Study of PV System for Electricity Production for Self-Consumption

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***Abstract*—Self-consumption for residential and industrial buildings is important in order to reduce energy consumption from the electricity grid. As energy prices rise, more and more consumers are installing PV systems for their self-consumption. Self-consumption systems have a number of specific difficulties to solve related to variations in solar energy production and the user's load profile. Each installed system will contribute to the reduction of CO_2 emissions and encourage the installation of low-power PV systems to produce green energy. In this way, users will reduce their dependence on the use of energy from the mains. The aim of this work is to develop simulation model for calculation of energy balance of PV system for self-consumption. Comparison of performance of two PV system types is done – without and with battery storage.**

Keywords— photovoltaic system, self-consumption, grid-connection, PV model, battery storage

I. Introduction

Since the free market of electricity for industrial users has been adopted, the cost of electricity for office buildings, service or production premises has increased significantly, making it difficult for many businesses. Many companies are looking for alternative options to optimize costs by installing photovoltaic generators. Photovoltaic systems for self-consumption can easily be installed on roofs, facades and sheds. One of the advantages of local electricity production is a significant reduction in transmission losses. Photovoltaics integrated in open parking lots are also often used, thus protecting cars from the external influences of the environment [1].

Currently, electricity prices for household needs in Bulgaria are the lowest in the EU. However, a large number of Bulgarian households have difficulties with their electricity bills. For business and industrial consumers, who are on the free electricity market, prices have risen more drastically, with the price reaching 400 euros for one MWh of energy. Therefore, industrial users may use this type of system for their own consumption to reduce electricity bills [2].

The use of such systems by the industry is effective because they have a good match with the load profile with the production from PV panels, which leads to a better coefficient of own electricity consumption. While it is difficult for consumers to use all the energy produced by a PV system, storage devices are often used to reduce the loss of unused energy from a PV system. For the correct sizing of such a system, the load profile of the user is of great importance. Its correct determination is necessary for correct sizing and optimization of the system.

Some studies show the development of self-consumption systems in Europe over the last 10 years [3], [4]. Other authors make a comparison between different types of self-consumption systems, with and without storage [5], [6].

Two case studies of PV systems for self-consumption will be considered in the paper, without and with energy storage. Both systems are connected to the grid. The results show the power exchange in the systems with step of 1 hour. Besides, the energy balance for one year is done. It was also made a comparison of system performance with two batteries with different capacity.

II. Self-Consumption Conception

A. Definition

Self-consumption systems are based on the definition that the energy produced by the system will first be consumed by the user, and the excess energy will be injected into the grid. The basic schema off self-consumption is shown in Fig. 1. The smart meter manages the flow of energy in both directions, when there is a shortage of energy, it is drawn from the grid, and the surplus is given back.

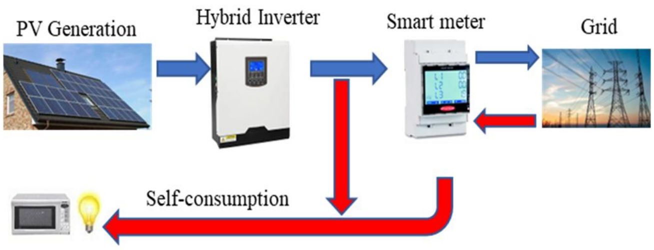

Fig. 1. Simple Schema of Self-Consumption.

The produced electricity from PV installation is primarily consumed at the place of production. In this way, the producer simultaneously produces and consumes its own energy without injecting or taking energy from the grid. The building will consume some energy from grid when generation is not enough to supply the whole load [8].

B. Different types of PV systems for self-consumption

There are different solutions for PV systems for self-consumption. One of them involves the use of a storage device. When there is a surplus of PV energy, it feeds the battery, and when there is a shortage - energy is consumed from the battery. In case the battery is discharged, the necessary energy is supplied from the mains. A hybrid inverter is used for photovoltaic systems in order to give the excess energy to the grid, and when there is a shortage to be compensated by the grid. By definition, the battery is charged first and then, if there is excess, it is consumed locally or fed into the grid. Such a system is shown in Fig. 2.

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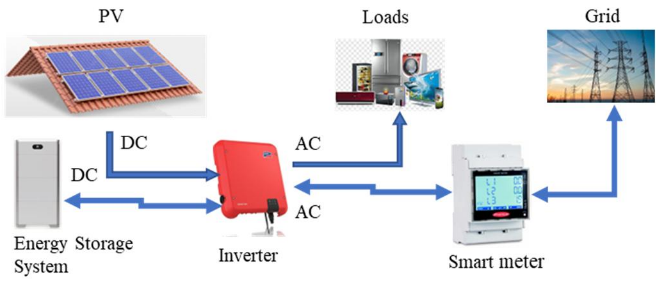


Fig. 2. PV system with storage system.

Systems without storage devices are also often used, where the energy produced by a PV system is consumed directly. A precise load profile is needed so that most of the PV energy produced can be consumed directly by consumers. The disadvantage is that when there is no enough consumption, the energy produced by the PV system will be injected back to grid or wasted. The advantage is that these systems are relatively cheaper than the systems with energy storage, which are still quite expensive. The system without storage is shown in Fig. 3.

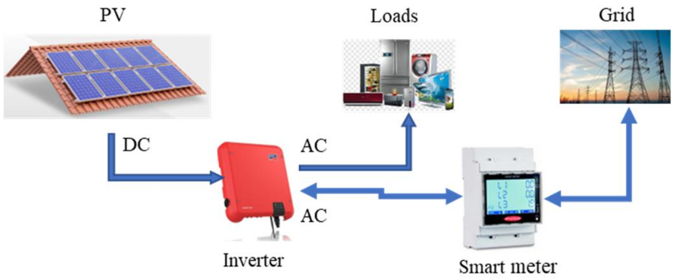


Fig. 3. PV system without storage system.

The PV systems for self-consumption also are distinguished according to the power exchange with the grid utility. There are two possibilities:

- PV system with export of extra power back to the grid. In this case, when PV panels produce more power than the load consumes, the surplus power is exported to the grid and sold to supplier.
- PV system without export of energy back to the grid. In this case, when PV power is greater than consumed one, the power of the solar inverter is limited to supply only the load. The grid power becomes zero for the time when solar power exceeds the load. For this PV system, a special energy meter and solar inverter are needed. The energy meter gives feedback to the inverter when the grid power changes its sign. The inverter starts to limit and regulate its output power, so the grid current is maintained to zero. The disadvantage of this solution is that the extra solar energy that can be produced, is not utilized.

Both PV systems mentioned above may contain battery or not. As a result, four combinations of PV systems for self-consumption may be configured and used according to the user needs, financial conditions, local regulations for grid utility and energy market.

III. Case Studies

Here are presented results of two case studies of PV systems for self-consumption.

- PV system without battery storage with export of extra power back to the grid.
- PV system with battery storage with export of extra power back to the grid.

The considered PV system is intended for supply of family house in North-East Bulgaria. The available data is:

- Load profile of the house for one year with 1 hour step (8760 points). The load profile is realistic obtained by measurements on a real object.
- Data for solar radiation in the region with 1 hour step.
- Data for ambient (air) temperature and wind speed in the region.
- Datasheets for solar panels, inverters, and batteries.

For the calculation of power produced by PV panels, information for global solar radiation on collector surface is needed. The available data for solar radiation is for a horizontal surface. That is why an approach for conversion of solar radiation from horizontal to arbitrary oriented solar panel is used. The detailed description of the method for this conversion is given in a previous work [7].

For the project, an orientation of solar panels to south is used with a tilt angle of 30 degrees. This angle is considered as optimal for Bulgarian territory. The PV generator is composed of 11 panels of monocrystalline silicon, each with power of 450Wp. The rated efficiency of chosen modules is 20.5% at STC. The total installed power of PV modules is 4950Wp, which is recommended for roof-mounted PV systems in Bulgaria.

The power produced by PV generator is calculated based on global radiation in panel plane and taking into account the influence of cell temperature on module efficiency. The module power at given global radiation and cell temperature P_{pvm} is calculated as follows:

$$P_{pvm} = \frac{G_{mp}}{G_{mp}} P_r \left(1 + k_{pm} \frac{(T_{cell} - 25)}{100} \right) \qquad (1)$$

where: G_{mp} is calculated global radiation in module plane, G_{ref}= 1000W/m^2 is standard solar radiation at STC, P_r – rated module power at STC, T_{cell} – cell temperature, k_{pm} = -0.35%/°C – temperature coefficient of module power.

The total power of PV generator is:

$$P_{pv} = 11 P_{pvm} \qquad (2)$$

The cell temperature is calculated from ambient temperature and solar radiation on the PV modules using the formula proposed by Ross [7]:

$$T_{cell} = T_a + hG_{mp} \tag{3}$$

where h is an empirical parameter for the considered PV panel.

Using the described mathematic model, a computer simulation model is developed in Excel environment. Below are presented the main results from the simulations for the two cases.

A. Case 1 - without battery

Here, the PV generator supplies the house appliances. If there are excess generated power, it is delivered back to the grid. When the consumption is greater than solar power the difference is delivered from the grid. In Fig. 4 is shown the load power profile and calculated power from PV generator for one year with 1 hour step.

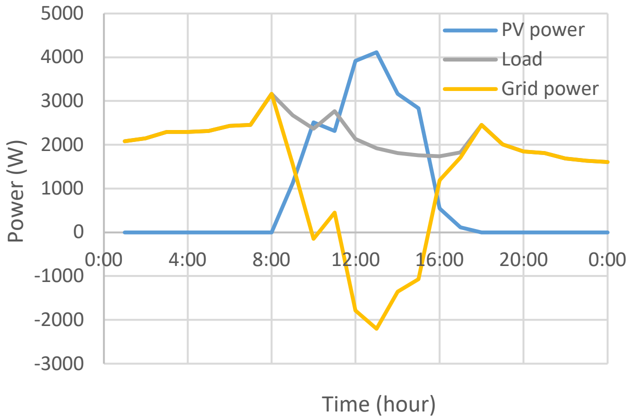


Fig. 5. Power of PV generator, load and the grid power for 2 January.

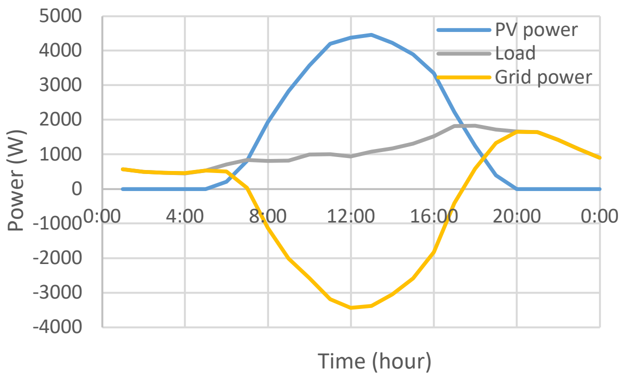


Fig. 6. Power of PV generator, load and the grid power for 27 July.

In Fig. 5 and Fig. 6 are shown the power from PV generator, load power, and grid power for 2 January and for 27 July. The grid power P_{gr} is determined as:

$$P_{gr} = P_L - P_{pv} \tag{4}$$

where: P_L is load power (consumption in the house).

The grid power can be:

- Positive – when the load power is greater than PV power. This means the power is consumed from the grid.
- Negative – when load power is smaller than PV power. In this case the power is exported from house to the grid.

For these particular days, during the day, there is enough PV power to supply the load and to export the surplus to the grid. But in cloudy days, when solar radiation is much smaller the PV power, is not sufficient to supply the load and all the time power is consumed from the grid.

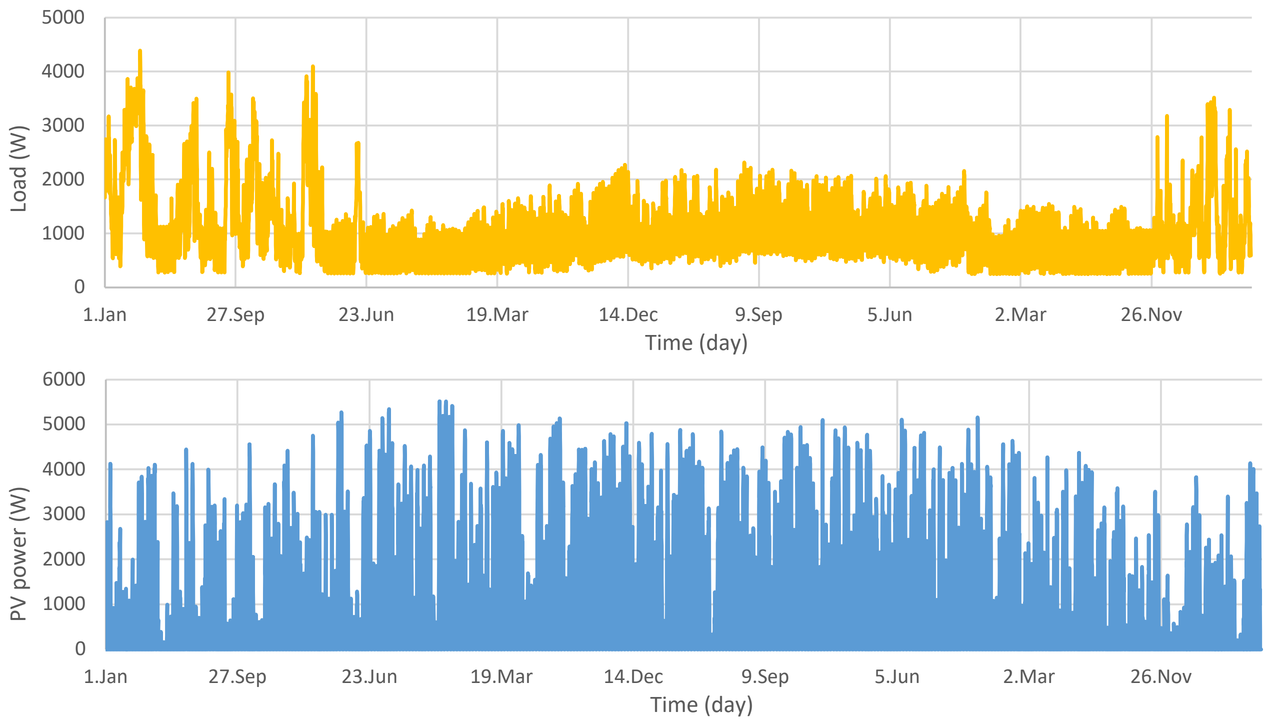


Fig. 4. Generated PV power (down) and load power (up) for one year.

B. Case 2 - with battery

Here, the PV generator is combined with a battery storage and suitable solar inverter. Two battery storage capacity were used -10 and 20kWh. These values correspond to batteries of 10kWh, which are common for several producers. An algorithm for battery usage is developed and implemented in Excel simulation model. In brief, the battery usage strategy consists in the following:

- When PV power is bigger than load battery is charged.
- When PV power is bigger than load and battery is fully charged, the excess power is exported to grid.
- When PV power is lower than load battery delivers power until fully discharged.

Examples from simulation results with 20kWh battery for the same days as in Case 1 are shown in Fig. 7 and Fig. 8.

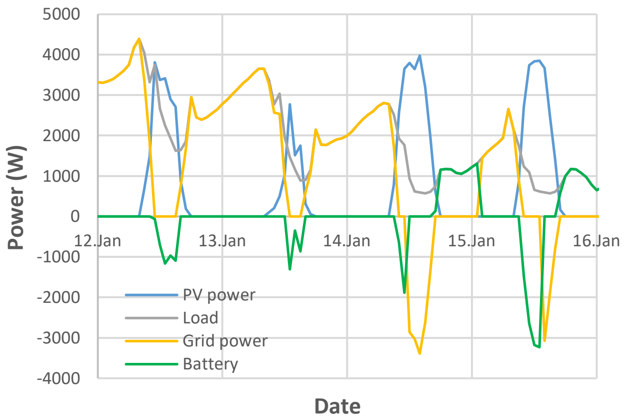


Fig. 7. Power of PV generator, load, grid, and battery for 12-16 January.

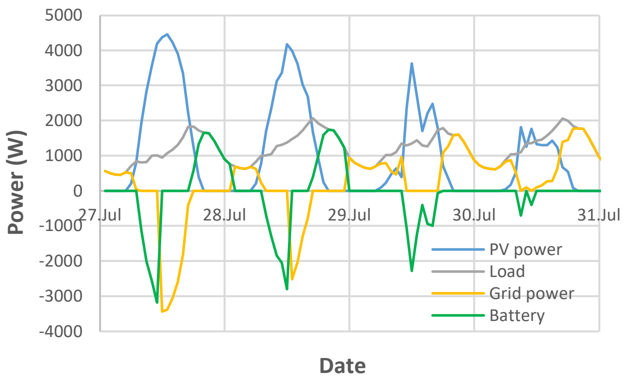


Fig. 8. Power of PV generator, load, grid, and battery for 27-31 July.

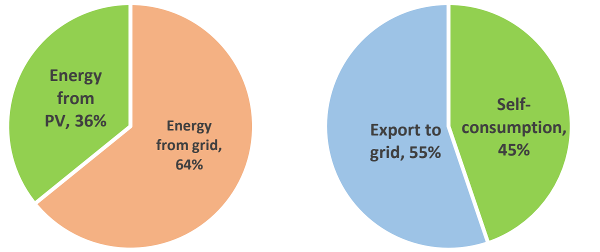
The convention for battery power is the following: the power is positive when battery is discharged and delivers power to load; the power is negative when battery is charged and stores energy.

As it can be seen from Fig. 7, when the battery is not fully charged it is not used during the night. This is because the strategy implies the battery to be used only when it is fully charged. This is necessary to decrease the number of recharge cycles and increase the battery life.

In the second example (during the summer) shown in Fig. 8, the solar energy is much bigger and is sufficient to recharge battery in the first half of the day. After that the excess power is injected to the grid. In the afternoon, when solar power decreases the battery starts to deliver power and consumption from the grid is annulled. The battery charge is not sufficient for the whole night and the rest of power is delivered from grid.

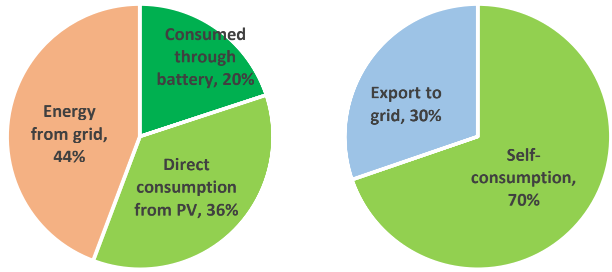
COMPARISONS

A graphical comparison was made in the form of a pie chart, which is shown in Fig. 9 and Fig. 10.



Load energy sharing. Produced PV energy sharing.

Fig. 9. Load energy sharing and produced PV energy - Case 1 – without battery.



Load energy sharing. Produced PV energy sharing.

Fig. 10. Load energy sharing and produced PV energy - Case 2 – with 20kWh battery.

Case 1 – without battery, the fraction of user needs supplied from PV is 36%, and the insufficient energy is covered by the main is 64%. Of the energy produced by photovoltaics 55% is exported to grid and 45% is used for self-consumption.

Case 2 – with 20kWh battery, the fraction of user needs supplied from PV is increased from 36 to 56%. Battery usage increases the self-consumption quota from 45 to 70% of produced PV energy.

TABLE I. COMPARISON OF ENERGIES FOR THREE CASES

Energies	**Case**		
	No battery	***With 10kWh battery***	***With 20kWh battery***
Load consumption, kWh	9125	9125	9125
Produced PV energy, kWh	7296	7296	7296
Self-consumption PV energy, kWh	3269	5111	5056
Energy from grid, kWh	5856	4014	4069
Exported to grid, kWh	4028	2185	2240
Energy converted through battery, kWh	0	1842	1787

The results from simulations are summarized in TABLE I. The results show that the increase in battery capacity does not contribute for bigger self-consumption quota. Even, in this particular case, the bigger battery leads to less self-consumed PV energy. This fact may be explained with more frequently use of full battery charge of smaller battery, which fits more flexibly to power fluctuations.

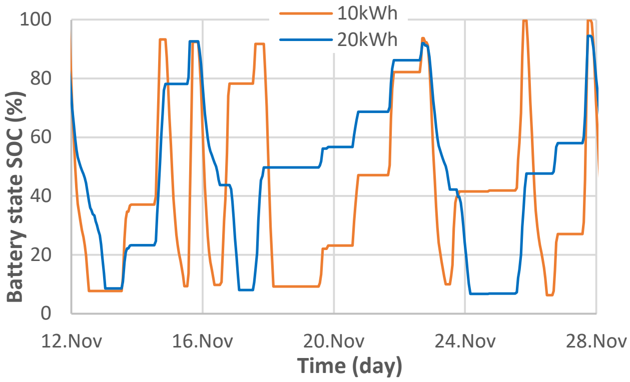


Fig. 11. Comparison of battery operation (State Of Charge, SOC) for two values of battery capacity – 10 and 20kWh.

Fig. 11 shows a comparison of battery operation with the two values of capacity – 10 and 20kWh. As it can be seen, the smaller battery reaches full charge 6 times whereas the bigger battery does it only 3 times.

Conclusion

The paper presents the grid-connected photovoltaic systems for generation of electricity for self-consumption. A classification according storage usage and mode of interaction with the grid is done. Mathematical model for calculation of PV system power taking into account panel orientation and influence of the cell temperature is presented. A computer simulation model of such a system is developed in Excel environment. A strategy for battery usage is also implemented in simulation model. Results from two case studies of PV systems for self-consumption are presented and discussed. The battery storage system increases the quota of self-consumption of solar energy. Despite still high prices of batteries this configuration may be particularly useful in contemporary conditions of very high electricity prices. Moreover, these prices are highest during the day where the PV system generates power. As the purchase price of energy is much higher than the selling one the bigger self-consumption is favorable from an economic perspective. The tool developed by the authors enables precise sizing of the battery capacity depending on the specific features of the load, PV system and meteorological data. In this way, a battery with a minimum capacity can be chosen, which will optimize financial costs.

In addition, the more detailed analysis of the simulation results in the case with battery shows that the step of 1 hour is too rough for precise calculations of battery state of charge SOC. This is more visible when the battery capacity is relatively small compared to PV array power. In the case with 10kWh battery fully charges for 2 hours with the rated power of PV array. This leads to mistakes in the calculation of battery SOC. The problem may be solved using smaller time step for simulations – for example 10 min instead of 1 hour. Further authors' efforts will be focused on developing algorithms and simulation models for PV systems with power limitation and different battery usage strategies, performed with small time step.

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References

[1] K. Ettalbi, H. Elabd, M. Ouassaid and M. Maaroufi, "A comparative study of energy management systems for PV self-consumption," 2016 International Renewable and Sustainable Energy Conference (IRSEC), 2016, pp. 1086-1091.

[2] Analytics. https://www.e3analytics.eu/.

[3] A. Tazarine and H. El Omari, "Designing of a photovoltaic system for self-consumption at the faculty of technical sciences of Settat," 2016 International Renewable and Sustainable Energy Conference (IRSEC), 2016, pp. 171-176.

[4] Worldwide electricity production from renewable energy sources "details by region and by country" – Italy- Fifteenth inventory 2013 edition.

[5] Gaetan Masson-IEA-PVPS, Jose Ignacio Briano & Maria Jesus BaezCreara "Review and analysis of PV Self-Consumption Policies".

[6] A. Tazarine and H. El Omari, "Designing of a photovoltaic system for self-consumption at the faculty of technical sciences of Settat," 2016 International Renewable and Sustainable Energy Conference (IRSEC), 2016, pp. 171-17

[7] G. Notton, V. Lazarov, L. Stoyanov, "Optimal sizing of a grid-connected PV system for various PV module technologies and inclinations, inverter efficiency characteristics and locations", Renewable Energy, 35 (2), 2010, pp. 541 – 554.

[8] B. Boychev, M. Malkovska and S. K. Filipova-Petrakieva, "Enhancing energy efficiency through the implementation of photovoltaics in municipal and household buildings," 2019 11th Electrical Engineering Faculty Conference (BulEF), 2019, pp. 1-2