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BAPV SYSTEM MODELING FOR THE SINGLE-FAMILY HOUSE – A CASE STUDY

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Abstract. *The community all over the World has to tackle the problem of depletion of fossil fuels, overusing the natural resources, and growing emission of greenhouse gases into the atmosphere. It is related to the growing demand for electricity due to global development in every field. The solution to this problem can be production clean, solar energy with the use of photovoltaic modules. However, the installation of PV system in urban areas is very often impossible because of high-density citie's architecture. The objective of this study was to analyze building applied photovoltaic system configurations for the flat rooftop of the detached house in Warsaw, Poland. Four configurations were analyzed taking into consideration the area of the rooftop, different tilt angles of PV modules, and shading areas. The system configuration as well as monthly energy output were carried out by the use of DDS-Cad software. The ecological aspect of the photovoltaic installation was also analyzed. A significant reduction of greenhouse gases was observed based on conducted calculations.*

Keywords: photovoltaic cells, renewable energy sources, energy conversion, PV systems, BAPV

MODELOWANIE SYSTEMU BAPV BUDYNKU JEDNORODZINNEGO – STUDIUM PRZYPADKU

Streszczenie. *Społeczeństwo na całym świecie musi zmierzyć się z problememami dotyczącymi wyczerpywania się zasobów paliw kopalnych, zbyt dużego wykorzystywania naturalnych zasobów oraz rosnącej emisji szkodliwych gazów cieplarnianych do atmosfery. Związane jest to bezpośrednio z rosnącym zapotrzebowaniem na energię elektryczną z uwagi na globalny rozwój w każdej dziedzinie. Rozwiązaniem tego problemu może być produkowanie „czystej" energii ze Słońca za pomocą modułów fotowoltaicznych. Jednakże, zastosowanie systemów fotowoltaicznych na obszarach miejskich bardzo często może być wręcz niemożliwa z powodu bardzo gęstej zabudowy miejskiej. Celem niniejszej pracy była analiza konfiguracji systemów fotowoltaicznych zlokalizowanych na dachu budynku wolnostojącego w Warszawie, Polska. Cztery konfiguracje systemu zostały poddane analizie przy uwzględnieniu dostępnej powierzchni dachu, kąta nachylenia modułów fotowoltaicznych oraz stref zacienienia. Konfiguracja systemu, jak również miesięczne uzyski energii elektrycznej zostały wykonane przy pomocy programu DDS-Cad. Ekologiczne aspekty zastosowania systemów fotowoltaicznych zostały również przeanalizowane w niniejszej pracy. Znacząca redukcja gazów cieplarnianych została zaobserwowana na podstawie przeprowadzonych obliczeń.*

Słowa kluczowe: ogniwa fotowoltaiczne, odnawialne źródła energii, konwersja energii, systemy fotowoltaiczne, BAPV

Introduction

The growing problem of air pollution, climate change and fulfil the energy demands needs a transformation of the energy infrastructure to clean and zero-emissions energy systems [7]. Industrial development all over the World requires higher energy consumption every day. The growing population and improvement of the living standards are also conditioned by access to electricity. The most commonly used energy acquisition process is still fossil fuels combustion which is claimed to be the main reason of greenhouse gases (GHG) emissions [10]. However, the share of coal in energy mix in 2019 achieved the lowest value in 16 years which was equal 27% [15]. Human activity has a tremendous impact on natural habitat and land use and thus deepening of the climate crisis. Carbone dioxide emissions grew by 0.5% taking into consideration countries all over the World in 2019, however for Poland decrease by 3.5% was noticed compared to the previous year. The new trend in energy consumption is clearly visible; renewable energy achieved the highest increase in consumption among all sources. What is more, clean energy and natural gas replaced coal in the energy mix. Among all energy sources, the fastest growth of wind and solar energy consumption was noticed which was equal to 1.4 EJ and 1.2 EJ respectively [15]. In many countries, photovoltaic (PV) installations gain social support due to harmless effect on natural habitat, no greenhouse gases emissions into the atmosphere, and generally positive life cycle balance [11]. The scheme of production and the use of energy should be sustainable because a great reduction in GHG emission should be achieved if the population want to prevent climate instabilities. The countries should strive to become climate neutral and think about zero-emission future for the next generations [12, 22]. In short-perspective terms, the power demand is predicted to rise by 90% due to electric transport, heating, and other electrical household goods [14, 19]. It can be summarized that the population should tackle environmental and energy problems, such as pollution caused by fossil fuels [21] and depletion of these sources [2]. All these factors mentioned above forced researchers to explore renewable energy sources which are considered as clean energy. Solar energy has great potential worldwide and it is achieving greater share among renewable energy sources. In 2019, the power generation from Sun rose by 11.6% in Europe, close to the main source – wind (14.6%). In Poland, the increase was even greater and equal to 32.2% in comparison with the previous year [15]. This big growth rate is due to microinstallations and individual investments. In terms of solar energy capacity, solar energy growth in Poland ranked in 5th position in 2019 among European countries. The total power installed in photovoltaic in 2019 was 1500 MW, while in May 2020 was above 1950 MW [16]. It is estimated that in 2025, the total installed capacity in photovoltaics in Poland is feasible to achieve 7.8 GW which will meet the assumptions of the National Plan for Energy and Climate for 2030.

The photovoltaic installation should be designed carefully according to design guidelines in order to increase the performance of the system. Designers should take into consideration many aspects such as the tilt angle [7, 8] or azimuth [4, 9] of photovoltaics modules which are key parameters since the power generation depends on the exposition to direct sunlight. The yearly energy output is affected also by its location and local weather conditions [24, 25]. Due to the essential role of solar irradiation, many research groups conducted an analysis of photovoltaic systems in different places under various climate conditions [1, 4, 5, 26]. Two types of photovoltaic installation can be distinguished: building integrated photovoltaics (BIPV) or building applied photovoltaics (BAPV). In newly build buildings, the application of the first type of installation is a better solution. The usage of active building materials, such as photovoltaic tiles instead of conventional ones, is characterized by good results without an additional place to install PV systems [3, 18].

Nowadays, there is insufficient free space for installing a PV system in the urban area. What is more, the city construction is considerably dense with a big number of skyscrapers and thus installation of a stand-alone photovoltaic system is far impossible. However, there is a possibility to exploit of existing buildings' roof and facades to produce energy by BAPV systems [23, 27]. In this field, it can be distinguished various sizes of the installation, from residential (few kWp) to large-area system, mostly installed on industrials roofs. Decentralised electricity generation could be the best solution for above mentioned problems because rooftop systems are profitable and should be considered as a part of the underlying property [20].

In this paper, the computational analysis was carried out in order to examine the most efficient orientation of building applied photovoltaic installation under variety of polish weather conditions for a single-family house. The simulations were conducted in terms of the maximum use of the rooftop area and the optimum tilt angle of photovoltaic modules. The designing process of the proposed installation was based on high-quality photovoltaic components, with superb performance parameters. The ecological aspects were also examined in terms of greenhouse gases emission reduction.

1. Case study side characteristics

A computational analysis of photovoltaic installation was carried out by the use of DDS-Cad software. In order to examine the efficiency of PV installation, four different configurations of PV system were simulated. The installations were designed especially for a detached house located in Warsaw, capital of Poland (52°23'N 21°01'E) with the high above the sea level equal to 130 m. The single-family house has two storeys and its provided to be full time inhabited by a family with two kids. The area of the residential object is about 280 m^2. The rooftop is flat and its area is about 134 m^2.

According to Polish classification [13], Warsaw is classified in summer second group and third winter group. This places is characterized by annual average outdoor temperature equals 7.6°C. The annual precipitation is about 501 mm. According to Köppen climatic classification Cfb or Dfb, Warsaw is located in the area characterized by a humid continental climate which means cold winters with snow; and warm, sunny summers with summer storms. There are four different seasons with full range of temperatures, for example the temperatures in winters variy from -6°C to 0°C, weather in summer average temperature is 11°C÷23°C. Due to the probable climate change, the temperature in June 2019 was 5.4°C above the average temperature from 1981-2010. By the use of Meteonorm software, the meteorological data was implemented to DDS-Cad software. Table 1 shows the values of *Gh* – Global radiation horizontal and *Dh* - Diffuse radiation horizontal. The highest values of horizontal irradiation appears in July and it is equal to 169 kWh/m^2/month, whereas diffuse irradiation achieves the highest value in June (83 kWh/m^2/month). The average value of solar irradiation for Poland is about 950 kWh/m²/year, thus yearly irradiation of the selected location (1068 kWh/m^2) is above the average.

2. Photovoltaic system description

In the following paper, four different variations of building applied photovoltaic installation on rooftop of the single-family house were analysed:

1) flat rooftop, photovoltaic modules mounted parallel to the roof slope (tilt angle of 0°);
2) flat rooftop, photovoltaic modules mounted on mounting triangle racks with the tilt angle of 36°;
3) flat rooftop, photovoltaic modules mounted on mounting triangle racks with the tilt angle of 24°;
4) flat rooftop, photovoltaic modules mounted on mounting triangle rack with the tilt angle of 24° with the azimuth orientation E-W.

The azimuth for the cases 1st – 3rd was the same, and equal to 0°. The azimuth of 4th case is corresponding with the type of PV system (East-West). All of them based on the high-quality BEP280 photovoltaic modules from Bruk-Bet Solar manufacturer made of polycrystalline technology. The efficiency of these 60-cell modules equals 17.21% with the nominate power of 280 Wp. The detailed information about the working parameters of the selected modules is presented in Table 2. The photovoltaic installations were designed with utmost care according to the designing steps [9].

Table 2. Performance parameters of Bruk-Bet Solar, BEP280, polycrystalline module

STC 1000 W/m^2, 25°C, AM1.5			
P_{max}	Maximum power	Wp	280
V_{mpp}	Voltage at Maximum Power	V	31.69
I_{mpp}	Current at Maximum Power	A	8.85
V_{oc}	Open Circuit Voltage	V	38.94
I_{sc}	Short Circuit Current	A	9.35
η	Panel Efficiency	%	17.21
β	Temperature Coefficient of Voc	%/°C	0.3
(H/W/D)	Panel Dimension	mm	1640×992×40

Firstly, the sizing of the PV systems was carried out based on the size of the rooftop. Then, the number of modules was calculated individually for each case. Subsequently, inverter sizing was carried out and the PV installation configurations were elaborated. The last step of the designing process was to simulate the energy yield of the proposed cases. The 3D visualizations of the designed PV system are presented in Fig. 1.

In order to provide the highest possible performance of the designed PV systems, modules are connected into series and then to MPPt (Maximum Power Point tracker). The configurations of the proposed installations are presented in Table 3. All selected inverters are high-quality devices from Fronius manufacturer. Due to different size of the installation, selected inverters have different powers, however, there are made of the same quality. Their working parameters are comparable.

Evaluations of the possible shading effects were carried out in order not to decrease the performance of the working installation. Firstly, shading areas were calculated and then simulated by DDS-Cad software. Required distances between each modules' rows were calculated from equation 1. The simulated shading areas on the roofs are shown for each case in Figure 2.

$$z = \frac{d \cdot \sin(180° - \alpha - \beta)}{\sin \alpha}\ [m], \tag{1}$$

where: d is PV module's length [m], α is angle of incidence of sunlight and β is tilt angle of PV modules.

Table 1. Horizontal radiation in selected location: Warsaw, Poland

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Σ
***Gh* [kWh/m² month]**	20	34	76	117	162	167	169	142	92	53	22	14	1068
***Dh* [kWh/m² month]**	15	21	42	65	69	83	81	68	46	31	15	11	547

Table 3. Configuration of the proposed PV systems

Case study	Inverter	Number of modules	Number of trackers	Number of strings	Configuration	
1st	Fronius, Symo 17.5-3-M	77 pcs.	2 trackers	5 strings	3 strings/1st tracker	13pcs./string
					2 strings/2st tracker	19 pcs./string
2nd	Fronius, Symo 7.0-3-M	28 pcs.	2 trackers	2 strings	1 string/1st tracker	14 pcs./string
					1 string/2st tracker	14 pcs./string
3rd	Fronius, Symo 8.2-3-M	35 pcs.	2 trackers	2 strings	1 string/1st tracker	18 pcs./string
					1 string/2st tracker	17 pcs./string
4th	Fronius, Symo 10.0-3-M	42 pcs.	2 trackers	2 strings	1 string/1st tracker	21 pcs./string
					1 string/2st tracker	21 pcs./string

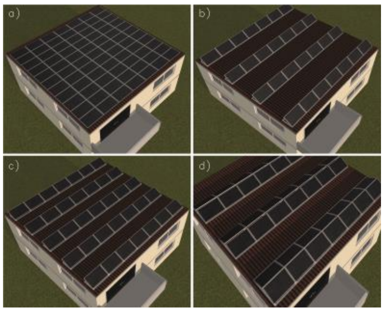

Fig. 1. The proposed PV installation on the flat rooftop of the single-family house: a) parallel to the rooftop; b) tilt angle of 36°; c) tilt angle of 24°; d) tilt angle of 24° (E-W)

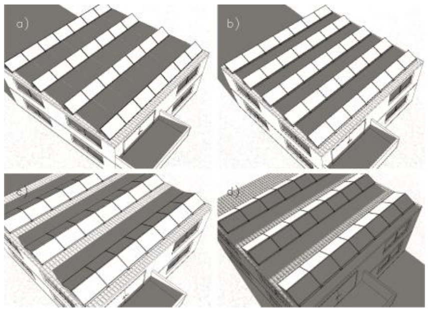

Fig. 2. Shading areas simulated at midday on 22 December for PV installation: a) tilt angle of 36°; b) tilt angle of 24°; and am and pm on 22 December for PV installation: c) tilt angle of 24° (azimuth: E); d) tilt angle of 24° (azimuth: W)

3. Results

3.1. Energy analysis

Figure 3 depicts the results of computational analysis of monthly energy output of each variation of proposed photovoltaic installationsThe maximum amount of energy was produced by the PV installation of 1st case study (16173 kWh/y) During the whole year, the energy yield achieved from this installation is significantly higher than from others. This study case can be considered as a model installation because it uses the whole rooftop area without any shading areas. The tilt angle is not optimum, thus the sunrise does not reach the surface of the PV module perpendicularly. However, relatively higher amount of the energy obtained is directly related to the quantity of the installed modules (77 pieces) in comparison to other cases. The rest of proposed installation achieved lower energy output, according to their smaller sizes.

In Table 4 the detailed information about energy yield from each designed installation, the size of installation and also the energy output per 1 kWp are presented. The power of the PV system are as follow: 1st – 21 560 kWp, 2nd – 7 840 kWp, 3rd – 9 800 kWp, 4th – 11 760 kWp. The installation with the tilt angle of 36° is the smallest one because of the largest shading areas. The total energy output for each case study is 16 173 kWh/y (1st), 7 494 kWh/y (2nd), 9 225 kWh/y (3rd), and 9 244 kWh/y (4th). Taking into consideration the model installation (1st case study), the energy yields achieved from other system are smaller (the installation with tilt angle of: 36° is -54%, 24° is -43% and for installation E-W is also -43%). The minimum energy yields were obtained in December and the lowest value is 105 kWh for installation E-W. The highest possible value to obtain in December was 206 kWh (1st case study).

The maximum energy output is achieved in June and July and it is equal 2532 kWh (1st case study). The months in which the energy yields were the highest is summer period (from May to July), and the lowest values were achieved in winter period (January, February, November, and December).

The energy obtained from 1 kWp of installed power are presented in Figure 4 and also in Table 4. The obtained results confirms that optimum tilt angle is one of the most important factors determining the energy yield. Increasing the angle of PV modules inclination has tremendous impact on energy output. Despite the fact that the installation with PV modules parallel to the rooftop achieved the highest energy output in general, the installation with tilt angle of 36° has the best results in terms on kWh per kWp (956 kWh produced per 1 kWp of power installed). However, very close to this results is PV system with 24° of inclination with the energy output equal to 941 kWh/kWp. In the summer period, from May to August, the study case 3 (24°) is slightly better than the second one (36°). However, the opposite situation occurs in the winter period. E-W installation achieved the average results among all presented variations, nonetheless, this kind of PV installation allows to better energy usage in terms of load consumption and direct consumption which are very important factors from the economical point of view. The worst results were obtained for the installation parallel to the rooftop (0°). The energy output per 1 kWp was 750 kWh.

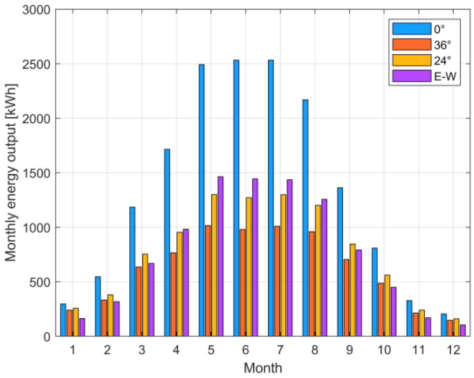

Fig. 3. Comparison of monthly energy production from PV installations under study

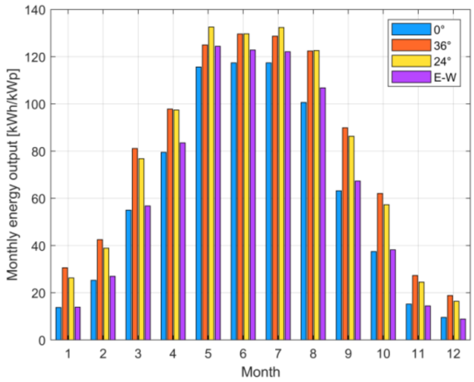

Fig. 4. Comparison of normalized monthly energy production from installations under study

Table 4. Simulation results of eergy production by BAPV systems

Case study	Power	Energy yield		Deviation	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	kWp			%	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
1st	21 560	16173	kWh/y	-	297	546	1185	1715	2492	2532	2532	2169	1363	808	328	206
		750	kWh/y/kWp	-	13.8	25.3	55.0	79.5	115.6	117.4	117.4	100.6	63.2	37.5	15.2	9.6
2nd	7 840	7494	kWh/y	-54%	240	333	636	767	980	1016	1009	960	705	487	214	147
		956	kWh/y/kWp	27%	30.6	42.5	81.1	97.8	125.0	129.6	128.7	122.4	89.9	62.1	27.3	18.8
3rd	9 800	9225	kWh/y	-43%	258	381	753	955	1299	1271	1298	1201	846	562	240	161
		941	kWh/y/kWp	25%	26.3	38.9	76.8	97.4	132.6	129.7	132.4	122.6	86.3	57.3	24.5	16.4
4th	11 760	9244	kWh/y	-43%	163	317	668	982	1463	1444	1436	1256	792	449	169	105
		786	kWh/y/kWp	5%	13.9	27.0	56.8	83.5	124.4	122.8	122.1	106.8	67.3	38.2	14.4	8.9

3.2. Ecological analysis

Fossil fuels combustion has significant impact on air quality due to the emissions of greenhouse gases into atmosphere. Implementation renewable energy sources into energy mix contributes to emission reduction, e.g. carbon dioxide (CO_2) or sulphur dioxide (SO_2).

In order to calculate the GHG emission reduction, the methodology and coefficients proposed by National Center for Emissions Balancing and Management in Poland [17] were used. On the basis of National Database on emissions of greenhouse gases and other substances for 2018, the coefficients for CO2, SO2, NOx, CO and dust were determined as 765 kg/MWh, 0.681 kg/MWh, 0.631 kg/MWh, 0.275 kg/MWh, and 0.036 kg/MWh respectively. The results of ecological analysis is shown in Table 5.

Table 5. Reduction of GHG emissions into atmosphere

Case study	CO_2 [kg/MWh]	SO_2 [kg/MWh]	NOx [kg/MWh]	CO [kg/MWh]	Dust [kg/MWh]
1^{st}	1 051	11.01	10.21	4.45	0.58
2^{nd}	487	5.10	4.73	2.06	0.27
3^{rd}	600	6.28	5.82	2.54	0.33
4^{th}	601	6.30	5.83	2.54	0.33

As can be seen from the Table 5, a significant reduction of greenhouse gases takes place if fossil fuels are replaced with a clean substitute as solar energy. According to the size of the installation and thus the energy yield for the biggest PV system (1^{st} case study) more than 1 ton of carbon dioxide, 11 kg of sulphur dioxide, and 10.2 kg of nitric oxide emission can be avoided. What is more, even for the smallest installation more than 480 kg of CO_2 emission reduction is possible.

4. Conclusion

The installation of building applied photovoltaic systems on the existing building is by far the best solution in high-density urban areas. In this paper, four configurations of the photovoltaic systems on the rooftop of single-family house were analysed. Applying PV modules parallel to the rooftop with the tilt angle equals 0° shows the best results in terms of yearly energy production due to the highest possible size of the designed PV system. However, taking into consideration the monthly energy production per 1 kWp of applied power, it turns out that the PV installation with tilt angle of 35° achieves the highest energy yield. The PV system with tilt angle equal to 24° is characterized by smaller shading area, and thus higher possible power capacity to install. However, the monthly energy production is lower than for the study cases mentioned above. E-W installation allows to better usage of the produced energy and increasing the direct energy consumption coefficient. The use of solar energy as the renewable source contributes to significant reduction of greenhouse gases emission into atmosphere. The ecological analysis show that for proposed installation the reduction of CO_2 is even 1051 kg, SO_2 – 11 kg and NO_x – 10 kg.

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