

## Article

# Monofacial and Bifacial Micro PV Installation as Element of Energy Transition—The Case of Poland

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**Abstract:** The several government subsidies available in Poland contributed to an increased interest in PV installations. Installed PV capacity increased from 100 MW in 2016 up to 2682.7 MW in July 2020. In 2019 alone, 104,000 microinstallations (up to 50 kWp) were installed in Poland. The paper determines the energy gain and the associated reduction of CO<sub>2</sub> emissions for two types of solar installation located in Poland. The monofacial solar modules with a power of 5.04 kWp (located in Lekki) and bifacial solar modules with a power of 6.1 kWp (located in Bydgoszcz). Both installations use mono-crystalline Si-based 1st generation PV cells. With comparable insolation, a bifacial installation produces approx. 10% (for high insolation) to 28% (for low insolation) more energy than a monofacial PV installation. Avoided annual CO<sub>2</sub> emission in relation to the installation capacity ranges from 0.58 to 0.64 Mg/kWp for monofacial and from 0.68 to 0.74 Mg/kWp for bifacial and is on average approx. 16% higher for bifacial installations. Cost-benefit analyses were made. For different electricity prices, the NPV for monofacial and bifacial was determined.

**Keywords:** photovoltaic; monofacial PV; bifacial PV; renewable energy source; CO<sub>2</sub> emission; my electricity; PV; Poland; Mój Prąd



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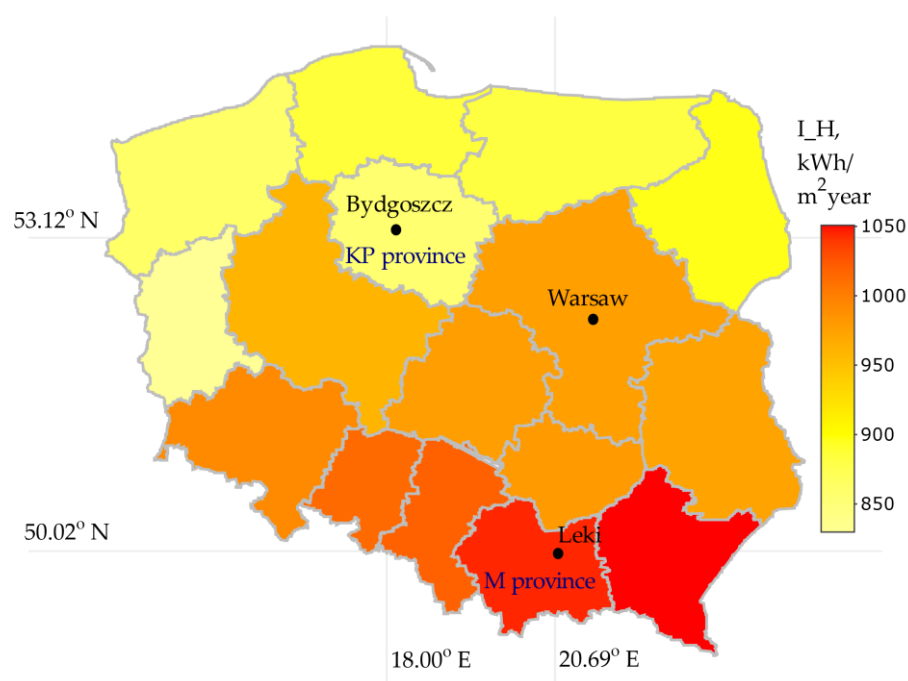


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## 1. Introduction

Currently, the development of the industry and technology has resulted in increased energy demand. At the same time, society is much more aware of the decreasing fossil fuel resources and other problems caused by burning fossil fuels such as climate change, eutrophication, acid rain, greenhouse gas (GHG), mercury and other pollutant emissions, etc. [1,2]. Poland is one of countries where fossil fuels, mainly coal, is widely used to supply energy [3] and is facing the urgent need for developing a proper solution to deal with problems caused by the energy sector from environmental, technology, and economic points of view [4]. Data from KOBiZE shows that GHG emissions were 413.8 million tons of CO<sub>2eq</sub> in Poland in 2017. Comparing to 1990 and 1988, emissions have been reduced by 12.8% and 28.3%, respectively. One of the pillars of decarbonisation of Europe could be solar photovoltaic (PV) power generation [5]. In the European Union (EU), solar PV electricity generation capacity increased from 1.9 GW in 2010 to over 133 GW in 2019. The year 2019 alone brought an increase in new installed capacity by 16.5 GW in EU [6]. At the end of 2019, from the installed PV power capacity both in EU and UK, around 150 TWh of electricity could be generated (which gives around 5.2% of the final electricity demand) [7]. Efficiency of solar PV system depends on the insolation, PV technology, system components

and suitable design. The performance of PV depends on many different environmental parameters such as irradiance level, temperature, angular losses, partial shading, and soiling losses [8,9]. Currently, the biggest photovoltaic market in European countries with temperate climates is observed in Germany, Netherlands or Poland [10]. For Poland, the estimated value of insolation during a year is about 1000 kWh/m<sup>2</sup> [11–13] (Figure 1). In Poland PV sector is the fastest developed renewable energy source (RES) sector with the highest power growth over the past three years [14]—from 100 MW/a in 2016 up to almost 700 MW/a in 2019 and 2682.7 MW data as of October 1, 2020 [15,16]. It is estimated that by 2030, the installed capacity in PV will increase by approximately 5–7 GW, while in 2040—by approx. 10–16 GW [15,17]. Poland (after Germany, Spain, Netherlands, and France) has been in fifth place in EU in terms of establishing new PV systems capacities.



**Figure 1.** Yearly horizontal insolation in Poland calculated per province’s capital city. KP province—Kuyavian-Pomeranian; M province—Lesser Poland. Source own study based on [18].

Jager-Waldau et al. [7] analyse the role of PV to obtain the long-term strategy of the European Commission for energy and climate change and set the target of GHG reduction from 40% to 55% by 2030. Achieving this can make Europe the first climate-neutral continent by 2050. Depending on the strategic policy scenario, reaching 55% GHG emissions reduction would be possible if the cumulative PV capacity both in the EU and the UK surge to 455–605 GW up to 2030.

Taking under consideration ambitious plans of 55% GHG reduction in the EU up to 2030, it has been important to analyse the potential of micro-PV installations for reduction CO<sub>2</sub> emission in Poland. Among the renewable energy technologies available in Poland, the greatest increase is observed in PV installations, usually microinstallations (especially up to 10 kWp) [16,19]. The reason for the increase in the number of micro-PV are subsidies in the form of government programs: “My Electricity” [14], Czyste Powietrze, Energia Plus, Prosument or Agroenergia (intended for farmers). These programs make it possible to subsidise the purchase and installation of new PV panels. In addition, the advantage of microinstallations is that annually from 25 to 30% of energy is consumed on site, and the rest of the energy can be consumed by neighbouring buildings within one microgrid (low voltage ≈ 230 V). The off-grid independent PV systems are suitable and attractive for many applications for technical, economical, safety, legal reasons [20,21]. In rural areas the

microscale installations are preferred due to their simplicity and stand-alone applications, wherein the investment in solar energy is strongly connected with the household income and wealth [22].

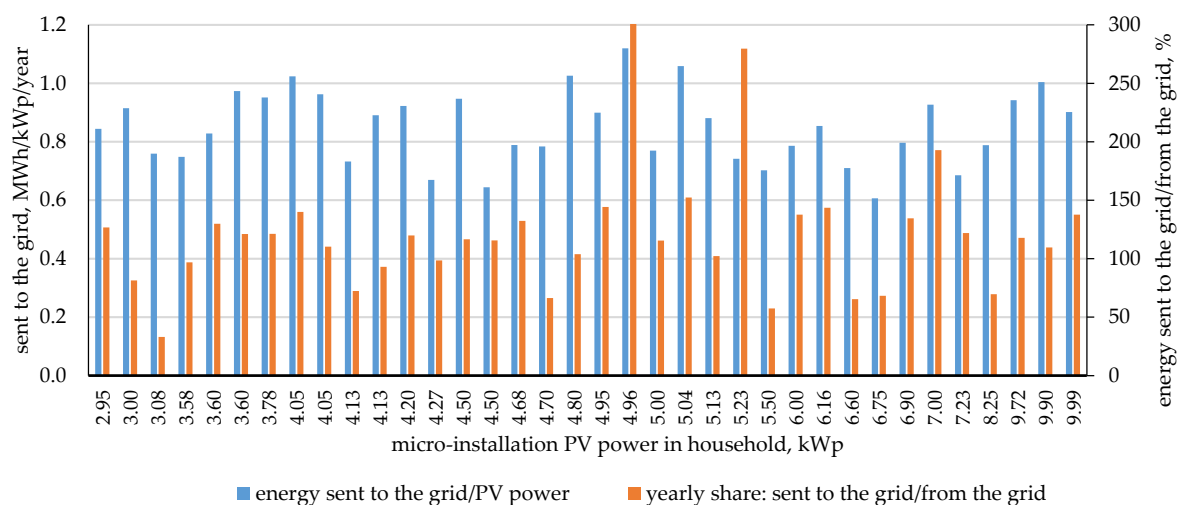
In contrast, the introduction of the auction support system has contributed to the development of large solar PV farms (over 1 MW) [23,24]. In addition, the energy price increases and PV investment cost drops (learning curve [25]), caused the popularization of the energy prosumer business model in which company invest in PV installations for its own needs [26].

In addition, in accordance with the Polish Energy Policy, a user without a PV installation uses electricity from the energy mix [27]. This means that every hour we have a different share of sources generating electricity, including residual amounts from RES. When we install renewable energy sources and have, for example, 1 MWh of our own energy, the use of energy from the mix decreases, and because renewable energy sources have priority, we reduce energy consumption from conventional sources. So 1 MWh of renewable energy replaces 1 MWh of nonrenewable energy, and not a mix with the current share of renewable energy [17,28], which is related to the reduction of CO<sub>2</sub> emissions [29].

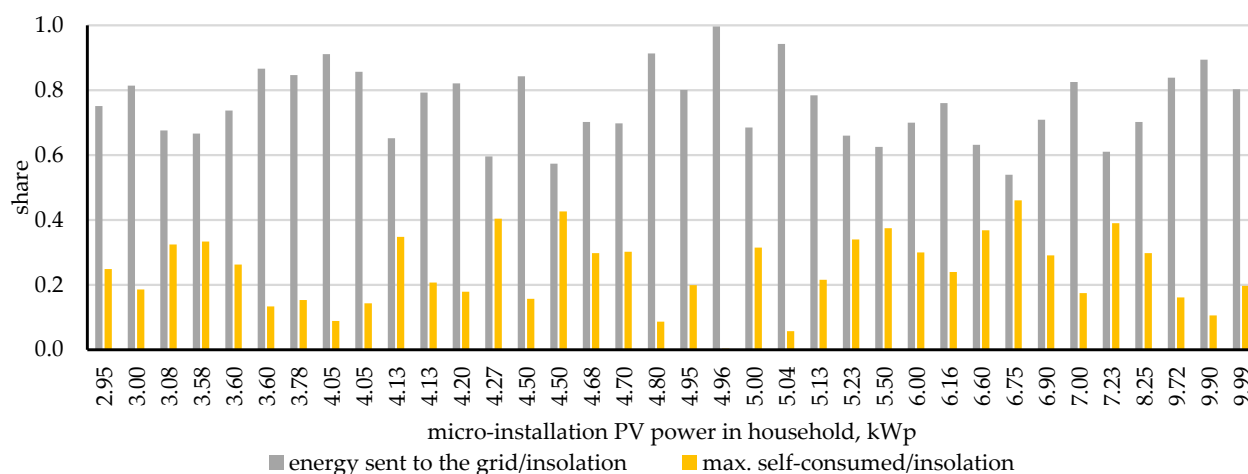
Taking under consideration the Polish conditions related to subsidies (grants per kWp [16]) and Prosumer rules, it is not profitable to oversize the installation [30].

In the Prosumer program, under which it is possible to settle energy from RES for microinstallations, a household can receive 80% (prosumer factor *PF*) for 10 kWp installation and 70% for 10 kWp to 50 kWp). For example, for 1 kWh supplied to the grid, a household can receive 0.8 kWh (up to 10 kWp), or 0.7 kWh (up to 50 kWp). For installations up to 10 kWp, a surplus of over 125% causes overproduction economically unprofitable for the household (the energy does not disappear in the grid, but the user gets nothing for surplus) [30,31].

Microinstallation up to 50 kWp do not need a building permit (when the installation height does not exceed 3 m), therefore the construction process is much more simplified. Microinstallations are typically installed on the roof or on ground/soil, but there is a condition that the ground should be for building purpose not for agriculture one. The paper focuses on microphotovoltaic installations located in the Kuyavian-Pomeranian and Lesser Poland province (localization-Figure 1). Characteristics of the energy production is represented by the annual values of energy sent to the grid. The amount of energy consumed from the grid is also presented [32]. Figures 2 and 3 show the performance characteristics for a selected group of installations in the Lesser Poland province.



**Figure 2.** Annual values of energy sent to the grid in relation to the installed capacity and the annual share of energy sent to the grid in relation to the consumed, in the Lesser Poland province 1 June 2019–31 May 2020. Source own study based on [32].

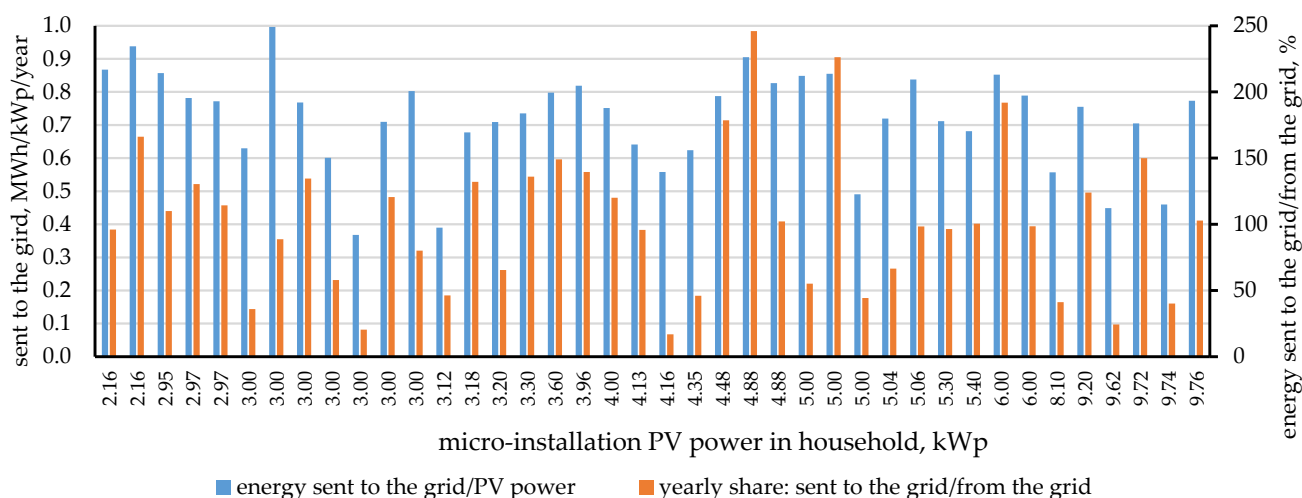


**Figure 3.** Annual values of energy sent to the grid in relation per kWp to insolation and the maximum annual self-consumed (max. self-consumed/insolation) share, in the Lesser Poland province, 1 June 2019–31 May 2020. Source own study based on [32].

Among installations with a capacity of 2.95 kWp to 10 kWp, 23 out of 36 installations sent more energy to the grid than they consumed during the year, of which in 13 this share was greater than 125%. On the other hand, one should bear in mind the ecological effects and avoided CO<sub>2</sub> emissions. The surplus energy is sent to the grid, thus reducing the use of fossil fuels.

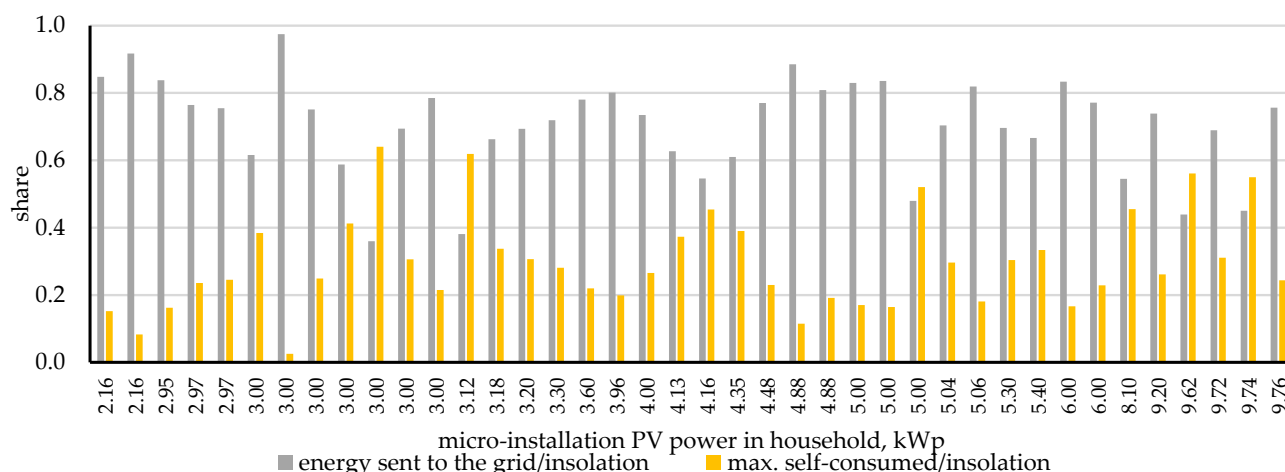
Based on insolation measured in Lesser Poland province (1124 kWh/m<sup>2</sup>/year [29]) and energy sent to the grid measured (Figure 2) in each installation theoretical maximum value of self-consumed energy was calculated (Figure 3). The average (for this province) maximum value of the self-consumed energy share was obtained as 24%. Mean value of selected PV installation power is 5.18 kWp but for above-mentioned the biggest grants program “My electricity” mean PV installation power value in 2019 was 5.39 kWp (obtained for 3060 microinstallations [15]). Theoretically, the more production is sent to the network, the lower the self-consumption rate can be.

A similar analysis was performed for a selected group of installations in the Kuyavian-Pomeranian province and shown in Figures 4 and 5.



**Figure 4.** Annual values of energy sent to the grid in relation to the installed capacity and the annual share of energy sent to the grid in relation to the consumed, in the Kuyavian-Pomeranian province, 2019. Source: own study based on [32].





**Figure 5.** Annual values of energy sent to the grid in relation to insolation and the maximum annual self-consumed (max. self-consumed/insolation) share in the Kuyavian-Pomeranian province, 2019. Source own study based on [32].

In the Kuyavian-Pomeranian province 18 out of 40 installations sent more energy to the grid than they consumed during the year, of which in 12 this share was greater than 125%.

Based on insolation measured in Kuyavian-Pomeranian province ( $1022 \text{ kWh/m}^2/\text{year}$  [33]) and energy sent to the grid measured (Figure 4) in each installation theoretical maximum value of self-consumed energy was calculated (Figure 5). The average (for this province) maximum value of the self-consumed energy share was obtained as 30%. Mean value of selected PV installation power is 4.74 kWp but for above-mentioned the biggest grants program “My electricity” mean PV installation power value in 2019 was 5.94 kWp (obtained for 1094 microinstallations [16]).

There are some studies considering the use of PV system to reduce  $\text{CO}_2$  emissions for example Ren et al. [34] analysed the impact of installed capacity on  $\text{CO}_2$  emissions in China, while Louwen et al. [35] analysed how 40 years of PV development influence energy sector and how contribute to GHG emissions avoidance. In Mohammadi et al. [36] research, a large-scale photovoltaic plant in southern coast of Iran has been considered. The analysis of 5 MW installation showed that using of such system can obtain 5259 ton/year of  $\text{CO}_2$  reduction compared to the natural gas power plant. Antonanzas et al. [37] compared in their research life cycle assessment (LCA) of fixed and single axis tracking systems (SATS) for PV. A better  $\text{CO}_2$  mitigation potential has been obtained for SATS which changed between 3.4 to  $14.5 \text{ MgCO}_2/\text{kW}$  compared to the fixed system for base case scenario [38,39]. Even though Prävälje and Bandoč’s research shows that PV technology is more polluting considering  $\text{CO}_2$  g per kWh in comparison to other energy sources technologies including wind, Concentrate Solar Power, hydro energy or nuclear energy [40]. PV technology is still preferable technology in light of carbon emission reduction in comparison to fossil fuels such as coal, oil and gas [40].

Typical installations used in Poland are systems with monofacial modules, while bifacial installations in Poland are practically nonexistent. Contrary to traditional monofacial modules, bifacial modules are assembled from cells that can effectively absorb and convert into electricity the radiation falling on both their front and back sides, which allows the use of diffused and reflected radiation (the size of which depends mainly on the albedo). According to research by Park et al. [41], depending on the albedo of the ground on which the panel is installed, the effective energy yield may be higher than 10% to 33% in relation to monofacial panels. The use of bifacial panels may cause self-consumption increase (direct) as production in the morning and evening hours is higher [42,43]. Gallegos et al. have shown that for latitudes above  $40^\circ$ , bifacial modules are more cost-effective than monofacial [44]. Based on a review of the LCA of PVs,  $\text{CO}_2$  emissions for mono-Si cells are 21 to  $250 \text{ gCO}_2/\text{kWh}$ , mean value by Kommalapati et al. estimated at  $85 \text{ gCO}_2/\text{kWh}$ .

The large discrepancy in values depend on the energy mix at every step of the supply chain [39]. The cleaner the mix, the cleaner the solar array production. Reich et al. stated that the intensity of GHG emissions may be zero g CO<sub>2</sub>-eq/kWh for energy based on renewable sources and nuclear energy up to 200 gCO<sub>2</sub>/kWh for energy only from coal [45]. The current GHG footprint is around 25 gCO<sub>2</sub>/kWh for mono-Si PV systems, down from 409 gCO<sub>2</sub>/kWh in 1986 [35]. There are few LCAs for bifacial modules; analysis by Gazbour et al. shows a value of 31 gCO<sub>2</sub>/kWh [46].

As shown in the paragraph above, the listed programs are not the main driving force behind the selection of bifacial PV panels. As shown on the Polish market, there is no research on the use of bifacial panels, for which a higher yield in the form of energy (from a limited area) can be achieved, and one of the goals of this work is to show how higher this yield is. Currently, due to the fact that bifacial PV panels are a newer solution than mono-facial panels (as well as less frequently used), they are more expensive, however, their popularization should affect their prices and attractiveness of use on global and Polish markets. The novelty of this paper is a comparison of a new solution for Polish climate conditions with bifacial panels to a traditional monofacial installation. Checking the economic (a profitability analysis) and ecological benefits (an assessment of the potential to avoid CO<sub>2</sub> emissions) of using solar installations in the implemented co-financing programs for this type of projects. On the basis of the conducted research, the energy gains of both installations and the amount of CO<sub>2</sub> emission reduction were determined. Depending on the structure of energy generation and the related CO<sub>2</sub> emission index, the unit cost of CO<sub>2</sub> reduction was estimated in the perspective of 20 years.

## 2. Configurations of Analyzed Monofacial and Bifacial Micro PV

Productivity analyses were carried out for two photovoltaic installations. Classic monofacial PV located in Lesser Poland with a capacity of 5.04 kWp and bifacial PV located in Bydgoszcz with a capacity of 6.1 kWp. Both installations use mono-crystalline Si-based 1st generation PV cells. A detailed analysis was carried out for June 2020.

### 2.1. PV Microinstallation in Leki (Lesser Poland Voivodship)

The photovoltaic installation located in the Lesser Poland province (the exact geographical coordinates are shown in Figure 1) consists of 14 monocrystalline panels by Longi-Figure 6 with a power of 0.36 kWp. The technical data of the panels are included in Table 1, and the installation configuration data in Table 2. The energy output from the inverter (Fronius 5.0 3M) was measured every 5 min and the energy sent to the grid and energy from the grid was monitored via a bidirectional electricity meter.



**Figure 6.** Panels on the roof of a single-family building in Leki.

The installation was built in 2020 at a cost of EUR 4250, of which EUR 1150 in subsidies [14,16], was obtained under the “My Electricity” program, and another EUR 250 was settled as a tax credit. The unit price without subsidies is EUR 843/kWp, and including subsidies, it is EUR 565/kWp.

In 2018–2019, an analysis of the demand for electricity was carried out for the building (the annual total is about 5600 kWh), detailed results are included in the work by Kryzia et al. [43]. The energy produced in the installation replaces energy from the electricity grid at a price of EUR 0.14/kWh, the surplus energy produced is “virtually stored in the grid” (energy sent to the grid) and can be downloaded by the user again (up to one year) with a reduction of 20% (for installation power up to 10 kWp) [47].

**Table 1.** Characteristics of PV panels. Source: own study based on [48,49].

Parameter	Unit	Leki	Bydgoszcz
Name		Longi HPH 360	BIFACIAL
Nominal power	kWp	0.36	0.305
Total length	m	1.776	1.664
Total width	m	1.052	0.996
Temperature coefficient of the short-circuit current	%/°C	0.057	0.029
Temperature coefficient of the open-circuit voltage	%/°C	−0.286	−0.224
Temperature coefficient of the power	%/°C	−0.370	−0.279
Technology		Mono-PERC	Bifacial, mono N

**Table 2.** Installation configuration.

Parameter	Unit	Leki	Bydgoszcz
Number of panels		14	20
Tilt angle	°	30	45
Direction		SW	S
Inverter		Fronius 5.0–3M	2xSolar Edge SE10k
Power of inverters	kW	5	6.1
Total PV panel power (PI)	kWp	5.04	6.1

## 2.2. PV microinstallation (Bifacial) in Bydgoszcz (Kujawsko-Pomorskie Province)

At the UTP University of Science and Technology in Bydgoszcz, at the Faculty of Mechanical Engineering at the Institute of Manufacturing Technique, a photovoltaic installation was built (Figure 7). This installation consists of 20 Hanplast bifacial photovoltaic panels, where each panel consist of cells made in smart-wire technology with a power of 0.305 kWp. The technical data of the panels are included in Table 1. The panels are facing south and inclined at an angle of 45°. They are located on the ground (meadow area), which has a positive effect on their gravity cooling compared to PV installed on the roof surface.

The modules are equipped with a P 370 type power optimiser. The entire system is protected with two SK 3K inverters with 10 PV modules connected to each of the inverters. The installation supplies teaching buildings, including server rooms, whose minimum power demand is greater than the energy production in the PV installation. All the energy produced is used on site. The installation was built at the beginning of 2020, its total cost was EUR 9800.

Detailed information about the panels is included in Table 1, and configuration data in Table 2.

The lower the values of the temperature coefficient of the open-circuit voltage and temperature coefficient of the power, the less the current efficiency of the panel depends on the panel temperature [50]. Bifacial panels are characterised by lower values.



**Figure 7.** Setting up  $5 \times 4$  panels on the ground in Bydgoszcz.

### 3. Methodology of Analyses

#### 3.1. Electricity Demand vs. Production

Based on the data on the structure of production and energy consumption in the analysed buildings, the degree of coverage of the demand by PV systems was determined. Two factors have been identified: self-consumption (SC) and self-sufficiency (SS) indicators. The first could show the amount of energy produced and consumed in the same building (electric installation) with respect to total energy production in installations, at the same period of time. The self-sufficiency coefficient (SS) is the amount of energy produced and consumed in the same building (electric installation) with respect to total energy consumption in installations, at the same period of time.

$$SC(\tau) = Esc(\tau)/Ep(\tau) \quad (1)$$

where:

$Esc$ —energy self-consumed from energy produced in PV installation directly in the building;  
energy consumption in the building minus energy from the grid

$Ep$ —energy produced

$\tau$ —time

$$SS(\tau) = Esc(\tau)/Ec(\tau) \quad (2)$$

where:

$Ec$ —energy consumption in the building

$\tau$ —time

#### 3.2. Annual Energy Gains

Based on the measured monthly data on energy production from both installations and statistical data on insolation on a horizontal surface and for angles characteristic for the installations under consideration (Figures 8 and 9), the correction factors for multi-year analysis were determined. The method used in calculation had been based on [31,51–53]. In terms of that the following correction factors were determined: insolation coefficient (IJC), changes in insolation for a given direction and angle of panel installation (IDA), solar



radiation conversion for the whole year (*JSHIA*). The following formula for annual energy gains (*EAG*) has been proposed:

$$EAG = \frac{1}{IJC \cdot IDA \cdot JSHIA} \cdot EMG, \frac{kWh}{year} \quad (3)$$

where:

*EAG*—Annual energy gains, kWh/year

*EMG*—Measured monthly energy gains, kWh/month

*IJC*—Insolation coefficient, kWh/kWh, Equation (4)

*IDA*—Correction for Insolation on the direction and angle, kWh/kWh

*JSHIA*—Converting the insolation from June to the whole year, month/year,

$$IJC = I_{H\_June}(2020) / \left( \sum_{year=2010}^{2020} (I_{H\_June}(year)) / 11 \right) \quad (4)$$

*I<sub>H\_June</sub>*—Horizontal Insolation in June in year, kWh/(m<sup>2</sup>·month)

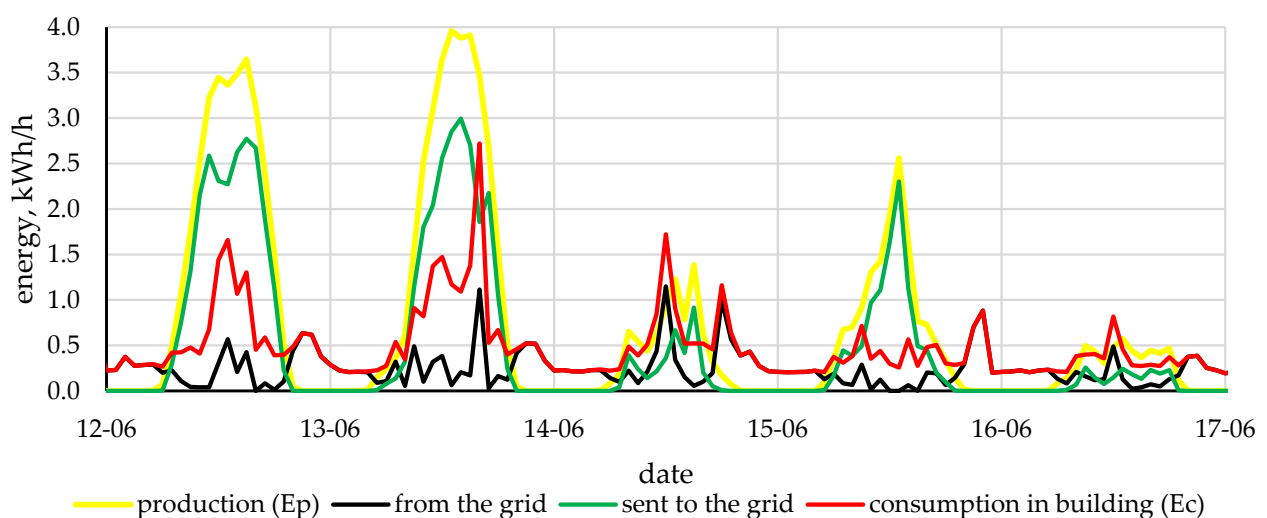
$$IDA(direction/location) = \begin{cases} I_{TRY\_SW30\_June} \text{ for monofacial} \\ I_{TRY\_S45\_June} \text{ for bifacial} \end{cases} / I_{TRY\_H\_June} \quad (5)$$

where:

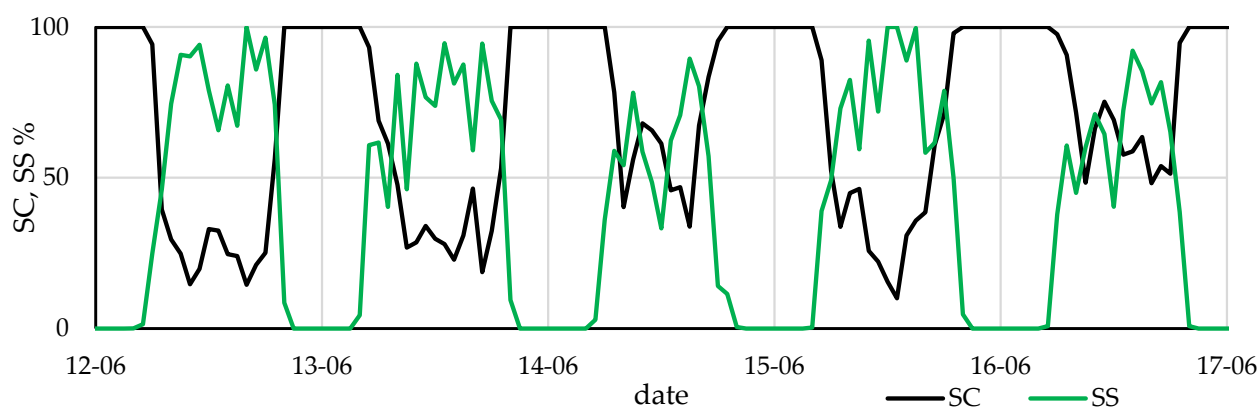
*I<sub>TRY\_H\_June</sub>*—Insolation for Typical Reference Year—Horizontal Surface, kWh/(m<sup>2</sup>·month)

*I<sub>TRY\_S45\_June</sub>*—Insolation for Typical Reference Year—south directed surface titled 45°, kWh/(m<sup>2</sup>·month)

*TRY\_SW30\_June*—Insolation for Typical Reference Year—south-west directed surface titled 30° [18], kWh/(m<sup>2</sup>·month)



**Figure 8.** Energy production in the PV installation Leki and energy: added to the grid, consumed and Energy consumption in the building, June 2020.



**Figure 9.** Self-consumption coefficient (SC) and self-sufficiency coefficient (SS) for several days of June 2020.

Based on the insolation data from 2010–2020 [33], the representativeness of insolation data for the analysed June 2020 (JSHI) was determined:

$$JSHI = I_{H\_June} / I_{H\_Year} \quad (6)$$

where:

$I_{H\_June}$ —Horizontal Insolation in June, kWh/(m<sup>2</sup>·month)

$I_{H\_Year}$ —Horizontal Insolation in whole year, kWh/(m<sup>2</sup>·year)

$JSHIA$ —is average (from 2010 to 2019 year) for value for JSHI, month/year

### 3.3. Reduce of CO<sub>2</sub> Emission

The main reason for the construction of PV installations is the ability to reduce greenhouse gas emissions. The analysis considered two factors, the benefit of reducing CO<sub>2</sub> emissions from the combustion of fossil fuels ( $E_{ECO_2}$ ) and CO<sub>2</sub> emissions that arise during the production cycle of PV panels ( $EPVCO_2$ ) [54].

In Poland, the CO<sub>2</sub> emission factor per kWh for end users of electricity (according to KOBIZE) is 0.765 kgCO<sub>2</sub>/kWh [3,28]. Since the emission factor depends on the type of fuel (brown coal, hard coal) the analysis of  $E_{ECO_2}$  has been carried out for a range of 0.4–1 kgCO<sub>2</sub>/kWh. It has been assumed that during PV production the  $EPVCO_2$  changes in the range of 20–85 gCO<sub>2</sub>/kWh.

$$ACO_2 = EAG \cdot (E_{ECO_2} - EPVCO_2) \quad (7)$$

$ACO_2$ —the amount of CO<sub>2</sub> emission avoided, Mg/year

$EAG$ —Annual energy gains, kWh/year

$E_{ECO_2}$ —energy electricity emission factor in Poland, kgCO<sub>2</sub>/kWh

$EPVCO_2$ —CO<sub>2</sub> emission factor for PV, kgCO<sub>2</sub>/kWh

Additionally, the indicator unit (investment) cost of CO<sub>2</sub> emission reduction factor ( $UCPVCO_2$ ) was calculated. The analysis was related to the 20 years of use of the investment and included the total installation costs ( $I_0$ ): Leki-EUR 4250, Bydgoszcz-EUR 9800.

$$UCPVCO_2 = \frac{I_0}{n \cdot ACO_2} \quad (8)$$

where:

$UCPVCO_2$ —Unit (investment) cost of CO<sub>2</sub> emission reduction factor, EUR/kgCO<sub>2</sub>

$I_0$ —initial investment value, EUR,

$n$ —lifetime of PV, year



### 3.4. Profitability Analyses

The purpose of the economic analysis was to compare the economic results using Net Present Value (NPV) (Equation (9)).

Moreover, it was assumed:

- Discount rate ( $r$ ), varies in range from 0 to 0.06 [55],
- Electricity price ( $ELP$ ) from 0.1 to 0.2 EUR/kWh [43,56] (in 2020,  $ELP = 0.15$  EUR/kWh),
- Decrease in the PV panels productivity by 0.5% per year

$$NPV(ELP, r) = \left[ \sum_{t=1}^n \frac{CF_t}{(1+r)^t} \right] - I_0 \quad (9)$$

where:

$CF_t$  is the cash flow in the year  $t$ , EUR (Equation (10)),

$t$ —year of the analysis,

$r$ —discount rate, %

$$CF_t(ELP) = EAG \cdot SC \cdot ELP + PF \cdot EAG \cdot (1 - SC) \cdot ELP - OC \quad (10)$$

where:

$CF_t$  is the cash flow in the year  $t$ , EUR,

$OC$ —operating cost, EUR/year,

$PF$ —prosumer factor,

$ELP$ —electricity price, EUR/kWh,

$SC$ —self-consumption, Equation (1)

For the Leki installation, which was covered by the subsidy program, the cost of reducing CO<sub>2</sub> emissions was calculated for the options with and without subsidies. For Bydgoszcz, the analysis was compared to the cost invested in the installation.

Additionally, NPV differences were calculated for different  $ELP$  values and for different  $r$  values:

$$diff.NPV(ELP, r) = NPV(ELP, r) \text{ for Leki} - NPV(ELP, r) \text{ for Bydgoszcz} \quad (11)$$

## 4. Results and Discussion

### 4.1. Electricity Demand vs. Production

Figure 8 presents the details of the energy production, flow and consumption in the building Leki for selected days with high and low energy production.

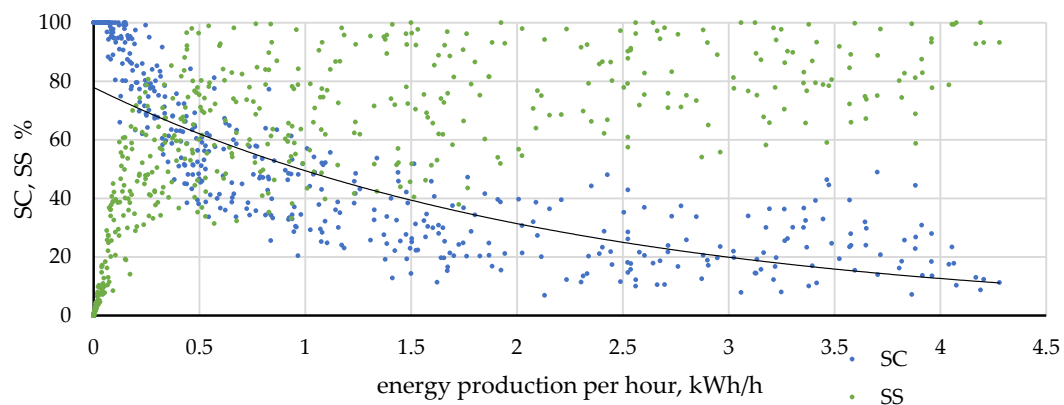
For the data presented in Figure 8, self-consumption (SC) and self-sufficiency (SS) indicators were determined.

High production was achieved on the 13 June and it was 32.22 kWh of which 21.98 kWh were sent to the grid. Consumption on the analysed day was 16.95 kWh, of which 6.71 kWh were obtained from the grid. For comparison, on June 14th, it was 8.04 kWh of which 3.65 kWh were sent to the grid. The consumption on that day was 11.91 kWh, of which 7.52 kWh were obtained from the grid.

The SC and SS coefficients were determined for 12–17 June, the obtained results are presented in Figure 9. Then the SC and SS were determined for all hours of June—Figure 10.

For various conditions that were observed from 12 June to 17 June, it was found that only for 4 h the SS value was 100%, it means that the PV installation fully covered the energy consumption only through 4 h. In whole June, it was, only for 31 h. The SC coefficient decreases with increasing productivity and is close to 100% only for low PV powers below 10% of nominal power, observed at low intensity of solar radiation (see Figures 8 and 9). The SS behaves the opposite (Figure 10). In the analysed period (June 2020), the average SC value was 30.4% and the SS was 48.9%.

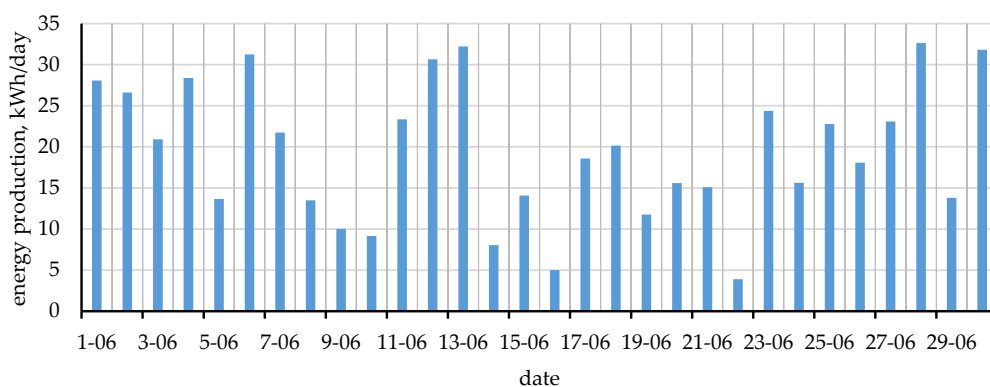
For bifacial installation, the energy produced by the system is used in the University buildings. The SC ratio is 100%.



**Figure 10.** Self-consumption coefficient (SC) and self-sufficiency coefficient (SS) as a function of energy production per hour. June 2020.

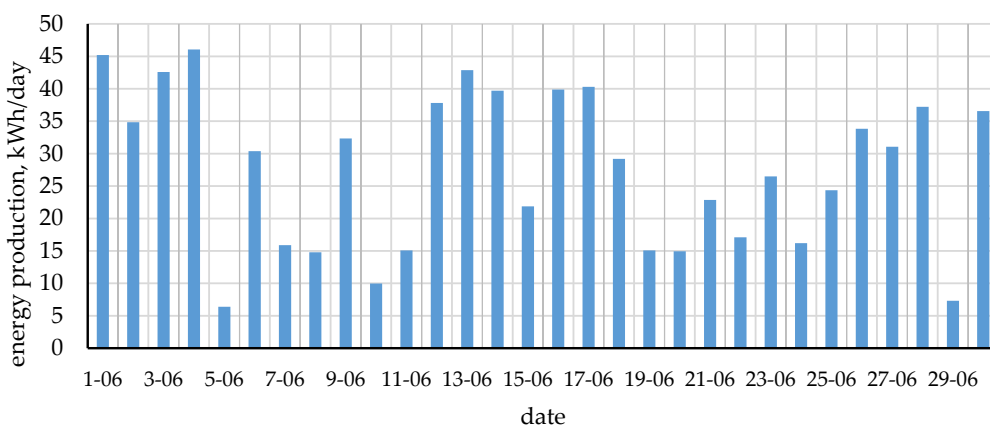
#### 4.2. Annually Gain

The amount of energy produced by the Leki installation in the form of daily sums is presented in Figure 11. The daily production of monofacial PV installation varied from 4 kWh to 32.5 kWh. In total, 583.87 kWh (EMG) was achieved in the period under examination.



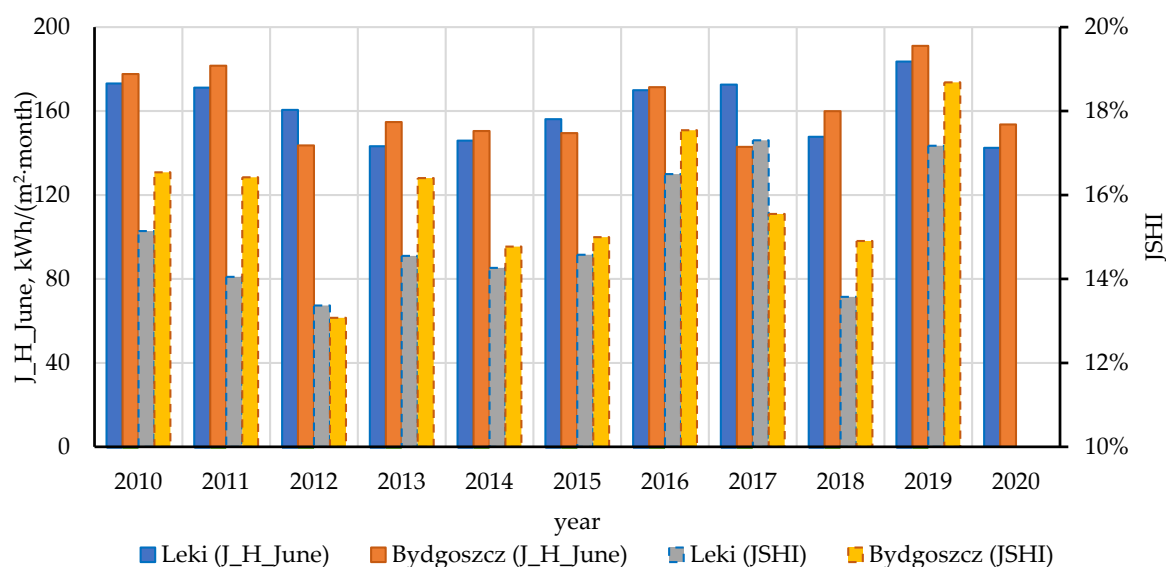
**Figure 11.** Daily energy production in PV installation (Leki), June 2020.

The daily production of bifacial PV installation in Bydgoszcz in June 2020 ranged from 6.4 kWh to 46 kWh (Figure 12). Total production for June was measured as 828.13 kWh (EMG).



**Figure 12.** Daily energy production in PV installation (Bydgoszcz), June 2020.

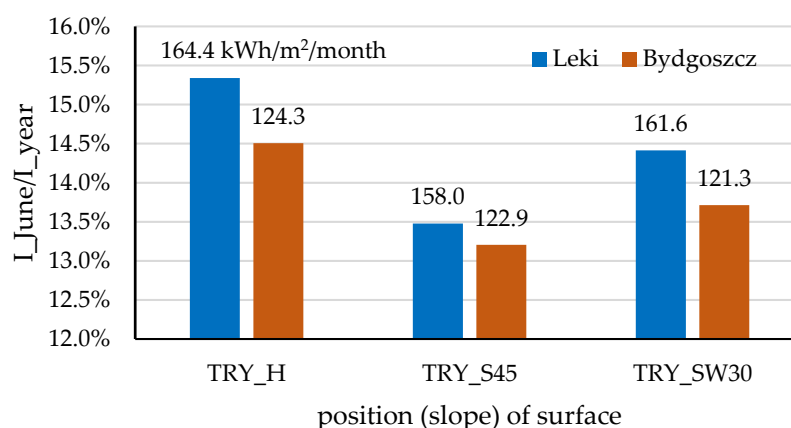
The recorded insolation values for each June in 2010–2020 for both locations are presented in Figure 13.



**Figure 13.** Comparison of insolation values varied from locations for June in the last 11 years. Source own study based on [18,33,57].

In 2010–2020, the value of insolation in June for Leki varied from 145 kWh/(m<sup>2</sup>·month) to 184 kWh/(m<sup>2</sup>·month), and for Bydgoszcz from 144 kWh/(m<sup>2</sup>·month) to 191 kWh/(m<sup>2</sup>·month). The value of insolation for Leki and Bydgoszcz in June 2020 was 142.45 kWh and 153.63 kWh (see also Figure 15) and was lower than the 11-year average by 11% and 5%. For further calculations it was assumed that the insolation coefficient IJC for the installation Leki and Bydgoszcz was 0.89 and 0.95, respectively.

On the basis of NASA Larc data [33], the average share of registered sunlight falling on the horizontal surface for June was determined for both locations in relation to the annual amount (TRY\_H). The solar representativity for the south (TRY\_S45) and south-west (TRY\_SW30) direction was also determined, referring to the percentage of insolation for June in the year (Typical Reference Year)–Figure 14.



**Figure 14.** Comparison of the insolation values for both locations for June against the Typical Reference Year data and different location of the surface. (TRY\_H–Typical Reference Year–Horizontal Surface, TRY\_S45–Typical Reference Year–south directed surface titled 45°, TRY\_SW30–Typical Reference Year–south-west directed surface titled 30° [18].

The average share of the registered insolation in June in relation to the annual value was 15% and 15.9% (Figure 13) and was lower by 0.3 percent point (Leki) and higher by 1.4 percent point (Bydgoszcz) compared to the Typical Reference Year (Figure 11). Taking into account the direction of the panels' installation, the insolation value for Leki differs by 0.9% compared to the Typical Reference Year-horizontal, while for Bydgoszcz by 1.2% compared to the Typical Reference Year-horizontal. For further calculations it was assumed that the insolation on the direction and angle coefficient (IDA) for the Leki and Bydgoszcz installations is 0.991 and 0.988, respectively.

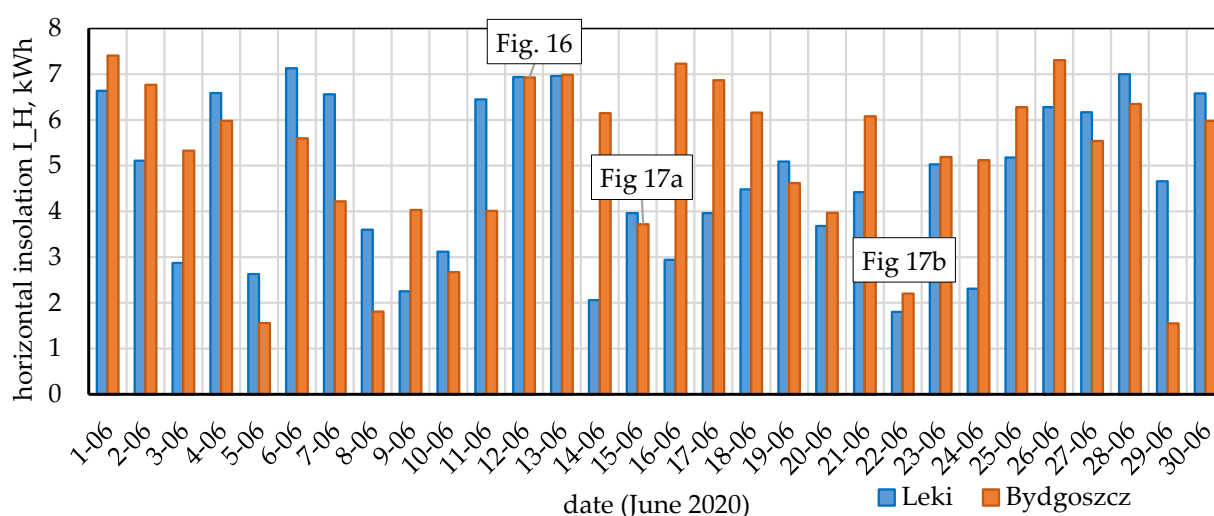
Taking into account the coefficients IJC, IDA, JSHIA (Table 3) for both locations, the annual energy gain (EAG) for Leki and Bydgoszcz was calculated as 4300 kWh, 6091 kWh.

**Table 3.** Energy production correction factors and annual energy gains.

Parameter	Unit	Leki	Bydgoszcz
Monthly energy gains, EMG	kWh	583.87	828.13
Insolation coefficient, IJC	-	0.89	0.95
Insolation on the direction and angle, IDA	-	0.991	0.988
Converting the insolation from June to the whole year, JSHIA	-	0.154	0.145
Annual energy gains, EAG	kWh	4300	6091
Annual energy gains per PI, EAG/PI	kWh/kWp	853	999

#### 4.3. Comparison of Solar Energy Production

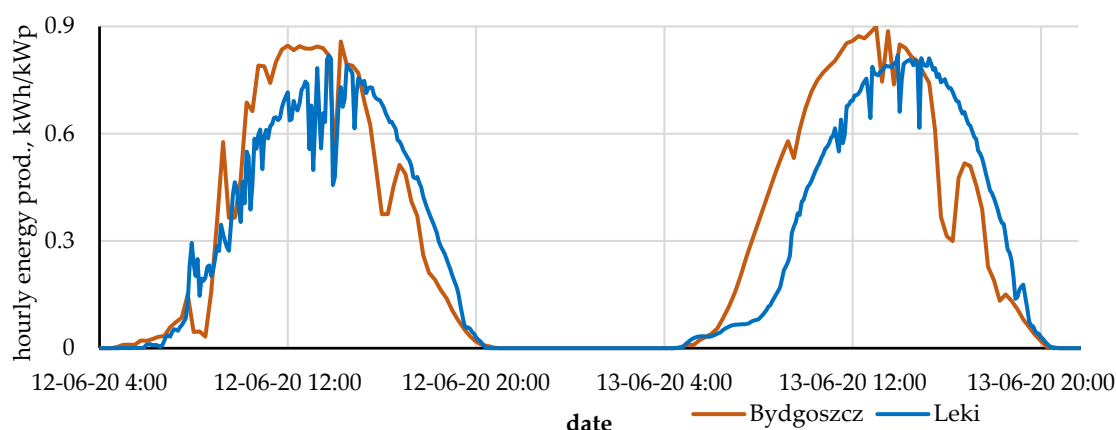
The value of insolation in June 2020 for both locations is shown in Figure 15 [33].



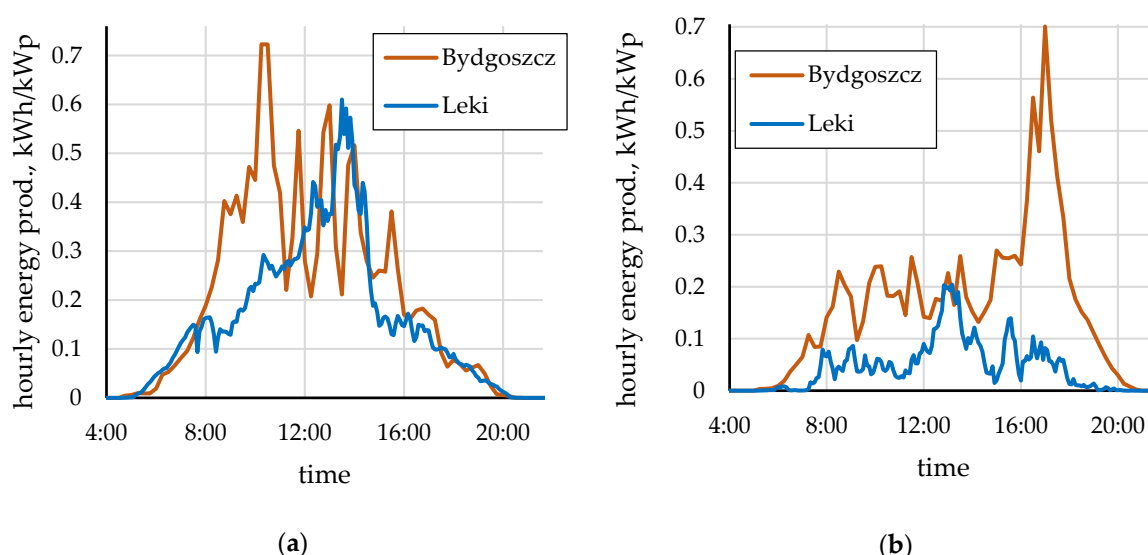
**Figure 15.** Comparison of insolation values for both locations for individual days in June. (References to detail figures are marked-energy production results for both installations.)

In order to compare the volume of energy production in both installations, two days were selected (Figure 16) for which high insolation was recorded in both installations, followed by days with low insolation.

On 12 and 13 June, both locations recorded comparable high levels of insolation of 7 kWh/m<sup>2</sup>/day (Figure 15). On selected days, the installation in Leki produced 6.08 and 6.39 kWh/kWp, respectively, and in Bydgoszcz 6.20 and 7.03 kWh/kWp. In both cases, the two-sided installation generated more energy. In addition, on 13.06, the influence of a different direction of PV panel foundation was observed (SW30 for Leki, S45 for Bydgoszcz), the installation in Bydgoszcz reached the maximum hourly production of 0.87 kWh/kWp at around 1:00 p.m., while Leki 0.8 kWh/kWp in the period of 2:30 p.m. (Figure 17).



**Figure 16.** Comparison of the unit results of energy production from installations for 12 and 13 June.



**Figure 17.** Comparison of the unit results of energy production in an installation, for: (a) 15 June; (b) 22 June.

On 15 and 22 June in the analysed locations, comparable low insolation was recorded (Figure 15), not greater than  $4 \text{ kWh/m}^2/\text{day}$  on 15 June and approx.  $2 \text{ kWh/m}^2/\text{day}$  on 22 June. Unit energy production on June 15 was 2.8 (Bydgoszcz) and 0.8 (Leki)  $\text{kWh}/(\text{kWp}\cdot\text{day})$ , and 22 June, respectively, 3.6 and 2.8  $\text{kWh}/(\text{kWp}\cdot\text{day})$ .

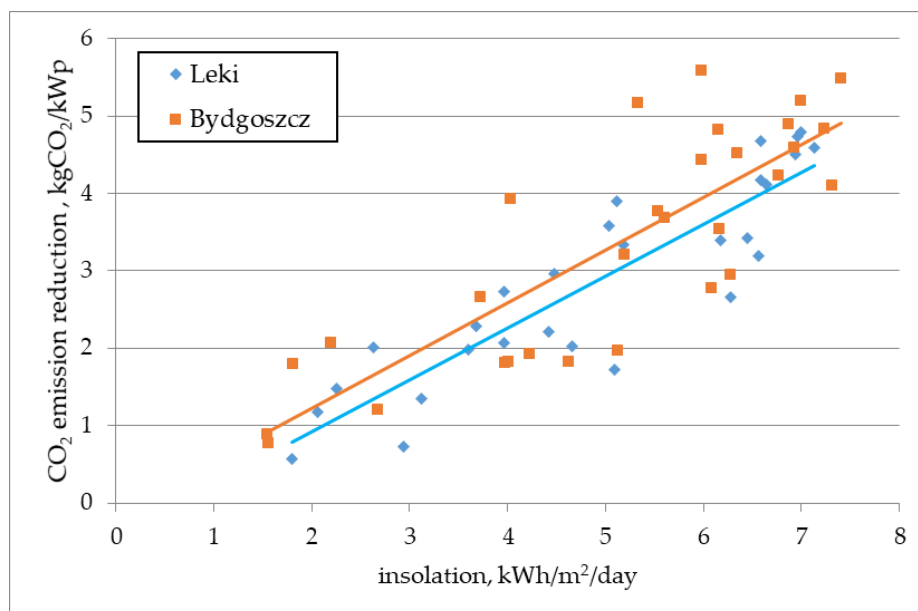
Analysing both cases (Figures 16 and 17), it can be seen that at lower values of insolation, two-sided panels produce more energy, which results in lower variability of the available/produced energy from bifacial PV installations compared to that of one-sided panels. That is also good for increasing direct consumption as peaks around midday are avoided and the broadening leads to longer time during the day in which electricity can be used, even more as, during midday, many people are not at home.

With comparable insolation, a bifacial installation produces approximately 10% (for high insolation) to 28% (for low insolation) more energy than a monofacial installation.

#### 4.4. Carbon Dioxide Emission Reduction Analyses

The installation in Leki produced 583.87 kWh of electricity in June and 4300 kWh per year (Table 3); the installation in Bydgoszcz produced 828.13 kWh, and 6091 kWh per year (Table 3). This makes it possible to avoid  $\text{CO}_2$  emissions at the level of 397 to 435 kg and 563 to 617 kg, which will amount from 2.9 to 3.2 Mg and 4.1 to 4.5 Mg per year.

Additionally, considering the power of the panels (Table 2), it was found that the annual energy production for Leki (monofacial panel) and Bydgoszcz (bifacial) is 853 kWh/kWp and 999 kWh/kWp, respectively. Avoided annual CO<sub>2</sub> emission in relation to the installation capacity is from 0.58 to 0.64 Mg/kWp and from 0.68 to 0.74 Mg/kWp and is on average approx. 16% higher for bifacial installations. Daily unit reduction of CO<sub>2</sub> emissions is depicted in Figure 18.



**Figure 18.** Daily reduction of CO<sub>2</sub> emissions as a function of insolation.

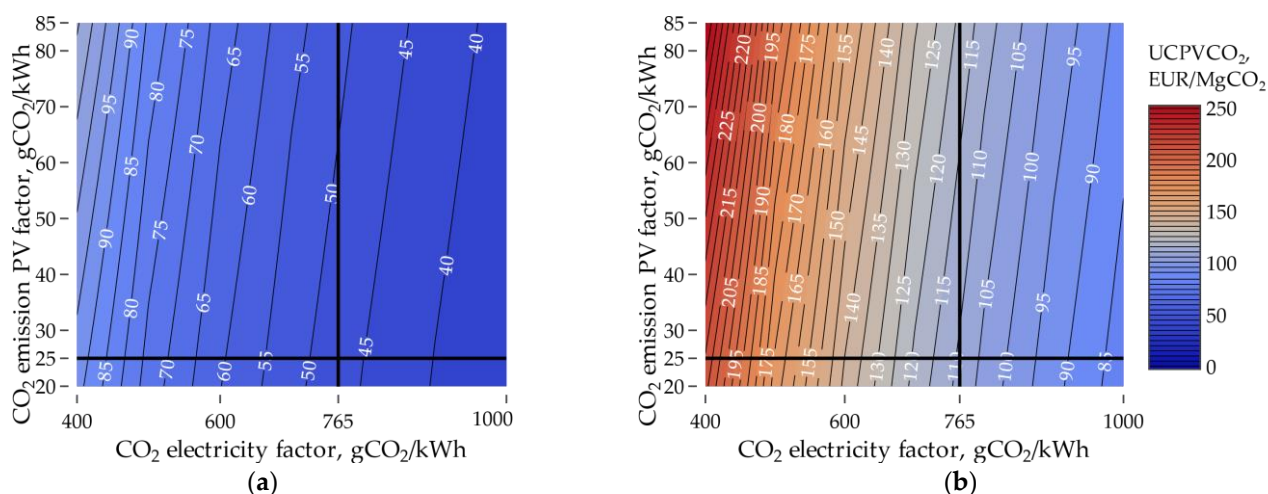
Analysing the daily energy production (Figures 11 and 12), which is closely related to insolation (Figure 15) and assuming the CO<sub>2</sub> emission factors for fossil fuels and the average emission factor resulting from PV production equal to 25 gCO<sub>2</sub>/kWh [58], the impact of the amount of insolation on reduction of CO<sub>2</sub> emissions.

The results presented in Figure 18 confirm the greater efficiency of the system with the bifacial installation and the resulting higher reduction of CO<sub>2</sub> emissions.

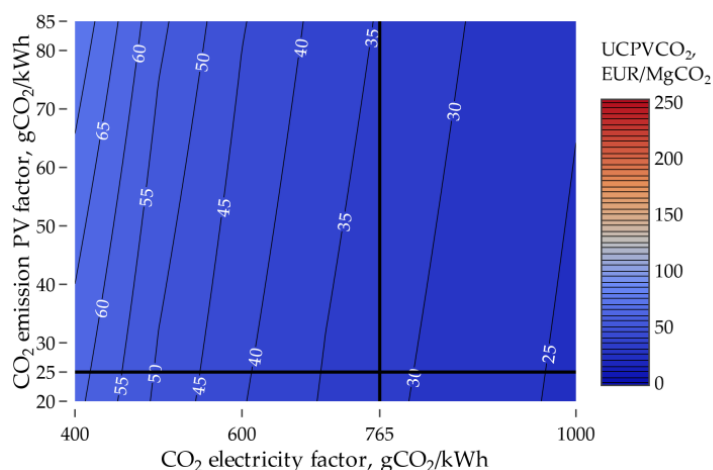
The cost of reducing CO<sub>2</sub> emissions depends on the share of energy sources in the structure of its production. An exemplary emission factor for electricity generated in a gas power plant is 400 kgCO<sub>2</sub>/MWh, while for a coal power plant, it is 850 kgCO<sub>2</sub>/MWh [59]. Forecasts for the development of the power industry in the perspective of 2060 are varied [54,60]. Depending on the variant depending on the costs of emission allowances, gas prices or the share of renewable energy, the share of coal energy in 2020–2040 changes from 62% to 55.7% for the variant with high costs for emission allowances from 51.6% to 13.4% for the option of reducing the emission level to 85 million Mg CO<sub>2</sub>.

With the current emission indicators related to the production of panels—25 gCO<sub>2</sub>/kWh and the indicator concerning CO<sub>2</sub> emissions related to electricity production in Poland 765 gCO<sub>2</sub>/kWh, the unit cost of reducing CO<sub>2</sub> emissions is about EUR 48 for monofacial and 110 for bifacial (without subsidies) per Mg CO<sub>2</sub>, taking into account 20 years of operation of the installation (Figure 19). In the case of a decrease in the emissivity of electricity production in Poland to the level of 400 gCO<sub>2</sub>/kWh, the unit cost increases to approx. 93 and 210 EUR per MgCO<sub>2</sub>. If the emission related to the production of PV panels was much higher, i.e., 85 gCO<sub>2</sub>/kWh, these values would be for monofacial 52 EUR/MgCO<sub>2</sub> and for bifacial 118 EUR/MgCO<sub>2</sub>, respectively. Considering the subsidy, these values are correspondingly lower (Figure 20).





**Figure 19.** Unit (investment) cost of CO<sub>2</sub> emission reduction as a function of CO<sub>2</sub> emission factor in the national grid and emissions related to the production of panels: (a) Leki; (b) Bydgoszcz.



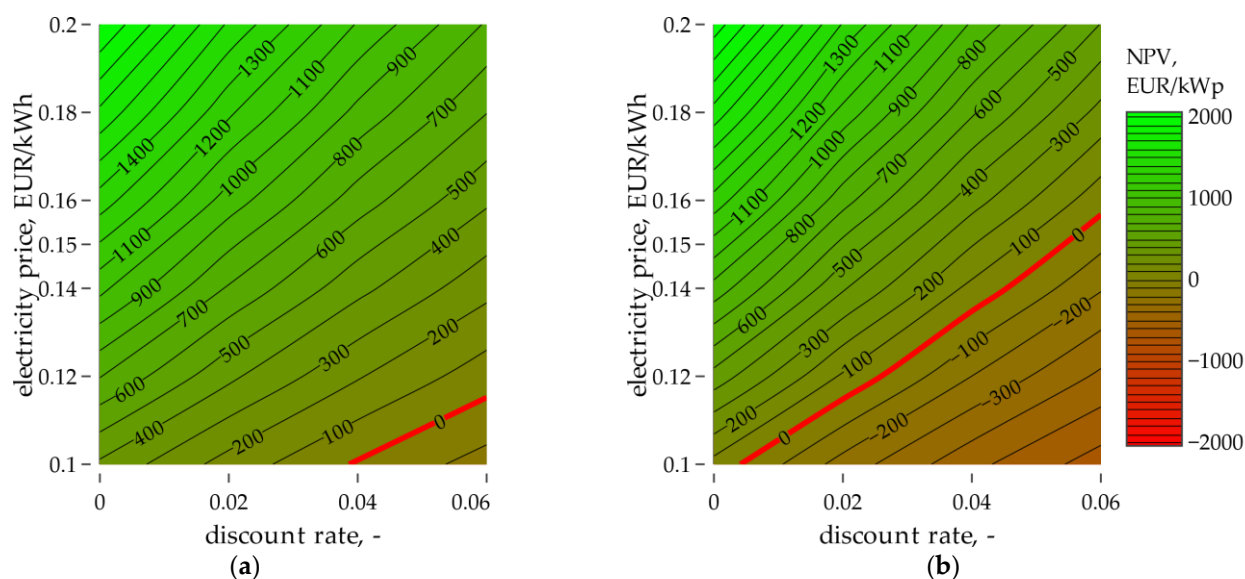
**Figure 20.** Unit (investment) cost of CO<sub>2</sub> emission reduction as a function of CO<sub>2</sub> emission factor in the national grid and emissions related to the production of Leki panels with subsidy.

#### 4.5. Profitability Analyses

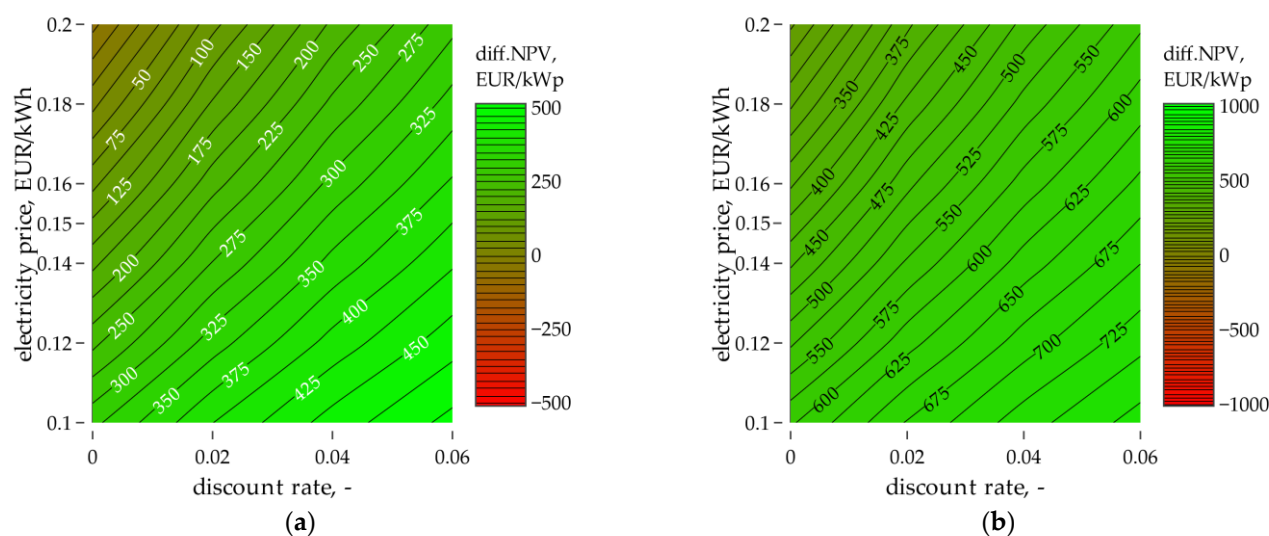
The results of the NPV analysis are presented in Figure 21. In addition, the NPV for Leki and NPV for Bydgoszcz (diff.NPV—Equation (11)) were determined differently (Figure 22a) and similarly, taking into account the subsidies for the Leki installation (Figure 22b).

Figure 22 shows under which economic conditions the bifacial panel's price reaches (Bydgoszcz case) a higher NPV than the monofacial PV panels (Leki case). As can be seen in Figure 22a, the installation in Bydgoszcz does not give a greater result in the form of NPV. Considering the subsidy in the scope of electricity price 0.1–0.2 EUR/kWh, the installation in Bydgoszcz is also in no case more profitable.

For EIP = 0.15 EUR/kWh and  $r = 0\%$ , unit NPV for monofacial is equal 1200 EUR/kWp, and for bifacial 1060 EUR/kWp. The difference of EUR 140/kWp is increased to EUR 410/kWp if the subsidy “My electricity” is taken into account.



**Figure 21.** Net Present Value (NPV) as a function of electricity price and discount rate value: (a) for Leki; (b) for Bydgoszcz. EIP = 0.15 EUR/kWh is actual electricity price in Poland.



In Poland, the share of fossil fuels (hard coal and lignite) in electricity generation is of importance, which gives the CO<sub>2</sub> footprint of 765 gCO<sub>2</sub>/kWh. The production of one kWh of energy from PV theoretically limits this value, but it practically replaces the most emitting carbon sources. In the analysed cases the annual reduction of CO<sub>2</sub> emissions, taking the emissions resulting from the production of panels into account, could be from 0.58 to 0.64 Mg/kWp for monofacial PV and 0.68 to 0.74 Mg/kWp for bifacial PV. Avoided CO<sub>2</sub> emission is on average approximately 16% higher for bifacial installations.

Spending 1 Euro for PV installations contributes to emission savings of 20.8 kgCO<sub>2</sub> (for 25 gCO<sub>2</sub>/kWh as environmental cost of PV installation) in the case of monofacial panels and in the case of bifacial panels to 9 kgCO<sub>2</sub>.

The installation subsidised under the “My Electricity” program can reach an NPV of EUR 6000 over 20 years with a discount rate  $r = 0$  and assuming an electricity price of 0.15 EUR/kWh. If this price is increased to 0.2 EUR/kWh, NPV will be 10,000 EUR.

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## Abbreviations

ACO <sub>2</sub>	amount of CO <sub>2</sub> emission avoided, Mg/year
CF	Cash flow, EUR
Diff.NPV	Difference of NPV in Leki and Bydgoszcz
E	East
EAG	Annual energy gains, kWh/year
Ec	energy consumption in the building
EECO <sub>2</sub>	energy electricity emission factor in Poland, kgCO <sub>2</sub> /kWh
EIP	Electricity price, EUR/kWh
EMG	Measured monthly energy gains, kWh/month
Ep	energy produced
EPVCO <sub>2</sub>	CO <sub>2</sub> emission factor for PV, kgCO <sub>2</sub> /kWh
Esc	energy self-consumed from locally produced: energy consumption in the building minus energy from the grid
GHG	greenhouse gas
I0	initial investment value, EUR
IDA	Correction for Insolation on the direction and angle, kWh/kWh
IJC	Insolation coefficient, kWh/kWh
I_H_June	Horizontal Insolation in June, kWh/(m <sup>2</sup> ·month)
I_H_Year	Horizontal Insolation in whole year, kWh/(m <sup>2</sup> ·year)
I_June	Insolation in June for TRY
I_Year	Insolation in whole for TRY
JSHI	June Share of Yearly Horizontal Insolation
JSHIA	Converting the insolation from June to the whole year, month/year
LCA	Life Cycle Analyses
N	north

n	lifetime of PV, year
NPV	Net Present Value, EUR
PI	Total PV panel power, kWp
PV	photovoltaic
r	discount rate
t	year
S	South
SATS	single axis tracking systems
SC	self-consumption
SS	self-sufficiency
TRY_H	Typical Reference Year–Horizontal Surface
TRY_S45	Typical Reference Year–south directed surface titled 45°
TRY_SW30	Typical Reference Year–south-west directed surface titled 30°
UCPVC <sub>CO2</sub>	Unit (investment) cost of CO <sub>2</sub> emission reduction, EUR/kgCO <sub>2</sub>
W	West
τ	time

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