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Energy performance of the photovoltaic system in urban area - case study

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Abstract. Nowadays, photovoltaic systems installed in urban areas may be essential for distributed generation and lead to increase energy security and improve economy of building exploitation. Unfortunately, in many cases their operation in urban area is not so efficient. It is connected with shadowing by neighbouring buildings, trees or by the HVAC systems installed on roofs (including such elements as fans, compressors, etc). Moreover, HVAC systems often occupy "the best" place on roofs. Level of shadowing varies during a day, and a year, significantly influencing on the power generation from PV installations. It caused serious difficulties in designing such installations (e.g. choosing position, orientation, number of modules etc.). In the paper a PV efficiency analysis was performed for the case of photovoltaic installation located on the roof of didactic building in Krakow centre. The projected power of the installation was 8.48 kWp (total nominal power of panels), and 7.5 kWp at the output of the inverters used for own building demand and car load station. The available area for PV system was strongly limited and achieving of the optimal tilting angle was impossible. Presented simulations have been conducted using two commercially available software: TRNSYS and Polysun. Results of the simulations were used for improving operation parameters of the installation. A three approaches was considered: avoiding the shadow, tilting angle optimization and redirecting of additional light stream.

1. Introduction

The global topic related to climatic change and environmental pollution caused a diffuse interest in renewable energy sources (RES). Many applications regarding the use of RES are constantly developed. One of them consists of photovoltaic (PV) technology, which can be applied to a wide range of applications: single-family houses, big buildings, photovoltaic farms, photovoltaic vehicles and plenty of small devices. One of the applications of PV in buildings is photovoltaic integrated with a building structure (BIPV-building integrated photovoltaics). Several examples of installations including such solution are adopted: tiles, shingles, skylights, standing seam products, curtain wall products, spandrel panels, glazing, etc.[1]. One of the commonly used tools for projecting and analysis of such system consists of mathematical and numerical modelling. Energy output, thermal behaviour, and other physical parameters can be calculated with such method. For example in [1] commonly used software tools for calculation of Energy, efficiency, exergy, thermal performance, etc. are described.

Generally, as shown by Haegermark et al. [2] such systems require special financial support to be economically viable. The PV systems feasibility is strongly affected by roof characteristics, electricity demand and consumption pattern.

Solar energy is especially important for net zero energy buildings (nZEB).The energy demand for the operation of such building scan be met by on site generated renewable energy. Buildings require energy in the form of heat and electricity, which can be provided by solar collectors and photovoltaics or by building integrated photovoltaic-thermal solutions (BIPV/T) [3]. Hybrid photovoltaic–thermal (PV/T) modules are an interesting technology for building applications, which can potentially lead to a higher total efficiency and lower use of space. A comparative simulation study of different solar energy solutions for a Norwegian residential building is performed by Good and Hestnes [3]. The study shows that the building only with high-efficiency PV modules comes closest to reaching a zero energy balance, but the results depend greatly on the nZEB definition, the boundary conditions and the design of the building's energy system.

BIPV systems can be integrated in most complex solutions, achieving power supply for specific regions without conventional power grid infrastructure. In [4] an example of such situation is described on basis of a Turkey region. A system including PV panels, diesel generator, battery storage system, working under Mediterranean climatic conditions is presented and simulated with TRNSYS software. It was found out that solar PV-diesel-battery hybrid power system with a 1.5 kWp power of photovoltaic panel scan produce 60.84 MWh energy and reduces CO_2 emission by 42.53 tons. Unit cost of generated energy was calculated as 0.24 €/kWh..

Another case study described in [5] shows an energy analysis regarding several BIPV systems located in Taiwan. Building Information Modelling (BIM) software tools are used to model the BIPV buildings and to carrying out the energy analysis. In the case study, simulation of electricity production from four BIPV panel systems located in the Industrial Technology Research Institute (ITRI), Hsinchu, Taiwan, are performed. A comparison of simulated results with three-year measured data is presented. It is shown that a reasonably good estimation of the electricity production of the BIPV systems at the building design stage was obtained in the case study. In particular the investigated and compared photovoltaics systems consisted in: Sun Shield, transom, side vertical and ordinary PV panels.

One of the options for BIPV is tracking solar position. A variety of technical solutionsare available for such purpose. According to [6-8] real possibilities of increasing the amount of generated energy can be adopted. The reported energy gain is about 30-35% for single axis systems. Rizk and Chaiko [6] used a tracking control based on voltage output analysis. A Wheatstone bridge with two light dependent resistors and two usual resistors were applied as a detector of a relative solar radiation angle by Aziz S and Hassan [7]. As reported by Bazyari et al. [8] there is no noticeable energy output gain for two axis tracking system comparing to single axis tracking system. The reported gain was only 4%.

These data was used to estimate energy gain for system described in this paper, what is described in further part of the paper.

2. Energy demand

Krakow is located in Malopolskie voivodeship in southern Poland (50°03′41″N latitude and 19°56′11″E longitude). Photovoltaic system has been designed to partially meet energy demands of the building of Faculty of Energy and Fuels. This building contains of several different rooms:

- two lecture rooms equipped with projector, PC computer, and sound system,
- one computer laboratory, equipped with PC computers,
- several laboratory rooms, equipped with different electrical devices (including computers, and specialist test rigs with electrical engines, fans, pumps, controllers etc.),
- several office rooms, equipped with PC computers, printers and other office devices,
- technical rooms (e.g. server room), social room, lodge, toilets, etc.

Each room is equipped with lighting and air-conditioning system (central system located on the roof). Building is typically used from 8 AM to 4 PM (offices) and 8 PM (lectures rooms and laboratories). The yearly power consumption is about 250 MWh (+/- 10%).

3. Analysis of existing system

3.1. System and software

The PV system is located at the roof of the Energy and Fuels Faculty building of the AGH University of science and technology, Cracow. It consists of:

- 14 polycrystalline panels Schuco MPE 245 PG 09 connected in 2 strings with 7 panels each, oriented on east. The angle between horizontal surface and the panel surface is equal to 10 degrees.
- As above but panels are west oriented
- 12 thin film panels SHARP NAE-135L5 connected in 2 strings with 6 panels each, oriented on south. The angle between horizontal surface and the panel surface is equal to 7.5 degrees.

Detailed data of the installation are presented in the table 1.

Table 1. Summary of the analysed installation.

	Schuco MPE 245 PG 09	SHARP NAE-135L5	unit
Module efficiency	14.9	9.6	%
Rated power (P_{mpp})	245	135	W_p
Rated voltage (U_{mpp})	29.92	47.0	V
Rated current (I_{mpp})	8.2	2.88	A
Open circuit voltage (V_{oc})	37.98	61.3	V
Short circuit current (I_{sc})	8.62	3.41	A
Temperature coefficient α (P_{mpp})	-0.47	-0.24	%/ºC
Temperature coefficient β (I_{sc})	+0.05	+0.07	%/ºC
Temperature coefficient X (V_{oc})	-0.34	-0.3	%/ºC
Normal Operating Cell Temperature (NOCT)	43	46	ºC
External dimensions	1652 x 994 x 40	1402 x 1001 x 6.7	mm
Module weight	20	24	kg
Performance warranty on 90% ($P_{mpp\ min}$)	12	10	years
Performance warranty on 80% ($P_{mpp\ min}$)	25	25	years

Two strings with the same orientation were connected to one inverter. The Fronius Symo 3.0-3 unit (nominal power of 3 kW and efficiency of 96.2%) and Fronius IG-15 (nominal power of 1.3 kW and efficiency of 91.4%) were used for polycrystalline panels and thin film panels, respectively. The diagram of the installation is presented in Figure 1.

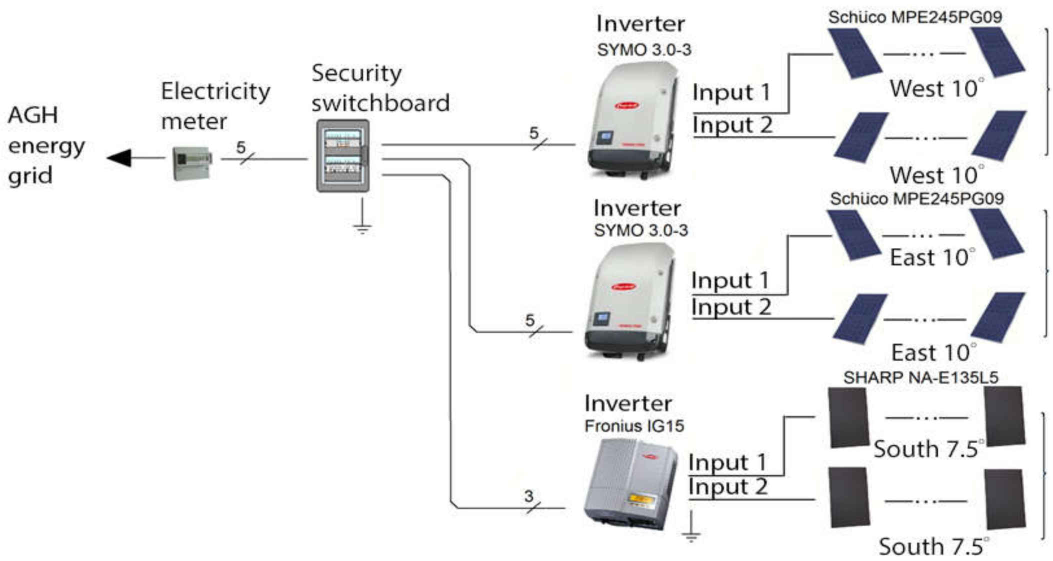

Figure 1. Diagram of the analysed PV installation.

The location of PV panels at the roof of the building is shown in Figure 2. Here, it is clearly shown that a significant part of the roofs occupied by the HVAC system of the building. In addition, the relatively small tilt angle of the PV panels was adopted due to the constraints imposed by the roof cover specifications. Therefore, It was impossible to mount dedicated frames allowing different tilt angles. The figure 2 shows the position of the panels. The panels are arranged into three fields.

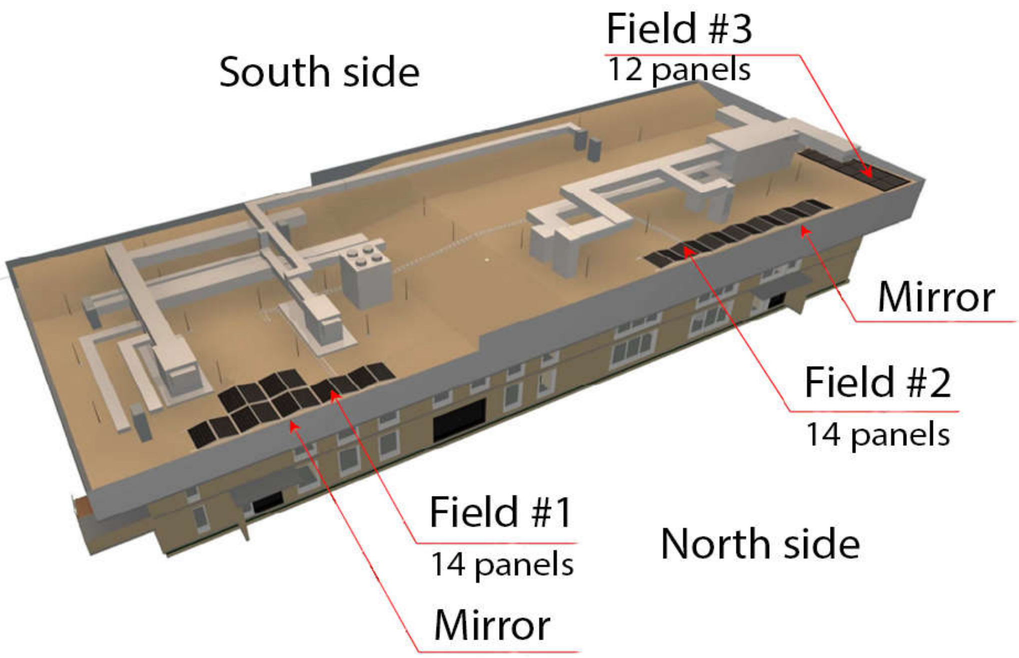

Figure 2. The roof view with indicated position of three fields with PV panels and mirrors.

The simulations of the system were carried out using two software, Transient System Simulation tool (TRNSYS) and Polysun. The TRNSYS software package allows the modelling and dynamic simulation of energy systems and processes, based on the build-in component library which models are validated and based on experimental and/or manufacturer data. The software is used for both scientific and commercial purposes., due to its capability to perform simple or complex analyses. The software allows the dynamic calculation of temperatures, solar insolation, powers and many other parameters of a investigated system as a function of weather data.

In the developed simulation, components based on manufacturer data, like the photovoltaic panels for the solar field (type 562a) and inverter unit (type 48a), and the Meteonorm weather data processor component (type 15-6) were used. The standard period 1996–2015 for irradiation data was taken. The power generated by photovoltaic array is a function of the absorbed solar energy, the amount of energy lost convectively from the top and back surface of the PV, as well as the amount of energy lost convectively from the top and back surface of the PV. Type 562 models photovoltaic array, basing its performance calculation on a provided overall array efficiency η_T (it was assumed as a constant in time), calculated according the Equation 1:

$$\eta_T = (1 + \eta_{T,coef}(T_{PV} - T_{ref}))(1 + \eta_{I,coef}(I_T - I_{T,ref}))\eta_{ref} \tag{1}$$

η_T - the overall efficiency of the photovoltaic array calculated via TRNSYS
$\eta_{T,coef}$ - a coefficient that describes the change of photovoltaic array efficiency as a function of cell temperature
T_{PV} - the PV cell temperature
T_{ref} - cell temperature at the condition under which the reference PV efficiency was measured
$\eta_{I,coef}$ - a coefficient that describes the change in photovoltaic array efficiency as a function of incident solar radiation
I_T - the total amount of solar radiation incident on the PV collector surface
$I_{T,ref}$ - the total amount of solar radiation incident on the PV collector surface at the conditions under which the reference PV efficiency was measured
η_{ref} - the overall efficiency of the photovoltaic array under reference conditions

The models of such components are available in the TRNSYS software reference [9], thus are here omitted. The each simulation of the developed system was performed assuming a one-year time period with a time step of 0.1 hours. Moreover, in order to perform the simulation, PV modules efficiency, solar field area, and emissivity were set accordingly to the available data of the investigated system. In addition, external data regarding the shading factor of the photovoltaic field has been used for the dynamic simulations.

Similarly to TRNSYS, Polysun software allows the simulation of energy systems. The software is based on a build-in component library including manufacturers data. The software has a user-friendly interface, which allows an easy and fast modelling of the systems under investigation. With this tool, energy produced by the installation in each month of the year can be calculated, using the Meteonorm weather data. In this software, the build-in components corresponding to the ones installed in the investigated plant are used. The parameters of the PV system are calculated by means of the H.G. Beyer model [10]. This model is based on the Equations (2,3) for the PV panel efficiency η_P:

$$\eta_{PMPP}(I, T_{ref}) = a1 + a2 + a3 \cdot \ln(I \cdot \frac{1}{[Wm^2]}) \tag{2}$$

$$\eta_{PMPP}(I, T) = \eta_{PMPP}(I, T_{ref}) \cdot (1 + \alpha(T - 25^oC)) \tag{3}$$

Where T_{ref} is 25ºC and a1 - a3 are device specific parameters. The performance at operation temperatures other than 25ºC may then be modeled by the standard approach using a single temperature coefficient α: Irradiance I at an operation temperature of 25ºC. T-current operation temperature. The parameters a1-a3 and α should be determined using procedure described in [10].

Furthermore, the shading of the photovoltaic modules has been included in the analysis, because the presence of the objects on the case study building roof has been considered within the Polysun software.

3.2 Results of simulations

Mean monthly data regarding the three-year operation of the photovoltaic system have been compared with the ones obtained by the simulation carried out with both software (Figure3, 4 and 5).

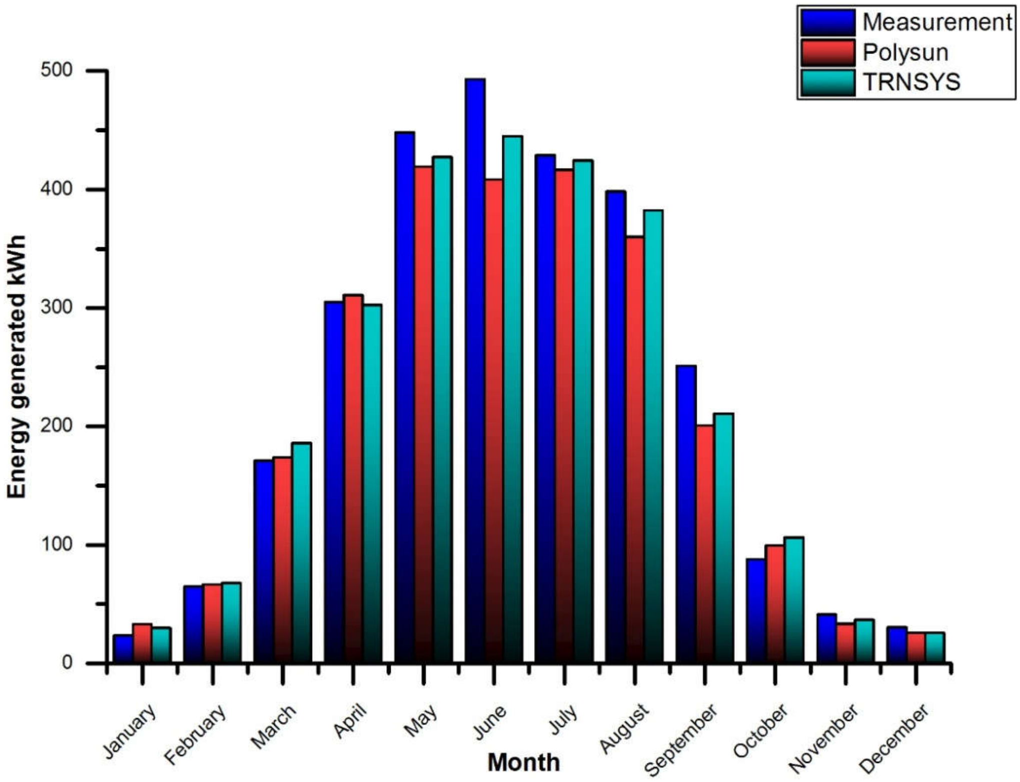

Figure 3. Comparison of measurements and simulations results for east side.

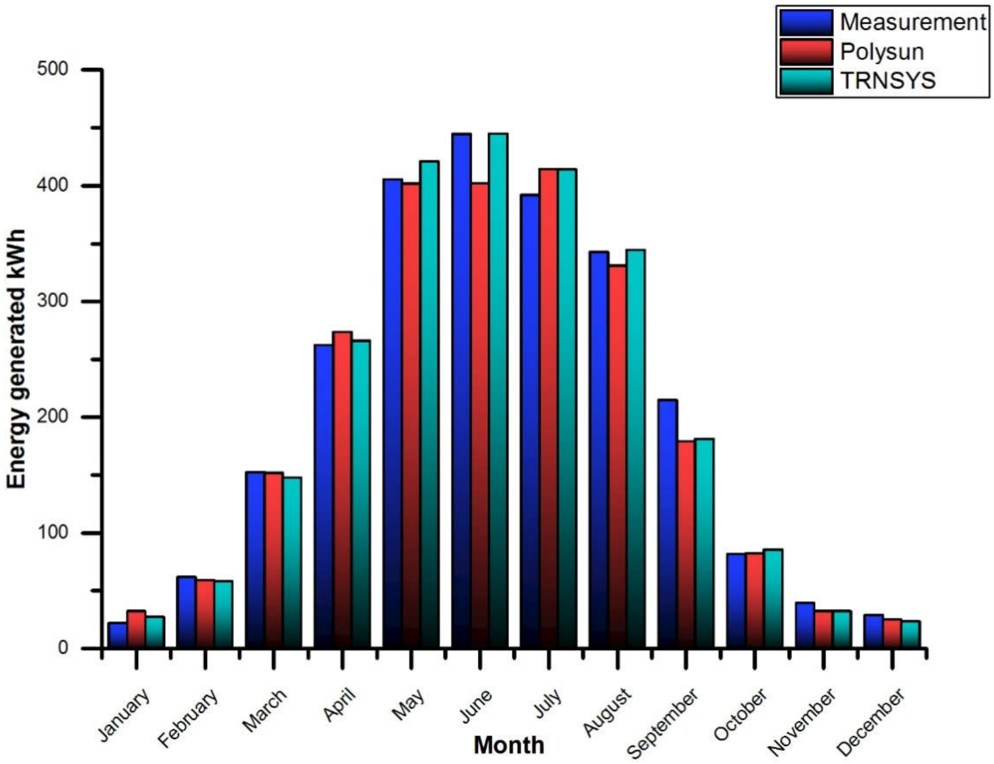

Figure 4. Comparison of measurements and simulations results for west side.

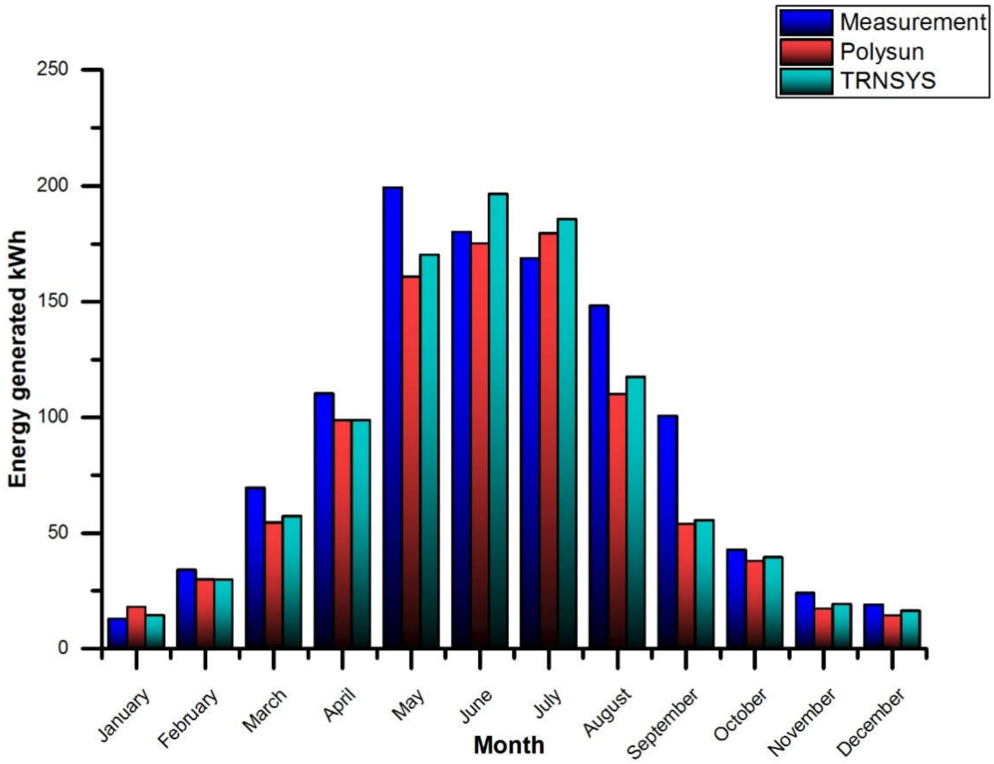

Figure 5. Comparison of measurements and simulations results for south side.

The mean annual production of electrical energy measured on the site resulted 6272 kWh, while 6096 kWh and 5888 kWh were calculated with TRNSYS and Polysun software, respectively.

Therefore, the simulation of the PV system with Polysun software showed that this software underestimates of 6.2% the annual electrical energy production, while the TRNSYS software underestimates the production of 2.9%. It may be resulted by accuracy of the meteorological data, especially data related to solar radiation. The TRNSYS base contains data averaged over period of 20 years which can statistically fluctuate comparing exact behavior of solar radiation in the three years of measurements. Therefore, discrepancy between measurements and simulation less than 3% is satisfactory. This results outlined that the simulations carried out with both software were performed correctly. The actual configuration of the PV field achieves an electrical energy production that a matches 2.5% of the overall electrical energy demand of the building.

4. Analysis of improvements

In this section, possible improvements of the existing PV field configuration are analysed in order to enhance the electrical energy production. In particular, the reduction of the shading on the PV field and the optimal PV modules orientation were considered. In Figure 6, the results of simulations carried out with both software is shown. The analysed configurations consist of: existing PV field with shading effects, existing PV field without shading caused by the surrounding HVAC equipment and south-oriented PV panels with the optimal inclination and without shading effects. According to a set of simulation, the optimal tilting angle is 37 degrees and for such angle Figure 6 was plot. The considered improvements in terms of optimal positioning of PV panels can be achieved lifting the PV panels support structure of about 2.5 m, in order to locate the PV field above the existing HVAC equipment.

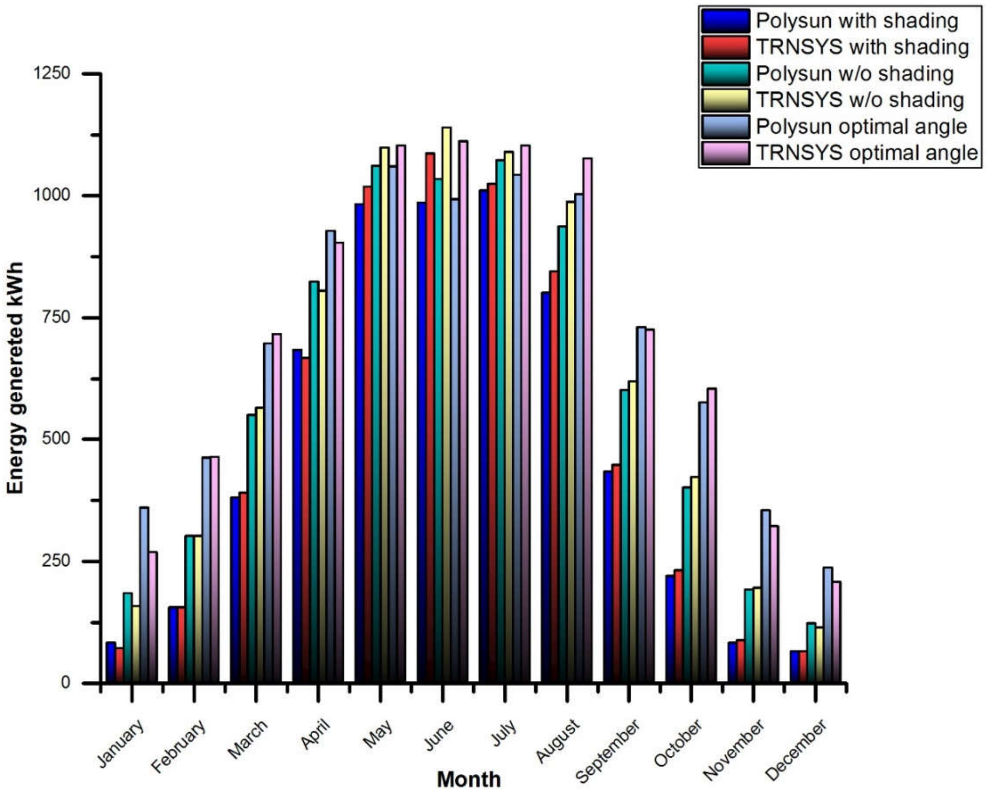

Figure 6. Comparison of simulations for each improvement.

According to the results, the lifting of the PV field and avoiding the shading effect it is possible to achieve an increase of the PV field energy production of 20%, without any modification of panel inclination, and 40% in case of the optimum inclination and south-oriented panels. Another method allowing the improvement of the electrical energy production consists of the reflection of solar radiation beam on the surface of the panels. This is possible with the installation of flat mirrors on the northern edge of the roof reflecting solar radiation on the panels. According [11], similar installation allows to increase efficiency of a photovoltaic system in range of 16 to 52%. Therefore, based on it, the analyses of configuration considered in this paper was performed for two variants with 20 and 40% enhancement due to extra mirrors. The PV field configuration was exactly the same as in previous case. The monthly energy results with and without mirrors are shown in Figure 7.

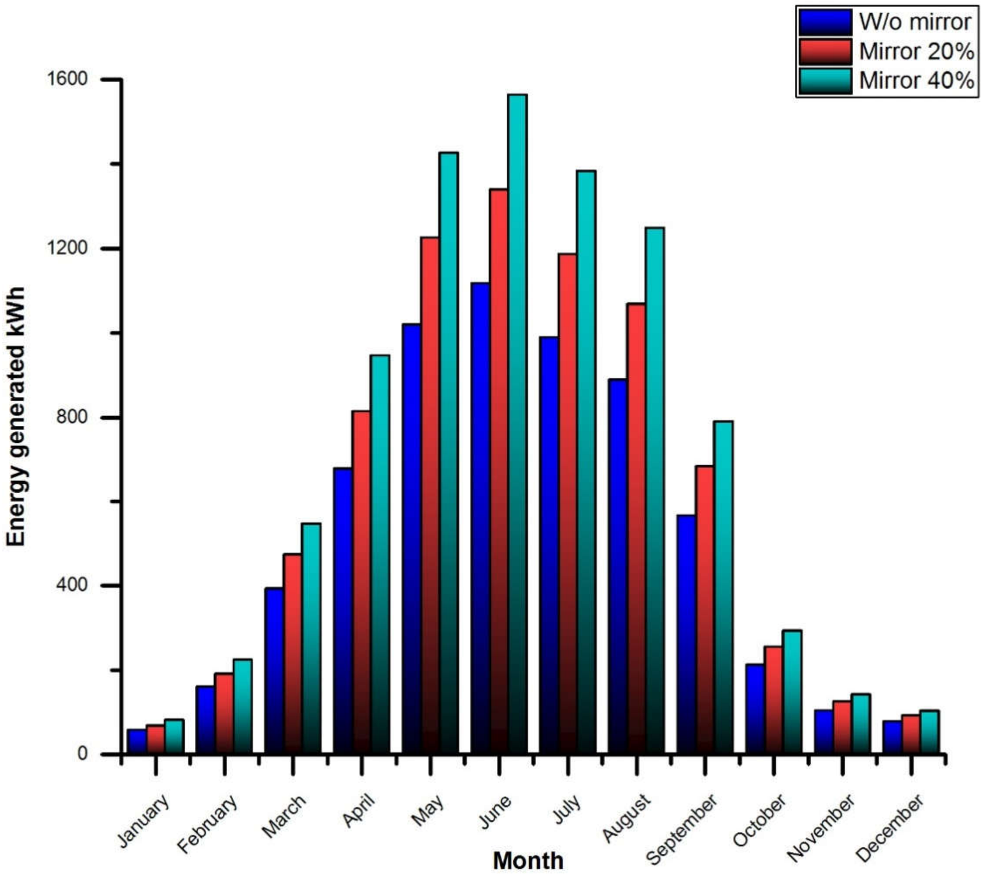

Figure 7. Simulation of energy generation for system with mirrors.

Cost of this improvement is assumed as costs of 63 m^2 field of mirrors (equal to PV panels surface) and is estimated as 2150 €. Price of electricity is 0.11 €/kWh, and the system annually allows to gain 1254 – 2508 kWh energy more than the existing installation, which increases profits in the range from 138 to 276 € yearly. Calculated SPBT is in the range of 7.5 to 15.0 years, while lifetime of the PV system is minimum 20 years, so it is economically viable.

5. Conclusions

The analyses developed in this study show a significant potential of electrical energy production improvement for the investigated PV installation. The proposed solutions allow an increase of the annual electrical energy output of about 20 – 45%, which could determine a decrease of the building operation cost and also environmental benefits. Considered improvements are supported by the economic analysis showing that SPBT is in range 7.5 -15.0 years. Analysis performed in [11-13] confirm the obtained results and shows that increase of PV system efficiency up to 52 % is possible. Further analysis will include the effect of additional solar radiation reflected by the mirrors on the PV panels temperature and, thus, on their electrical efficiency.

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