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MODELING AND SIMULATION OF THE OPERATION OF PHOTOVOLTAIC SYSTEM FOR MEETING ELECTRICITY CONSUMPTION OF RESIDENTIAL HOUSE CONSUMERS, INCLUDING ELECTRIC VEHICLE

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RESEARCH ARTICLE

ABSTRACT: In this paper, the sizing of the solar photovoltaic (PV) system which would meet the total yearly electricity needs of the existing single-family residential house in the territory of the city of Kragujevac (Serbia), was carried out. Two cases were considered. In the first case (case 1), the solar system would produce electricity that corresponds to the actual yearly electricity consumption of the existing electricity consumers in the house. On the other hand, in case 2, the basis for the system sizing would be the sum of the consumption of existing consumers and electricity consumption of the electric vehicle (EV). The energy and economic performance of the house with and without EV load were evaluated. Its energy behavior was simulated for real weather data by using EnergyPlus software. According to the simulation results, the shortest payback period for the installation of the PV system in case 1 is 6 years, and in case 2, for the installation of the PV system and purchasing an EV is 19 years.

KEY WORDS: *PV panel, electricity, electric vehicle, EnergyPlus, simulation*

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MODELIRANJE I SIMULACIJA RADA FOTONAPONSKOG SISTEMA ZA PODMIRIVANJE POTROŠNJE ELEKTRIČNE ENERIJE POTROŠAČA STAMBENE KUĆE KOJI UKLJUČUJU I ELEKTRIČNO VOZILO

REZIME: U ovom radu izvršeno je dimenzionisanje solarnog fotonaponskog (PV) sistema koji bi podmirivao ukupne godišnje potrebe za električnom energijom postojeće jednoporodične stambene kuće na teritoriji grada Kragujevca (Srbija). Razmatrana su dva slučaja. U prvom slučaju (slučaj 1) solarni sistem bi proizvodio električnu energiju koja odgovara stvarnoj godišnjoj potrošnji električne energije postojećih električnih potrošača u kući. S druge strane, kod slučaja 2 osnov za dimenzionisanje sistema bio bi zbir potrošnje postojećih potrošača i potrošnje električne energije električnog vozila (EV). Izvršene su procene energetskog i ekonomskog učinka kuće sa i bez opterećenja EV. Njeno energetsko ponašanje simulirano je za stvarne podatke o vremenskim prilikama upotrebom softvera EnergyPlus. Prema rezultatima simulacija najkraći period otplate troškova ugradnje PV sistema u slučaju 1 iznosi 6 godina, a u slučaju 2, troškova ugradnje PV sistema i kupovine EV, 19 godina.

KLJUČNE REČI: *PV panel, električna energija, električno vozilo, EnergyPlus, simulacija*

MODELING AND SIMULATION OF THE OPERATION OF PHOTOVOLTAIC SYSTEM FOR MEETING ELECTRICITY CONSUMPTION OF RESIDENTIAL HOUSE CONSUMERS, INCLUDING ELECTRIC VEHICLE

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INTRODUCTION

Electric vehicle (EV) will become an important component of household energy consumption globally under the plans to replace cars based on internal combustion engines [1]. The vehicle electrification is conceived as vehicle efficiency improvement [2]. The EV usage gives new hope that they can represent an alternative that is more likely to support not only the development of sustainable transport, but sustainable development in the broadest sense [3]. Well-built infrastructure for recharging the EV batteries is considered as one of the key issues for the success of the EV, in addition to their price [4]. Many studies indicate that the most important location for EV charging is at home, followed by work, and then public locations. [5]. According to Ref. [6] 45% of the private EV owners say they would charge their EV using renewable energy source either via rooftop solar panels (PV panels) and household battery (31%) or via an electricity contract which utilises green power or carbon offset (14%). The demand of PV panels and EV is expected to increase in the future. An example of their simultaneous growth is represented by the Californian market, where about 40% of EV owners also own solar PV systems [7]. Kobashi and Yarime [8] found that the integration of PV and EV technology would reduce yearly energy costs by 68% and CO2 emissions by 92% in 2030 of households in Japan. Manns [9] conducted a techno-environmental analysis of the German multi-family buildings with rooftop PV systems and EV charging stations. He revealed that 2 to 4 tonnes of CO2-equivalent emissions can be saved annually per residential home, depending on the building size (number of flats). Chowdhury et al. [10] optimized the operation of the existing PV system installed in the Institute of Energy of Dhaka University that would be integrated with the EV. It was concluded that 21% of the total electricity production can be used for EV charging thus reducing greenhouse gas emissions by 52,944 kg/year. The EV charging substantially affects the optimal size of the PV system for self-production and self-consumption of electricity. Piazza et al. [11] considered the impact of the electric mobility on the optimal design of a PV system. The developed optimization model applied to the campus building of the University of Genova demonstrates that the presence of EV increases the optimal size of the PV system from 15% to 25%. Munkhammar et al. [12] studied the impact of the EV charging on the size of a PV system within a net-zero energy building (NZEB) in Sweden. It was revealed that the integration of EV and residential house caused the increase of the yearly household electricity load and PV system size by 37%. Two existing single-family houses located in Netherlands and Belgium that meet NZEB standards (PV system installed) were used to analyze the energy and environmental performance of the building with and without EV load [13]. It was shown that the house with EV load can have 27 to 95% higher energy demands but lower total emissions by 11 to 35%. The effect of EV home charging and PV electricity production on the household electricity use as a future scenario in the city of Westminster was investigated in [14]. According to the obtained results the EV charging leads to the increase of the household electricity use by 14% to 61% depending on the number of occupants. Also, it was pointed out that the EV charging hours should be synchronized with the hours of PV electricity production.

A small-scale PV system could be profitable if its investment costs are low or subsidies are provided [15]. The territory of the Republic of Serbia has quite satisfactory conditions for the exploitation of resources obtained from the Sun, with yearly solar radiation reaching around 1400 kWh/m2 [16]. Low electricity prices in Serbia extend the simple payback period (SPB), making investing in the solar PV system a questionable decision. The incentive in the form of a state subsidy made this procedure more affordable by lowering investment costs and reducing the SPB. Preradović [17] compared the solar energy potential of six different cities, in six different countries, Freiburg (Germany), Graz (Austria), Maribor (Slovenia), Banja Luka (Bosnia and Herzegovina), Niš (Serbia), and Athens (Greece). The results show that Athens has the highest potential for solar energy production with 2108.31 kWh/m2 of yearly solar radiation, and that Niš stands second with 1662.62 kWh/m2. It was concluded that SPB is the shortest for the countries where the electricity price is the highest and vice versa. In other words, in Germany the SPB for installed PV system is the shortest, and in Serbia the longest.

Unfortunately there are no publications concerning the energy and economic viability of a system consisting of the grid-connected rooftop PV and EV within the residential house in the Serbian climatic conditions. The contribution of this paper refers to the answer to the question of whether a small-scale PV system is profitable in the current conditions of the Serbian electricity and EV market. As an example, a household in the city of Kragujevac was chosen. This analysis was carried out for two cases. Case 1 implies the installation of a PV system for a household without EV charging, while case 2 will provide the calculation for the chosen household but which includes EV load. For both cases the size of the PV system and SPB were determined.

1. METHODOLOGY

The software used in this paper enabled the realization of all the necessary tasks. For the creation of the 3D model of a residential building the software "SketchUp2016" was selected [18]. Using the tools of the "Open Studio" software, a 3D model from the "SketchUp2016" was inserted into the "EnergyPlus" software, in which the sizing and simulation of the PV system were carried out [19]. Geometric models of the household buildings were made on the basis of already existing buildings, located on the territory of the city of Kragujevac. They are two separate buildings (Fig. 1), a residential house and an auxiliary building, both consisting of two floors and an attic, and representing the home of a family of five.

The position of the surface on which the PV panels should be installed (roof of the auxiliary building) is determined by orientation of 200˚ and tilt angle of 39.1˚. This angle approximately corresponds to the yearly optimal tilt angle of the solar collector, of 37.5˚, for the city of Kragujevac. The average monthly household electricity consumption, calculated on the basis of the actual electricity bills, is about 500 kWh.

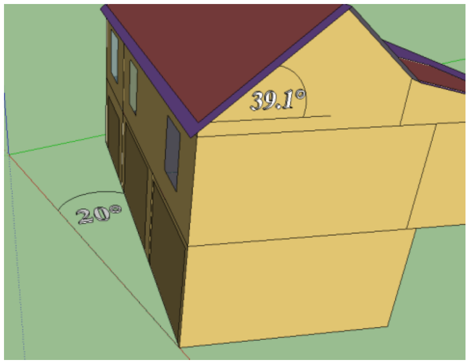

Figure 1. Isometric view of the analyzed residential and auxiliary building (left) and position of the auxiliary building selected for PV system installation (right)

When choosing the EV, an analysis of the entire market was carried out. Preference was given to those with the highest possible range, the highest possible efficiency and the lowest possible price. The analysis was performed for new vehicles that can serve as a family car for a family of five. The vehicle currently owned by the household is "Citroën C4", whose dimensions served as a reference value when choosing an EV. It was decided that the electric car most suitable for this household is the "Volkswagen ID.3 Pro S". The specifications of this car are given in Table 1 [20], while in Fig. 2 its appearance and dimensions are shown.

Table 1. Specifications of the adopted EV [20]

Battery capacity (100%) (kWh)	Useful battery capacity (60%) (kWh)	Average efficiency (Wh)	Range (km)	Top speed (km/h)	Power (kW)	Charging time (100%) (h)	Charging time - fast charger (70%) (h)	Vehicle price (€)
82	49.2	171	450	160	150	8h 15min	71 min	43,603.00

Figure 2. Appearance and dimensions of the adopted EV [21,22]

In order to make the investigation results as comprehensive as possible, the investigation will be conducted in two cases. Case 1 represents a case in which the calculation will be based on the existing current electricity consumption of the residential building without an EV. In Case 2, the total electricity consumption of residential building consumers, which include an EV, is considered.

For the purposes of the PV system sizing, it is necessary to determine the amount of electricity that the system should cover. In order to be able to carry out this procedure, the PV panel was first selected. The PV panel, adopted after market analysis, is a panel from the German manufacturer "LUXOR" under the name "Solar ECO Line HC BF M120 375W" [23]. The adopted average panel efficiency is based on the information provided in the technical documentation. The specifications of the selected PV panel, are presented in Table 2. After choosing the PV panel, it is necessary to draw a surface corresponding to the dimensions of that PV panel (1.755 m × 1.038 m) within the 3D building model. This model is imported into the EnergyPlus software, in which the simulation of the PV panel operation for the period of one year is carried out. To simulate weather conditions of the city of Kragujevac (latitude of 44.02˚N, longitude of 20.92˚E) the EnergyPlus weather file was used. Through simulations, it was obtained that the total yearly produced electricity of the selected panel is 664.57 kWh. This data affects the size of the PV system.

Table 2. Specifications of the adopted PV panel [24]

Power (W)	Efficiency (%)	Average efficiency (%)	Lifetime (years)	Warranty (years)	Temperature range (˚C)	Area (m^2)
375	20.94	19.09	25	15	- 40 to 85	1.82

Unlike case 1, in case 2 the total electricity consumption also depends on the consumption of electricity necessary to charge the battery and drive the EV. Its consumption is determined on the assumption that the vehicle is used for half of the year, i.e. in the winter and summer months, in harsh operating conditions when the heating and air conditioning system is used (ambient temperature lower than -10˚C (winter) and higher than 26˚C (summer)), and the rest of the year in ideal conditions. Due to the lack of data, it was assumed that the behavior of the car battery in winter and summer operating conditions is the same. Ideal conditions imply vehicle operation at an outdoor temperature of 23˚C without operation of the heating and air conditioning system. Car battery capacity is recommended never to be charged above 80% and never discharged below 20%, which reduces the battery capacity by 40% [25]. Also, on the basis of the household needs, it was adopted that the daily distance travelled by car is 40 km (Table 3).

The value of the average yearly consumption for case 2 is calculated according to the data taken from [20]. Data on consumption per kilometer for both harsh and ideal conditions are multiplied by the daily travelled distance, whereby the average daily consumption of the vehicle in these conditions is obtained. The number of days in harsh and ideal conditions is obtained by summing the number of days in the months for which these operating conditions apply. The product of the number of days in certain conditions with the daily consumption for those conditions gives a number that represents the total consumption for part of the year in those conditions, so the sum of consumption in ideal months and consumption in harsh months gives the total yearly consumption in case 2. If the yearly consumption is divided by the number of months, the average monthly consumption of an EV is obtained. Dividing this value by the battery capacity gives the number of charges per month, that is, the time spent on the charger during one month. It is possible to calculate the car range if the battery capacity is divided by the average efficiency of the battery. The average efficiency is determined by dividing the yearly consumption of an EV by the product of the number of days in a year and the distance travelled on a daily basis (Table 3).

Table 3. Calculation of the vehicle operational characteristics (case 2)

Battery capacity (100%) (kWh)	Battery capacity (60%) (kWh)	Daily distance traveled (km)	Consumption per km in ideal conditions (kWh/km) [20]	Daily consumption in ideal conditions (kWh)	Consumption per km in harsh conditions (kWh/km) [20]	Daily consumption in harsh conditions (kWh)
82	49.2	40	0.148	5.92	0.203	8.12
Number of days in ideal conditions	Number of days in harsh conditions	Yearly consumption (kWh)	Average monthly consumption (kWh)	Number of battery charges during a month	Average consumption per km (kWh/km)	Range with full battery (km)
183	182	2561.2	213.43	4.34	0.175	280.46

2. RESULTS AND DISCUSSION

2.1 Size of the PV system

As already explained, the size of the PV system is determined by the total yearly consumed electricity of the considered residential building (for the appropriate case) and the total yearly produced electricity of one PV panel (Table 4). For case 1, it was found that the required number of PV panels is 10 (Fig. 3 (left)). The required number of PV panels in case 2, calculated according to the values of the parameters shown in Tables 3 and 4, is 13 (Fig. 3 (right)) (Table 4). Based on the number of PV panels, the appropriate power of the inverter is adopted, which efficiency is also taken into account during the simulation of the PV system operation (Table 4).

Table 4. Size of the PV system for both cases

Case	Yearly electricity production of one PV panel (kWh)	Total electricity consumption (kWh)	Number of PV panels	Adopted number of PV panels	Inverter power (W)	Inverter efficiency (%)
1	664.57	6027.96	9.07	10	4200 [26]	97.60% [26]
2	664.57	8591.23	12.93	13	5000 [27]	97.50% [27]

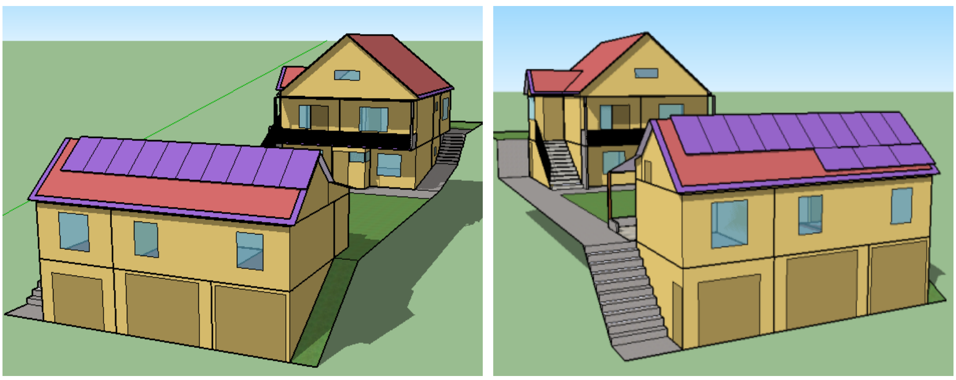

Figure 3. 3D models of a residential house with the required number of PV panels for case 1 (left) and case 2 (right)

Fig. 4 shows a diagram of the electricity production and consumption in both cases. As a reminder, electricity consumption was adopted on the basis of the actual household bills, and it can be concluded that it is the lowest during the summer months and the highest during the winter months. The difference between consumption in case 2 and case 1 corresponds to the amount of electricity needed to charge the EV battery, while the difference in production between these two cases exists because of the higher number of PV panels adopted in case 2. Electricity production in both cases has a completely opposite pattern of behavior in relation to its consumption during the year. The highest production occurs during the summer months, when the intensity of direct solar radiation is high and the share of diffuse radiation in the total radiation is small, while the lowest production is during the winter months. The total amount of produced electricity is 6645.65 kWh, which exceeds the needs for the same by about 600 kWh, while in the second case it is equal to 8639.35 kWh, with a surplus of about 50 kWh.

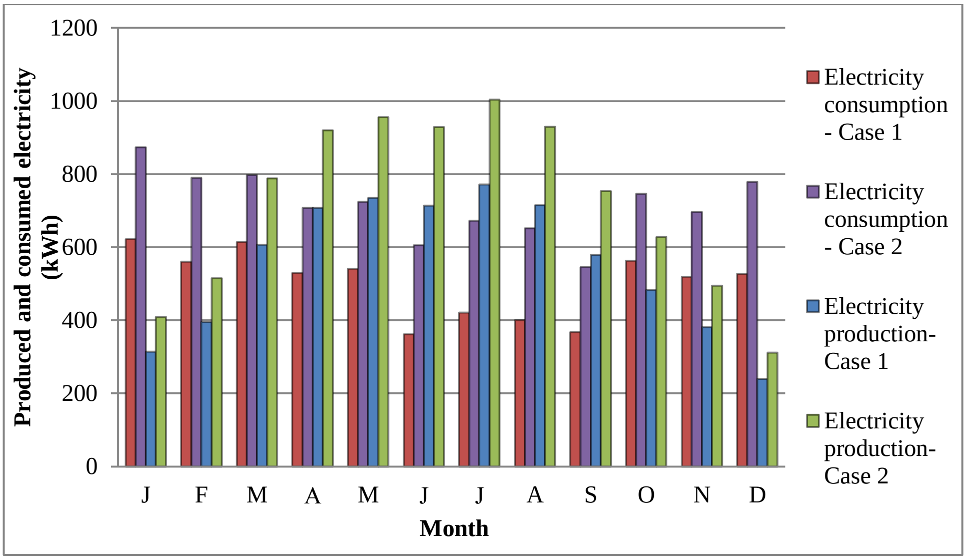

Figure 4. Monthly electricity consumption and production in both considered cases

2.2 Cost-effectiveness analysis

Before analyzing the profitability of installing the system, a couple of terms should be defined. First of all, it is necessary to clarify what is behind the term prosumer. A buyer of electricity who produces electricity from renewable energy sources within his facility, uses the produced electricity to meet his own needs, and hands over the surplus to the network, is called a prosumer. Before becoming a prosumer, the buyer of electricity can apply for a subsidy for the PV system installation. Subsidies represent financial assistance from the state for investments by citizens in which the state has an interest. Subsidies for the installation of PV systems, provided by the Republic of Serbia, cover 50% of the total investment costs, with the condition that the maximum power of the system for which these privileges can be realized is 6 kW [28]. It is also important to note that in case 2, the right to a subsidy for purchasing an EV, which amounts to €5,000.00 for the fully EV, can be earned, too [29].

In Table 5 the yearly costs of electricity after the PV system installation are given. Based on the actual consumption bills, total household electricity costs amount to 40,208.00 RSD. These costs are calculated without including additional costs in the form of fees to the supplier. As they do not disappear after the installation of the PV system and it is impossible to predict them, for the purposes of this work, their influence is not considered. The principle of calculating electricity costs after installing a PV system is as follows. In months when consumption exceeds production, electricity costs will be calculated based on the amount of electricity consumed under the lower tariff increased by the difference between the electricity consumed under the higher tariff and the electricity produced.

The electricity prices of the corresponding zone in the corresponding tariff are adopted according to [30]. In months when production exceeds consumption, or they are equal, electricity costs will be calculated based on the electricity consumed within the lower tariff. According to [31], the unused part of electricity can be carried over to the next month and used in months when the production does not meet the consumption until 1st of April of the next year.

Table 5 Monthly electricity costs in both considered cases (1 € = 118 RSD)

Month	Production (kWh)		Consumption- higher tariff (kWh)		Consumption- lower tariff (kWh)		Difference between produced and consumed electricity at the end of the month (kWh)		Cost of electricity for both cases (RSD)
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	
A	708	920	406	584	124	124	302	337	267.22
M	735	955	404	588	137	137	633	704	295.24
J	714	929	276	520	86	86	1071	1113	185.33
J	772	1004	400	652	21	21	1443	1466	45.26
A	715	930	326	578	74	74	1832	1818	159.47
S	579	753	302	480	66	66	2109	2092	142.23
O	483	628	450	634	113	113	2142	2086	243.515
N	381	495	403	581	116	116	2120	2001	249.98
D	240	312	395	647	132	132	1965	1666	284.46
J	314	409	486	738	136	136	1793	1337	293.08
F	396	515	439	668	122	122	1750	1184	262.91
M	607	789	464	648	150	150	1893	1325	323.25
Sum	6646	8639	4751	7314	1277	1277	1893	1325	2,751.95

From Table 5 and Fig. 4, it can be concluded that electricity production meets consumption in all months. The calculation results also indicate a problem related to the system oversizing. Guided by the idea that the system should have as many solar panels as necessary to meet the yearly electricity consumption, a mistake is being made. Since the produced electricity can be used only in the tariff in which it was produced, which is certainly only within the higher tariff, the electricity consumed in the lower tariff should then be excluded from the calculation. Also, according to [20], after 1st of April all the unused electricity is actually "gifted" to electricity provider, which further complicates the system sizing. From the table above, it can be concluded that the system is oversized in the first case by almost 3 PV panels and in the second by almost 2 PV panels. Investment costs for both cases are given in Table 6.

Table 6 Investment costs for both considered cases in thousands of RSD (1 € = 118 RSD)

PV panel price (in 000 RSD) [24]		Inverter price (in 000 RSD) [26][27]		Roof truss price (in 000 RSD) [32]		Price of other elements and system mounting (in 000 RSD) [33]		Price of smart electricity meter (in 000 RSD) [34]		Price of EV with subsidy (in 000 RSD) [20]	
Case											
1	2	1	2	1	2	1	2	1	2	1	2
220.66	286.86	75.00	118.80	38.72	52.34	65.00		44.35		0	5,113.52

According to Table 6, the total cost of installing the PV system for case 1 is 443,735.00 RSD without subsidy and 221,867.50 RSD with subsidy. In case 2, the installation cost without subsidy amounts to 5,094,493.92 RSD, and with the subsidy for the installation of the PV system, 4,810,821.42 RSD. The subsidy for buying the selected EV is 586,372.68 RSD [29]. A few more things need to be emphasized. As the EV is charged using electricity produced within the home, its charging is free (if the vehicle is charged within a higher tariff). Therefore, the fuel savings are equal to the yearly fuel costs for the currently used household car, which are 190,530.00 RSD. Also, the price of the EV, which is a replacement for the mentioned vehicle, can be reduced by the market value of that car, which is 410,789.00 RSD. When all the necessary parameters are calculated, the SPB can be determined. For case 1, the SPB without the participation of the state in the form of subsidy for the installation of solar PV system is 11 years, 10 months and 4 days, while with the subsidy it is 5 years, 11 months and 2 days. For case 2, the SPB without the subsidy amounts to 20 years, 6 months and 15 days, while with the subsidy it amounts to 19 years, 3 months and 18 days.

3. CONCLUSIONS

In this paper, the sizing of the solar PV system which would meet the total yearly electricity needs of a residential house in the territory of the city of Kragujevac, was carried out. Two cases were considered. In the first case (case 1), the solar system would produce electricity that corresponds to the actual yearly electricity consumption of the existing electricity consumers in the house. On the other hand, in case 2, the basis for the system sizing would be the sum of the consumption of existing consumers and electricity consumption of the EV. Sizing was preceded by the creation of a 3D house model in the software "SketchUp2016" and a PV panel model in the software "EnergyPlus", in which its energy behavior was simulated for real weather data for the city of Kragujevac. According to the simulation results, the shortest payback period for the installation of the PV system in case 1 is 6 years, and in case 2, for the installation of the PV system and purchasing an EV is 19 years.

Certain assumptions were adopted before making the calculations. The efficiency of the solar PV panel of 19.09% is adopted as average and constant for 25 years, which means that in the first half of its lifetime the efficiency of this panel will be slightly lower, while in the second half it will be higher. In reality, it will be lower and variable due to operating conditions that differ from the test conditions of the PV panel. In this regard, the influence of temperature and soiling of the receiving surface of the panel on its efficiency was neglected. Also, it was adopted that the habits of the householders do not change. After installing the PV system, using the large electricity consumers within the lower tariff becomes the most unprofitable option. Regarding case 2, it can be noticed that EV prices still are not low enough, or in other words, the efficiency and range of cheaper ones are not yet satisfactory. Since it is a still rising technology, a drop in the price and an improvement in the car characteristics can be expected. Also, the PV panel technology development is on the rise, so in the future their profitability for both cases could be shorter.

According to the currently available data on electricity bills, recently sent to households that received the status of prosumer, it seems that the sizing of the PV system according to the total yearly electricity needs is wrong, that is, the system is oversized. The reason for this lies in the calculation of electricity consumption within the lower tariff and the fact that the prosumer loses the possibility of using "accumulated" electricity produced from previous months after 31st of March. The solution to this problem would be a purposeful increase in electricity consumption by installing electric heating systems (heat pump...), where the investment would pay off in another field. On the other hand, a potential solution to the problem would be the possibility of calculating the "accumulated" produced electricity in the next accounting period or meeting the electricity consumed in a lower tariff (at night), with the cancellation or reduction of the corresponding fees. Due to the impossibility of determining the amount of fees and charges that increase the amount of the bill, there was not much to say about it in this paper, and the problems and advantages related to it remain the subject of some subsequent research.

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