

Studies on PV power plant designing to fulfil the energy demand of small community in Poland

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Abstract. Although the total energy production from fossil fuels in Poland has been decreasing for the past few years, still at least 80% of the total energy consumption derives from coal. To reduce this high consumption rate alternative energy sources should be developed. One of the most promising is photovoltaics. This paper presents modeling studies of large scale PV power plant design to fulfil the electricity needs of a small community located in Poland. Based on the energy demand prognosis and monthly solar radiation data PV power plant capacity and a number of modules were computed. The distance between rows of the modules was also determined to avoid the shadowing effect. System configuration and energy production simulations were carried out using DDS-Cad software. Results of energy calculations were compared with the yearly energy needs of the studied community. Reduction of greenhouse gases emission was estimated. Modeling results show that proposed 3.1 MWp photovoltaic plant can produce enough energy to fulfil the yearly energy demand of the households in the studied area. Moreover, significant reduction of CO₂ emission and other gaseous pollutants were observed.

1 Introduction

The renewable energy sector in Poland has been rapidly growing during the last few years. From 43.4 GW of total power capacity installed in Poland about 8.5 GW (19.6%) belongs to renewable energy sector which contains 5.8 GW (70%) of wind power, 1.4 GW (16%) of biomass, about 1 GW (12%) of hydropower plants, 0.2 GW (3%) of biogas. The installed capacity of photovoltaics around 0.12 GW represents only 1 % of renewable energy sources (RES). Total energy production at the end of 2017 was noticed as 166 TWh and it was generated mainly in power plants as a result of combustion of hard coal or lignite. The share of renewable energy in the gross final energy consumption reached 11.3% [1, 2] which is still below the 2020 Polish RES target established by the European Parliament and Council of Europe in Directive 2009/28/EC and EU energy policy up to 2030. Poland, as an EU member, is forced to increase the share of renewable energy with decreasing energy production derived from coal to reduce CO₂ emission [3, 4]. Another aspect of using renewable energy sources is the improvement of air quality [5]. Coal power plants are responsible for 11% of primary particulate matter (PM_{2.5}), 51% of sulphur dioxide (SO₂)

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and 31% of nitrogen oxides (NO_x) emissions. It leads to serious health problems due to air pollution [6]. Using large scale photovoltaics power plants locally, as it was shown in this study, allows to fulfil European targets on one hand and improve the quality of life in the given municipality on the other.

World cumulative global installed PV capacity at the end of 2017 was equal to 385.7 GWp. About 106.6 GWp of installed PV capacity is situated in European Union countries, mainly in Germany (42.4. GWp), Italy (19.7 GWp), United Kingdom (12.8 GWp), France (8.2 GWp) and Spain (about 5 GWp). The position of Poland with about 0.3 GWp of total installed PV capacity is ranked at the bottom of the list [7] despite the similar solar conditions as in Germany [8]. Many of the installed PV systems are of a size below 40 kW due to Prosumer subsidies for RES micro-installations. According to the program, prosumer produces PV energy at the point of consumption to meet their own electricity needs, which is economically profitable. In works of [9–11], example analyses of photovoltaic systems for single-family houses were presented including solar conditions, simulation of energy production or load consumption. Besides the roof-based solar system, the use of photovoltaic tile in households is more common [12]. The balance between energy production and energy demand of the household is fulfilled. Economic analysis shows the important role of subsidies in reducing the payback time of the installation. Some examples of using photovoltaic systems were shown in papers of [13–15]. However, small size PV systems are of high importance, especially for private house-owners, only large-scale PV power plants allow to increase significantly the total installed capacity and thus share of photovoltaic energy in the final energy consumption in Poland. One of the suitable locations of developing large-scale PV power plants are marginal areas, like waste dumps, or other buffer zones, which cannot be used for houses buildings but can be easily adapted to build photovoltaic installations [16, 17]. Moreover, existing analyses of photovoltaic installations working under temperate (Polish) conditions help investors to make the right choice in the investment process. Analyzing both factors which have the highest influence on PV installation performance, i.e. solar radiation data or module temperature reveal the potential of PV power plants in Poland [18–20].

This study presents modeling results of a photovoltaic plant designed to fulfil the yearly energy demand of the households in Knyszyns' municipality, Poland. The detailed designing process was carried out in order to project the solar system and its configuration based on the high-quality components, with excellent performance parameters. The ecological analysis was also carried out in terms of greenhouse gases emission reduction into the atmosphere.

2 Study site characteristics

A computational analysis by the use of DDS-Cad software was carried out for a small community located in Poland in order to fulfil its electricity demand with the proposed photovoltaic installation. The size and components of the system were selected individually for this case study. Three dimensions model of the PV farm was prepared in the DDS-Cad software by considering the configuration of the installation and land characteristic available for RES investment. Estimation of the load consumption was based on projected energy demand by the end of 2030. In order to reduce the greenhouse gases emissions decrease fossil fuels combustion, renewable energy acquisition become particularly important. Knyszyns' region is characterized by favorable solar irradiation condition to implement the devices to convert solar energy into electricity. An overview of solar irradiation distribution in Poland with a highlighted location of Knyszyn municipality is shown in Fig. 1. As can be seen from Fig. 1 the study region is located in north-eastern

Poland, in Podlaskie district. The total area equals 128 km², while the population is 5214. The study region consists of 20 small communities (towns and villages), however, farmland and forests are 59% and 34% of the area region respectively. Geographical localization of the selected site is 53°18' N 22°55' E, whereas height above sea level equals 158.5 m.

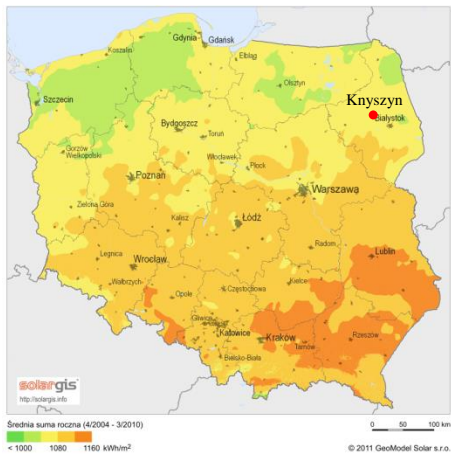


Fig. 1. Global irradiation map of Poland.

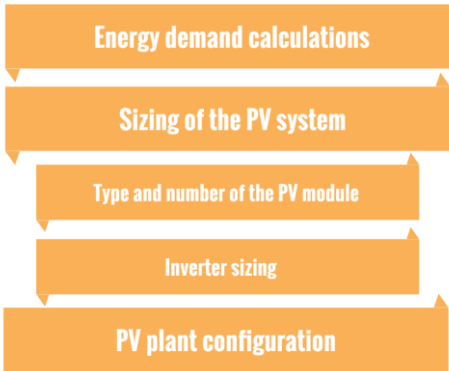


Fig. 2. Designing steps of the PV system.

The climatic conditions of the district are of high importance because the quantity of the consumed energy and thus total energy demand is mainly influenced by the external temperature. According to Polish classification, Knyszyn land is located in the winter fourth group and summer second group. It is characterized by average values of outside and annual temperature equal to -22°C and 7.1°C respectively. The annual precipitation is 520 mm. In Poland two climate zones can be distinguished: Cfb Climate (warm, humid climate) in the southern parts and Dfb Climate (humid, snow climate) in the mountainous regions. Average autumn-winter temperature is in the range 3-5°C, whilst in the spring and summer season is about 17°C. In the coldest month, the average external temperature decreases to -4°C. It is noticed, that the number of days with a temperature below 0°C and -10°C are 55 and 27 respectively. Meteorological data obtained from the Metenorm 7.1 were implemented for the system sizing calculation. Irradiation data of the selected case study is presented in Table 1. Annual solar irradiation on the horizontal surface is about 1047.3 kWh/m², while the annual average daily irradiation value is about 2.83 kWh/m²d. The solar irradiation varies from 0.4 kWh/m²d in December to 5.5 kWh/m²d in June and July. Considering relatively high rate of solar radiation and low average temperatures of the analyzed location as a perfect conditions for PV systems, photovoltaics seems to be a good choice of energy production from RES in the study region.

Table 1. Annual average irradiation.

Month		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average irradiation	kWh/m ² /month	19	32	72	117	164	164	169	130	85	51	21	12
Average irradiation	kWh/m ² /day	0.61	1.14	2.32	3.90	5.29	5.5	5.5	4.2	2.8	1.6	0.7	0.4

3 PV power system sizing

In order to fulfil the energy demand, it is enormously important to size the PV system correctly with the use of detailed calculations. The designing process is consisted of the following main steps: energy demand estimation, PV modules sizing, PV inverter sizing, the configuration of photovoltaic system and PV modules deployment considering the characteristics of the land and required space between rows, taking into account shadowing effect. The required designing steps are presented in Fig. 2. In the following case study, the use of high-quality 72-cells monocrystalline silicon modules with an efficiency of 18.52% was proposed. The performance parameters of the modules are shown in Table 2.

Table 2. PV module specification used in the proposed photovoltaic power plant.

Module type		monocrystalline silicon
STC 1,000 W/m ² , 25°C, AM1.5		
Peak power output watt [Wp]	P_{max}	360
Short circuit current [A]	I_{sc}	9.57
Open circuit voltage [V]	V_{oc}	47.77
Rated current [A]	I_{MPP}	9.14
Rated voltage [V]	V_{MPP}	39.46
Module efficiency		18.52%
Dimensions (H x W x D) [mm]		1960 x 992 x 40
Weigh [kg]		21.3 kg

Energy demand estimation should be carried out firstly in order to design the PV system for the annual energy balance of Knyszyn’ region. The energy demand was obtained from the Knyszyn’ Project for electricity, heat and gaseous fuels demands for years of 2015–2030 [21]. According to the information presented in the Project, the estimation of current and future energy demand were carried out on the basis of information collected directly from recipients and statistical data provided by the Polish Central Statistical Office. Some of the data was obtained from public data, considering data for the Podlasie region which is also representative of municipalities located in this area. On the basis of collected data, it should be emphasized that electricity use in a household is 1054.27 kWh/y for a single inhabitant. Prediction of electricity consumption in households in the years 2015–2030 in the Knyszyn region is presented in Table 3.

Table 3. Electricity consumption in households in the years 2015–2030.

Year	2015	2016	2017	2018	2019	2020	2021	2022
Electricity consumption [GWh/y]	3.8	3.7	3.6	3.6	3.5	3.5	3.4	3.4
Year	2023	2024	2025	2026	2027	2028	2029	2030
Electricity consumption [GWh/y]	3.3	3.3	3.2	3.1	3.1	3.1	3.0	3.0

The total PV power capacity required for estimated electricity demand E_k can be calculated on the basis of equation (1) [22].

$$P_{PV} = \frac{E_k \cdot STC}{Z \cdot WKN \cdot WW} [Wp],$$

(1)

where E_k is the amount of electricity consumption [kWh/y], solar irradiance at standard test conditions (1 kW/m²), Z – global horizontal irradiation [kWh/ m²/y]; WKN – irradiation correction factor, WW - performance coefficient. Detailed calculations are presented below.

$$P_{PV} = \frac{3 \cdot 10^6 \frac{kWh}{y} \cdot 1 \frac{kW}{m^2}}{1036 \frac{kWh}{m^2/y} \cdot 1.13 \cdot 0.85} = 3014.84 kWp = 3.0 MWp$$

Calculation results show that the total power size of the system should not be less than 3 MWp. Based on the specification of selected PV modules (Tab. 2), the number of PV panels can be calculated by equation (2).

$$No. of PV modules = \frac{P_{PV}}{P_M} [pcs.] \quad (2)$$

where P_M is the power of the PV module at standard test conditions. Calculation of the PV modules amount was presented in equation (2).

$$No. of PV modules = \frac{3014.84 kWp}{0.36 kWp} = 8374.55 \approx 8375 pcs.$$

Based on the above-mentioned equations, a number of 8,375 PV modules are required to build a photovoltaic farm. The calculation results show that the total power capacity of the PV plant is 3015 kWp. The modules are considered as ground mounted with south-facing at 24° tilt angle. The angle of 24° was chosen in order to minimize the self-shading effects of the modules. The distance between rows of PV modules is determined taking into account α – solar elevation angle, β – PV module tilt angle, H – the length of the PV generators, which consists of the length of the two longer edges of the modules (2·1960 mm) and the mounting distance (20 mm). The minimum distances between rows can be calculated from equations (3) and (4).

$$x = \frac{\sin\beta \cdot d}{tg\alpha} [m] \quad (3)$$

$$z = \frac{d \cdot \sin(180^\circ - \alpha - \beta)}{tg\alpha} [m] \quad (4)$$

where x is the distance between the beginning and the end of the PV modules' row, z is the distance between rows. The minimum distance between the beginning and the end of the PV modules row and the minimum distance between rows are 6.77 m and 10.35 m, respectively. In order to avoid energy losses resulting from shading effect, the distance should be even longer. In Fig. 3 the visualization of the PV solar farm is presented. The total area of the PV modules is 17771.08 m². Taking into account required minimum distances between rows, dimensions of the land needed for installation are 299.5 m x 106.7 m.

The size of the inverter depends mostly on the total power size of the system and it should be sufficient to operate the required total amount of watts peak. For the proposed PV solar plant, 136 pieces of inverters characterized by the AC power equals to 20700 W (1st) was selected. Additionally, 4 inverters with the power of 15000 W (2nd) and 12360 W (3rd) (two of each) were picked out. The performance parameters of the inverters are listed in Table 4.

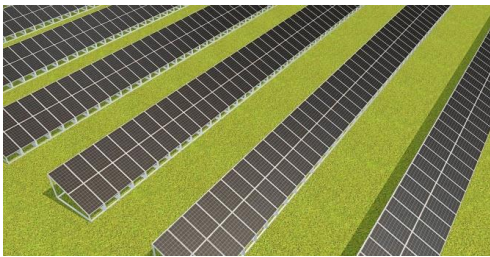


Fig. 3. The visualization of the projected PV solar plant.

The maximum DC voltage is 880 V for each inverter, while the maximum DC current equals 20.2 A, 16 A and 13 A for the 1st, 2nd and 3rd type of the inverter respectively. Inverters are characterized by high maximum efficiency ranged from 97.3 % for the 3rd type to 98% for the 1st type.

Table 4. The performance parameters of the selected inverters.

Inverter	Max. DC Power [kW]	Max. DC voltage [V]	Max. DC Current [A]	MPP(T) Voltage Range [V]	No of MPP Trackers [pcs]
1 st	20.8	880	20.2	351-710	3
2 nd	15.9	880	16.0	351-710	3
3 rd	12.9	880	13.0	351-710	3
	Max. AC Power [kW]	Output AC Voltage Range [V]	Max. DC Current [A]	Nominal AC Current [A]	Max. efficiency [%]
1 st	20.70	184–480	29.0	29.0	98.0%
2 nd	15.00	230–400	21.7	20.0	97.4%
3 rd	12.36	230–400	17.9	16.3	97.3%

The configuration of the designed photovoltaic system assumed, that the 360 Wp modules are firstly connected in series and then strings are connected in parallel to maximum power point trackers (MPPT) of inverters. To MPPT Only strings with the same number of modules can be connected to MPPT. It provides the highest possible efficiency of the PV installation. The configuration for the first type of inverter is as follows: for each of three MPP trackers, 2 string are connected. The module circuit is created by 11 pieces of modules. Thus, one inverter handles 66 modules. Nevertheless, the number of modules in series, for the second type of inverter, is 15 for every MPP tracker. The third group of inverters handles 13 pieces of modules for the first MMP tracker and 12 for second and third ones.

4 Results

Electricity usage calculated for a common household located in the study area on the basis of data collected by electricity provider was found to be 1054.27 kWh/y for a single inhabitant. The total energy demand for the region under study estimated for the next ten years is about 3 GWh. The total yearly energy production from the proposed PV system of 3 MWp size was computed as 3.1 GWh which is the amount that fulfils requirements for yearly energy demands of the study region. Results of monthly energy production of the proposed power plant are shown in Fig.4. As can be seen, the monthly minimum energy of 63.1 MWh is produced in December and the maximum energy of 435.5 MWh in May. Similarly, a high level of energy production can be observed in June and July. Fig. 5 shows monthly energy balance between average energy demand (258.3 MWh) and energy

produced from photovoltaic installation. As can be seen, in the period from April to September, the amount of energy produced from photovoltaics is higher than energy consumption by the municipalities of the Knyszyns’ region. Moreover, energy generated by the solar panels in summer months supplies the energy needs and has to be transferred into the grid. This amount of energy can be taken away from the grid in the period from October to early March when energy production from PV is insufficient to fulfil energy demand (Fig. 5).

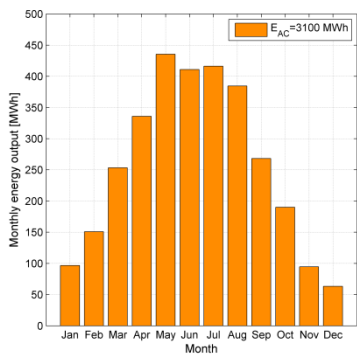


Fig. 4. The predicted monthly energy output of 3 MWp PV array obtained with the use of DDS CAD software.

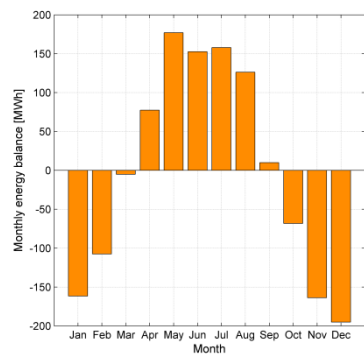


Fig. 5. The monthly energy balance of PV production and consumption for the studied region.

Conversion of solar energy into electricity does not cause greenhouse gases emission (GHG) into the atmosphere. What is more, using a photovoltaic lead to a reduction of emissions gaseous pollutants, such as carbon monoxide (CO), carbon dioxide (CO₂), sulfur dioxide (SO₂) and nitrogen compounds (NO_x) and dust. On the basis on the methodology proposed by [23] and the emissivity ratios (CO₂ – 778 kg/MWh, SO₂ – 0.729 kg/MWh, NO_x – 0.8741 kg/MWh, CO – 0.65 kg/MWh, dust – 0.044 kg/MWh) the amount of the GHG emission reduction was calculate, which are shown in Table 5.

Table 5. Reduction of GHG emission.

Predicted energy output	Pollutants				
	CO ₂	SO ₂	NO _x	CO	Dust
[MWh/y]	[t]	[t]	[t]	[t]	[t]
3100	2411.8	2.26	2.30	2.02	0.14

5 Conclusion

The conception of a photovoltaic energy system to fulfil the energy demand of the Knyszyns’ municipality was presented. Total PV power capacity of the proposed installation (3 MWp) was calculated on the basis of yearly energy consumption delivered by the electricity provider (about 3 GWh). PV power plant was designed with the use of DDS- Cad software including solar radiation in the location of the region under study and modules tilt equal to 24°. The optimal distance between rows of PV modules to avoid self-shading effect was also computed. Results of simulations show that yearly energy production of about 3.1 GWh is sufficient to fulfil the energy demand of the studied region. In the period from April to September, the energy production is higher than monthly average energy consumption by municipalities. In summer months (from May to July), the

energy excess is in the range of 150–180 MWh. What is more, developing the photovoltaic plant leads to reduce 2411.8 t, 2.26 t, 2.30 t, 2.02 t, 0.14 t of the CO₂, SO₂ and dust emission into the atmosphere respectively. All the above mentioned reasons cause photovoltaic perfect substitution for fossil-fuel based electricity generation, which does not have harmful effects on the environment and climate changes.

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