INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Int. Agrophys., 2025, 39, 175-189
doi: 10.31545/intagr/200377

Development of photovoltaic power plants in the context of their impact on the agricultural production space

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Received August 26, 2024; accepted January 22, 2025

Abstract. The purpose of this study is to assess the impact of utility-scale photovoltaic power plants on the agricultural production space in Poland. The research, based on constructed power plants under exploitation, provides important information on the scope of knowledge concerning the impact of these power plants on the environment in the context of reducing available agricultural land and arable soil. The results of this study reveal that the cumulative impact of solar energy development on the subject of the study is low, despite the fact that on a local scale, land transformation for photovoltaic power plants seems to highly affect land use. Overall, the results indicate that the mean land use intensity of photovoltaic power plants is 1.24 ha per every 1 MW of installed capacity, what translates into the wheat yield loss reaching 5.96 Mg per 1 MW annually. Significantly, the results show that even large amounts of installed capacity from photovoltaic power plants do not significantly impact agricultural production space. Research also emphasises the necessity of best quality arable soil preservation and calls into question, whether the development of agrophotovoltaic and floating solar power plants is reasonable in Poland, considering accessible land.

Keywords: land use change, power density, land use intensity, photovoltaic power plants, arable soil loss

1. INTRODUCTION

Agriculture is a crucial and fundamental part of human history. Farming led primeval societies to abandon their previous style of living – characterised by gathering, hunting, and collecting activities. As a result, the vast majority of humans have shifted from the gather-hunting to sedentary lifestyle (Barker, 2006). This process is called the Neolithic (or Agricultural) Revolution and expresses the appearance of agriculture in different geographical regions. Due to easier access to food (resulting from the plant production in the vicinity of first villages and domestication of animals), the human population and its density could increase. The Agricultural Revolution has also caused cultural consequences, which were fundamental for civilisation development – enabling the development of technology and even written languages (Scanes, 2018). Furthermore, during a large part of the history of mankind, most of the population was farmers. This was changed until after the II World War, in the modern history (Tauger, 2010).

Currently, despite the negative impact of farming on the environment on a global scale (Ramankutty *et al.*, 2018), agriculture is the foundation that provides food security and meets the demand for food. Due to this, agriculture is still a crucial sector within modern society (Fusco, 2021), being a subject of policies of governments around the world. For instance, while the United State's policy focuses, among others, on technological development, the European countries' policy emphasize the importance of sustainable practices, and also resilience (Guindo and Hak, 2024).

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Taking into consideration the momentous role that farming still plays in the modern world, it is understandable that governments introduce appropriate legal frameworks that protect agricultural production space, possibilities of its development and regulate land market in general (Vranken *et al.*, 2021). As an example, Polish regulations favour individual farmers when it comes to purchasing agricultural property and form the legal basis providing strengthening the agricultural farm area structure (Suchoń, 2017).

Farm activity, together with its ancillary infrastructure, has created a specific agricultural landscape, the components of which are especially arable land, rural buildings, and shelterbelts. This type of landscape was formed by both natural and human factors (Andersen, 2017). Nevertheless, the agricultural landscape is still evolving, which is related to the development of civilisation. Importantly, the transformation of the landscape is associated with changes in land use. Rural areas are subjected to a process of urbanisation, launching new activities (like mining exploitation) or introducing unique types of development, including warehouses, industrial and production buildings.

The above-mentioned changes in land use impact on agricultural production space by reducing it. One more industrial type of infrastructure, which is capable of having an impact on the problem under discussion, are utility-scale photovoltaic power plants. Installations of this type of renewable energy sources require the development of large areas. Contrary to the current share of photovoltaic power plants in energy systems, it may be necessary to allocate substantial amounts of land for the future development of these facilities (Van De Ven *et al.*, 2021).

According to current research in this field, the land demands for photovoltaic power plants vary depending on the irradiation, the type of modules used in the power plants, and even the surface of the land.

Research conducted on the basis of installations constructed in the Southwestern United States highlights that power plants, for which fixed-tilt photovoltaic construction was used, require 5.7-13.5 m^2 MW h^{-1} of direct land use per year, and from 5.7 up to 7.6 m^2 MW h^{-1} of direct land use per year, if one-axis construction is used. Their demand for total land use equals 9.4 and 10.6 m^2 MW h^{-1}, respectively (Bukhary *et al.*, 2018).

The research based on 92% of utility scale photovoltaic power plants in the United States (for which purposes the authors assumed that this type of installations are those with installed capacity larger than 5 MW of alternating current) shows that the power density factor reaches 0.28 and 0.18 MW $acre^{-1}$ for tixed-tilt plants versus tracking plants, respectively (Bolinger and Bolinger, 2022).

Also, one more study conducted in the United States shows the differences between land demand depending on the type of photovoltaic construction used and, furthermore, depending on the size of the photovoltaic power plants (in terms of installed capacity). Interestingly, the results of that study points out that total land requirements for installations under discussion are lower for large photovoltaic power plants (with installed capacity larger than 20 MW) than for small one (with installed capacity between 1 and 20 MW) in terms of factor expressing ratio between land occupancy and electricity generation, which equals 3.4 and 4.1 acres GW h^{-1} $year^{-1}$, respectively. Nonetheless, the same study shows that, in general, in terms of direct land use, large power plants need 1.3 acres more area per 1 MW of installed capacity, than their small equivalent (Ong *et al.*, 2013).

When it comes to studies based on the conditions in the United States, it is worth highlighting that the power density of renewables, compared to fossil fuel and nuclear power plants, is much lower (Van Zalk and Behrens, 2018). In result, renewables, including photovoltaic power plants, need much more land than conventional and nuclear power plants to produce the same amount of electricity, what affect on higher land footprint (Miller and Keith, 2019).

A recent study from the Czech Republic showed that photovoltaic power plants occupy circa 100 times more land compared to nuclear power plants, and it is necessary to allocate about 6.1 m^2 of land for 1 kWp of photovoltaic modules, not taking into account the rest of the infrastructure of a power plant – if so, we should multiply the indicated value at least twice (Martinec, 2022).

The study carried out by Japan researchers highlights that if photovoltaic power plants were installed in the available area of 3 428 km^2 (which represents 0.9% Japanese land), their installed capacity would reach the level of 230 GW, which translates to annual electricity generation to 250.4 TWh, equivalent to 28% electricity demand (Obane *et al.*, 2020).

In China, 10% of the land, which area is capable of producing 131.942 PWh of electricity (23 times more than electricity power demand in 2015), can be considered suitable for the development of photovoltaic power plants. However, what is interesting is that areas of the highest photovoltaic potential are characterised by low population and low electricity demand (Qiu *et al.*, 2022).

One study was conducted on example of a 102 MW photovoltaic power plant located in Australia (Central West New South Wales), covering an area of 250 ha. The development of the project has caused a loss of about 0.02% of the agricultural area within the boundaries of the local government, which consequently is equivalent to a reduction in the annual wheat yield reaching 1 500 Mg (Guerin, 2019). From that study, it is revealed that in the case investigated by the author, the factor expressing installed capacity-land requirements, equals 0.408 MW ha^{-1}. It also means that for installing 1 MW of photovoltaic power plant, it is necessary to exclude 2.451 ha of land from agricultural production.

Interesting research was carried out by Italian scientists. They highlight the strong correlation between soil consumption and electricity consumption. Furthermore, the assessment of the achievement of the renewable energy share in energy consumption target set for 2030 only by using photovoltaic systems indicates that in most country's provinces, the use of 10% of the so far consumed soil can be adequate to meet that target (Mancini and Nastasi, 2020).

The Greek study investigates the installed capacity requirements of photovoltaic systems which can satisfy the electricity demand in Crete. Interestingly, to avoid land use conflicts between traditional ground-mounted photovoltaics and current land use (providing, among others, food production), the author indicates, according to the results of study, that approximately 18.5% of annual Crete energy demand can be achieved by placing photovoltaic installations on the roofs of 20% of residential buildings. This research also indicates the high potential of agrophotovoltaics in the island under consideration, which can provide the dual use of arable soils for food and energy production. Furthermore, the study shows that if only photovoltaics were used for electricity generation, the area covering 0.56% of Crete would be sufficient to meet an annual electricity demand (Vourdoubas, 2024).

Recent Portugal study demonstrate that land use intensity of utility-scale photovoltaic power plants in continental part of the country reaches the average value of 3.336 ha MW_{DC}^{-1}. This research also estimates that in 2050 land requirement for photovoltaics will reach 0.3% of the Portugal area (its continental part). This demand is comparable to the equivalent of 1.3% of agriculture (Tavora *et al.*, 2020).

In Vietnam, land demand for photovoltaic power plants varies for different types of technology. Direct land use ranges from 3.69 to 6.67 m^2 MW h^{-1} $year^{-}$ and total land use (understanding as a fenced area of the power plant) ranges from 7.18 to 8.26 m^2 MW h^{-1} (Sanseverino *et al.*, 2021).

Considering the limited amount of land and the fundamental role of agriculture for society, this study aims to investigate the land demands for utility-scale photovoltaics in Poland and, essentially, assess the impact of development of this type of installations on the agricultural production space.

2. MATERIALS AND METHODS

In order to describe the land use in Poland, I have used the data from Eurostat and the data collecting by the Polish Statistical Office. Additionally, the Summary of Cadastral Parcels and Buildings from 2023 (access through geoportal) was helpful in this field. I used that document to analyse the share of individual classes of arable soils in the structure of national arable soils register area. For purposes of characterising agricultural land in Poland, I have defined them in line with binding legislation. Furthermore, to characterise the distribution of arable soils in Poland on voivodeship level, I had used the summary mentioned above and conducted a spatial analysis using the QGIS programme (version 3.22.9).

To indicate agricultural production from the crops in Poland, the data from the Polish Statistical Office was employed (Statistics Poland – Local Data Bank). Applying that data, I had averaged the wheat yields of 1 ha (10 000 m^2) from the period 2013-2023. That factor was later implemented to evaluate the impact of the development of utility-scale photovoltaic power plants on future crop production as a representative equivalent of potential yields in Poland. We can express a mean yield of wheat from 1 ha from recent years as:

$$Y_n = \frac{1}{n}\sum_{i=1}^{n} y_i\,, \tag{1}$$

where: Y_n is the mean yield of wheat in n years (Mg ha^{-1}) and y_i is wheat's yield in i year. To calculate the mean yield, the period 2013-2023 was taken into consideration.

To estimate the area necessary for the development of utility-scale photovoltaic power plants in Poland, I have used data made available by the Energy Regulatory Office (RES installations – status of December 2023). Using this data, I have found the location of the installations. On this basis, it was possible to assess the area required for the power plants discussed.

To assess the impact of these installations on space use in light of reducing agricultural production space, I have used three factors. First of them is land use intensity factor (I), which can be expressed as the Eq. (2) shows:

$$I = \frac{A}{C}\,, \tag{2}$$

where: A is the area required for power plant and C is the installed power of power plant. As the unit expressed in ha MW^{-1} is most vivid, I have applied it.

Above-described factor expresses the area required for 1 MW of power plant. To calculate amount of capacity that can be installed in a unit area (expressed in hectare) we can use a reciprocal of land use intensity factor, what the Eq. (3) shows:

$$L = \frac{1}{I}\,, \tag{3}$$

where: L is land-capacity factor describing the amount of installed capacity per 1 ha of the land.

The last gauge is a power density factor (P) proposed for the purposes of this work. This factor may be helpful to assess the impact of power plant on land use in the context of estimated energy production. We can express it as:

$$P = \frac{A}{C\,F}\,, \tag{4}$$

where: F is an estimating power output from 1 MW of installed capacity of power plant. To apply the estimated power output, I have used the data of the photovoltaic power potential in Poland from Global Solar Atlas (Global Photovoltaic Potential by Country, Global Solar Atlas). I have used GIS data of the long-term yearly average of potential photovoltaic production and applied appropriate values of electricity production to the localisation, where the individual power plants are located.

In addition, I have assessed the affect of photovoltaic power plants on potential yields by comparing averaged potential wheat's yield which could be harvested from the area occupied by the power plant. It was possible using Eq. (5):

$$D = \frac{Y_n A}{C}, \tag{5}$$

where: D is a factor that allows us to assess the wheat yield loss per 1 MW of installed capacity of a power plant per year.

From the data that is shared by the Energy Regulatory Office mentioned above (RES installations – status of December 31, 2023), I have selected utility-scale power plants of different installed capacity higher than 9 MW, which were possible to find using: orthophotomap, google map (which was used when it seemed to be more actual), the Topographic Objects Database (BDOT10k) and OSM map. As a result, I have found 13 power plants, for which I had a reliability of their shape – as they were seeable using satellite maps. Not without significance was also the fact, that these power plants are presented on satellite maps in their final, built shape. To assess land use, I have considered all infrastructure which consists of power plant: modules, substations, internal roads, fences, *etc*. I did not exclude parts of the land that were inside of power plants, where it is not possible to carry out agricultural activity.

3. RESULTS AND DISCUSSION

3.1. Land use in Poland

According to data on land use and land cover shared by Eurostat (Eurostat, 2022), Poland has a relatively high percentage of cropland land cover. Higher rates have just Hungary (43.5%) and Denmark (47.7%). In terms of socioeconomic land use, 50.4% of the land is used by agriculture. Furthermore, according to data collected by Polish Statistical Office, agricultural use of the land is the most commonly type of land use in Poland (Polish Statistical Office), what shown in Fig. 1. According to the data that the Head Office of Geodesy and Cartography shares (the Summary of Cadastral Parcels and Buildings from 2023), arable soils accounted for 70.5% of agricultural land in 2023. The total percentage of built-up areas reaches 5.83% of the total register area of Poland. The share of residential areas in built-up and urbanized areas accounts for approximately 22%. The share of individual type of land in the register area in Poland shows Fig. 2.

3.2. Agricultural land and arable soils in Poland

The classification of land in Poland is based on the Regulation of the Council of Ministers of 12 September 2012 on the soil classification of land (Official Gazette, item 1246). The Appendix to this normative act contains soil valuation classification in terms of economic assessment and environmentally-agricultural criteria. On this basis, agricultural lands are divided into nine quality classes of arable soils: the best quality (class I), very good quality (class II), good quality (class IIIa), medium-good quality (class IIIb), medium-quality, higher (class Iva), medium-quality, lower (class IVb), poor quality (class V), poorest quality (class VI), and poorest quality, permanently dry or too wet (class VIRz) (Korzeniowski, 2018). Furthermore, meadows, pastures, and wastelands are also three more types of agricultural land in terms of land classification. It is worth noting that arable soils of classes I-III are under special legal protection on the basis of Act of 3 February 1995 on the protection of agricultural land and forests (consolidated text, Official Gazette from 2024,

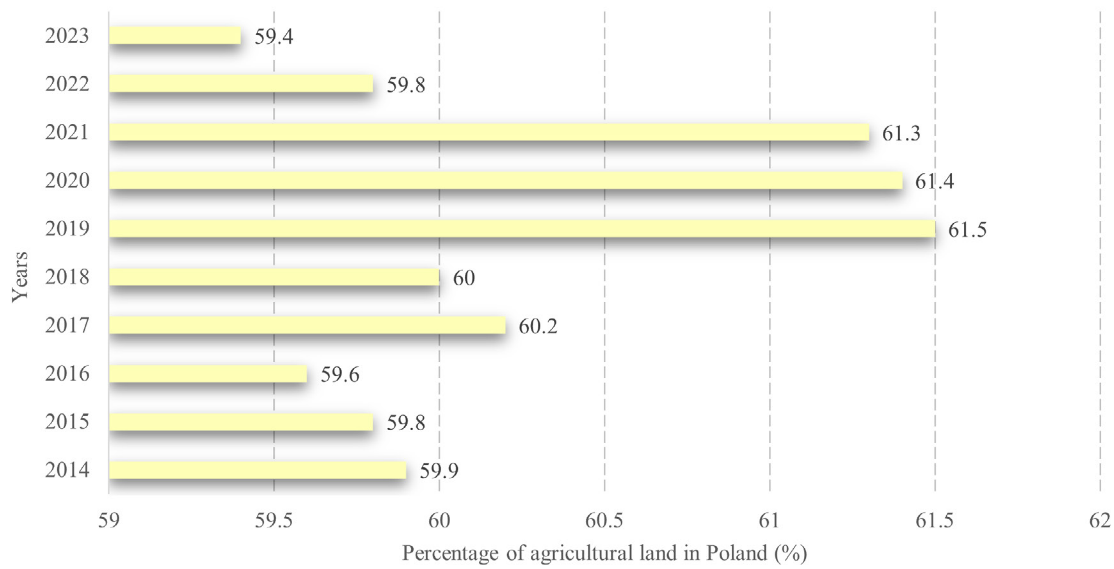

Fig. 1. Percentage of agricultural land in Poland in the recent years. Own elaboration based on the data from Polish Statistical Office.

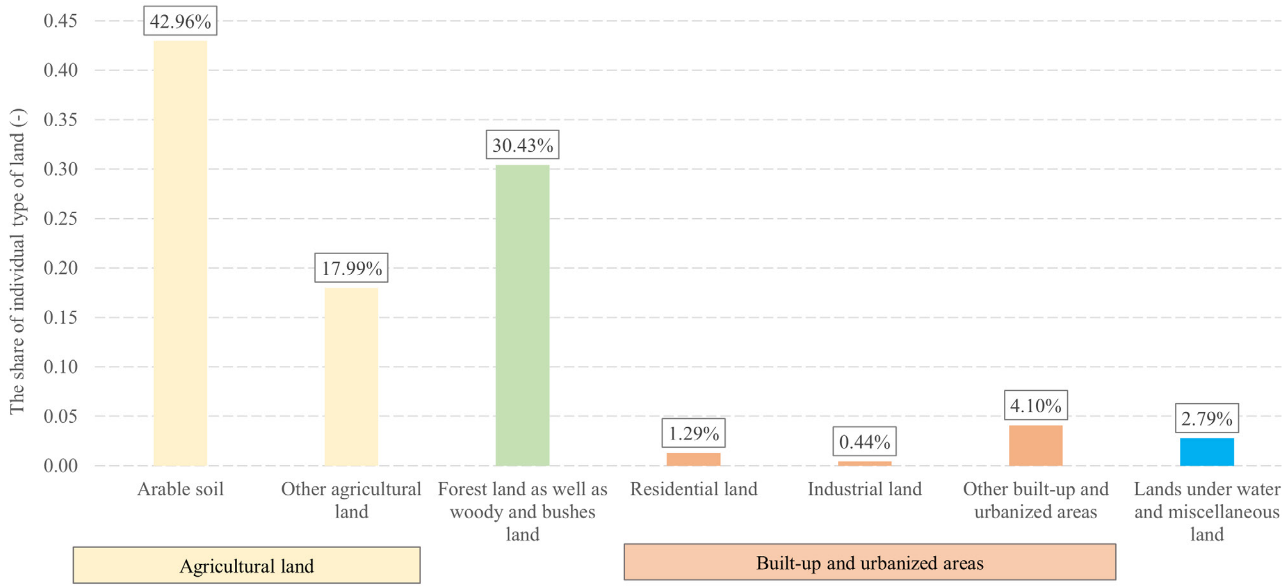

Fig. 2. Share of individual type of land in register area in Poland. Own elaboration based on the Summary of Cadastral Parcels and Buildings 2023.

item 82) and their designation for other than agricultural purposes demand formal approval of Agricultural Ministry and, in general (not taking into account soils located in areas of supplementing buildings) is allowed just on the basis of local spatial development plan (Kurowska *et al.*, 2020). For utility-scale photovoltaic power plants, it is mandatory to exclude arable soil classes I-III from agricultural production and is related to high fees. This translates into the reduction of available areas for the development of solar projects, as investors avoid incurring additional costs. The distribution of arable soils classes varies from administrative unit to administrative unit. Figure 3 shows the percentage of individual arable soils in the arable soil structure in Poland and in the voivodeship level.

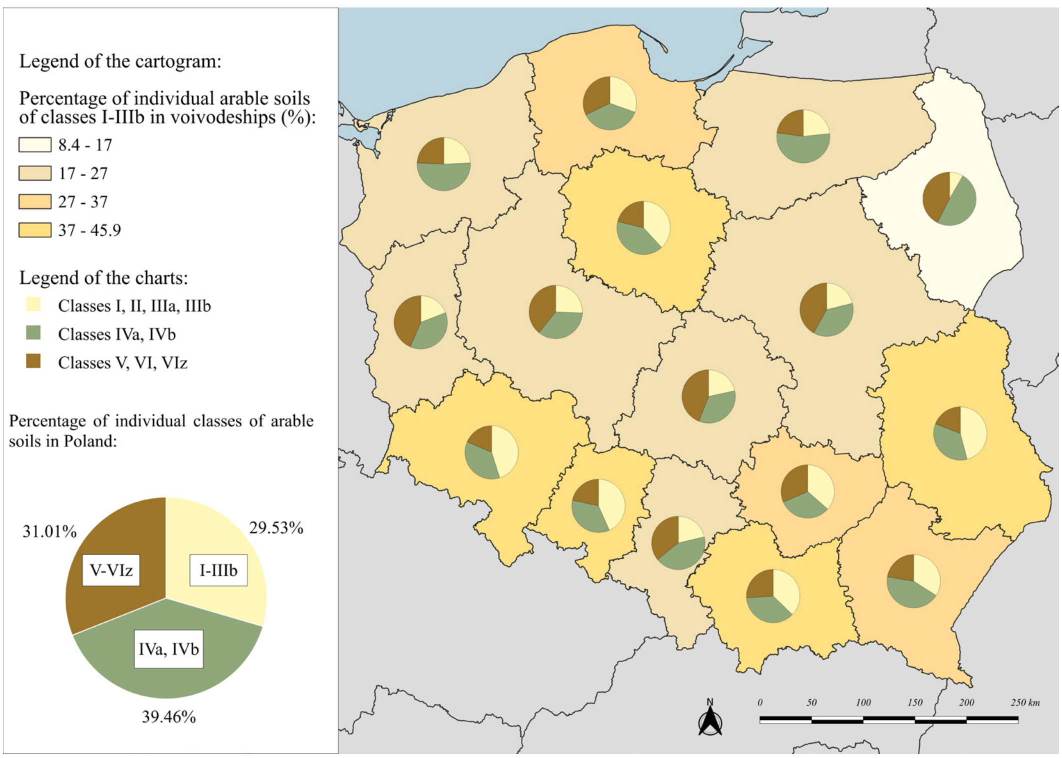

Fig. 3. Share of individual type of arable soils in voivodeships and in Poland. Own elaboration based on Summary of Cadastral Parcels and Buildings 2023.

Table 1. Optimal crops for cultivation on selected arable soils. Own elaboration on the basis of Regulation on the soil classification of land indicates arable crops

Arable soil class	Selected examples of optimal arable crop for arable soils class
IVa	wheat, sugar beet, rye
IVb	oat, cabbage, rutabaga
V	oat, lupine, potatoes
VI	oat
VIz	not suitable for cultivation

3.3. Agricultural production

The appendix to the aforementioned Regulation on the soil classification of land indicates arable crops, that are most optimal for the cultivation for each type of arable soil class. For the development of photovoltaic power plants, the following classes of arable soils are the most desirable: IVa, IVb, V, VI, and VIz. Optimal crops to cultivate on these arable soils are shown in Table 1.

As shown in Table 1, different species of arable crops are suitable for cultivation on individual types of arable soil classes. Thus, to find the optimal factor applicable for the purpose of investigation, it is important to choose a proper crop and its yield as a representative equivalent. To do this, statistical data shared by the Statistic Office were used (Statistics Poland – Local Data Bank). As can be seen in Fig. 4, vast part of agricultural land is occupied by wheat cultivation. Despite a high sugar beets yield, area occupied by this kind of arable crop is relatively small (due to the weight of this crop). By virtue of a large area occupied by cereal cultivation, in order to evaluate the impact of photovoltaic power plants on future potential yields on a national scale, in addition to determination of reduction of agricultural production space, the conceivable influence of these installations on the decrease in yields was investigated applying averaged yields of wheat from 2013-2023. The mean value of the wheat yield for that period equals 4.82 Mg ha^{-1}, what is presented on the Fig. 5.

3.4. Photovoltaic installations in Poland – current status, land demand and potential of reducing agricultural production space

According to data sharing by the Energy Regulatory Office, at the end of 2023, there were 1.4 milion photovoltaic microinstallations (up to 50 kW of installed capacity) in Poland, whose installed capacity was 11.316 GW (Energy Regulatory Office). Furthermore, at that time, there were 4411 small photovoltaic installations (from 50 kW to 1 MW of installed capacity) with a capacity of 3.565 GW (Energy Regulatory Office). It is worth indicating that 4634 photovoltaic installations with installed capacity higher than 0.05 MW were under exploitation at the end of 2023. Table 2 shows percentage of the individual types of photovoltaic installations (small installations and utility-scale installations) in The interesting fact is that most of the type of photovoltaic power plants are small installations. This type represents 91.65% of photovoltaic power plants in terms of number and 65.64% in regard to installed capacity. Nonetheless, utility-scale photovoltaic power plants represent 8.35 and 34.36% of photovoltaic power plants in respect of number and installed capacity respectively.

For the purposes of this study, utility-scale power plants and their land demand were investigated. To assess the impact of the utility-scale power plants on agricultural production space, I have selected 13 of them (following the method described in previous chapter). The smallest power plant in the sample has installed capacity of 9.999 MW and the largest: 203.373 MW, what is described in the Table 3.

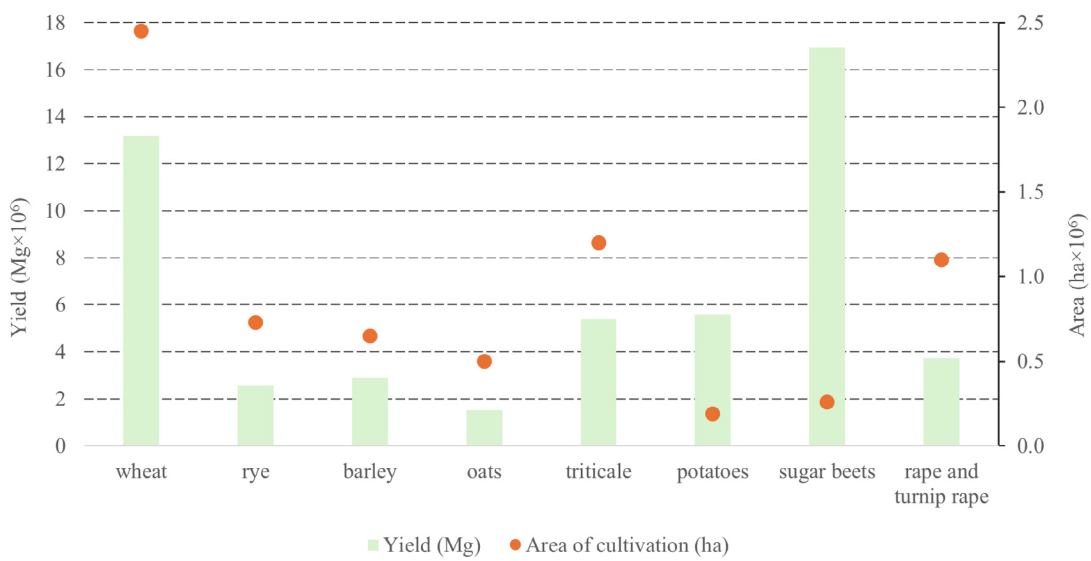

Fig. 4. Yield of selected arable crops in Poland in 2023. Own elaboration based on the data from Polish Statistic Office (Statistics Poland – Local Data Bank).

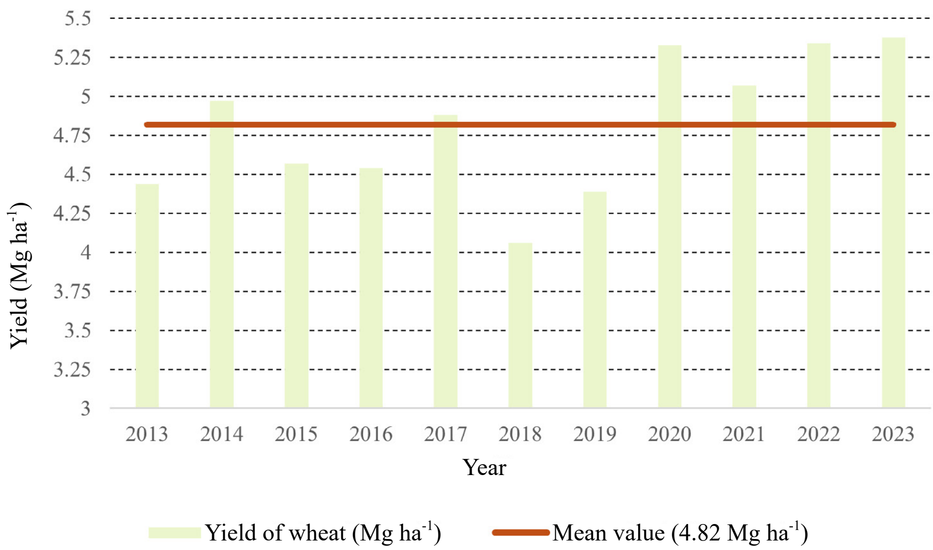

Fig. 5. Yields of wheat in years 2013-2023 with a mean value. Own elaboration based on Statistics Poland – Local Data Bank.

Table 2. Distribution of photovoltaic power plants in Poland in total number and total installed capacity of this type of renewable installations. Own elaboration based on Energy Regulatory Office data (RES installations – status of December 31, 2023)

Type of installation by installed capacity	0.05-0.5 (MW)	0.5-1 (MW)	1-2 (MW)	2-10 (MW)	10-30 (MW)	Higher than 30 (MW)
Share of installation type in total number of installations	19.12%	72.53%	6.34%	1.60%	0.13%	0.28%
Share of installation type in total installed capacity	4.21%	61.43%	7.26%	7.34%	2.89%	16.87%
General type of installation	Small installations/small power plants		Utility-scale power plants			

From the analysis conducted, it is clear that utility-scale power plants in Poland require large acreage of land. The mean value of the land use intensity factor is equal to 1.24 ha per every megawatt of installed capacity. It translates into reducing agricultural production space and potential annual crop yield. The annual loss of wheat (selected representative equivalent of crops in Poland) ranges from 4.59 to 7.56 Mg per 1 MW of an installed capacity of a photovoltaic power plant with mean value of 5.96 Mg MW^{-1}.

Consequently, utility-scale photovoltaic power plants in Poland are capable of reducing agricultural production space, causing loss of available cropland at the level of 1.24 ha per every 1 MW of installed capacity or, in other words, at the level of approximately 1.15 ha per each generated GWh. It results in a decrease in the yield of crops that could be planted at area occupied by power plants.

The European Union has obtained a binding target for the share of renewable energy in the gross final energy consumption in 2030 at a level of 42.5% at least on the basis of the RED III directive (Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance), 2024). However, this regulation does not establish any obligatory objectives for individual countries. Nonetheless, the current Energy Policy in Poland until 2040 assumes that the share of renewable energy in the power industry system will be not less than 32%. This document also presupposes that installed capacity of photovoltaics in Poland will reach the level of 5-7 GW in 2030 and 10-16 GW in 2040. Also, Transmission System Operator (TSO) in the Development Plan assumes that installed capacity of photovoltaic power plants will reach a level of 20 GW of installed capacity in 2034. Nevertheless, 25 GW of installed capacity is predicting by TSO, taking into account the scenario of dynamic transformation (Development plan for meeting the current and future electricity demand for 2025-2034).

Considering the prediction of continuous growth of electricity production from photovoltaic power plants and their introduction into agricultural lands resulting in land

Table 3. Research sample and main results

Ordinal number	Installed capacity (MW)	Estimated annual electricity generation (GWh)	Land use intensity (*I*) (ha MW^{-1})	Land-capacity factor (*L*) (MW ha^{-1})	Power density factor (*P*) (ha GWh^{-1})	Annual wheat yield loss factor per installed capacity (*D*) (Mg MW^{-1})
1	203.373	217.87	1.22	0.82	1.14	5.89
2	82.386	89.46	1.26	0.79	1.16	6.08
3	73.978	78.49	1.09	0.92	1.03	5.25
4	60.003	63.62	0.95	1.05	0.9	4.59
5	59.998	67.19	1.08	0.93	0.97	5.22
6	59.955	61.36	1.38	0.72	1.35	6.65
7	57.499	63.21	1.44	0.69	1.31	6.96
8	49.962	53.31	1.57	0.64	1.47	7.56
9	37.138	40.29	1.53	0.65	1.41	7.37
10	29.999	30.95	1.06	0.94	1.02	5.09
11	29.961	32.69	1.12	0.89	1.02	5.37
12	25.074	27.02	1.02	0.98	0.95	4.92
13	9.999	10.83	1.37	0.73	1.26	6.58
	Mean		1.24	0.83	1.15	5.96
	Median		1.22	0.82	1.14	5.89
	First quartile (Q_1)		1.08	0.72	1.02	5.22
	Third quartile (Q_3)		1.38	0.93	1.31	6.65
	Standard deviation		0.2	0.13	0.19	0.98
	The lowest value		0.95	0.64	0.9	4.59
	The highest value		1.57	1.05	1.47	7.56

transformation, prudence suggests it is essential to assess the impact of utility-scale installations on available agricultural space and, in result, on crop production.

Hence, the potential loss of agricultural land (as a total), arable soils, and wheat yield was measured to assess the impact of the share of photovoltaic power plants in energy production on these parameters. Results of that analysis shows Fig. 6. Also, Table 4 contains selected values resulting from the conducted research.

The results of the conducted research allow to assess the impact of utility-scale photovoltaic power plants on agricultural production space with reference to agricultural and arable soils loss as well as potential harvest loss in regard to decrease of wheat yield (as equivalent of croplands).

It is clear that the development of this type of renewable installations affects a land use structure reducing available arable soils. Relatively low value of the capacity factor of this type of power plants in comparison to other renewable and non-renewable generation units, together with low annual insolation in Poland, make it necessary to allocate large areas of land to the development of solar energy (to produce a certain amount of energy). Nonetheless, the conducted research proves that an increase in the level of installed capacity of photovoltaic power plants does not significantly affect the availability of land for agriculture on a national scale. Even a high level of installed capacity of solar energy does not substantially limit the acreage of farmlands.

It is significant that if in the Polish energy system 40 GW of installed capacity comes from photovoltaic power plants, the accessible land for agriculture would be reduced merely by 0.26%. In that situation, we would have 0.39% less arable soils, the worst agricultural soil classes would be diminished by 0.49% and so high level of solar power plants percentage in the energy system would recede wheat yield by approximately 2.07% (in relation to current, averaged harvest). Despite this fact, due to the transformation of agricultural land, larger and larger areas will become built-up areas, enlarging this type of land use.

This research shows that the mean land use intensity factor of utility-scale power plants in Poland amounts to 1.24 ha MW^{-1}, what translates to reducing wheat yields on average 5.96 Mg per one megawatt of installed capacity annually. The main findings of this study related to reduction

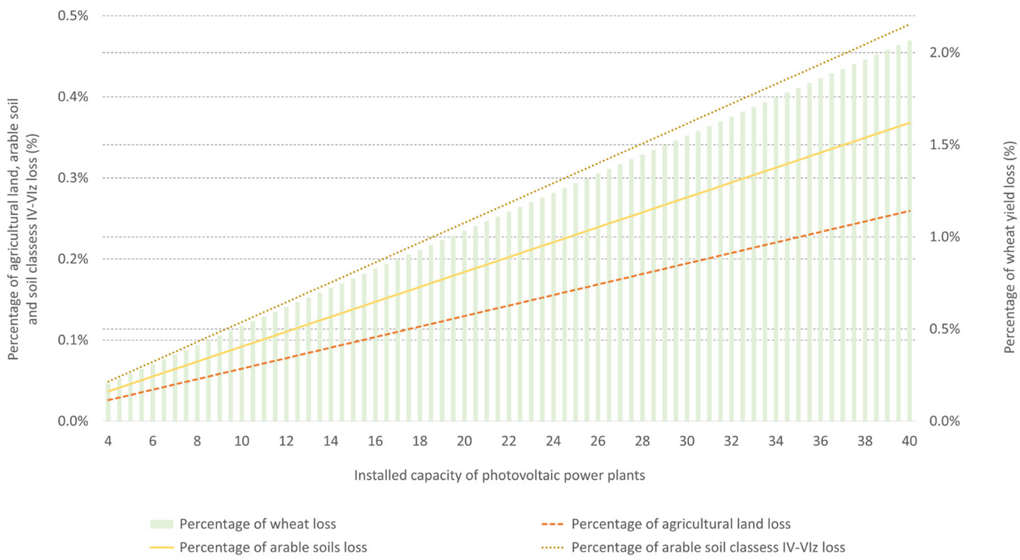

Fig. 6. Percentage of wheat, agricultural land, arable soils and arable soils classes IV-VIz loss caused by solar energy development.

Table 4. Comparison of installed capacity of photovoltaic power plants and its impact on selected factors

Installed capacity of photovoltaic power plants (GW)	Percentage of arable soils loss (%) (with area (ha))	Share of Poland area (%)	Increase of industrial and other buil-up areas (%)	Percentage of wheat loss (%)	Polish city of similar area to arable soils loss area (ha)
5	0.037 (6200)	0.02	2.01	0.032	Żory (6200)
10	0.092 (12400)	0.04	4.03	0.065	Bielsko-Biała (12445)
15	0.138 (18600)	0.06	6.04	0.775	Dąbrowa Górnicza (18873)
20	0.184 (24800)	0.08	8.06	1.033	Poznań (26191)
25	0.230 (31000)	0.10	10.07	1.292	Kraków (32685)
35	0.322 (43400)	0.14	14.10	1.808	Gdynia (39151)

of agricultural production space were collected in the Table 5, so that it would be more comparable for purposes of research that may be conducted in future.

In light of photovoltaic power plants capability of reducing agricultural production space in Poland, not without significance is fact, that Poland is a large country (nineth European country and sixth European Union country in terms of area), with high percentage of arable land. In fact, the development of this renewable energy installation, despite their relatively high land requirements, does not impact significantly on agricultural lands in Poland.

Table 5. Main findings of research in the context of reducing agricultural production space and yield losses

Parameter	Parameter values
Land use intensity factor	1.24 ha MW^{-1}
Land-capacity factor	0.83 MW ha^{-1}
Power density (per year)	1.15 ha GW^{-1}
Wheat loss factor	5.96 Mg MW

However, it is still highly important to protect high-value arable soil classes. Taking into account the land use intensity factor of photovoltaics and the small amount of the best quality soils class, every 1 GW of installed capacity on these soils reduces their total area by 1.93%. For very good and good quality arable soils, the decrease is 0.26 and 0.08%, respectively.

Furthermore, the fact that photovoltaic power plants do not impact significantly on agricultural production space is not tantamount to introduce these installations in arable land in first order. There are more factors which should be taken into account in decision making process concerning location of solar energy systems, such as presence of nature conservation forms, the principle of spatial order, character of considered area, impact on landscape, compliance with an idea of sustainability development, and correspondence with surrounding architecture. Primarily, these power plants should be developed in industrial areas and their neighbourhood (due to preservation of spatial order), in lands devastated by anthropogenic activity (like post-mining areas), in neighbourhood of available grid connection points, or close to roads, as pollutions from transport can have an adverse effect on adjacent to roads soils and crops (Kalavrouziotis *et al.*, 2007; Kibblewhite, 2018; Muthu *et al.*, 2021). On the contrary, due to the size of photovoltaic power plants and the demand for renewable energy, it is unavoidable to develop them on arable soils. Nonetheless, the proper order of location choice should be asserted.

Beyond the above considerations and the results of the agricultural land requirements for solar energy, it is still important to assess the less tangible effects of the power plants on agricultural production space. Recent study indicates, that this type of renewable installation is capable of having a moderate impact on soil desiccation, soil efficacy, vegetation, and terrestrial habitat (Rahman *et al.*, 2022). The investigation from Italy, which was based on soils that for seven years have been occupied by photovoltaic power plant proves that ground mounted photovoltaic panels can affect the physical and chemical properties of the soil. Photovoltaic modules change the distribution of soil temperature and irradiation. The soil water content decreases in the soils underneath the modules, while between the arrays this coefficient has a higher value, even with respect to the control area. The study also points out that the soils in power plants are characterised by a high amount of plant litter (respecting to total biomass). Furthermore, soil carbon and nitrogen storage are reduced because of the photovoltaic power plant, due to the coverage of surface by modules. Also, soil organic matter was lower with regard to previous state, before power plant construction (Moscatelli *et al.*, 2022). Moreover, the soil moisture distribution is heterogeneous at photovoltaic power plants due to the presence of modules (moisture concentrates along their lower edges) and arrays (Choi *et al.*, 2020). One short-term study proves that utility-scale power plants affect soil temperature by changing the vertical distribution of temperature of soil layers located in power plant by lowering it. What is interesting is the fact that during winter power plants under discussion can have an insulation effect on soil (Wu *et al.*, 2021). Increased shading caused by modules can make biological activity slower. The effect of shading can also reduce plant photosynthesis, as photovoltaic modules limit solar radiation. In addition, because photovoltaic construction is inclined at a certain angle, rainwater can induce soil erosion. Despite that, researchers claim, that the negative impact on the soil is implausible, but it is crucial to assess the impact of ground-mounted photovoltaic on soils taking into account soils variability and different climate conditions (Dvořáčková *et al.*, 2024). Thus, it is necessary to verify properties of soils in photovoltaic power plants in the Polish conditions. It would provide a wider view of the impact of photovoltaic power plants on arable soils and, in fact, on agricultural production space, as properties of soils are one of the most essential factors in agriculture.

3.5. Is agrophotovoltaics a solution to crop yield losses?

It is important to highlight the concept of so-called agrophotovoltaic power plants, which enable the simultaneous engagement in two activities on the same land: electricity production as well as agricultural production (Libra *et al.*, 2024). Currently, there is a lack of dedicated legal framework for the development of these photovoltaic installations in Poland and the provisions applying to traditional ones are also binding for agrophotovoltaic power plants. Moreover, the projects of such power plants are not broadly developed in Poland. Potentially, this kind of renewable energy power plant can mitigate the impact of photovoltaic systems on agricultural lands and, consequently, on the expected yield of crops, as it is feasible to conduct agricultural activity together with energy production. Nonetheless, not all crop species are suitable for agrophotovoltaic installation. Furthermore, when it comes to the development of agrophotovoltaic installations in Poland, there is a concern of the kind that allowance for wider development of such installations on arable soils will cause the possibility of covering the highest valuation soil classes by them. Thus, it would be a tremendous challen-ge for the legislator to introduce adequate amendments establishing provisions concerning agrophotovoltaic power plants.

Predicting potential crop yield losses resulting from the replacement of traditional photovoltaic systems with agrophotovoltaic installations is particularly challenging especially in the case of wheat yield estimates. There is a notable research gap in studies on Polish conditions. Nonetheless, certain ideas how to measure it may be recommended for this and future analysis. Therefore, let us assume that the realisation of the agrophotovoltaic power plant causes changes in the yield of selected crop. For the purposes of this work let us assume the potential yields of wheat (as calculations for traditional power plants are based on yield for that plant). To estimate the wheat yield from the agrophotovoltaic power plant from 1 ha (Y_{APV}) as the yield from normal agricultural production obtained from 1 ha (Y_A) – derived, for instance, from the control sample – correlated by the predicting (or investigated, if it would be the case) level of yield change (Δ) – probably expressing decrease of yield. Then the wheat yield from agrophotovoltaic power plant can be expressed using Eq. (6):

$$Y_{APV} = \Delta Y_A . \tag{6}$$

It should be highlighted that agrophotovoltaic power plant may require more acreage to be built in comparison to traditional photovoltaic power plant for the same amount of capacity. In consequence, it affects the land use. Thus, let us express the land-capacity factor for agrophotovoltaic power plant (L_{APV}) and land use intensity factor (I_{APV}) for that kind of renewable in the form demonstrated by Eqs (7) and 8:

$$I_{APV} = \frac{A_{APV}}{C_{APV}}, \quad (7)$$

$$L_{APV} = \frac{1}{I_{APV}}, \quad (8)$$

where: A_{APV} is an area occupied by agrophotovoltaic power plant and C_{APV} is its installed capacity.

In order to compare land use intensity factor of agrophotovoltaic and traditional power plant, Eq. (9) can be used:

$$\alpha = \frac{I_{APV}}{I}, \quad (9)$$

where: α is a factor demonstrating difference for land requirements between two types of photovoltaic systems under discussion.

Since agrophotovoltaic power plant allows to conduct agricultural activity, the impact of agrophotovoltaic on agricultural production space can be defined as potential losses in yield per every installed MW of capacity. First, it is crucial to evaluate the yield from an agrophotovoltaic power plant with the same capacity as a traditional system. The total yield from installation under discussion (Y_{TAPV}) can take the form of Eq. (10):

$$Y_{TAPV} = C\, I\, \alpha\, Y_{APV}, \quad (10)$$

where: C and I are respectively capacity of photovoltaic power plant of the same amount of installed capacity as agrophotovoltaic one and its land use intensity factor.

Then, if the yield from the same area as area occupied by agrophotovoltaic power plant is Y_{TA}, the loss of yield caused by this renewable installation (D_{APV}) can be expressed as:

$$D_{APV} = Y_{TA} - Y_{TAPV}. \quad (11)$$

The difference in area between these two types of photovoltaic power plants (DA) can take the form of Eq. (12):

$$DA = CI\alpha - CI = CI(\alpha - 1) \quad (12)$$

The yield of crops from the area, where only agricultural activity has place ($Y_{TA(DA)}$), will be equal to the following expression Eq. (13):

$$Y_{TA(DA)} = DA\, Y_A. \quad (13)$$

Finally, to compare the yield of crops from agrophotovoltaic power plant (where crops are cultivated underneath the infrastructure on the same land – Y_{TAPV}) with the potential yield from photovoltaic power plant (from land not occupied by photovoltaic power plant, but potentially occupied by agrophotovoltaic one – $Y_{TA(DA)}$), we can introduce yield comparison factor ($F_{APV/PV}$), expressed by Eq. (14):

$$F_{APV/PV} = \frac{Y_{TAPV}}{Y_{TA(DA)}} = \frac{CI\alpha Y_{APV}}{CI(\alpha-1)Y_A} = \frac{\alpha Y_{APV}}{(\alpha-1)\, Y_A} = \frac{Y_{APV}}{Y_A}\frac{\alpha}{(\alpha-1)} = \Delta\frac{\alpha}{(\alpha-1)} \quad (14)$$

Above equation is true if $\alpha \neq 1$. Otherwise, Eq. (14) simplifies and takes the form of Eq. (15):

$$L = \Delta Y_A I C_{APV}. \quad (15)$$

Equations (14) and (15) demonstrate how many more yield of crop could be obtained if agrophotovoltaic power plant would be built instead of traditional one. Furthermore, to predict by how much the yield will be reduced if traditional photovoltaic systems would be built instead of agrophotovoltaic power plants ($F_{PV/APV}$), we can use a reciprocal of yield comparison factor can be used, so the Eq. (14) will take the form of the following equation:

$$F_{PV/APV} = \frac{1}{F_{APV/PV}}. \quad (16)$$

To clarify the equations presented, an illustrative example is necessary. Let us consider a photovoltaic installation of the installed capacity of 100 MW built on the area of 124 ha (as it was demonstrated that the mean land use intensity factor is 1.24 ha MW^{-1}). Moreover, let us assume that the potential wheat yield from that area, if a power plant would not be built, is able to reach 597 Mg. Under these assumptions, and with $\alpha = 2$, $\Delta = 0.8$, agrophotovoltaic power plant could be characterised by the installed capacity of 100 MW and would require 248 ha of land. In considering case, the yield comparison factor ($F_{PV/APV}$) is 0.6 what means that 60% of wheat yield less from photovoltaic installation would be harvested in comparison to the situation, when the agrophotovoltaic power plant was developed (from the area not covered by photovoltaic power plant – 148 ha). Then, $F_{APV/PV} = 1.66$ what means that 1.66 times more (66%) of crop yield would be obtained using agrophotovoltaic in comparison to the situation when traditional installation was built.

Therefore, as we see, the efficiency of agricultural activity of agrophotovoltaic power plant significantly depends on a species of crop cultivated (and how do ther react on shadow) and the land use intensity, as shown in Fig. 7.

What is more, we can express the yield loss caused by agrophotovoltaic (D_{APV}) using Eq. (17) (to obtain a value) or Eq. (18) (to obtain the percentage of crop's yield loss), as this is the difference between yield from normal agricultural production and installation under discussion:

$$D_{APV} = Y_A - Y_{APV}, \quad (17)$$

$$D_{APV} = \frac{Y_A - Y_{APV}}{Y_A}. \quad (18)$$

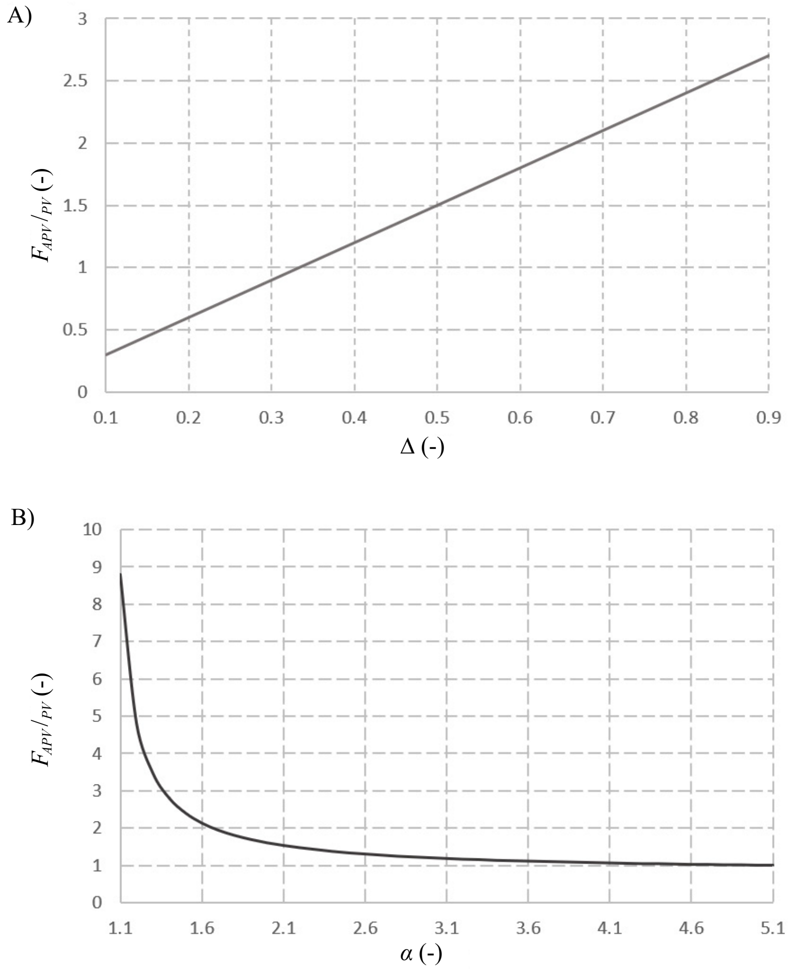

Fig. 7. Course of the function of $F_{APV}/_{PV}$ for two variants: A) $F_{\frac{APV}{PV}}(\Delta)$, α = const = 1.5 and B) $F_{\frac{APV}{PV}}(\alpha)$, Δ = const = 0.8. The course of function confirms strong dependence of agrophotovoltaic efficiencty (of agricultural activity on land occupied by an installation) that rely on land use intensity and the efficiency of agricultural production for selected crop.

Table 6. Potential share of agrophotovoltaic power plants in the area of Poland and estimated percentage of wheat losses on the basis of assumed values of Δ and α

Installed capacity of agrophotovoltaic power plants (GW)	Share of Poland area (%)	Percentage of wheat loss (%)
5	0.03	0.078
10	0.06	0.155
15	0.09	0.233
20	0.12	0.311
25	0.15	0.389
35	0.21	0.544

Table 6 demonstrates, similarly to Table 4, the dependence of the installed capacity of agrophotovoltaic power plants in the Polish power system with predictions of the share of these power plants in area of Poland and estimated wheat yield losses. The calculations were carried out with the assumptions of $\Delta = 0.8$ and $\alpha = 1.5$.

Conducted analysis demonstrates that despite agrophotovoltaic power plants may have a positive impact on agriculture in comparison with traditional power plants in terms of potential amounts of yield, those installations require more land to be developed if their land use intensity factor is higher than photovoltaic systems.

4. CONCLUSIONS

The cumulative impact of photovoltaic power plants on agricultural production space in Poland is low, as it emerges from this study. Even large amounts of installed capacity of utility-scale power plants do not affect significantly the availability of arable soils. Although solar energy requires a large acreage of land – as was demonstrated, the mean land use intensity of this type of renewable installation is 1.24 ha per 1 MW of installed capacity – it is not reflected in a significant loss of farmland. Furthermore, these power plants are responsible for a loss of approximately 5.96 Mg of wheat yield for each 1 MW installed. Thus, in spite of land demand and the fact that in a local-scale photovoltaic power plants seem to transform large space, these installations have low impact on agriculture space in national scale and, consequently, on food security.

In the context of the impact of photovoltaics on arable soils and possibilities of their reclamation, there is still a lack of knowledge, when it comes to the Polish conditions. Therefore, further research should focus on investigation of influence on arable soils and how soil properties change during the operation phase of solar power plants. Considering the findings of this study and results arising from the studies concerning photovoltaic impact on environmental elements (especially arable soil and its properties), it is crucial to evaluate and estimate mentioned impacts at local, regional and national scale. Therefore, further studies should be focused on the assessment of the cumulative influence of photovoltaics on soils, as well as on other components of the environment.

Taking into account the findings of this research, it is important to assess whether the development of agrophotovoltaic – a new type of photovoltaic installations, which allows the combination of agriculture and energy production (Sirnik *et al.*, 2023; Weselek *et al.*, 2019) – is reasonable, while on national scale traditional photovoltaic power plants would not have a significant impact on crop production. In terms of land use, it is better to carry on these two types of business activity at one land. Nevertheless, it is worth to suggest that when in public life we would face a dilemma between the development of agrophotovoltaics on the best quality arable soils and the developing normal power plant on worse soils, the best choice is to develop a traditional photovoltaic power plant (or agrophotovoltaic) on worse quality soils, as the impact of power plant in terms of land use and agricultural production space in regional and national scale is low. It is worth mentioning that the same agrophotovoltaic power plant needs more land than its equivalent of the traditional power plant, when comparing the same amount of installed capacity. Agrophotovoltaics is an advantageous when it comes to agricultural production, because, contrary to traditional power plants, it does not transform arable soil into industrial area entirely. Notwithstanding, introduction of agrophotovoltaics would be beneficial only when it would be well studied in the Polish conditions and when it would turn out that in Polish climate it improves crop yield (for example for crops that need shading). Furthermore, this study calls into question validity of development of floating photovoltaics. Considering accessible land for traditional power plants in Poland, together with inland water status and its ecological, social and economic functions, it is crucial to intellectualise, whether in first order agricultural lands should be allocated for energy production purposes against inland waters (lands under standing surface waters occupy just 0.19% of Poland).

The research also points out that proper order in location choice of these power plants should be guaranteed. Therefore, the implementation of the provisions of the RED III directive on renewables acceleration areas is awaited, as adopted rules can contribute to the more sustainable development of photovoltaic power plants, increasing the share of solar energy in the energy system in accordance with the protection of the most valuable agricultural areas simultaneously.

This study has demonstrated the impact of photovoltaic power plants on agricultural production space. Additionally, this impact was compared to the predicted influence of agrophotovoltaic power plants on subject matter. Calculations that enable a comparison of these impact (despite the technical parameters of agrophotovoltaic systems being unknown due to the current development stage of these installations in Poland) have been presented and may prove useful for future studies on this topic.

Conflict of interests: The Author declare he has no conflict of interest. Any professional or private situation of the Author had no influence on the research and its result. The Author confirms he is an employee at Valorem Energies Poland (renewable company).

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