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Assessing the potential for agri-PV in Swiss agriculture

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Cover picture: Mixed field bean/oat crop under photovoltaic modules. Photo: Mareike Jäger, July 2023

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Summary

Agri-photovoltaics (Agri-PV) refers to the dual utilisation of land for agricultural purposes and energy production with photovoltaics. As Agri-PV systems are typically located outside of building zones, licences for their construction are only be granted if they are site-specific (e.g. located in less sensitive areas) and provide benefits for agricultural production or are used for scientific research.

This study quantifies the potential for electricity production from agrivoltaics in Switzerland, taking the existing agricultural land into account. Only areas that are located within a buffer of 1000 m around building zones are considered. Areas that intersect with national conservation interests are excluded. This also applies to alpine grazing areas and biodiversity promotion areas as well as areas with horizontal irradiation below 1000 kWh/m^2/y. The remaining areas are then categorised into the three crop groups "open arable land", "permanent crops" and "permanent grassland" based on the crop grown on them. A typical agri-PV system is defined for each crop group and its electricity yield is calculated.

Due to a lack of practical experience in Switzerland regarding the benefits of photovoltaics for agricultural production, only a few restrictions were placed on the type of crops that can be grown on agricultural land in combination with PV systems. The calculated potential therefore represents a theoretical maximum potential, while the practical potential may be significantly lower. The effects on agriculture should be demonstrated in the coming years through appropriate research in Switzerland.

A theoretical total potential of 323 TWh/y was calculated for agri-PV in Switzerland. The potential is distributed over an area of 583,499 ha and thus covers 56 % of the agricultural land available in Switzerland in 2022 (excluding grazing areas). If a maximum distance of 300 metres to a feed-in point for the electricity is taken into account, the theoretical potential is reduced to 113 TWh per year.

Most of the potential with a maximum distance of 300 m from the feed-in point lies on open arable land at 92.2 TWh/y. This potential amounts to 17.8 TWh/y for permanent grassland and 3 TWh/a for permanent crops. In the case of permanent crops, areas with vineyards account for the largest share of the potential, followed by orchards (apples, stone fruit, pears). The geographical distribution shows a concentration of potential on the Central Plateau, particularly in the cantons of Bern, Vaud and Fribourg.

The average specific annual yield is 1194 kWh/kWp. On average, 29 % of the annual yield is produced in the winter half-year. The average specific winter electricity yield of agrivoltaics is therefore around a third higher than the average specific winter electricity yield of PV systems on roof surfaces.

Agri-PV systems should not be seen as a replacement, but as a supplement to PV systems on roof surfaces and other existing infrastructures. Due to the higher specific production in winter and the synergy effects with agricultural production, agri-PV systems appear to be a sensible complement.

The electricity generation costs were also calculated for 1 MWp agri-PV systems at the reference site. The investment and operating costs (incl. grid connection), an imputed interest rate of 2 % and subsidies from GREIV in 2022 were taken into account. The production costs for systems on permanent grassland are the lowest at 6.0 Rp./kWh due to the simple system design. For arable crops, 7.8 Rp./kWh is to be expected, and 8.4 Rp./kWh for permanent crops. In particular, the more complex construction increases the investment costs for systems on arable and permanent crops, resulting in higher production costs.

Assuming an annual electricity production of 7 to 8 TWh through agrivoltaics (corresponding to approx. 10% of the expected electricity demand in 2050), 1 to 2 % of Switzerland's agricultural land would be affected, depending on the crops selected. These areas would by no means be lost, but could continue to be used for agriculture and also benefit from the synergies of agrivoltaics.

Terms and abbreviations

Agri-PV	Combined land use that locates agricultural production and photovoltaic infrastructure on the same area
GWh	Gigawatt hour
kWh	Kilowatt hour
kWh/kWp	Specific yield (per year or winter half-year), which was normalised to the nominal output of the PV modules under standardised test conditions.
kWp	Kilowatt peak. Specification of the nominal power of PV systems under standardised test conditions
LN	Utilised agricultural area, according to LBV (agricultural terminology regulation) without summering area
PV	Photovoltaics
RPV	Spatial Planning Ordinance (Raumplanungsverordnung)
Summer half-year	Period from 01 April to 30 September
TWh	terawatt hours
Winter half-year	Period from 01 January to 31 March & 01 October to 31 December
ZHAW	Zurich University of Applied Sciences

1 Introduction

Agri-PV or agrivoltaic refers to the dual use of land for agricultural purposes and energy production with photovoltaics (Jäger et al., 2022). It differs clearly from ground-mounted PV systems, where the land is used mainly or entirely for energy production. As agrivoltaic systems are located on agricultural land, exemption permits for their construction are only granted if it can be proven that they are tied to a specific location. According to Article 32c of the Spatial Planning Ordinance (RPV), agrivoltaic installations are deemed to be site-specific if they are located in less sensitive areas and provide advantages for agricultural production or serve corresponding experimental and research purposes. Special requirements apply to crop rotation areas. For example, it must be proven that yields do not decrease as a result of agri-pv utilisation. It should be noted that crop rotation area is a purely spatial planning term and does not necessarily only refer to arable land. In some cantons, many permanent crop areas are also located on crop rotation areas. Recently, as part of the parliamentary debate on the framework decree, the new Art. 24b of the Federal Spatial Planning Act (E-RPG) has created a basis for the authorisation requirements for PV systems on agricultural land. On 29 September 2023, the National Council and the Council of States adopted the framework decree in the final vote. However, the deadline for the optional referendum has not yet expired. This means that the Agri-PV would have been regulated not only at ordinance level but also at legislative level, at least in principle.

In 2022, the ZHAW published a feasibility study on the topic of Agri-PV in Swiss agriculture (Jäger et al., 2022). This included an estimate of the yield potential, which put the annual potential for agri-PV in Switzerland at 132 TWh/y. The requirements of Article 32c of the RPV were taken into account by selecting agricultural land (LN) in a 1000 m buffer around building zones and excluding national protected areas. This was intended to take account of the aspect of "less sensitive areas".

More precise data sources for irradiation have now revealed a significantly higher theoretical yield potential for agrivoltaics in Switzerland. This report aims to quantify this potential and thus update the results of the feasibility study. The methodology used by Jäger et al. (2022) is slightly adapted in the following points:

- Updating the irradiation data source:
  The typical horizontal irradiation is calculated with monthly and annual resolution based on Meteonorm (version 8). In the feasibility study, a GIS tool (Solar Radiation Tool from ArcGIS Pro) was used, which shows irradiation forecasts that are too low when compared with real measurement data.
- The agricultural crops suitable for Agri-PV are adapted.
- A meanwhile updated data set on agricultural land from 2023 is used.

In addition to updating the annual potential for electricity generation, more detailed information is provided on the winter electricity yield of agrivoltaics. In addition, the influence of the national protection criteria taken into account in the underlying spatial analysis is analysed in more detail and the geographic distribution of the yield potential is shown.

Due to a lack of practical experience in Switzerland regarding the benefits of photovoltaics for agricultural production, only a few restrictions were placed on the type of crops that can be grown on agricultural land in combination with PV systems. The calculated potential therefore represents a theoretical maximum potential, while the practical potential may be significantly lower. The effects on agriculture should be demonstrated by appropriate research in the coming years.

2 Methods

The methods used to calculate the theoretical potential of agri-PV in Switzerland are described below. They are largely based on the methodology used in the Agri-PV feasibility study by Jäger et al. (2022), which was also prepared by the authors of this study.

2.1 Identification of suitable agricultural land

The selection of areas potentially suitable for Agri-PV was carried out under consideration of different criteria:

2.1.1 Proximity to building zones:

The areas taken into account are located in the vicinity of building zones (consideration of "less sensitive areas" from the RPV). For this purpose, a 1000 m wide buffer was created around building zones (Figure 1). Chapter 4.3 shows how the potential changes with other buffer sizes.

If there is a spatial overlap between utilised agricultural areas (UAA) and the buffer around building zones, only the part of the UAA that is located within the buffer is taken into account. The result of this procedure is visualised using a section of the map in Figure 1. The construction zone is shown in red, the buffer around construction zones in blue. The agricultural land for agri-PV cut to the buffer is coloured yellow.

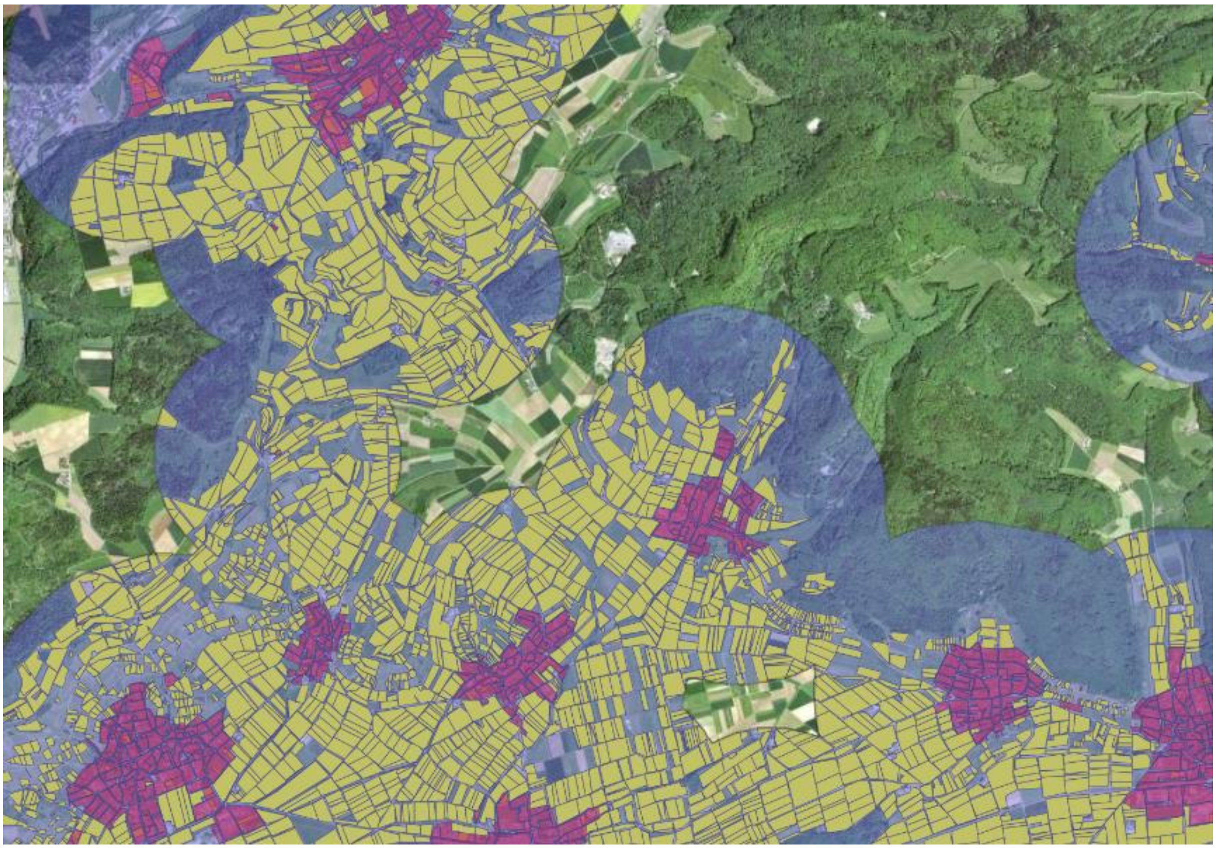

Figure 1: Map section with building zones (red), 1000 m buffer around building zones (blue) and agricultural land (yellow). Only (partial) areas located in the buffer are included in the theoretical potential.

2.1.2 Utilised agricultural area (UAA) and suitability for Agri-PV:

Agricultural land within the 1000 m buffer around building zones was selected. The UAA are based on the model "Cultivated agricultural areas identifier 153" (FOAG, 2023) and were assigned a management status based on the crop grown on them. These are "open arable land", "permanent grassland", "permanent crop", "protected cultivation", "summering areas" and "biodiversity areas (BFF)".

All areas that are categorised as BFF or summering areas are not included in the calculation of potential. Summering areas do not count as agricultural land according to the agricultural definition ordinance and biodiversity promotion areas may not be equipped with photovoltaic modules according to the direct payment ordinance.

The same applies to some special cases, such as high-stem orchards, which are not considered suitable for agrivoltaics. The allocation of the different types of agricultural land to the respective management status and their inclusion in the calculation of the PV potential can be seen in detail in the Table 7 in the appendix.

2.1.3 Irradiation conditions:

Subsequently, potential areas for Agri-PV are excluded that have an annual horizontal global radiation < 1000 kWh/m^2. Chapter 3.4 shows what influence the choice of a different limit value for irradiation would have on the theoretical potential for agrivoltaics. A raster data set with a spatial resolution of 100 m is used as the data source for irradiation. This contains the irradiation in a typical meteorological year per month or a whole year and was generated with Meteonorm Version 8 (Meteotest, 2022). The far horizon is taken into account. In contrast, in the analysis by Jäger et al. (2022), the irradiation was calculated using a digital elevation model with the Solar Radiation Toolset from ArcGIS Pro, taking the distant horizon into account. A comparison of these two irradiation data sources with MeteoSwiss measuring stations in the canton of Zurich showed that the irradiation with the Solar Radiation Toolset of ArcGIS Pro was underestimated by 9 to 12 % annually. In the winter months, the irradiation was even underestimated by 20 to 30 %. The typical irradiation from the grid data set with Meteonorm Version 8 (Meteotest, 2022) shows a very high level of agreement with the measuring stations, with deviations of 1 to 2 %.

2.1.4 Exclusion criteria:

Finally, exclusion criteria were defined based on national protection interests and areas located within these were excluded. This also takes into account the "less sensitive area" aspect of the RPV by reducing the protection interests that conflict with the Agri-PV. The protection criteria taken into account are:

- Federal Inventory of Landscapes and Natural Monuments (BLN)
- RAMSAR and SMARAGD nature reserves
- Nature parks
- Bogs (raised bogs and fens)
- Amphibian sanctuaries
- National Park
- Biosphere reserves
- UNESCO World Heritage Natural Sites
- Dry meadows and pastures
- Water protection zones S1 to S3

It should be noted in particular that the Spatial Planning Ordinance (RPV) only requires the least possible conflicting protection interests for the Agri-PV. This means that areas in BLN areas, for example, do not necessarily have to be excluded (Jäger & Anderegg, 2023).

2.2 Calculation of the theoretical PV potential

The PV yield calculation for suitable areas in accordance with section 2.1 is based on the irradiation and the area at the respective location as well as the type of system suitable for the management status. In the feasibility study by Jäger et al. (2022) a suitable system type was defined for each management status. A yield simulation was then carried out for each system type at the reference site in Kloten (ZH), where the typical irradiation corresponds to the average irradiation in the Central Plateau. The system types selected for each crop group are briefly described below.

Covered PV systems with bifacial modules and wide row spacing (around three times the module table width) were used **for open arable land** (e.g. potatoes or wheat). The simulation is based on fixed modules with a tilt angle of 20° and an orientation of 30° south west (Figure 2). This achieves as homogeneous an irradiation distribution as possible on the underlying crop (Trommsdorff et al., 2021) and mechanical cultivation of the arable land is still possible due to the mounting height and the wide distances between the supports (Jäger et al., 2022).

Figure 2: System example for "open arable crop" management status. Agri-PV trial system (APV Resola) with non-tracking modules in Heggelbach (Germany). The modules are installed at a height of 5.5 m and the distance between the supports in the longitudinal direction is 19 m (Hofgemeinschaft Heggelbach, n.d.).

In permanent grassland (natural meadows or pastures), two superimposed bifacial modules in landscape format are assumed, which are mounted vertically in an east-west orientation (Figure 3). The lower edge of the module of systems already in use in Germany is approx. 0.8 m from the ground, so the total height of the system is around 3 m. The mounting height minimises shading of the PV modules due to agricultural use and the green strip below the modules is easy to maintain.

Figure 3: System example for the "permanent grassland" management status. Vertical APV system from Next2Sun in Donaueschingen (Germany). The bifacial modules are vertically elevated, orientation of the module surfaces to the east or west, row spacing 10 m (Next2Sun, 2020).

In the area of **permanent crops** (e.g. vines or orchards), the yield of the reference system was calculated using bifacial, semi-transparent modules with a light transmission of 50 %. The light transmission of modules must be selected considering the permanent crop grown and may differ from the reference system depending on the project. A module inclination of 12° and an orientation of 30° south-west was assumed (see Figure 4). The row spacing is significantly smaller than for open arable land due to the light transmission and the requirements for crop protection.

Figure 4: System example for "permanent crops" and "protected cultivation" management status. Agri-PV system above an orchard in Gelsdorf (DE). With the APV system (left in the picture), the existing crop protection measures (right in the picture) could be substituted (Energy experts, n.d.).

The nominal PV power that can be installed per hectare and the typical specific annual and area yields for the reference site in Kloten ZH are taken from Jäger et al. (2022) and are summarised in Table 1.

The annual PV yield per APV area (E_{APV}) is then calculated using the horizontal irradiation ($E_{horizontal}$) on site in a typical meteorological year (Meteotest, 2022) and the irradiation at the reference site in Zurich Kloten (E_{Ref}). In addition, the area yield of the associated management status from Table 1 (E_{FL}) and the soil area (A) according to formula (1) is included. The reference irradiation for the area yield from Table 1 is 1163 kWh/m^2/y.

$$E_{APV} = \frac{E_{horizontal}}{E_{Ref}} * \; E_{Fl} * A \tag{1}$$

Table 1: Assumptions for calculating the yield of Agri-PV systems with bifacial modules from Jäger et al. (2022). Calculated for a reference site in Zurich Kloten with a horizontal global radiation of 1163 kWh/m^2/y.

Management status	Nominal output in MWp/ha	Typical annual yield in MWh/MWp	Area yield E_{Fl} in MWh/ha/y
Open farmland	0.612	1200	735
Permanent grassland	0.293	1000	293
Permanent crops	0.737	1170	862

Single-axis or dual-axis tracked systems are not considered in this report. The possible area yield should therefore be interpreted as a conservative estimate and could be increased by approx. 15 % with module tracking (Jäger et al., 2022).

3 Results

3.1 Total theoretical potential of agri-PV

The identification of potentially suitable agricultural land results in an area potential of 583’499 ha (56 % of the agricultural land available in 2022, excluding alpine grazing areas in Switzerland). Using the calculation methods described, the maximum installable nominal capacity of agrivoltaic systems in Switzerland is 271 GWp. This leads to a potential electricity yield of 323.3 TWh/y and thus to an average specific annual yield of 1194 kWh/kWp. This means that the theoretical potential for agrivoltaics is more than 6 times higher than Switzerland's total electricity production in 2022 (SFOE, 2023). The high annual yield of agrivoltaics can be explained, among other things, by the use of bifacial modules and the system design (assumed orientation and inclination as well as low mutual shading due to large row spacing).

On average, 29.2 % of the yields from agrivoltaic systems would occur in the winter half-year, which corresponds to 94.6 TWh or a specific winter yield of 349 kWh/kWp. In comparison, systems on roof surfaces with an average annual yield of around 970 kWh/kWp (Hostettler, 2020; Hostettler & Hekler, 2021, 2022, 2023) and 27 % share of winter electricity (Bucher & Schwarz, 2021) have an average specific winter electricity yield of 262 kWh/kWp. This means that the specific winter electricity yield of agrivoltaics is on average 33 % higher than the specific winter electricity yield of roof areas. The reason for this high winter electricity yield is primarily the high specific annual yield of 1194 kWh/kWp on average in combination with a moderate share of winter electricity.

3.2 Theoretical potential per cultivation status and crop

The largest contribution to the theoretical potential is made by agricultural land with the cultivation status "open arable land" with 225 TWh/y, followed by permanent grassland with 85 TWh/y and permanent crops with 13 TWh/y. Table 2 and Figure 5 break down the potential per cultivation status. The Table 2 also shows the most relevant crops.

Table 2: Theoretical potential of agri-PV in Switzerland taking into account the exclusion criteria with breakdown by cultivation status and crops (in italics). The crops with the highest potential are shown, the others have been summarised under "Other". WH = winter half-year from Jan-March and Oct-Dec.

Utilisation	Potential in TWh/y	Potential in TWh/WH	Winter electricity share in %
Open farmland	225.3	66.9	29.7
... Artificial meadows	*64.4*	*19.2*	*29.9*
... Winter wheat (without feed wheat)	*42.6*	*12.6*	*29.6*
... Silage and green maize	*26.4*	*7.8*	*29.6*
... Winter barley	*15.4*	*4.6*	*29.6*
... Winter oilseed rape for edible oil production	*14.5*	*4.3*	*29.6*
... Grain maize	*10.6*	*3.1*	*29.5*
... Other open arable land	*51.4*	*15.2*	*29.6*
Permanent grassland	84.6	23.7	28.0
... Permanent meadows (without pastures)	*68.8*	*19.3*	*28.0*
... Willows	*15.7*	*4.4*	*27.8*
... Other green spaces	*0.2*	*0.0*	*27.2*
Permanent culture	13.4	4.1	30.7
...vines	*5.8*	*1.2*	*31.6*
... Orchards (apples)	*3.1*	*0.9*	*30.1*
... Orchards (stone fruit)	*1.3*	*0.4*	*29.4*
... Orchards (pears)	*0.6*	*0.2*	*30.1*
... Other permanent crops	*2.3*	*0.6*	*30.1*
Total	323.3	94.6	29.2

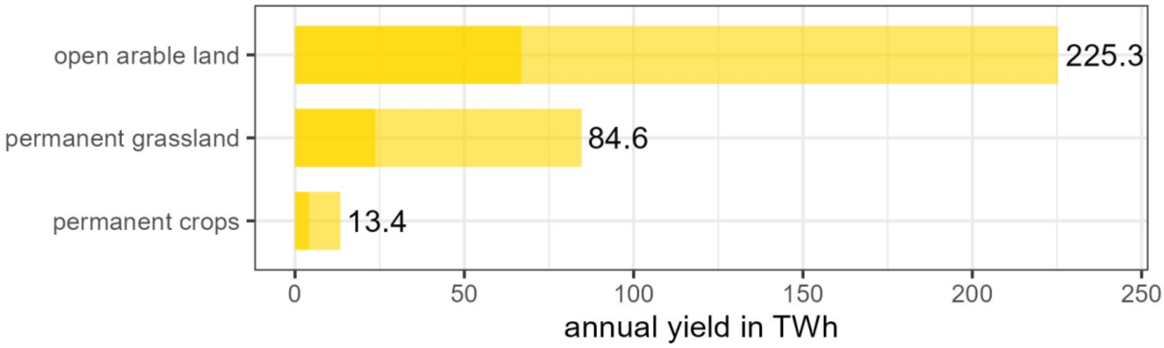

Figure 5: Theoretical potential of agrivoltaics in Switzerland per cultivation status, taking into account the exclusion criteria including areas with maize cultivation. The potential in the winter half-year is shown in dark, the potential in the summer half-year in light.

The potential on arable land is dominated by artificial meadows, followed by areas cultivated with winter wheat, silage maize and green maize. Artificial meadows are sown mixtures, mainly consisting of grass and clover species, which are cultivated on arable land for fodder purposes. Due to crop rotation, the crop cultivated per utilised area varies over time on open arable land. The breakdown roughly shows the frequency with which crops occur in arable farming in Switzerland.

Maize cultivation (including grain maize) contributes 37 TWh/y to the potential (11.4 % of the total potential), but is less suitable for dual utilisation with agrivoltaics due to its low shade tolerance (Jäger et al., 2022; Jäger & Anderegg, 2023). If areas with maize cultivation are deducted from the total, a potential of 286 TWh/y remains.

In permanent grassland, permanent meadows (excluding pastures) show the highest potential of 69 TWh/y. In the case of permanent crops, areas with vineyards and various fruit crops show the highest potential (Figure 6).

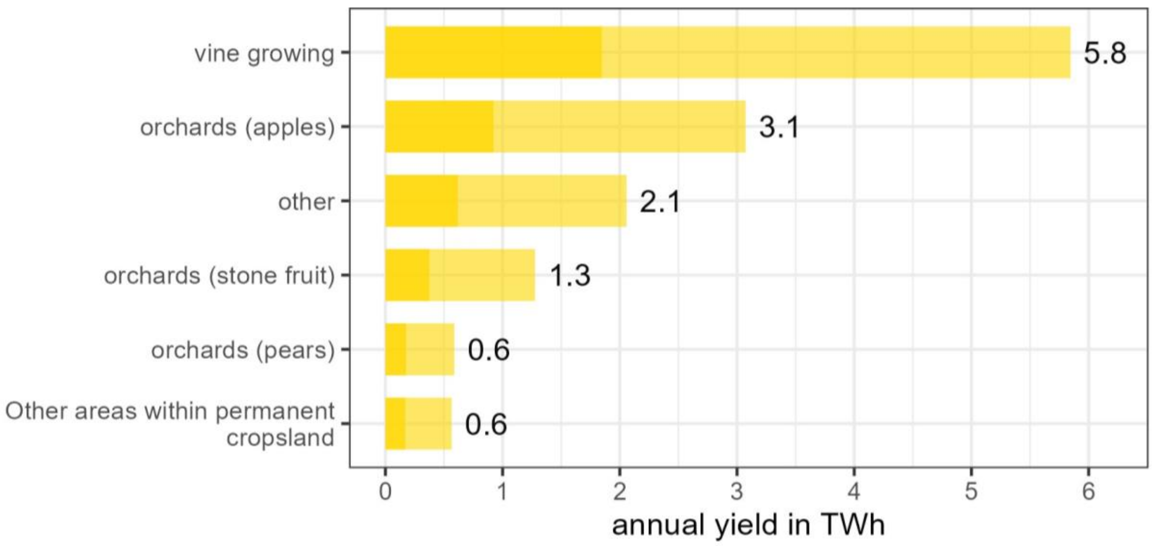

Figure 6: Theoretical potential of agrivoltaics with permanent crops in Switzerland, taking into account the exclusion criteria. The highest potential of permanent crops lies with vines and orchards. Crops with a contribution < 0.5 TWh/y were summarised under "other". The potential in the winter half-year is shown in dark, the potential in the summer half-year in light.

3.3 Geographical distribution of the theoretical potential

The geographical distribution of the theoretical annual yield potential of Agri-PV systems is shown in Figure 7. There is a concentration of potential on the northern side of the Alps in the Central Plateau.

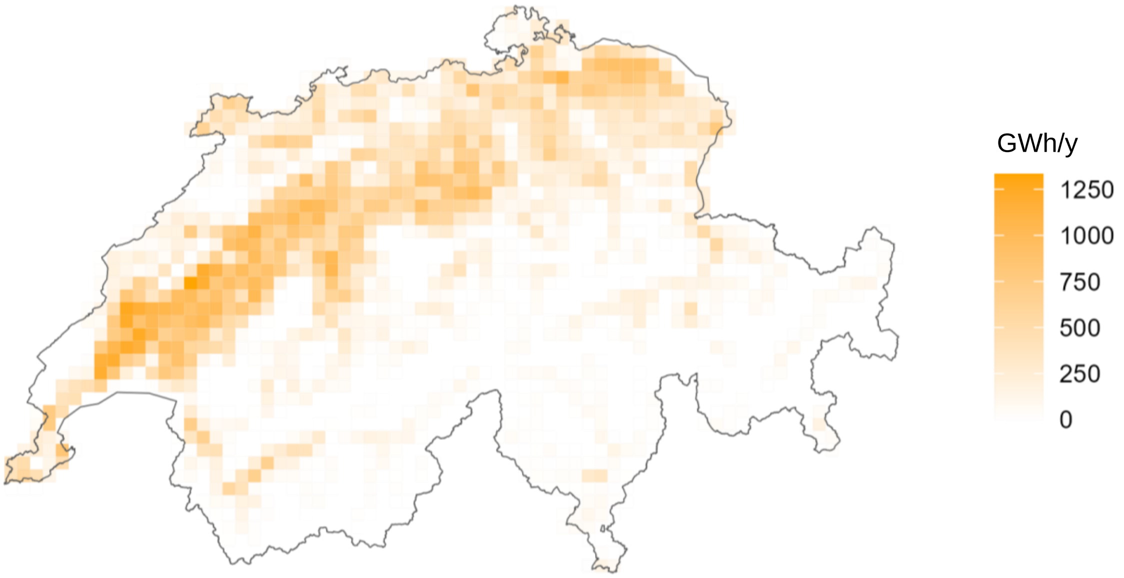

Figure 7: Geographical distribution of the theoretical potential in GWh/y for agrivoltaics, taking into account the exclusion criteria, including areas with maize cultivation. The potential was totalled in a grid with a cell size of 5 km x 5 km. The largest share of the potential is located on the Central Plateau.

The highest potential of 60 TWh/y is in the canton of Bern. The western Swiss cantons of Vaud (50 TWh/y) and Fribourg (34 TWh/y) also have very high potential. The potentials per canton are shown in Table 3.

Table 3: Theoretical potential of agrivoltaics per canton, taking into account the exclusion criteria, including areas with maize cultivation. The cantons with a potential > 5 TWh/y are shown; the complete list can be found in Table 8 in the appendix. WH = winter half-year (Jan-March and Oct-Dec).

Canton	Potential in TWh/y	Share of total potential in %	Potential in TWh/WH
Berne	59.6	18.4	17.7
Vaud	50.2	15.5	15.1
Fribourg	34.4	10.6	10.3
Zurich	25.9	8.0	7.4
Lucerne	21.6	6.7	6.3
Aargau	21.1	6.5	6.0
Thurgau	20.4	6.3	5.7
St.Gallen	16.9	5.2	4.8
Solothurn	10.2	3.2	2.9
Wallis	9.4	2.9	2.9
Grisons	9.4	2.9	2.9
Law	9.4	2.9	2.7
Basel-Landschaft	6.1	1.9	1.7
Geneva	5.1	1.6	1.5

3.4 Influence of the exclusion criteria

The applied exclusion criteria reduce the theoretical annual yield potential of Agri-PV by a total of 81.2 TWh/y. Nature parks (26.6 TWh/y) and BLN areas (20.8 TWh/y) have the greatest impact. In addition, water protection areas (S1 to S3) lead to a reduction in potential of 11.3 TWh/y. All other exclusion criteria reduce the potential of Agri-PV by less than 1 % in each case. Various areas with an annual potential totalling 16.8 TWh/y are subject to several exclusion criteria, which is why they were not assigned to a specific exclusion criterion. The influence of the exclusion criteria is shown graphically in Figure 8.

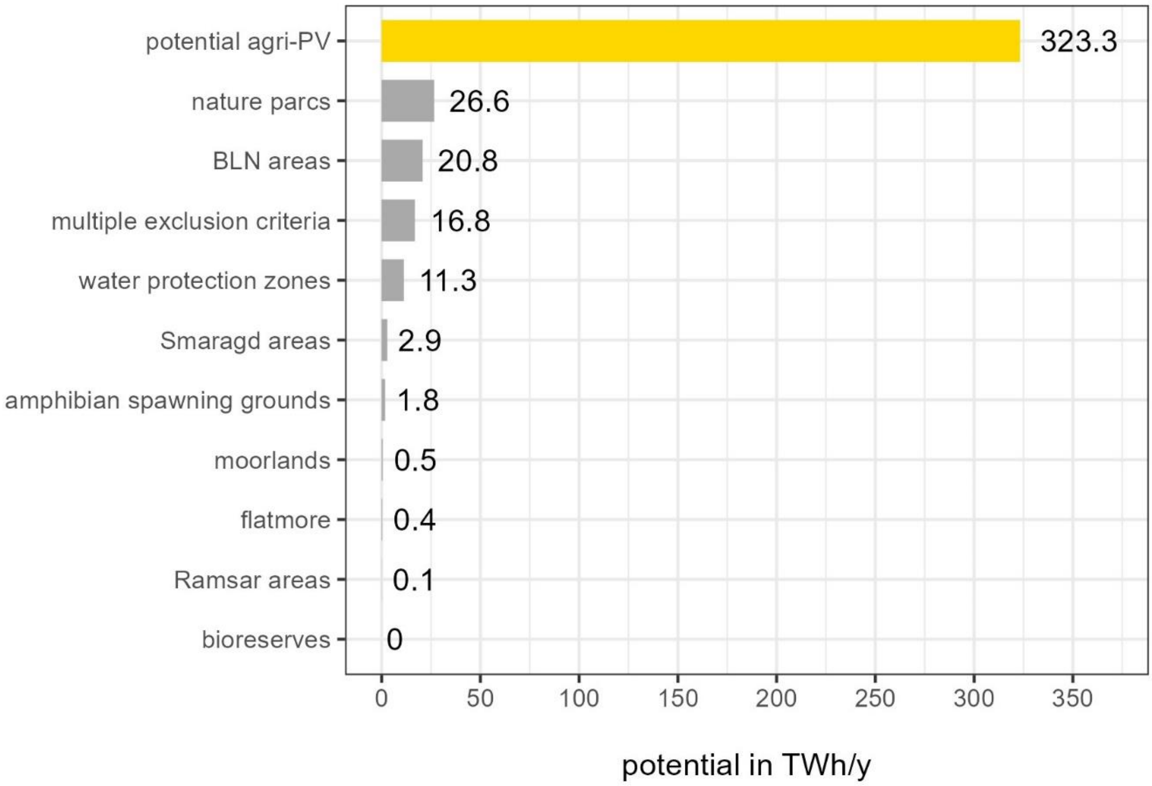

Figure 8: Influence of the applied exclusion criteria on the yield potential of agrivoltaics. After applying the exclusion criteria, a potential of 323.3 TWh/y remains. Nature reserves and BLN areas have the greatest influence on the potential. Areas with more than one exclusion criterion are summarised under "multiple exclusion criteria".

The geographical distribution of the reduction in potential due to the exclusion criteria is shown in Figure 9.

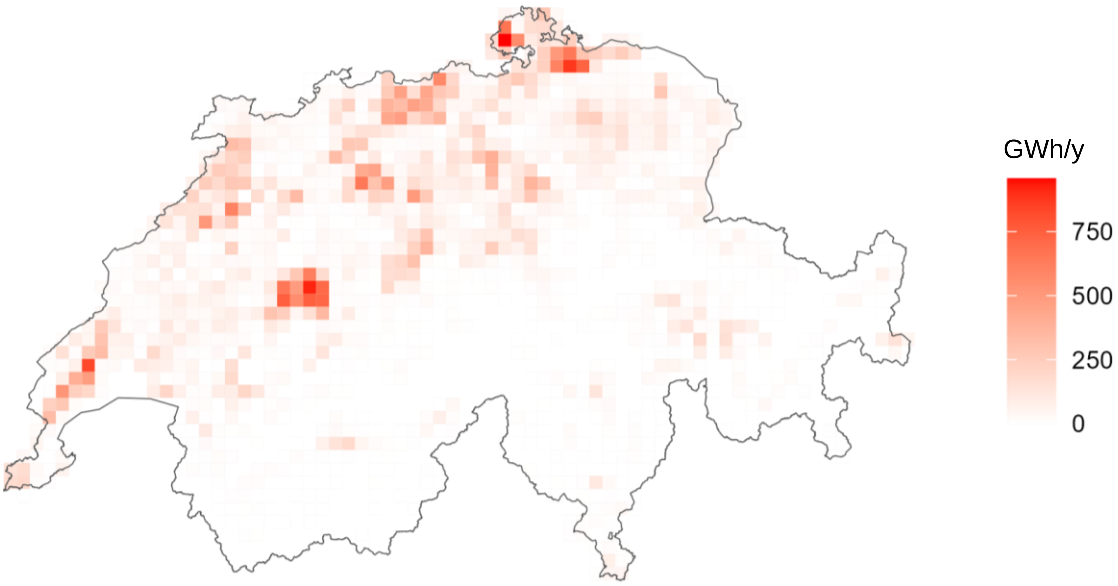

Figure 9: Spatial distribution of the yield potential of agrivoltaic systems in Switzerland excluded on the basis of the defined exclusion criteria in GWh/y.

The average irradiation on the areas suitable for agrivoltaics is 1234 kWh/m²/y with a standard deviation of 93 kWh/m²/y. By excluding areas with irradiation < 1000 kWh/m²/y, there is only a minimal reduction in potential (Figure 10).

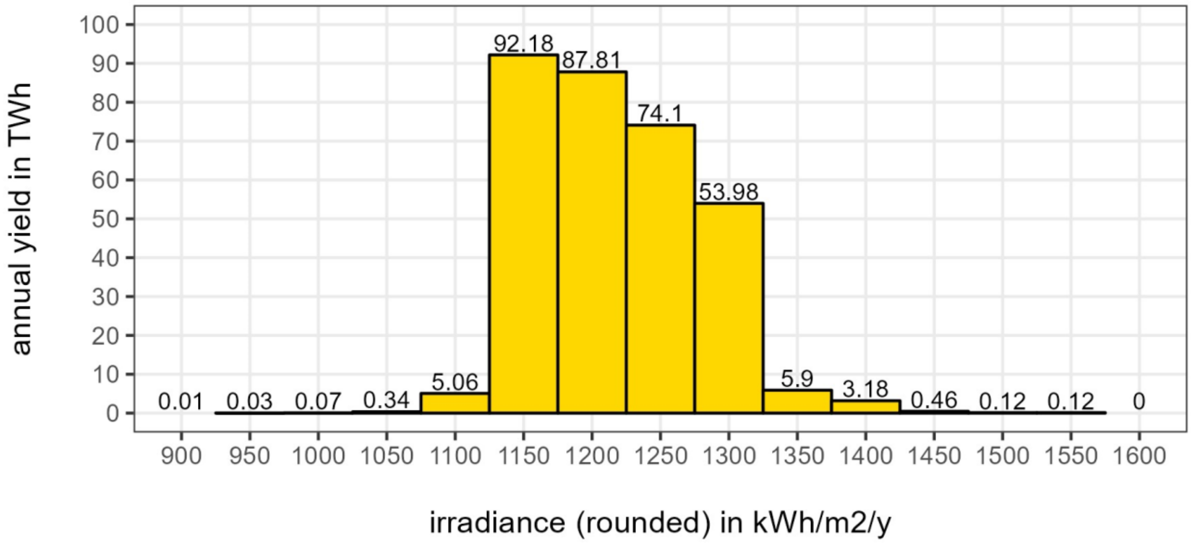

Figure 10: Distribution of the yield potential of Agri-PV grouped according to the horizontal irradiation on the ground surface. Classes were formed with a bandwidth of 50 kWh/m²/y. Mean 1234 kWh/m²/y, median 1222 kWh/m²/y, standard deviation 93 kWh/m²/y.

Figure 10 shows the distribution of the yield potential by irradiation class. Areas with irradiation between 1125 kWh/m²/y and 1325 kWh/m²/y (columns at 1150 to 1300 kWh/m²/y) make the largest contributions to the potential. From Figure 10 it can also be seen what influence a different limit value for irradiation would have on the potential of agrivoltaics in Switzerland. For example, a limit value of 1125 kWh/m²/y would result in a reduction in potential of 5.5 TWh/y.

3.5 Identification of areas with high irradiation and high yield

The areas with the highest horizontal irradiation are concentrated in southern Switzerland. For example, areas with horizontal irradiation > 1325 kWh/m²/y (classes 1350 to 1600 kWh/m²/y from Figure 10) are geographically distributed across the cantons of Valais, Graubünden and Ticino (Figure 11). In the Lake Geneva region, for example, there are many areas with irradiation between 1275 and 1325 kWh/m²/y.

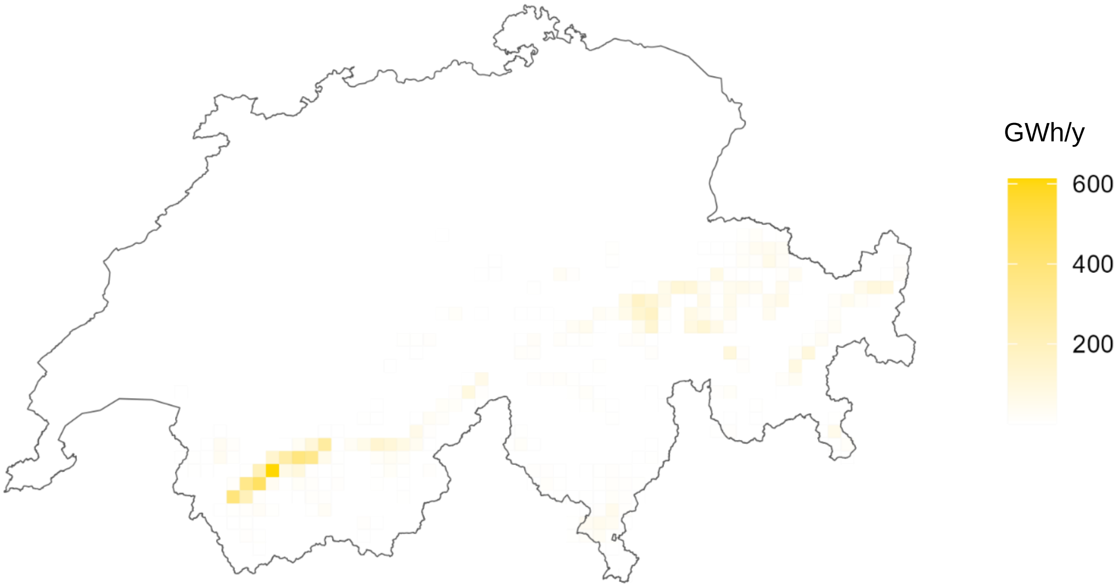

Figure 11: Geographical distribution of the yield potential of agrivoltaic systems in Switzerland with very high horizontal irradiation (> 1325 kWh/m²/y). The areas are concentrated in southern Switzerland, focussing on the cantons of Valais and Graubünden.

The specific annual yield of the areas for Agri-PV depends not only on the regional differences in radiation (Figure 10), the specific annual yield depends heavily on the crop group and the type of system suitable for it (Chapter 2.2). The largest share of the potential in permanent grassland has a specific annual yield of 1000 to 1100 kWh/kWp. This is achieved with vertical bifacial systems orientated east-west. In contrast, the specific annual yield of bifacial agrivoltaic systems above permanent crops is between 1150 and 1450 kWh/kWp. High-mounted PV systems above open arable land can be expected to achieve specific annual yields in the order of 1200 to 1350 kWh/kWp. Figure 12 shows the potential categorised according to the specific annual yield per crop group.

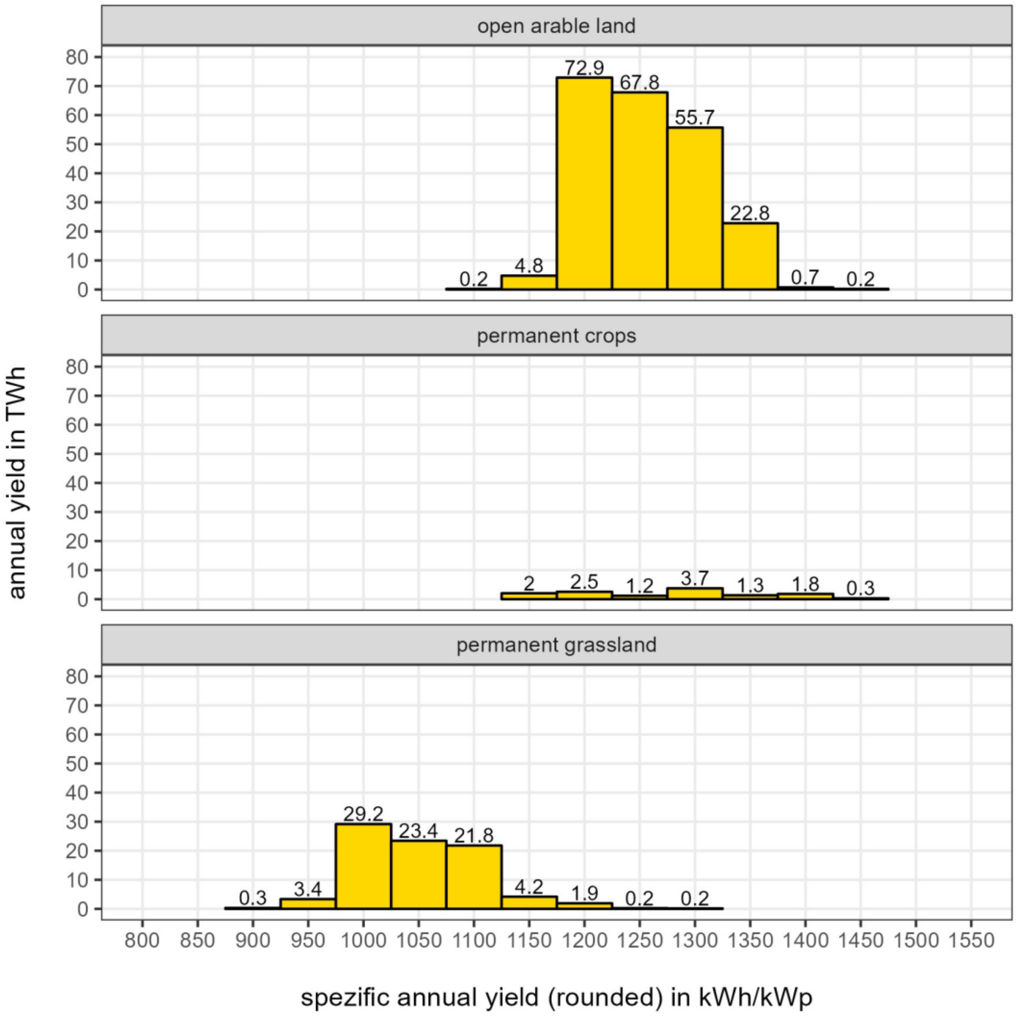

Figure 12: Distribution of the yield potential of agrivoltaics grouped according to the specific annual yield of the systems. Classes with a bandwidth of 50 kWh/kWp were formed.

3.6 Production cost of electricity

As part of the feasibility study on photovoltaics in Swiss agriculture (Jäger et al., 2022) the production costs for electricity from agrivoltaics were determined. These include the investment and operating costs as well as subsidies from the large one-off payment (GREIV) for the systems described in chapter 2.2 with a nominal output of 1 MWp.

In addition to materials, project planning and installation, the investment costs also include typical costs for the expansion of the grid infrastructure with a cable length of 250 metres. The operating costs include the one-off replacement of the inverters, system management, maintenance and insurance. In addition, a minimal loss of agricultural land due to the construction is included by means of typical lease payments.. A summary of the investment and operating costs can be found in the Table 4.

Table 4: Cost structure of agrivoltaic systems per cultivation status according to Jäger et al. (2022).

	Permanent grassland	**Open arable land**	**Permanent crops**
Investment costs in CHF/kWp	779	1419	1546
Grid connection costs in CHF/kWp	272.5	272.5	272.5
Operating costs in CHF/kWp/y	17.3	16.5	15.9
(operating costs in Rp./kWh)	*(1.73)*	*(1.38)*	*(1.36)*

The profitability was analysed in Jäger et al. (2022) with a term of 30 years, a calculative interest rate of 2 % per year and a linear degradation of the module output to 85 % of the output power after 25 years. The subsidies were calculated for commissioning in January 2022 and are based on the corresponding subsidy rates of the one-off remuneration for large photovoltaic systems (GREIV).

For the reference systems, this results in electricity generation costs of 6.0 cents/kWh for vertical systems on permanent grassland, 7.8 cents/kWh for systems on arable land and 8.4 cents/kWh for systems that cover permanent crops. The differences in the production costs are primarily due to the significantly higher investment costs of roofed systems compared to vertically mounted systems, which are due to the support and substructure of the systems as well as higher module costs. Some of these additional costs compared to systems on permanent grassland can be compensated for with higher specific yields, so that the electricity generation costs for arable crops is 30 % higher than for permanent grassland and 40 % higher for permanent crops than for permanent grassland.

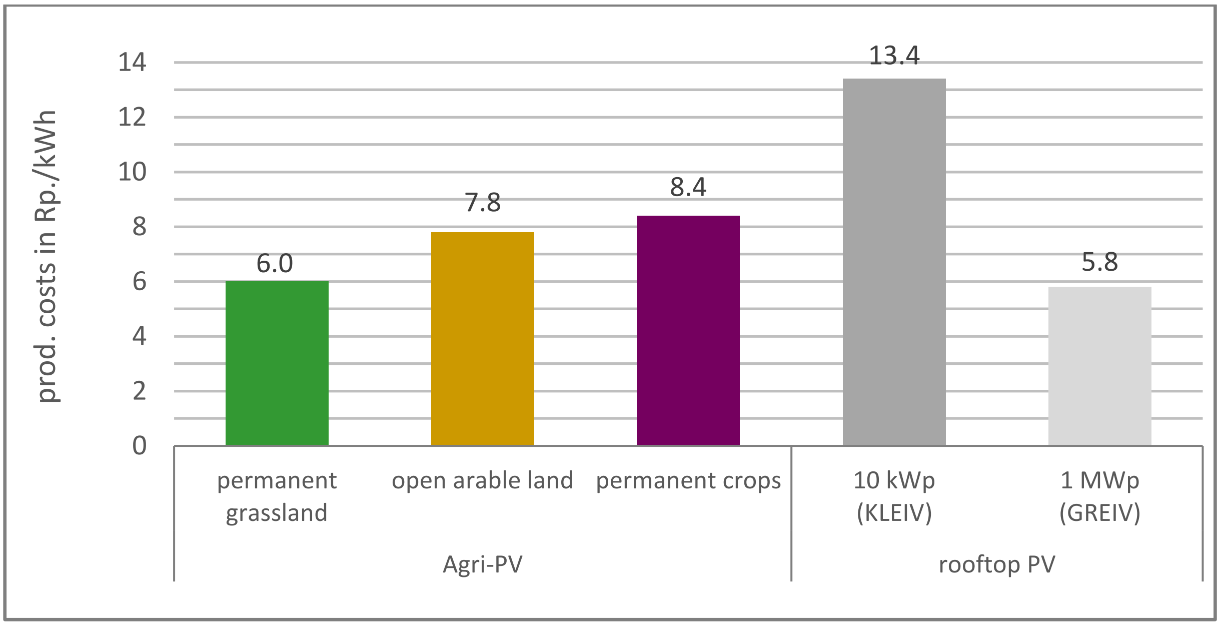

Figure 13: Production costs of Agri-PV reference systems at the Kloten ZH site with a nominal output of 1 MWp. Typical production costs for PV roof systems with 10 kWp and 1 MWp are shown for comparison. Investment costs (incl. grid connection), operating costs, a calculative interest rate of 2 % and the subsidies from GREIV in 2022 are taken into account.

Compared to a typical system on roof surfaces (cf. Figure 13) with a nominal output of 10 kWp, the production costs of Agri-PV are significantly lower, which can be explained by economies of scale (size of the Agri-PV reference system). For large systems on roof surfaces (reference system with 1 MWp), however, lower production costs can be expected than for agrivoltaics.

4 Discussion

4.1 Theoretical potential higher than previously assumed

In the feasibility study by Jäger et al. (2022) the theoretical potential of agri-PV in Swiss agriculture was estimated at 132 TWh/y. In this report, the theoretical potential is quantified 2.4 times higher at 323 TWh/y. The main reason for this large deviation is the use of a more accurate data source for irradiation. The Solar Radiation Tool in ArcGIS Pro was used in the feasibility study. In contrast, the present study is based on irradiation values in a typical meteorological year from a high-resolution grid (100 m mesh size) from Meteonorm (Meteotest, 2022). A comparison of the two data sources with long-term measurement data from MeteoSwiss has shown a much higher level of agreement for Meteonorm. However, the lower irradiation alone cannot fully explain these deviations. Rather, the sometimes severe underestimation of irradiation with the Solar Radiation Tool meant that many agricultural areas did not reach the irradiation limit of 1000 kWh/m^2/y and were therefore excluded from the calculation of potential. In this report, the limit of 1000 kWh/m^2/y is retained. In addition Figure 10 shows how the potential would change if other irradiation limits were used.

4.2 Proximity to the power grid

In Jäger et al. (2022) the proximity of areas for agrivoltaics in Switzerland to the electricity grid was shown based on an analysis by Wang (2022). Although the present analysis of potential includes considerably more areas, it can be assumed that the distance of the areas to the electricity grid will not change significantly. The reason for this assumption is that only the irradiation basis was changed, but not the distance of the areas to building zones and thus the proximity to existing infrastructure. Table 5 shows the proportion of land per crop group, broken down into various suitability categories. For example, 27 % of permanent crops and permanent grassland are a maximum of 500 m from the electricity grid. In the case of open arable land, which has the greatest potential, more than half (53 %) of the land is within 500 m of the electricity grid. Around a third of permanent crops and areas of permanent grassland are a maximum of 1000 m away from the electricity grid. Almost three quarters (71 %) of open arable land is located at a maximum distance of 1000 m from the electricity grid.

Table 5: Share of agri-PV potential divided by suitability based on the distance to the electricity grid. Areas with a maximum distance of 1000 m from the electricity grid are generally considered potentially suitable. A distinction is made between very good, good, moderate and little suitability.

Cultural group	Suitability based on the distance to the power grid				
	Very good (< 100 m)	good (100-300 m)	Moderate (300-500 m)	Little (500-1000 m)	Total (0 - 1000 m)
Permanent crops	14 %	8 %	5 %	6 %	33 %
Permanent grassland	14 %	7%	6 %	9 %	36 %
Open arable land	27 %	14 %	12 %	18 %	71 %

With regard to the proximity of agricultural land to the grid, it should be mentioned that the analysis is based on modelled locations of medium and low-voltage grids (Wang, 2022). As shown in Table 5, this makes it possible to estimate the order of magnitude of the proximity of agri-PV to the grid on average in Switzerland. The modelled locations are not meaningful for individual areas, which is why individual areas require a site-specific assessment.

4.3 Buffer around building zones

The calculated theoretical potential of the Agri-PV is based on a buffer of 1000 m around building zones. No distance is defined at ordinance or statutory level that corresponds to the criterion of "low-sensitivity area". However, the potential of Agri-PV is heavily dependent on the buffer size selected. The areas of the buffer zones with and without the actual building zone are shown in Table 6. Building zones in Switzerland cover an area of 2’343 km^2. This area is increased by a buffer of 1000 m to 21’504 km^2 (19’161 km^2 without the building zone itself). In contrast, the area without a building zone, for example with a 500 m buffer, is only 11’577 km^2.

Table 6: Area of building zones in Switzerland and areas of building zones including various buffer sizes based on the harmonised building zones in Switzerland (ARE, 2022). A buffer size of 1000 m was assumed for this study.

Kind	Area with building zone in km^2	Area without building zone in km^2	Scaling factor
Building zone without buffer	2'343	0	0
Building zone with buffer of 500 m	13'920	11'577	0.60
Building zone with buffer of 1000 m	21'504	19'161	1.00
Building zone with buffer of 1500 m	26'228	23'885	1.25

Taking the areas without building zone from Table 6 into account it can be roughly estimated to what extent the potential of agri-PV would change if a different buffer size were used. A buffer of 500 m would therefore result in a 40 % reduction in potential (scaling factor 0.6), whereas a buffer of 1500 m would mean a 25 % increase in potential (scaling factor 1.25).

5 Literature

ARE. (2022). *Building zones Switzerland (harmonised)* [Gpkg]. Federal Office for Spatial Development. https://www.kgk-cgc.ch/geodaten/geodaten-bauzonen-schweiz

SFOE. (2023). *Swiss Electricity Statistics 2022.* Swiss Federal Office of Energy SFOE. https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/elektrizitaetsstatistik.html

BLW. (2023). *Cultivated agricultural areas Identifier 153 Reference year 2023.* https://www.blw.admin.ch/blw/de/home/politik/datenmanagement/geografisches-informationssystem-gis/landwirtschaftliche-kulturflaechen.html

Bucher, C., & Schwarz, R. (2021). *Study Winter Electricity Switzerland-Final Report V3*.

Energy experts. (n.d.). *Gelsdorf: Agri-PV system for climate-friendly fruit growing*. energie-experten. Retrieved 12 October 2021, from https://www.energie-experten.org/projekte/gelsdorf-agri-pv-anlage-fuer-klimafreundlichen-obstanbau

Hofgemeinschaft Heggelbach. (n.d.). *Renewable energies - Hofgemeinschaft Heggelbach*. Retrieved 16 November 2021, from https://hofgemeinschaft-heggelbach.de/energie

Hostettler, T. (2020). *Solar energy market survey 2019*. Swissolar. https://www.swissolar.ch/fileadmin/user_upload/Markterhebung/Marktumfrage_2019.pdf

Hostettler, T., & Hekler, A. (2021). *Statistics on solar energy reference year 2020*. Swiss Federal Office of Energy, Bern. https://pubdb.bfe.admin.ch/de/publication/download/10539

Hostettler, T., & Hekler, A. (2022). *Statistics on solar energy reference year 2021*. Swiss Federal Office of Energy, Bern. https://pubdb.bfe.admin.ch/de/publication/download/10986

Hostettler, T., & Hekler, A. (2023). *Statistics on solar energy reference year 2022*. Swiss Federal Office of Energy, Bern. https://pubdb.bfe.admin.ch/de/publication/download/11461

Jäger, M., & Anderegg, D. (2023). *Potential analysis of agrivoltaics in the canton of Schaffhausen*. Zurich University of Applied Sciences ZHAW.

Jäger, M., Vaccaro, C., Boos, J., Junghardt, J., Strebel, S., Anderegg, D., Rohrer, J., & Schibli, B. (2022). *Feasibility study on agrivoltaics in Swiss agriculture.* https://doi.org/10.21256/zhaw-25624

Meteotest. (2022). *GHI (TMY) raster dataset, 100m resolution, annual and monthly totals*.

Next2Sun. (2020). *Opening of Next2Sun's first commercial agrivoltaic system in Donaueschingen with prominent guests and live demonstration. Press release.*

Trommsdorff, M., Kang, J., Reise, C., Schindele, S., Bopp, G., Ehmann, A., Weselek, A., Högy, P., & Obergfell, T. (2021). Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany. *Renewable and Sustainable Energy Reviews*, *140*, 110694. https://doi.org/10.1016/j.rser.2020.110694

Wang, J. (2022). *Assessment of Agrivoltaics for the Transition of the Swiss Electricity System*.

Appendix

Table 7: Allocation of the management status per agricultural area according to identifier 153 for the calculation of Agri-PV potential. The column "considered" shows whether the areas are categorised as potentially suitable. The areas with management status BFF and summering areas were primarily excluded. Areas with standard trees and some special cases were also excluded.

Code	Designation	Management status	considered
501	Spring barley	Open arable land	Yes
502	Winter barley	Open arable land	Yes
504	Oats	Open arable land	Yes
505	Triticale	Open arable land	Yes
506	Mischel feed grain	Open arable land	Yes
507	Feed wheat according to swiss granum variety list	Open arable land	Yes
508	Grain maize	Open arable land	Yes
510	Durum wheat	Open arable land	Yes
511	Emmer, einkorn	Open arable land	Yes
512	Spring wheat (excluding feed wheat of the...	Open arable land	Yes
513	Winter wheat (excluding feed wheat of the...	Open arable land	Yes
514	Rye	Open arable land	Yes
515	Mischel bread grain	Open arable land	Yes
516	Spelt	Open arable land	Yes
519	Seed maize (contract farming)	Open arable land	Yes
520	Dried rice	Open arable land	Yes
521	Silage and green maize	Open arable land	Yes
522	Sugar beet	Open arable land	Yes
523	Fodder beet	Open arable land	Yes
524	Potatoes	Open arable land	Yes
525	Seed potatoes (contract farming)	Open arable land	Yes
526	Spring rape for edible oil production	Open arable land	Yes
527	Winter oilseed rape for edible oil production	Open arable land	Yes
528	Soya	Open arable land	Yes
529	Wet rice	Open arable land	No
531	Sunflowers for edible oil production	Open arable land	Yes
534	Flax	Open arable land	Yes
536	Beans and vetches for grain production	Open arable land	Yes
537	Peas for grain production	Open arable land	Yes
538	Lupins	Open arable land	Yes
539	Oil pumpkins	Open arable land	Yes
540	Chickpeas	Open arable land	Yes
541	Tobacco S	Open arable land	Yes
543	Grain ensiled	Open arable land	Yes
544	Camelina	Open arable land	Yes
545	Annual outdoor vegetables, without preserves...	Open arable land	Yes
546	Outdoor tinned vegetables	Open arable land	Yes
547	Roots of the forcing chicory	Open arable land	Yes
548	Buckwheat	Open arable land	Yes
551	Annual berries (e.g. strawberries)	Open arable land	Yes
552	Annual renewable raw materials	Open arable land	Yes
553	Annual aromatic and medicinal plants	Open arable land	Yes
554	Annual outdoor horticultural crops	Open arable land	Yes

556	Coloured fallow land	BFF	No
557	Rotating fallow	BFF	No
559	Fringe on arable land	BFF	No
566	Poppy seeds	Open arable land	Yes
567	Safflower	Open arable land	Yes
568	Lenses	Open arable land	Yes
569	Mixtures of beans...	Open arable land	Yes
570	Mixtures of lenses...	Open arable land	Yes
572	Beneficial insect strips on open arable land	BFF	No
573	Mustard	Open arable land	Yes
574	Quinoa	Open arable land	Yes
575	Hemp for using the seeds	Open arable land	Yes
576	Hemp for fibre use	Open arable land	Yes
577	Other hemp	Open arable land	Yes
578	Millet for grain production	Open arable land	Yes
579	Millet for use whole plant	Open arable land	Yes
580	Sorghum for grain production	Open arable land	Yes
581	Sorghum for use whole plant	Open arable land	Yes
590	Spring rape as a renewable raw material	Open arable land	Yes
591	Winter oilseed rape as a renewable raw material	Open arable land	Yes
592	Sunflowers as a renewable raw material	Open arable land	Yes
594	Open arable land, eligible, BFF	BFF	No
595	Other open arable land	Open arable land	Yes
597	Other open arable land, eligible for contributions	Open arable land	Yes
598	Remaining open arable land, non-contrib...	Open arable land	Yes
601	Artificial meadows (without pastures)	Open arable land	Yes
602	Other artificial meadow, eligible for contribution	Open arable land	Yes
611	Extensively used meadows (without pastures) BFF	BFF	No
612	Less intensively utilised meadows (without pastures)	BFF	No
613	Other permanent meadows (without pastures)	Permanent grassland	Yes
616	Pastures (home pastures, other pastures without summer pastures)	Permanent grassland	Yes
617	Extensively used pastures BFF	BFF	No
618	Wooded pastures (without wooded area) BFF	BFF	No
621	Hay meadows in summering areas, other meadows	Summering area	No
622	Hay meadows in summering areas, extensive type	BFF	No
623	Hay meadows in the summering area, type little int...	BFF	No
625	Wooded pastures (without wooded area)	No LN	No
631	Forage legumes for seed production	Open arable land	Yes
632	Forage grasses for seed production	Open arable land	Yes
635	Riparian meadows (without willows) BFF	BFF	No
693	Region-specific biodiversity promotion area	BFF	No
694	Region-specific biodiversity promotion area	BFF	No
697	Other green space (permanent green space), contributing...	Permanent grassland	Yes
698	Other green space (permanent green areas), not used...	Permanent grassland	Yes
701	Vines	Permanent culture	Yes
702	Orchards (apples)	Permanent culture	Yes
703	Orchards (pears)	Permanent culture	Yes
704	Orchards (stone fruit)	Permanent culture	Yes
705	Perennial berries	Permanent culture	Yes

706	Perennial aromatic and medicinal plants	Permanent culture	Yes
707	Perennial renewable raw materials (China...	Permanent culture	Yes
708	Hops	Permanent culture	Yes
709	Rhubarb	Permanent culture	Yes
710	Asparagus	Permanent culture	Yes
711	Mushrooms (open field)	Permanent culture	Yes
712	Christmas trees	Permanent culture	No
713	Nursery of forest plants outside ...	Permanent culture	No
714	Ornamental shrubs, ornamental trees and ornamental perennials	Permanent culture	No
717	Vineyards with natural biodiversity BFF	BFF	No
718	Truffle plants	Permanent culture	No
719	Mulberry plants (feeding silkworms)	Permanent culture	No
720	Well-tended Selven (chestnut trees)	Permanent culture	No
721	Perennial outdoor horticultural crops	Permanent culture	Yes
722	Nurseries of vines	Permanent culture	Yes
723	Fruit and berry nurseries	Permanent culture	Yes
724	Other tree nurseries (roses, ornamental perennials, etc.)	Permanent culture	Yes
725	Permaculture	Permanent culture	Yes
730	Orchards aggregated	Permanent culture	Yes
731	Other orchards (kiwi, elderberry, etc.)	Permanent culture	Yes
735	Vines (region-specific biodiversity promo...	BFF	No
750	Other permanent crops, eligible for contributions, agg...	Permanent culture	Yes
797	Other areas with permanent crops, contribut...	Permanent culture	Yes
798	Other areas with permanent crops, not contributing...	Permanent culture	Yes
801	Vegetable crops in greenhouses with fixed ...	Protected cultivation	Yes
802	Other speciality crops in greenhouses with ...	Protected cultivation	Yes
803	Horticultural crops in greenhouses with f...	Protected cultivation	Yes
804	Berry cultures in greenhouses with solid soil...	Protected cultivation	Yes
807	Other speciality crops in protected cultivation o...	Protected cultivation	Yes
808	Horticultural crops in protected cultivation without...	Protected cultivation	Yes
810	Mushrooms in protected cultivation with a firm foundation...	Protected cultivation	Yes
811	Vegetable crops in protected cultivation without ...	Protected cultivation	Yes
812	Vegetable crops in protected cultivation without ...	Protected cultivation	Yes
813	Berry crops in protected cultivation without fixed...	Protected cultivation	Yes
814	Berry crops in protected cultivation without fixed...	Protected cultivation	Yes
830	Crops in year-round protected cultivation, with...	Protected cultivation	Yes
847	Other crops in protected cultivation without fixed...	Protected cultivation	Yes
848	Other crops in protected cultivation with fixed...	Protected cultivation	Yes
849	Other crops in protected cultivation without fixed...	Protected cultivation	Yes
851	Litter areas in the LN BFF	BFF	No
852	Hedge, field and riparian woodland (with herbaceous...	BFF	No
857	Hedge, field and riparian woodland (with buffer str...	BFF	No
858	Hedge, field and riparian woodland (with buffer str...	BFF	No
897	Remaining areas within the LN, contribut...	Permanent culture	Yes
898	Remaining areas within the LN, non-contrib...	Permanent culture	Yes
901	Forest	No LN	No
902	Other unproductive areas (e.g. mulched fields)...	No LN	No
903	Areas without a main agricultural purpose are...	No LN	No
904	Ditches, ponds, pools BFF	BFF	No

905	Ruderal areas, cairns and stone walls BFF	BFF	No
906	Dry stone walls BFF	BFF	No
907	Unpaved, natural paths	No LN	No
908	Region-specific biodiversity promotion area	BFF	No
909	Home gardens	No LN	No
911	Agricultural production in buildings	Protected cultivation	Yes
921	Standard fruit trees (areas only) BFF	BFF	No
922	Nut trees (areas only) BFF	BFF	No
923	Chestnut trees in well-tended meadows	BFF	No
924	Native, site-appropriate individual trees and...	BFF	No
926	Other trees	Permanent culture	No
927	Other trees (region-specific biodiversity...	BFF	No
928	Other elements (region-specific biodiversity,...	BFF	No
930	Summer pastures	Summering area	No
933	Communal pastures	Summering area	No
935	Hay meadows with supplementary feeding during the summer...	Summering area	No
936	Scattered areas in the summering area	Summering area	No
950	Field protection strips BFF	BFF	No
951	Cereals in wide rows BFF	BFF	No
998	Other areas outside the LN and SF	No LN	No

Table 8: Potential of Agri-PV per canton, taking into account the exclusion criteria, incl. areas with maize cultivation.

Canton	Potential in TWh/y	Share of total potential in %
Berne	59.6	18.4
Vaud	50.2	15.5
Fribourg	34.4	10.6
Zurich	25.9	8.0
Lucerne	21.6	6.7
Aargau	21.1	6.5
Thurgau	20.4	6.3
St.Gallen	16.9	5.2
Solothurn	10.2	3.2
Wallis	9.4	2.9
Grisons	9.4	2.9
Jura	9.4	2.9
Basel-Landschaft	6.1	1.9
Geneva	5.1	1.6
Neuchatel	4.9	1.5
Schwyz	4.1	1.3
Ticino	2.8	0.9
Appenzell Ausserrhoden	2.2	0.7
Zug	2.0	0.6
Schaffhausen	1.7	0.5
Obwalden	1.6	0.5
Appenzell Innerrhoden	1.4	0.4
Glarus	1.4	0.4
Uri	0.9	0.3
Nidwalden	0.7	0.2
Basel City	0.1	0.2