Article

Agricultural Land: Crop Production or Photovoltaic Power Plants

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Abstract: Mitigation of climate change requires a decrease in greenhouse gas emissions. It motivates an increase in renewable electricity generation. Farmers can develop renewable energy and increase their profitability by allocating agricultural land to PV power plants. This transition from crop production to electricity generation needs ecological and economic assessment from alternative land utilization. The novelty of this study is an integrated assessment that links economic and environmental (carbon dioxide emissions) indicators. They were calculated for crop production and solar power generation in a semi-arid zone. The results showed that gross income (crop production) ranges from USD 508/ha to USD 1389/ha. PV plants can generate up to 794 MWh/ha. Their market cost is EUR 82,000, and their production costs are less than wholesale prices in Ukrainian. The profitability index of a PV project ranges from 1.26 (a discount range is 10%) to 3.24 (a discount rate is 0). The sensitivity analysis was carried out for six variables. For each chosen variable, we found its switching value. It was revealed that the most sensitive variable is a feed-in tariff. Operational expenses and investment costs are the most sensitive variables. Carbon dioxide footprints range from 500 to 3200 $kgCO_2$/ha (depending on the crop). A 618 kW PV plant causes a release of carbon dioxide in the range of 5.2–11.4 gCO_2/kWh. The calculated carbon dioxide payback period varies from 5 to 10 months.

Keywords: photovoltaic; carbon dioxide; emission; agricultural land; profitability index; sensitivity analysis; crop production

1. Introduction

An increase in greenhouse gas (GHG) emissions is a challenge for modern civilization [1]. World society increases the use of low carbon renewable energy to mitigate climate change. These kinds of energy show fast growth and absolute consumption [2]. However, currently, the transformation of world energy systems does not meet the requirements of the Paris Agreement [3].

The social-economic development expects an increase in second-generation biofuels and energy production from renewable energy, including solar power [4,5]. Annual power generated by solar photovoltaic (PV) needs to be in the range from 54 to 396 EJ to reach limiting warming (the 1.5 °C target by 2100) [5,6]. The development of bioenergy and PV requires the extent of land area. It can cause conflict with food production and, therefore, food security [7–9]. The solving of this problem requires using energy management planning [10,11]. The use of abandoned cropland for creating renewable energy infrastructure is a promising solution to reduce competition for arable land [12–14].

Abandoned agricultural land can be used for ground-mounted PV panels [15,16]. Due to a decline in specific installed PV system costs [2], solar power plants are expected to play a significant role in power supply systems [17]. As to farmland, about 30% of its area is

suitable for PV [18–20]. There are a lot of studies concerning the utilization of land for solar energy [13,21–23].

Global electricity scenarios predict that the share of solar energy will be in the range of 20–60% and up to 90% in specific regions [24,25]. van de Ven et al. [26] studied the potential solar land requirements and carbon dioxide emissions. They found that solar power plants may occupy up to 5% of total land. The carbon dioxide emission payback period of solar energy is lower as compared to bioenergy [26,27].

Energy Return on Energy Investment (EROEI) is an important indicator for energy resources [28]. For sustainable development of human society, any kind of energy must surpass the "break-even point" (EROEI = 1) [29]. Moreover, the value of EROEI should minimize risks. The minimum values of EROEI were suggested in the range from 10 [29–31] to 20 [32]. Capellán-Pérez et al. [30] suggested a classification for EROEI. EROEI for solar PV ranges from 8.7 to 34.2 [33]. It is higher as compared to biofuels (EROEI = 0.69–11.26) [34]. According to the risk classification, solar PV is in the "no-risk" category.

A decrease in the cost of PV makes solar electricity competitive [35]. In the countryside, marginal land is especially promising for solar electricity generation [36,37]. The use of arable land for ground-mounted PV has been tested for agriculture [38]. A trade-off between food and green energy production was analyzed by Sacchelli et al. [39]. The environmental impact of photovoltaic infrastructure was studied by Maye [40]. Life cycle assessment was applied by Turconi et al. [41], Dubey et al. [42], and Hastik et al. [43]. Some studies [44,45] considered site characteristics and suitable degrees for photovoltaic energy generation on farmland. Calvert and Mabee [45] used market parameters to find a trade-off between solar electricity and energy crop production in Ontario, Canada. Dupraz et al. [46] optimized PV and crop cultivation in the same area to maximize energy efficiency. However, the impacts driven by PV plants were explored insufficiently. According to numerous scientific works, there is a conflict between farm photovoltaics and crop production. Nevertheless, the analysis revealed that it is necessary to carry out an integrated economic and environmental assessment for solar power generation and crop production in a semi-arid climate zone.

This study hypothesizes that PV is more profitable and environmentally friendly compared to crop production in a semi-arid climate zone. The purpose of this study is an integral economic and environmental (carbon dioxide emissions) assessment of a PV power plant in farmland and a comparison of the results obtained with crop production. Specific of our work is the analysis that was carried out for semi-arid climate zone. Several objectives were put forward to achieve this purpose:

- The clarifying of weather conditions in the area of field experiments;
- The determining of gross income and profit of crop production;
- The analysis of the actual status of power generation, including renewables;
- The assessing of the net present value and the profitability index of PV plants;
- The calculation of the carbon dioxide footprint of crop production and solar power generation;
- The carrying out of the sensitivity analysis of a PV project.

Farmers and policymakers can use the results obtained for economic and environmental analyzes of solar power plants. This study is intended to compare crop production versus PV electricity generation.

2. Materials and Methods

This study is based on the State Statistics Service of Ukraine, reports, research papers, actual prices, personal communication with stakeholders, etc. A semi-arid zone in the South of Ukraine (Mykolaiv province) is the subject of research.

The current study comprises seven steps (Figure 1). In the first step, we analyzed climate and weather conditions. We paid attention to precipitation, air temperature, wind, and solar radiation. In the second step, the power generation and the status of photovoltaics in Ukraine were analyzed. The third step was devoted to an analysis of crop growing. We used such indicators as crop yield and a crop rotation factor. In the fourth step, gross

annual income from crop production was determined. Crop yields, crop rotation factors, and market prices were taken into account. In the fifth step, the profitability of a PV plant was estimated. We used the following indicators: net present value (NPV) and profitability index (PI). We factored in the feed-in tariff as the current support mechanism. In the sixth step, carbon dioxide emission savings were estimated. Finally, the sensitivity analysis of a PV plant was carried out.
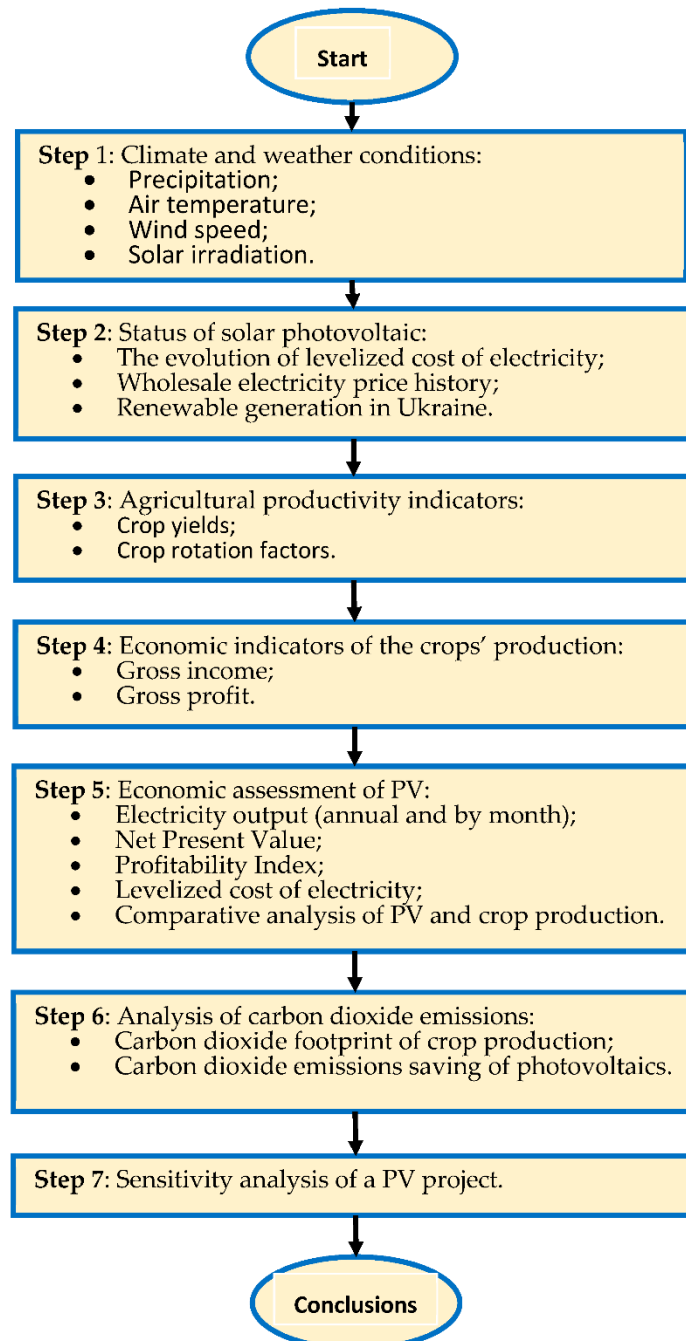
Figure 1. Steps of the research methodology.

2.1. System Boundary

Crop production comprises many technological processes such as soil preparation, sowing, fertilization, crop protection, etc. These processes require technological materials and energy (diesel fuel, electricity, petrol, etc.). Direct and indirect carbon dioxide emissions were taken into account in this study (Figure 2). The boundary system for photovoltaics

comprises two subsystems: the environmental system and the PV system (Figure 3). The PV system includes three main phases: manufacturing and construction, operation and maintenance, and dismantling. The environmental system was used to find carbon dioxide emissions savings.
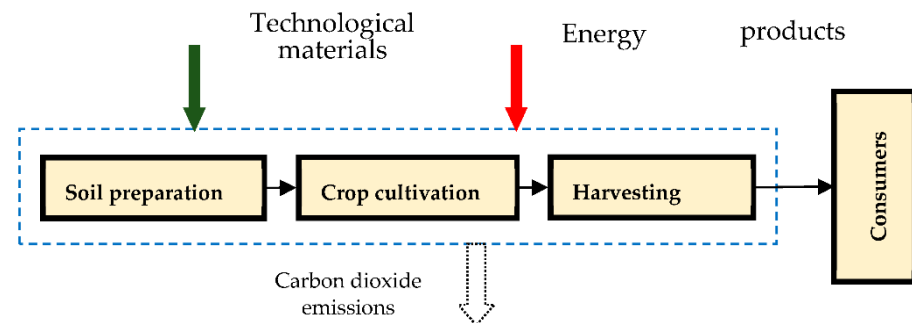

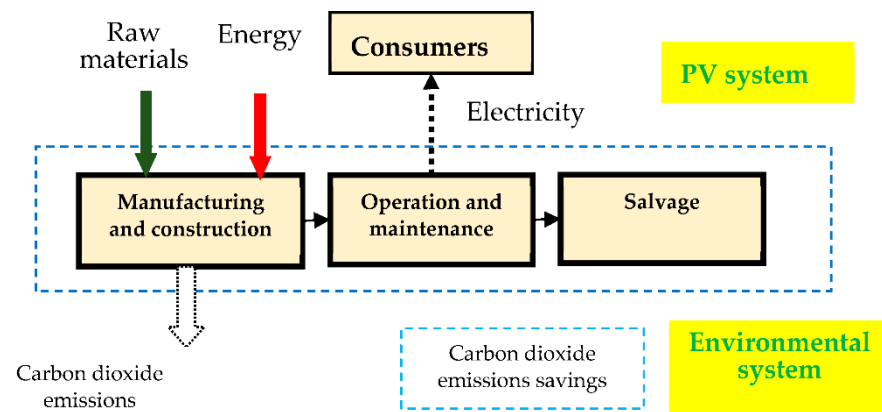**Figure 2.** The system boundaries for crop production.

Figure 3. The system boundaries for photovoltaics.

2.2. Economic Indicators

The investment costs in a PV power plant include several components such as PV modules, inverters, cabling, transformers, mounting, and power management devices. In our case, since farmers use their own land, land availability is not a problem. Thus, land costs are discarded. The lifetime of PV modules is expected to be 25 years. Inverters have a lifetime of 10–15 years. Their anticipated time of replacement is 15 years [47].

Savage value is the worth of a PV plant after the completion of its operation. It depends on each PV panel weight, used panel price, and the number of panels [47].

$$SV = \frac{NP \cdot WTP \cdot Ppr}{1000 \cdot (1 + 0.01 \cdot d)^{-LT}}, \tag{1}$$

where NP is the number of PV panels; WTP is the weight of PV panel, kg; Ppr is the used panel price, EUR/t; d is the discount rate, %; LT is the lifetime of the project, year.

The net present value is determined by the following equation [48]:

$$NPV = \sum_{i=0}^{LT} \left(\frac{B_i - OC_i}{[1 + 0.01 \cdot d]^{-i}} \right) - Io - \frac{Ia}{[1 + 0.01 \cdot d]^{-LTR}} + SV, \text{ EUR}, \tag{2}$$

where B_i is the benefit in the ith year, EUR; OC_i is the operating costs in the ith year, EUR; kg; Io is the initial investment costs, EUR; Ia is the replacement costs, EUR; LTR is the lifetime of replacement equipment (inverters), year.

The profitability index is equal to [49]

$$PI = \frac{\sum\limits_{i=0}^{LT}\left(\frac{B_i-OC_i}{[1+0.01\cdot d]^{-i}}\right)}{Io + \frac{Ia}{[1+0.01\cdot d]^{-LTR}} - SV}.$$

(3)

The payback period is found from the condition that *NPV* = 0

$$NPV = 0 = \begin{cases} \sum\limits_{i=0}^{PBP}\left(\frac{B_i-OC_i}{[1+0.01\cdot d]^{-i}}\right) - Io & if\ PBP\ <\ LTR \\ \sum\limits_{i=0}^{PBP}\left(\frac{B_i-OC_i}{[1+0.01\cdot d]^{-i}}\right) - Io - \frac{Ia}{[1+0.01\cdot d]^{-LTR}} & if\ PBP\ >\ LTR \end{cases},$$

(4)

where *PBP* is the payback period, year.

2.3. Levelized Cost of Electricity

In this study, we determined the levelized cost of electricity (LCOE). LCOE is a function of several variables such as investment costs, a discount rate, amount of electricity generated, lifetime, etc. [50]:

$$LCOE = \frac{Io + \sum\limits_{i=1}^{LT}\frac{AC_i}{(1+0.01\cdot d)^i}}{\sum\limits_{i=1}^{LT}\frac{W_i}{(1+0.01\cdot d)^i}}, \ EUR/kWh,$$

(5)

where W_i is the electricity generated by a PV plant in the *i*th year, kWh; AC_i is the costs in the *i*th year, EUR.

The solar cell efficiency is a function of ambient temperature, the reference temperature, and the cell efficiency at the reference temperature [51]

$$\eta = \eta_0 \cdot [1 - \beta \cdot (Ta - Tr)],$$

(6)

where η_0 is the cell efficiency at the reference temperature; β is the solar radiation coefficient; *Ta* is the ambient temperature, K; *Tr* is the reference temperature, K.

Annual electricity generation is [52,53]

$$W_i = 0.001 \cdot \sum\limits_{l=1}^{365}(SR_l \cdot \eta \cdot APV \cdot 24), \ kWh,$$

(7)

where SR_l is the solar irradiation hitting the PV system on the lth day, W/m^2; *ARV* is the area of the PV system, m^2.

2.4. Carbon Dioxide Emissions

The substitution of fossil fuels used by conventional power plants results in carbon dioxide savings. They can be calculated by the formula [54,55]:

$$CDES = W \cdot EFe, \ kg\ CO_2/ha,$$

(8)

where *W* is the electricity generated by a PV plant, kWh; *EFe* is the emission factor of conventional power generation, kg CO_2/kWh.

2.5. Sensitivity Analysis

The purpose of sensitivity analysis is to investigate the impact of changes in key variables on the viability of a project. The Profitability Index (*PI*) is assumed as a financial criterion. The sensitivity analysis procedure comprises the following steps [47,56,57]:

- The identification of key variables;
- The determination of their switching values;
- The identification of crucial variables.

The switching value of any variable turns the *PI* to 1.2 (a minimum acceptable value for business) or the *NPV* to 0. Switching values can be shown in natural form and percentage change. The switching value (the percentage change) for the ith variable is calculated by the formula [57]

$$SV_i = 100 \cdot \frac{V_i^* - V_i^0}{V_i^0}, \ \%, \tag{9}$$

where V_i^0 is the value of *i*th variable in the base case; V_i^* is the value of *i*th variable in the case if *NPV* = 0 or *PI* = 1.2.

2.6. Solar Field

We assessed the profitability of crop production and solar power generation. We used data from a PV plant that is mounted nearby the town of Novii Buh, Mykolaiv province (47°41′18″ N, 32°34′33″ E). The examined solar field occupies 2 hectares. The landowner is an agricultural limited liability company. This company owns 2000 hectares of arable land. The solar field is shown in Figure 4.


Figure 4. The solar PV power field (Mykolaiv province).

Reduction of carbon dioxide emissions and diversification of business activity are the primary motives for PV. Since green electricity substitutes fossil fuels, carbon dioxide savings were found. Farmers look for the opportunity for diversification of their business activity. Global warming, an increase in air temperature, and droughts force them to look for alternatives. Solar energy may be an alternative to crop production. Economic indicators for solar power generation and their comparison with crop cultivation were carried out.
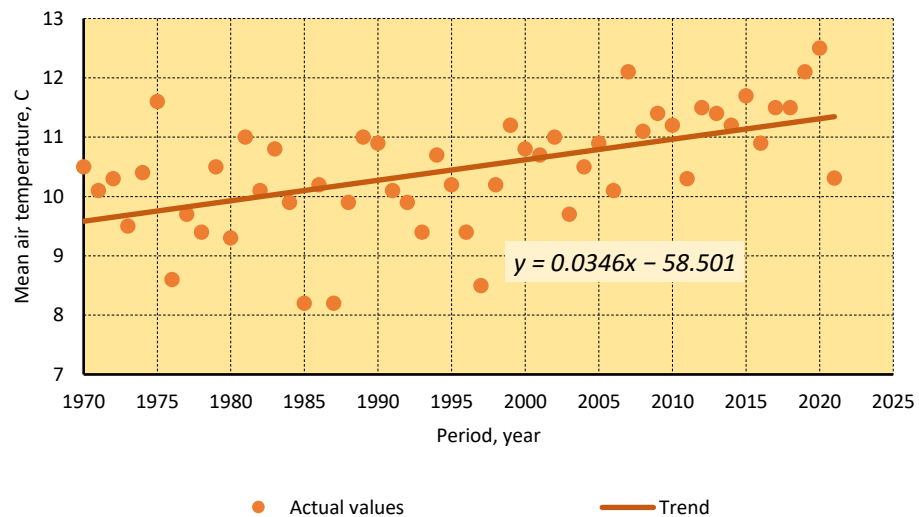
3. Results

3.1. Climate and Weather Conditions

Experiments were performed in the Mykolaiv province. The weather conditions were as follows. Despite the significant fluctuation (from 240 to 750 mm), there was a drop in annual precipitation (Figure 5) [58]. Since 1970, it has decreased from 450 mm to around 380 mm in 2020 (or 12%). The average atmospheric temperature has increased from 9.6 °C to 11.25 °C (Figure 6) [58]. It constitutes 17%. These facts must be taken into account for PV projects.
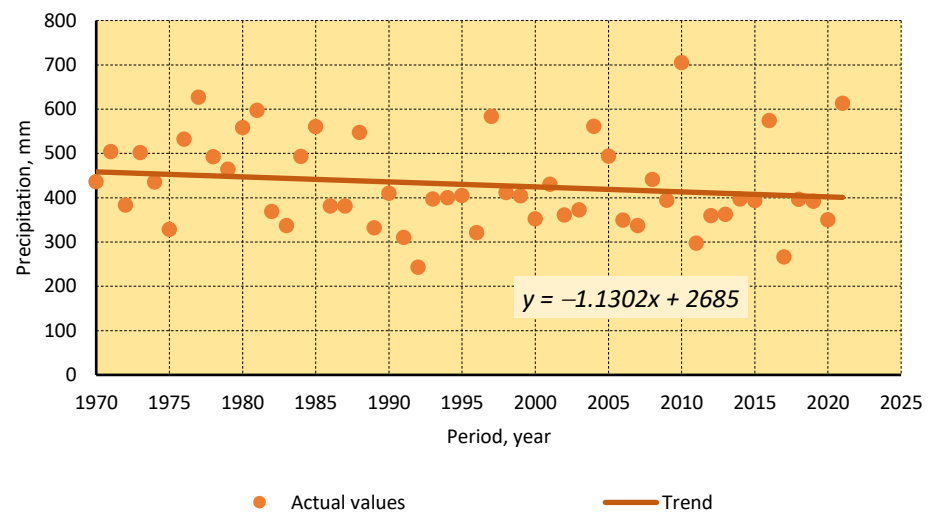
Figure 5. Precipitation for the Mykolaiv province (the South of Ukraine, 1970–2020).

Figure 6. Average annual air temperature in the Mykolaiv province.

In 2021, we observed air temperature, solar irradiation, and wind speed. The results are depicted in Figures 7–9. These parameters impact the power generated by PV. In summer, the average daily air temperature did not exceed 30 °C. In winter, it dropped down to −17 °C. As can be seen from Figure 5, there is a significant fluctuation in sun irradiation due to weather conditions. It lowers the amount of power generated by PV. Figure 6 represents wind speed. The graph demonstrates that the average wind speed is less than 4 m/s. Therefore, wind cannot impact PV efficiency.
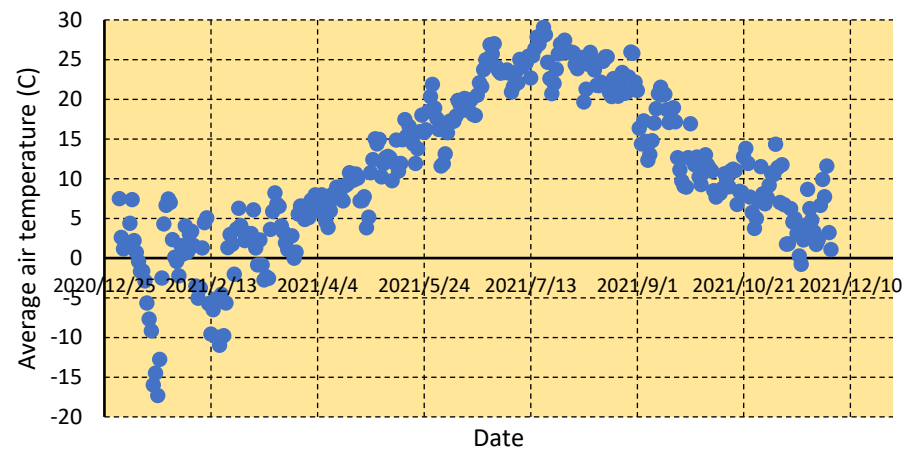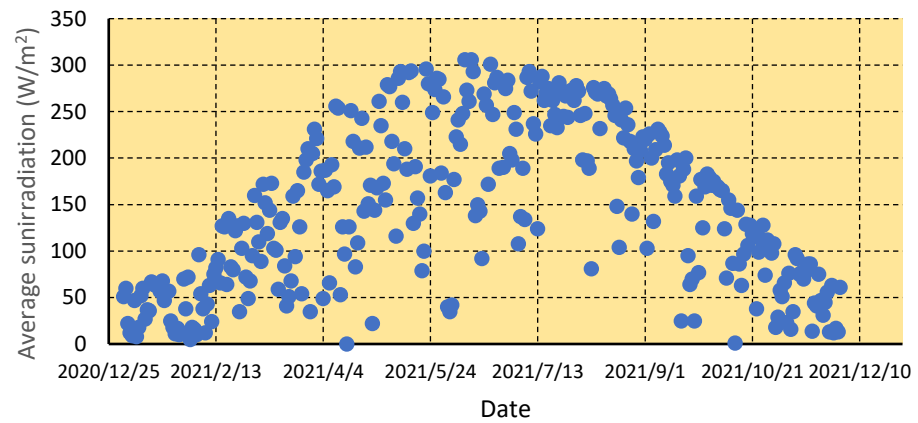
Figure 7. Air temperature during 2021.

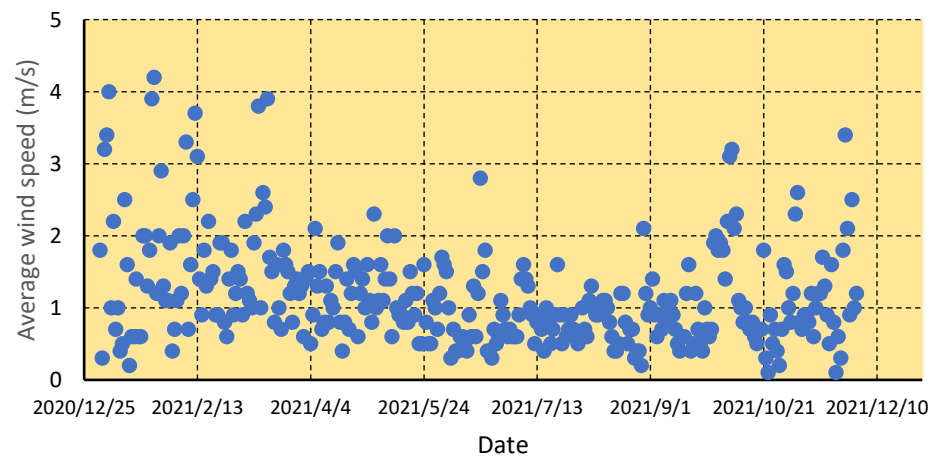**Figure 8.** Sun irradiation during 2021.

Figure 9. Average wind speed during 2021.

3.2. Status of Solar Photovoltaic

The global average levelized cost of electricity (LCOE) of PV power plants is decreasing. Since 2010, the average LCOE has decreased from USD 381/MWh to USD 57/MWh in 2020 (Figure 10) [59]. In the same period, the global average LCOE of biomass-based electricity declined from USD 76/MWh in 2010 to USD 66/MWh in 2019. In 2020, India and China had the lowest LCOE (from USD 57/MWh to USD 60/MWh). The most expensive solar electricity is in Europe (USD 87/MWh) and North America USD 97/MWh [59].
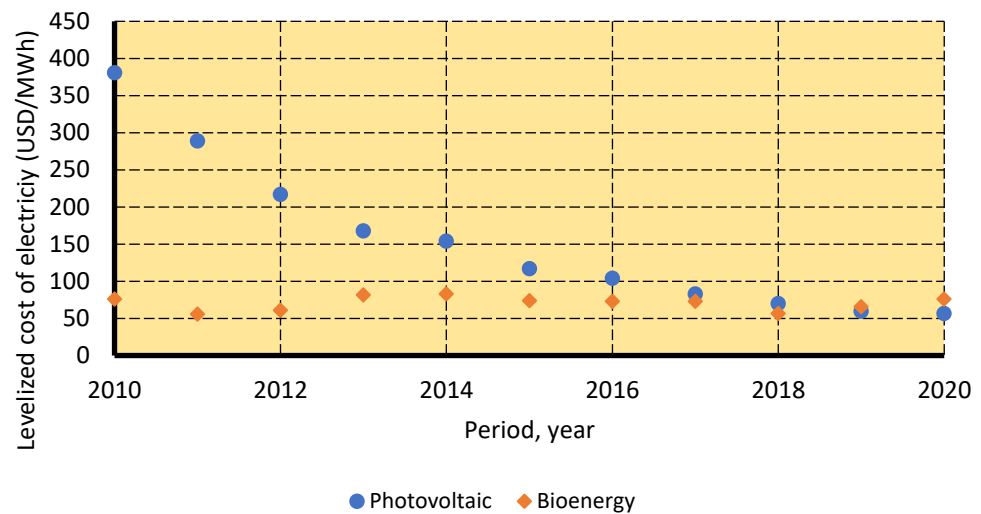
Figure 10. Levelized cost of electricity.

In Ukraine (March 2021), the price for households was USD 62/MWh, and the price for businesses was USD 90/MWh. These prices were lower than the average prices in the world (USD 135/MWh and USD 124/MWh, respectively) [60]. The average leverized cost of electricity generated by Ukrainian power plants was as follows, USD/MWh: thermal power plants—79.4; nuclear power plants—21.0; hydropower—26.5 [61,62]. The feed-in tariff for solar power plants is EUR 109.7/MWh (since 2020 for the industry) [63]. In the world, LCOEs for coal plants are in the range from USD 64.7/MWh (India) to USD 148.76/MWh (USA). For nuclear plants, LCOEs vary from USD 27.41/MWh (Russia) to USD 146.06 (Slovak Republic). Levelized costs of electricity for solar power plants ranged from USD 24.39/MWh (France, utility-scale) to USD 302.97/MWh (Italy, residential) [64].

Last year (2021), wholesale electricity prices increased. This was a result of numerous factors, such as a rise in fossil fuel prices (primarily natural gas) and a decrease in wind power generation. Electricity prices were the highest in Germany and Italy. Finland and Sweden had the lowest electricity prices (Figure 11) [65,66]. Since 2008, the average prices in the European Union have increased by around 30% [67]. High wholesale prices made favorable conditions for the development of PV.
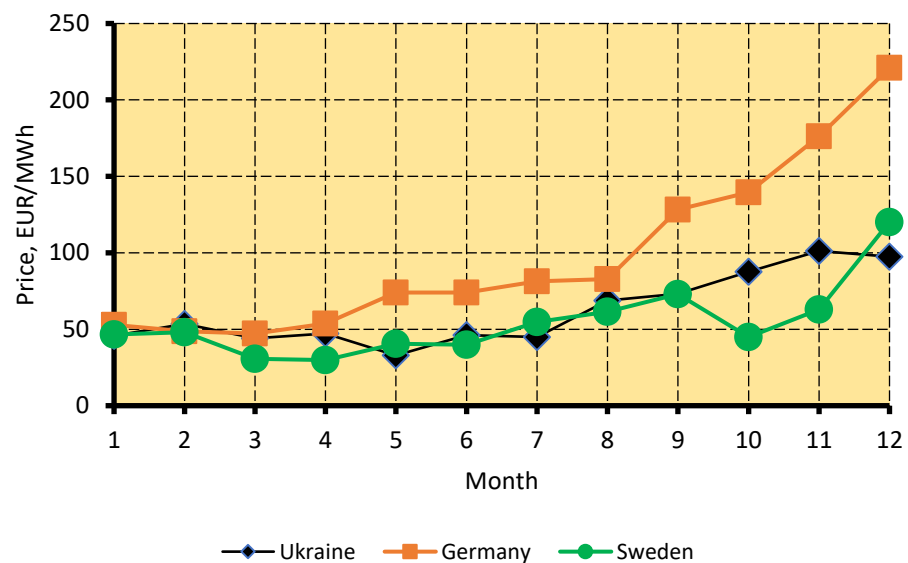
Figure 11. The evolution of wholesale electricity price in Ukraine and selected EU countries in 2021.

Primary energy consumptions are presented in Table 1. Ukraine consumes less renewables and hydroelectricity compared to the world. Global electricity generation by renewables exceeded 12% in 2020. In Europe, the share of renewables and hydroelectricity is around 42% [68]. Electricity generation in the world and Ukraine by fuels is shown in Table 2. The specific production of green electricity in Ukraine is 2.5 times less than the average in the world.

Table 1. Primary energy consumption.

Indicator	Unit	World	Ukraine
Total	Exajoules	556.63	3.31
Hydroelectricity	Exajoules	38.16	0.06
Renewables	Exajoules	31.71	0.09
Total hydroelectricity and renewables	Exajoules	69.87	0.15
Share of hydroelectricity and renewables	%	12.55	4.53

Table 2. Electricity generation.

Indicator	Unit	World	Ukraine
Total	TWh	26,823.2	149.0
Hydroelectricity	TWh	4296.8	6.3
Renewables	TWh	3147.0	9.7
Total hydroelectricity and renewables	TWh	7443.8	16.0
Share of hydroelectricity and renewables	%	27.8	10.7

In Ukraine, renewable electricity capacity is 24% of the total electricity capacity or 13,764 MW [69]. The largest part of them (53.26%) is solar energy (Figure 12). The share of PV generation was 29%. This is a result of a relatively low capacity factor. The average capacity factor of PV reached 16.1% in 2020 [59]. Hydroelectricity is ranked first (Figure 13).
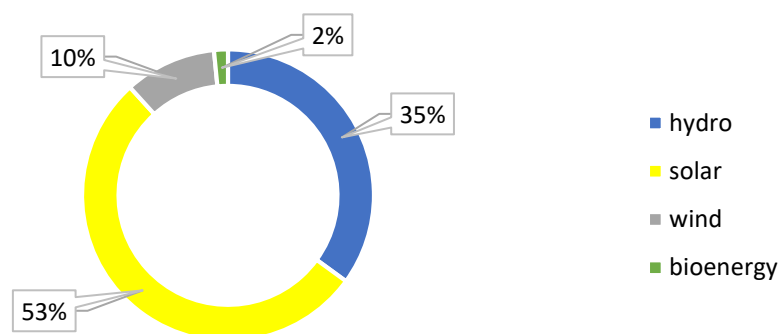
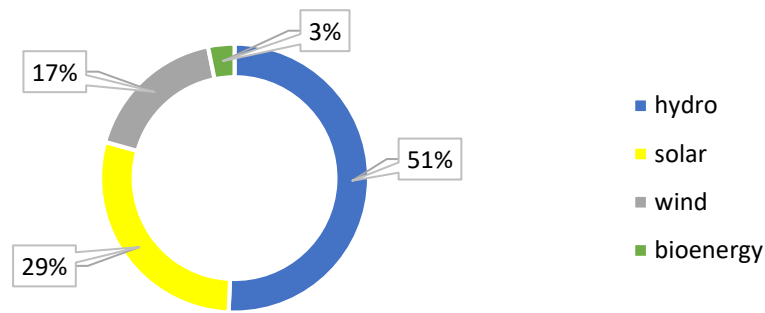
Figure 12. Shares of renewables.

Figure 13. Shares of renewable generation.

3.3. Efficiency of Crop Production

To evaluate the efficiency of crop production, we suggest introducing a new indicator—the crop rotation factor. This indicator is the ratio of each crop area to the total available farmland. The crop rotation factor for the *i*th crop is

$$CRF_i = \frac{ACA_i}{\sum\limits_{i=1}^{n} ACA_i},$$

(10)

where ACA_i is the area of ith crop, ha; n is the number of crops.

The crop rotation factors were calculated for the main crops in Mykolaiv province (Table 3). Corn has the highest yield (Figures 14 and 15), and sunflower has the lowest yield (Table 4). Despite the lowest yield, sunflower has the highest crop rotation factor. The primary reason for this fact is the highest profitability of sunflower seed growing. Our calculations are based on statistical data [70–72].

Table 3. Crop rotation factors.

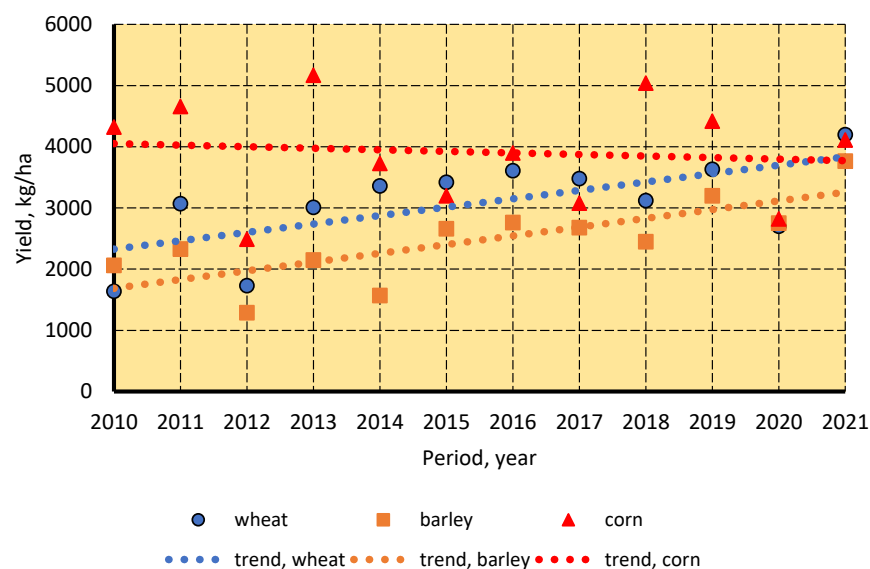| Crop	Minimum	Maximum	Average
Wheat	0.248	0.306	0.290
Barley	0.194	0.327	0.237
Corn	0.040	0.103	0.082
Sunflower	0.303	0.412	0.356
Rapeseed	0.007	0.060	0.035

Figure 14. Yield history of cereal crops.
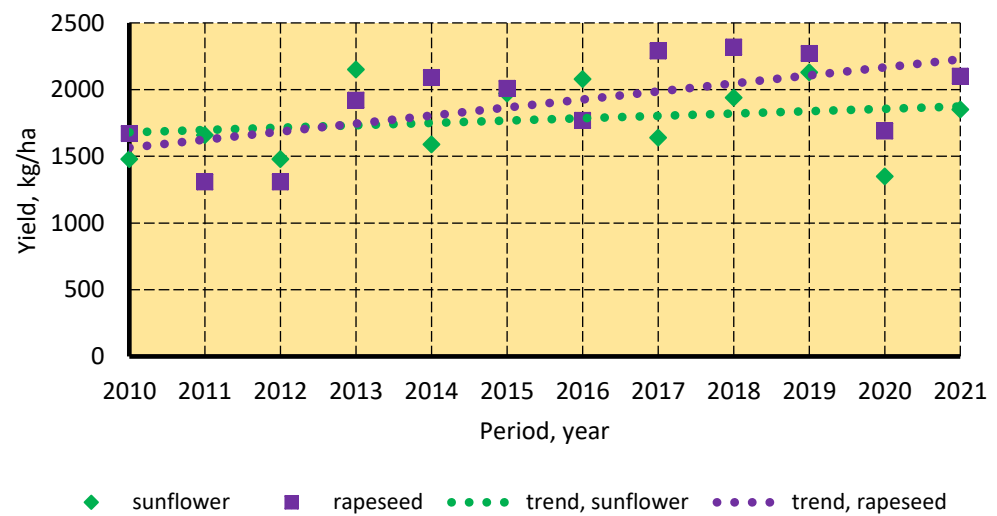
Figure 15. Yield history of oil crops.

Table 4. Crops yields, t/ha.

Crop	Minimum	Maximum	Average
Wheat	1.640	4.199	3.081
Barley	1.290	3.766	2.556
Corn	2.490	5.170	3.912
Sunflower	1.350	2.170	1.803
Rapeseed	1.310	2.576	1.936

3.4. Gross Income and Profit of Crop Production

In December 2021, crop prices were as follows, USD/t: wheat—from 251 to 330; barley—from 256 to 290; corn—from 225 to 294; sunflower—from 580 to 716; rapeseed—from 530 to 710 [73]. The average gross income from hectare is

$$GIC = \sum_{i=1}^{n}(CRF_i \cdot Y_i \cdot MP_i), \text{ USD/ha,} \qquad (11)$$

where Y_i is the yield of the ith crop, t/ha; MP_i is the market price of the ith crop, USD/t.

Crop production gives the following profit

$$GP = \sum_{i=1}^{n}(CRF_i \cdot Y_i \cdot (MP_i - PC_i)), \text{ USD/ha,} \qquad (12)$$

where PC_i is the production costs of the ith crop, USD/t.

We analyzed gross income and gross profit. Official State Statistical data, reports, and current prices are used to calculate the above [74–78]. The gross annual income from crop production ranges from EUR 506/ha to EUR 1389/ha (Figure 16). It mainly depends on weather conditions and market prices. Thus, droughty weather (annual rainfall was 350 mm) results in lower yields in 2020. As a consequence of this, there was a minimum income per unit area. Favorable weather and market prices resulted in the highest gross income in 2021 (Figure 17). There has been a significant fluctuation in gross income and profit. In a favorable year, the maximum gross profit exceeds the minimum one (in an unfavorable year) by around ten times.
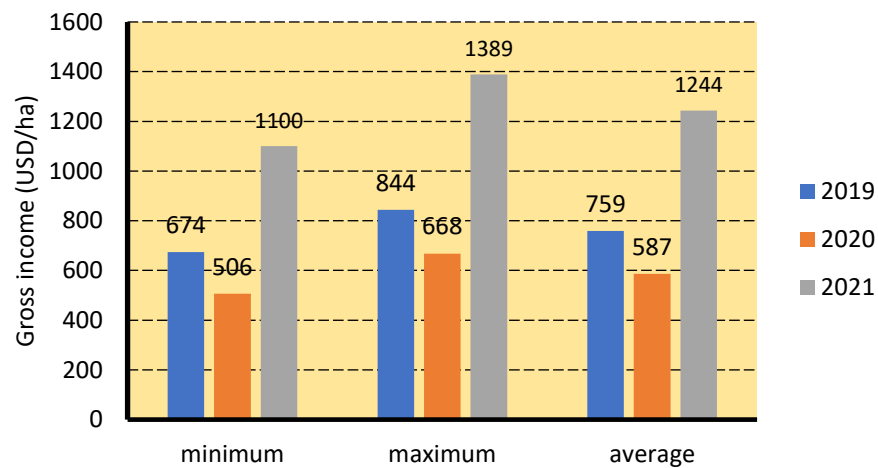
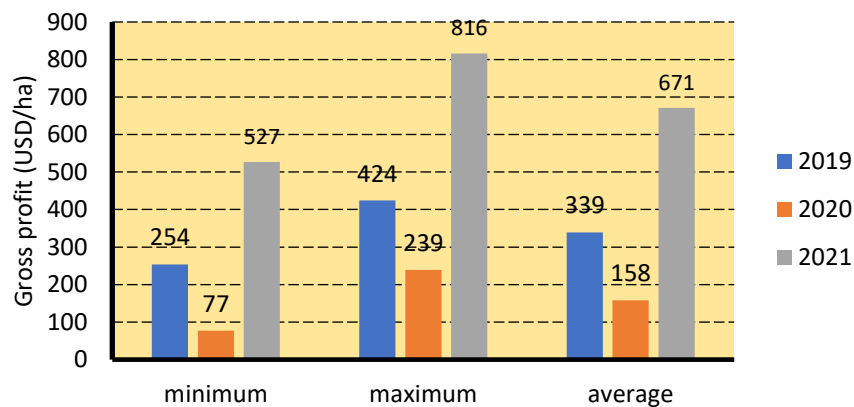**Figure 16.** Gross income from crop production.

Figure 17. Gross profit from crop production.

3.5. Power Generation

In Mykolaiv province, the solar field can reach a nominal capacity of 618 kWp/ha. Electricity generation is uneven during the year (Figure 18). The annual generation is around 769.8 MWh. In June 2021, due to cloudy weather, the PV plant generated less than in May 2021. The gross income from PV (82.37 thousand EUR/ha) exceeds one of crop production. Annual gross profit is around 63.8 thousand EUR/ha. However, the payback period exceeds 6 years (Figure 19). Its value has a strong dependence on the discount rate. If the discount rate is 10%, the payback period is more than 15 years. For all cases the profitability index is more than 1.2: discount rate = 0%—*PI* = 3.24; discount rate = 5%—*PI* = 1.91; discount rate = 10%—*PI* = 1.26 (Figure 20). It means that the PV projects are profitable.
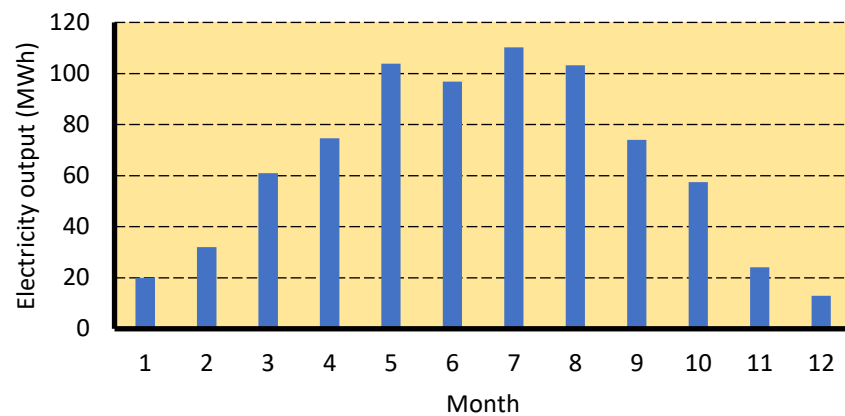
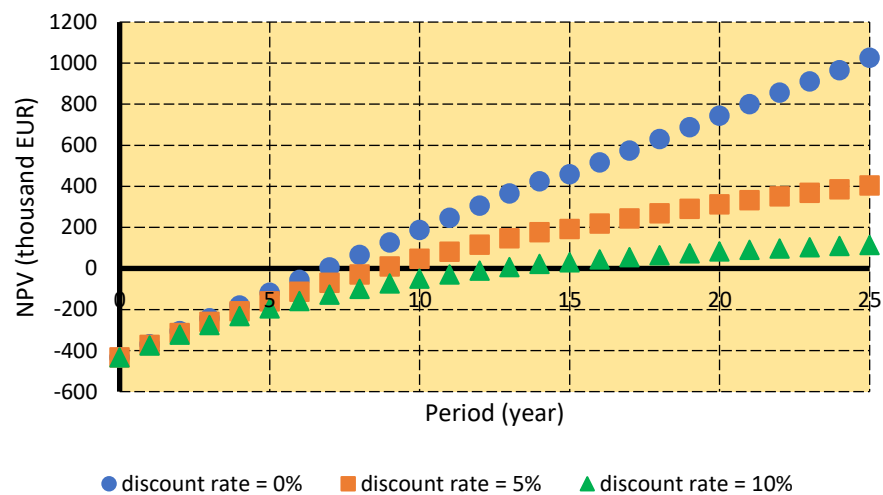**Figure 18.** Electricity output by month (2021).

Figure 19. Net present value.

Figure 20. Profitability index.

The evolution of PV LCOE was analyzed as a function of a discount rate. The discount rate varied between 0% and 10%. The results of the modeling are depicted in Figure 21. Our calculations show that LCOE may be described by a linear dependence on a discount rate. Calculated LCOEs correspond to other research studies. Rodríguez-Martinez and Rodríguez-Monroy [79] modeled photovoltaic systems in Spain. They found that their LCOE ranged from EUR 32/MWh to EUR 62/MWh. Rodriguez-Ossorio et al. [80] reported that LCOE varied from EUR 20/MWh to EUR 40/MWh depending on a discount rate and project lifetime. In 2020 in Europe, utility-scale PV LCOE ranged from EUR 30/MWh in Spain to EUR 50/MWh in Finland. Meanwhile, in Spain and Italy, wholesale electricity prices were lower than PV LCOE [81]. Industrial electricity prices exceeded the PV LCOE. Ukraine had the same situation.
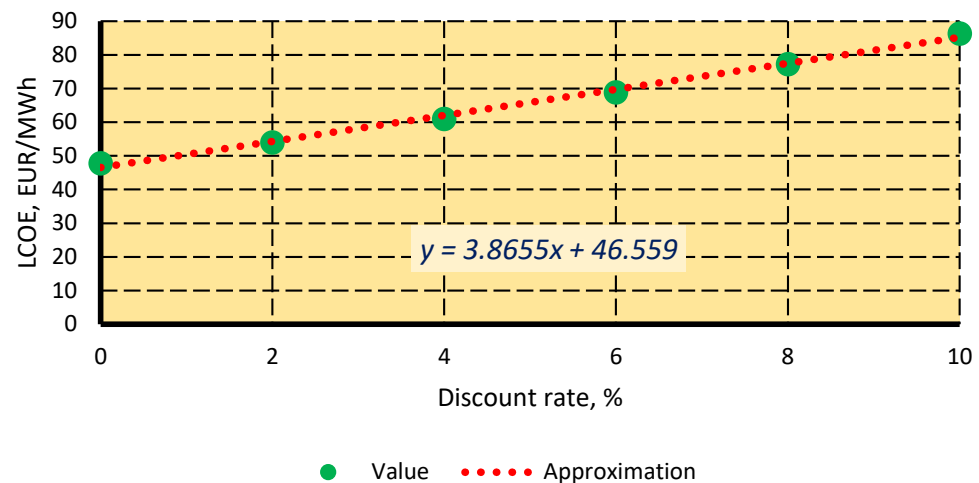
Figure 21. LCOE versus a discount rate.

To compare the profitability of PV and crop production, we suggest using an electricity profit to crop production ratio

$$RP = \frac{PVprof}{Cprof},$$ (13)

where *PVprof* is the profit from solar power generation, USD/ha; *Cprof* is the profit from crop production, USD/ha.

The profit from solar power generation is equal to

$$PVprof = W \cdot (FT - PCE), \text{ USD/ha,}$$ (14)

where *PCE* is the production costs of solar electricity, USD/kWh; *FT* is the market price of green electricity or feed-in tariff, USD/kWh; *W* is the solar electricity generated by a PV plant, kWh.

The profit from crop production is

$$Cprof = \sum_{i=1}^{n} (CRF_i \cdot Y_i \cdot (MP_i - PC_i)), \text{ USD/ha.}$$ (15)

After substituting Formulas (11) and (12) into Formula (10), we obtain the following expression

$$RP = \frac{W \cdot (FT - PCE)}{\sum\limits_{i=1}^{n} (CRF_i \cdot Y_i \cdot (MP_i - PC_i))}, \text{ USD/ha.}$$ (16)

If the above ratio is more than 1, then electricity generated by land-mounted PV is preferable compared to crop production. PV-to-crop production ratio is depicted in Figure 22. The ratio depends on a discount rate, weather, and market conditions. In any case, its value is not less than 23. Therefore, PV plants have higher profits compared to crop production.
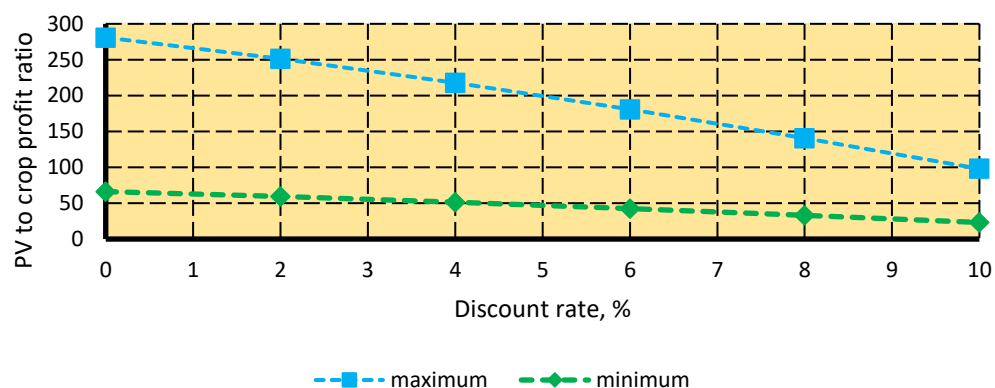
Figure 22. PV-to-crop production ratio versus a discount rate.

3.6. Carbon Dioxide Emission Saving

The average emission factor of the Ukrainian power generation system is equal to 0.97 $kgCO_2$/kWh [82]. The carbon dioxide emission factor for the Ukrainian coal-fired power plants varies from 0.967 $kgCO_2$/kWh (Zaporizka thermal power plant) to 1.628 $kgCO_2$/kWh (Myronivska thermal power plant). Its average value was 1.105 $kgCO_2$/kWh [83]. Ukrainian nuclear power plants use pressured water reactors. Their carbon dioxide emission factor is in the range of 0.013–0.220 $kgCO_2$/kWh. These values include all life cycle phases such as upstream, operational, and downstream processes [84]. Kadiyala et al. [85] studied the life cycle of carbon dioxide emissions from different hydropower plants. They found that large hydropower plants have a carbon dioxide emission factor in the range of 0.00219–0.237 $kgCO_2$/kWh. Based on the above and a World Nuclear Association report [86], we assume the following carbon dioxide factors, $kgCO_2$/kWh: coal-fired power plants—1.105; nuclear power plants—0.029; hydropower plants—0.026; combined heat and power plants—0.499; wind power plants—0.026.

In 2020, a generation mix was as follows: nuclear power plants—51%; thermal power plants—27%; combined heat and power plants—9%; hydropower plants—5%; renewables—8% [87]. In this case, the average carbon dioxide emission factor is 0.318 $kgCO_2$/kWh. The carbon dioxide intensity of electricity generated in the European Union (average) is 0.407 $kgCO_2$/kWh. Sweden and France have the lowest indicators of 0.025 and 0.092 $kgCO_2$/kWh. Estonia has the worst result (1.152 $kgCO_2$/kWh) [88].

Carbon dioxide emission for PV module production depends on its type. This value ranges from 170 $kgCO_2$/kWp (poly-crystalline) to 360 $kgCO_2$/kWp (mono-crystalline) [47, 89]. In any case, the carbon dioxide payback period does not exceed one year (Figure 23). Crop production requires the use of fossil fuels, electricity, fertilizers, chemicals, etc. It results in carbon dioxide emissions. Its value depends on crop cultivar, practice, climate, etc. For most common crops, carbon dioxide emissions range from 500 to 3200 $kgCO_2$/ha (Figure 24) [90–95]. The figures reveal that sunflower growing has the smallest carbon dioxide footprint, and corn growing has the highest carbon dioxide emissions. Therefore, PV plants were less carbon dioxide footprints.
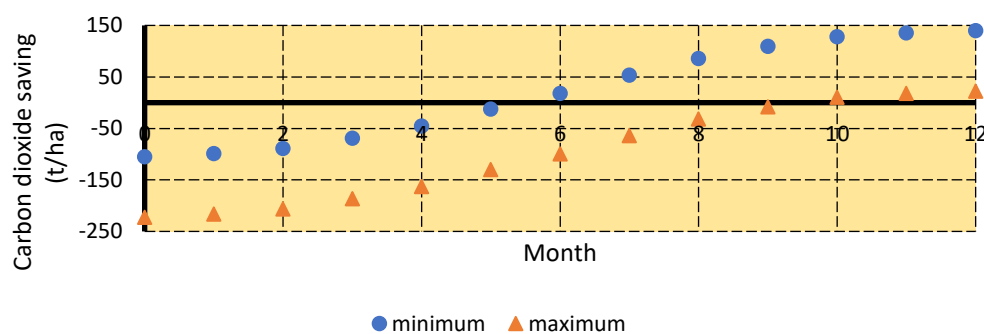
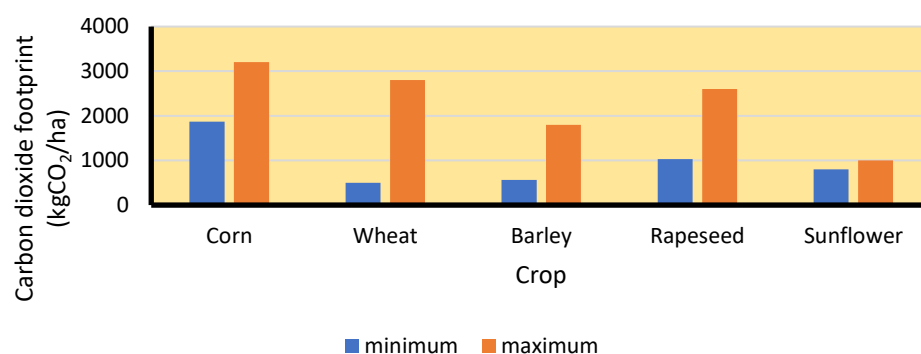**Figure 23.** Carbon dioxide emission savings.

Figure 24. Carbon dioxide footprints of crop cultivation.

3.7. Sensitivity Analysis

The sensitivity analysis examined the possible impact of different variables on the PI. Investment costs, lifetime, annual electricity generation, feed-in tariff, and operational expenses were selected for the sensitivity analysis. The switching value for each variable was calculated. The analysis was carried out for different discount rates (0, 5, and 10%). The base values of variables are summarized in Table 5.

Table 5. Sensitivity variables and their base value.

Parameter	Unit	Value
Investment costs	Thousand EUR	432.85
Lifetime	Year	25
Gross income	Thousand EUR	82.37
Annual electricity generation	MWh	794.87
Feed-in tariff	EUR/MWh	107.00
Operational expenses	Thousand EUR	18.50

The sensitivity evaluation is presented in Figures 25 and 26. Observation shows that if the discount rate is 0%, then the feed-in tariff has the greatest impact on the PI. Operational expenses have the lowest impact. An increase in the discount rate changes the situation drastically. Operational expenses remain the least sensitive variable. The feed-in tariff also has a significant influence on the PI.
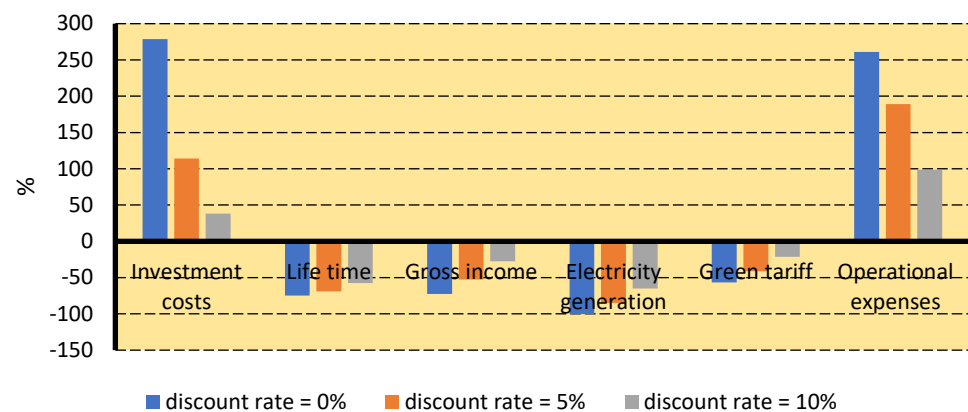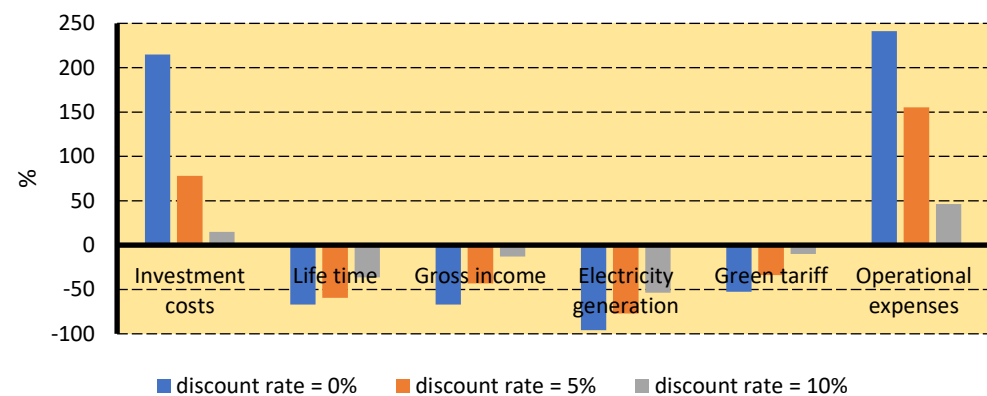
Figure 25. Sensitivity analysis (NPV).

Figure 26. Sensitivity analysis (PI).

4. Conclusions

There is a trade-off question regarding land allocation between crop cultivation and renewable power generation. Farmers and authorities need to have awareness and tools for decision making. This paper presents an analysis concerning the operating of a PV plant in farmland. This analysis proved that solar power generation reduces the risk to agricultural businesses. The results obtained can be applied to further projects in semi-arid zones. The integrated assessment of economic and carbon dioxide emissions saving for ground-mounted farm PV plants is the novelty of this study.

Climate change results in a rise in air temperature and a decrease in precipitation. Weather conditions make it difficult to get high yields and, therefore, reduce the profitability of an agricultural business. In a recent decade (in Ukraine), there has been a rise in all crop yields, with the exception of corn. In 2021 favorable market prices and weather conditions ensured a high average gross income of USD1244/ha. In less favorable 2020, farmers could get only USD587/ha. Therefore, there is a significant fluctuation in profitability. Similar results were found by Farja and Maciejczak [96].

Solar power generation may be an alternative for farmers. Currently, in Ukraine, a share of renewables and hydroelectricity is 10.7% of the total power generation. Solar power covers 29% of all renewables. Due to advanced technologies, there is a drop in the levelized costs of solar electricity. This fact and the growth of market electricity prices motivate a larger share of renewable power generation, including PV.

In Mykolaiv province, a solar field can have a capacity of 618 kWp and an annual generation of 794.87 MWh. Having sold green electricity (by feed-in tariff), stakeholders can get up to 82.37 thousand EUR/ha. It exceeds revenue from crop cultivation. The profitability index ranges from 1.26 (if a discount rate is 10%) to 3.25 (if a discount rate is 0%). The payback period varies from 6 to 12 years. It depends on the discount rate.

Carbon dioxide footprints of crop production range from 500 to 3200 kgCO$_2$/ha. Corn cultivation has the most emissions. Unlike crop production, PV power plants do not emit greenhouse gases during their operation. However, there are emissions during the manufacturing process. These emissions are in the range of 100–230 tCO$_2$ per hectare of a solar field. Despite the significant value, the carbon dioxide payback period varies from 5 to 10 months. Therefore, life cycle emissions of solar energy are less compared to crop cultivation. The PV systems have proven to be an environmentally friendly energy source. Thus, the results of this study have proved the advanced hypothesis: photovoltaics provides less carbon dioxide emissions and higher profitability than widespread farm practices.

Switching values were calculated for the NPV and PI. The sensitivity analysis indicated that the most significant input variable was a feed-in tariff or electricity price. Operational expenses are the least crucial.

Further research could examine the performance evaluation of hybrid renewable energy sources. Due to Ukrainian farmers' production being more than 80 million tons of crop residues, we plan to focus on biomass-based combined heat and power plants.

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