV1 is 15, which means that the installed DC power of PV1 will be 5.55 kW, while PV2 requires 11 PV panels, which means that the DC installed power of this PV system will be 4.07 kW [5].

For both PV systems, it is most convenient to connect all PV panels in series, because the maximum current of parallel connected PV panels is generally higher than the current that inverters with power of up to 10 kW can accept at their input. The optimal inverter for PV1 is an inverter with an output power of 5 kW (MOD 5000 TL3-X inverter manufactured by Growatt³), while for PV2, an inverter with an output power of 4 kW was selected (MOD 4000 TL3-X inverter manufactured by Growatt).

III. SIMULATION

In order to compare costs of electricity in previously designed PV systems, simulation of work of the PV systems was carried out using PV*SOL software.

Figs. 4-6 show direct consumption, exported energy and imported energy for both PV systems for each month in higher and lower tariff in the first year of use. Consumption in higher and lower tariff are denoted as HT and LT, respectively. Based on the values shown in Fig. 4, direct consumption is much higher in PV1 than in PV2, due to the higher consumption of energy in the period of the day around the noon in PV1 and the greater energy production in PV1. One part of energy produced in PV system in the period of the day when the consumption isn't at its peak is directly consumed in the household, while the other part is exported to the grid. Due to the higher installed DC power of PV1, exported energy in previously mentioned part of the day is higher in PV1 than in PV2, which leads to greater energy export on monthly bases as well as shown in Fig. 5. PV systems don't produce any energy through the night and produce very small amount of energy in the early morning hours, causing direct consumption and exported energy in lower tariff for both PV systems to be negligible. As PV systems don't produce almost any energy in lower tariff, significant amount of energy is imported from the grid in lower tariff in PV2, as shown in Fig. 6. Imported energy in higher tariff in both PV systems is present because of lower production in PV systems in cloudy weather conditions.

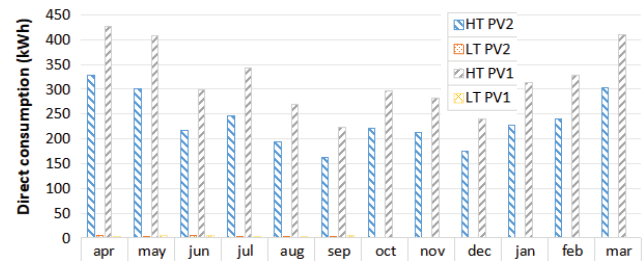


Fig. 4. Direct consumption in both PV systems in higher and lower tariff for each month in the first year of use

In case of both PV systems, the amount of exported energy is high enough to make the price of all of the kWh imported in higher tariff discounted. As consumption in the lower tariff in PV2 is significant, a lot more energy is paid at a standard price in case of this system than in PV1, as shown in Fig. 7. However, as the consumption in the lower tariff in PV2 doesn't exceed 350 kWh in any month, all kWh paid at a standard price would cost 4.153 RSD. Fig. 8 shows that all of the energy imported in higher tariff and a negligible part of energy imported in lower tariff for both PV systems are paid at the discounted price. As consumption in the higher tariff in case of PV system PV1 is higher than in PV system PV2, costs for discounted kWh in the higher tariff are bigger in case of PV1, as expected.

² <https://www.canadiansolar.com/>

³ <https://growatt.tech/>

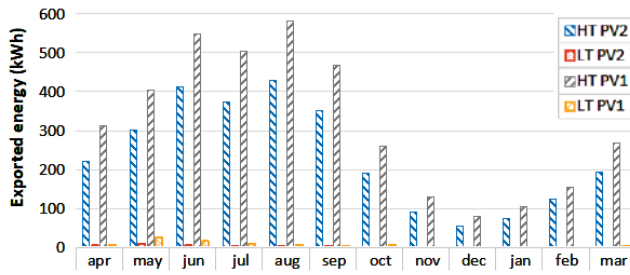


Fig. 5. Exported energy in both PV systems in higher and lower tariff for each month in the first year of use

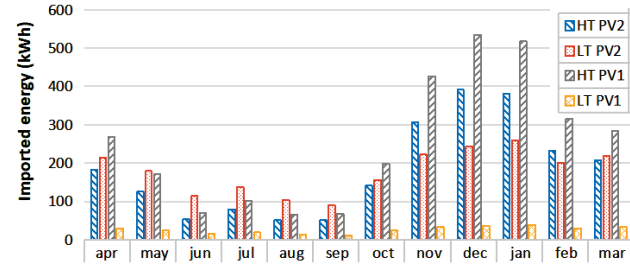


Fig. 6. Imported energy in both PV systems in higher and lower tariff for each month in the first year of use

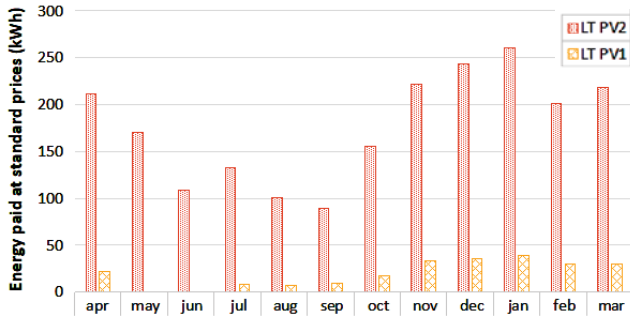


Fig. 7. Energy paid at standard prices in lower tariff for both PV systems for each month in the first year of use

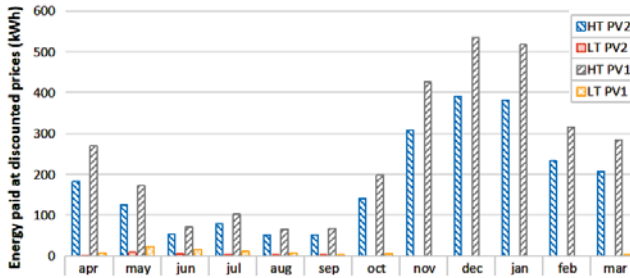


Fig. 8. Energy paid at discounted prices in higher and lower tariff for both PV systems for each month in the first year of use

However, difference in the energy paid at a standard price in lower tariff between the PV systems PV1 and PV2 is higher enough than the difference between the energy paid at a discounted price in higher tariff to make electricity costs slightly higher in every month for PV2, as shown in Fig. 9. Total electricity costs in PV1 are 2906 RSD less than in PV2. Compared to the electricity costs in the household without PV system, both of the PV systems reduce the electricity costs significantly in every

month, with the most noticeable savings achieved in the winter.

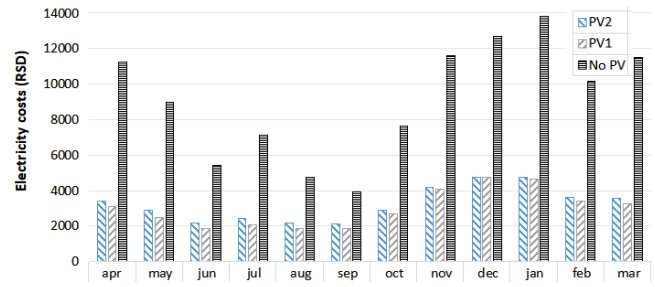


Fig. 9. Electricity costs without PV system and for both PV systems in the first year of use

IV. CONCLUSION

In this paper, the impact of consumption profile on costs of electricity in low-power grid-connected PV systems in Republic of Serbia is analyzed. Results of simulation indicate that PV systems designed for consumption profile which maximizes direct consumption and minimizes imported energy generate slightly higher savings than PV systems designed for consumption profile with lower peak of consumption in the period around the noon and significant consumption in lower tariff.

Overall, although both PV systems significantly reduce electricity costs compared to the household without PV, PV1 achieves slightly lower total costs than PV2, with the greatest savings observed during the winter months.

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