Empowering farmers in Central Europe: the case for agri-PV

Unlocking the vast potential of agri-PV brings benefits for farmers and energy systems in Central European countries.

Published date: 29.08.2024

Authors: Dr Paweł Czyżak and Tatiana Mindeková

Contents

About

This report explains the key benefits of agri-PV and examines the agri-PV potential in selected countries in Central Europe: Czechia, Hungary, Poland and Slovakia. By analysing crop yield impacts and electricity generation opportunities, the paper provides land use efficiency estimates. Agri-PV policies in different European countries are compared, providing best practices and recommendations for countries that have not yet introduced agri-PV legislation.

Highlights

16%

Agri-PV can increase crop yields by up to 16%. Land is used more efficiently thanks to combined electricity and food production.

180 GW

Central Europe countries could deploy 39 GW of agri-PV above shade benefitting crops. Vertical solar panels between cereals can add 141 GW.

3x

Central Europe could produce 191 TWh of clean power from agri-PV, almost tripling the current renewable electricity generation (73 TWh).

Executive Summary

Agri-PV presents a growing opportunity for Central Europe

Combining Central Europe's agricultural backbone with solar electricity can bring benefits to farmers and the wider economies, while optimising the use of precious land.

Agri-PV - the combined use of land for food production and solar electricity generation - can bring significant benefits for farmers, providing solutions to some of the demands tabled during the 2024 farmers' protests. Czechia's recent introduction of agri-PV legislation started a debate on the topic, but the potential of agri-PV remains unrecognised in Central Europe, and countries like Hungary, Poland and Slovakia are still lacking regulatory frameworks.

Several years of intensive research across Europe and beyond has shown that agri-PV can increase crop yields by up to 16% in the case of fruits or berries. With less shade-tolerant crops like wheat, yield losses are kept below 20% thanks to vertical solar panels with wide row spacing. The added revenues from the sale of electricity far outweigh the reduced revenues from grains. A case study shows that an annual profit of €1268 per hectare is possible from combined electricity and wheat sales. This contrasts with traditional wheat production (without agri-PV) that is estimated to be generating net losses in 2024.

Ember's analysis reveals that Czechia, Hungary, Poland and Slovakia could deploy a total of 180 GW of agri-PV and almost triple Central Europe's annual renewable electricity production from 73 TWh to 191 TWh. Using just 9% of that generation could cover the entire electricity needs of farming and food processing. Consequently, agri-PV would significantly contribute to the 2030 solar capacity targets set in the revised National Energy and Climate Plans. These equate to 60 GW for the four countries combined, compared to the current 25 GW of total installed solar capacity.

Introducing legislation to enable agri-PV would benefit both energy and food security across Central Europe and beyond.

01 Agri-PV can increase crop yields by up to 16% and drive farmers’ profits

Agri-PV above fruits and berries increases yields by up to 16% and produces 63% of the electricity of a traditional solar farm (per hectare). Land use efficiency can reach 178% compared to plots used separately for solar or agricultural purposes. Even less shade-tolerant crops, such as wheat, still achieve 80% or more of their typical yield and grain losses are more than offset by revenues from the sale of electricity.

02 Central Europe could almost triple its current renewable electricity generation with agri-PV

The combined potential of agri-PV generation across Central Europe countries is 191 TWh - 10 times more than the electricity demand from agriculture and food processing (17 TWh). This is also equivalent to 68% of today’s electricity demand in Czechia, Hungary, Poland and Slovakia and almost three times the countries’ combined current renewable electricity generation (73 TWh).

03 Central European countries could install 180 GW of agri-PV if enabled by legislation

Shade-benefitting crops alone, such as berries, could be covered by 39 GW of agri-PV. Vertical solar panels between cereals could add another 141 GW. The agri-PV capacity also brings benefits for power grid balancing. Czechia is the only Central European country that has agri-PV legislation.

Far from reducing food production, agri-PV actually increases yields for some crops. Agri-PV combines the best of both worlds - electricity and food production, preserving precious land for agriculture, yet still enabling the energy transition to move forward, benefitting societies and economies. Governments in Czechia, Hungary, Poland and Slovakia can capitalise on the agri-PV opportunity, increasing food and energy security while simultaneously combating the climate and cost of living crises.

Dr Paweł Czyżak
Regional Lead - CEE, Ember

Our project was launched at the beginning of May 2024 on an area of 2,000 m2 on land that was revitalised after oil extraction. A total of 1,500 seedlings of Riesling and Donauriesling varieties were planted under the PV plant in a 2 x 0.6 m spacing. In our experience, the agri-PV has not been known to adversely affect the growth of the seedlings compared to comparable vineyards planted this year outside the agri-PV and we were able to use the soil preparation machines in the row spacing and between the seedlings without any problems. However, excessive soil compaction by construction machinery must be avoided during PV construction. The PV panels must be installed in such a way that the water does not flow directly onto the seedling row but into the inter-row grassed area due to soil erosion.

Pavel Mikuš
Vine farmer from Hodonín, Czechia

Agri-PV brings benefits for farmers

The benefits of agri-PV span from crop protection, higher yields and increased profits for farmers to easier grid balancing and reduced curtailment of solar power.

Agri-PV, also known as agrivoltaics, involves the simultaneous cultivation of crops and production of solar electricity on the same land with a primary focus on food production. Solar panels are placed in a way that does not compete with the crops - either above crops that benefit from shading, like berries, or between crops to enable the use of farming machinery. In the latter case, any reduction in crop yields is offset by revenues from the sales of solar electricity.

Utilising agri-PV technology offers numerous benefits for crops as it can create a modified microclimate beneath the solar panels by altering factors like air temperature, relative humidity, wind speed, wind direction and soil moisture. It shields crops from both excessive solar radiation and adverse weather conditions, such as hail, and promotes more efficient water usage, potentially reducing water consumption and stabilising yields during dry years. Furthermore, agri-PV helps farmers sustain their businesses and protects agricultural land from being converted into other uses, while supporting biodiversity and contributing to climate change mitigation through sustainable agricultural practices.

This is particularly important in Central Europe. The four countries cover 19% of the EU's arable land and produce substantial volumes of certain crops - 20% of the bloc's wheat, 29% of oats, 37% of rye and 57% of berries. This food production is now at risk due to declining financial conditions for farmers, the volatility of fertiliser prices and the impacts of climate change.

What is agri-PV?

Agri-PV combines agriculture with solar electricity generation, enhancing crop quality and yield, optimizing land use, and providing bill savings or additional revenues for farmers.

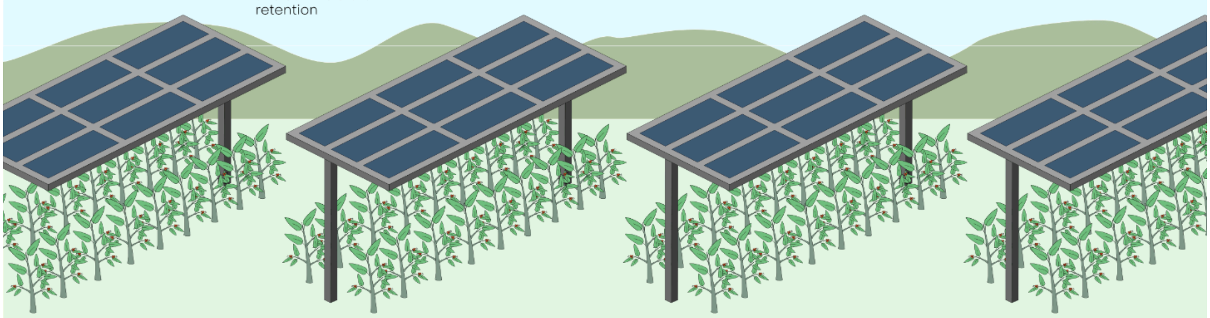
Improved microclimate conditions
Shade and temperature regulation, frost protection

Optimised water usage and efficient irrigation
Reduced evaporation and soil moisture retention

Protection from extreme weather events
Shielding crops from strong winds, hail and excessive rainfall

Reduced pest and disease pressure
Supports integrated pest management strageties

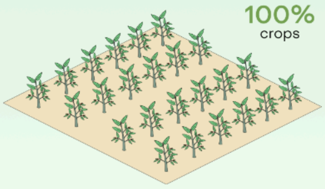
Clean electricity
For farmers' self-consumption or additional revenues



Types of agri-PV systems

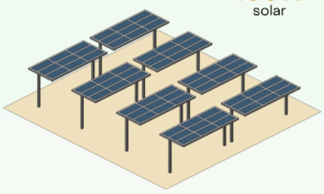
Agri-PV comes in different shapes and sizes, ranging from small solar greenhouses to utility-scale solar farms. The two main categories are described below.

Before agri-PV
Land is used either exclusively for crops or for solar panels



100%
crops

or



100%
solar

A Overhead agri-PV
Growing shade-tolerant crops underneath solar panels

land use efficiency

63% solar + 90–116% crops = 153–178% total efficiency

suitable for

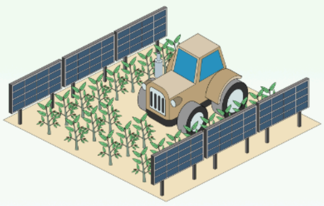
Fruits *Apples, apricots, grapes*

Leafy greens *Lettuce, spinach, kale, arugula*

Fruity vegetables *Cucumbers, peppers, tomatoes*

Berries *Strawberries, raspberries*

B Interspaced agri-PV
Growing crops between vertical solar panels, with enough row spacing to accommodate farming machinery



land use efficiency

25% solar + 83–113% crops = 108–123% total efficiency

suitable for

Root vegetables *Carrots, radishes, beets, turnips*

Cereals *Wheat, oat, barley*

Forages *Grasses*

Source: Ember

EMBER

Agri-PV systems can range from solar greenhouses, through overhead solar above fruit and berry plantations, to industrial-scale interspaced solar between main crops like wheat or oats. In overhead systems, a clearance of two to four metres ensures sufficient space for plants underneath. In interspaced systems, row-to-row spacing can exceed 10 metres to accommodate farming machinery. Solar trackers, which vary the position of the panels in relation to the sun, are often installed to optimise both electricity production and crop shading patterns.

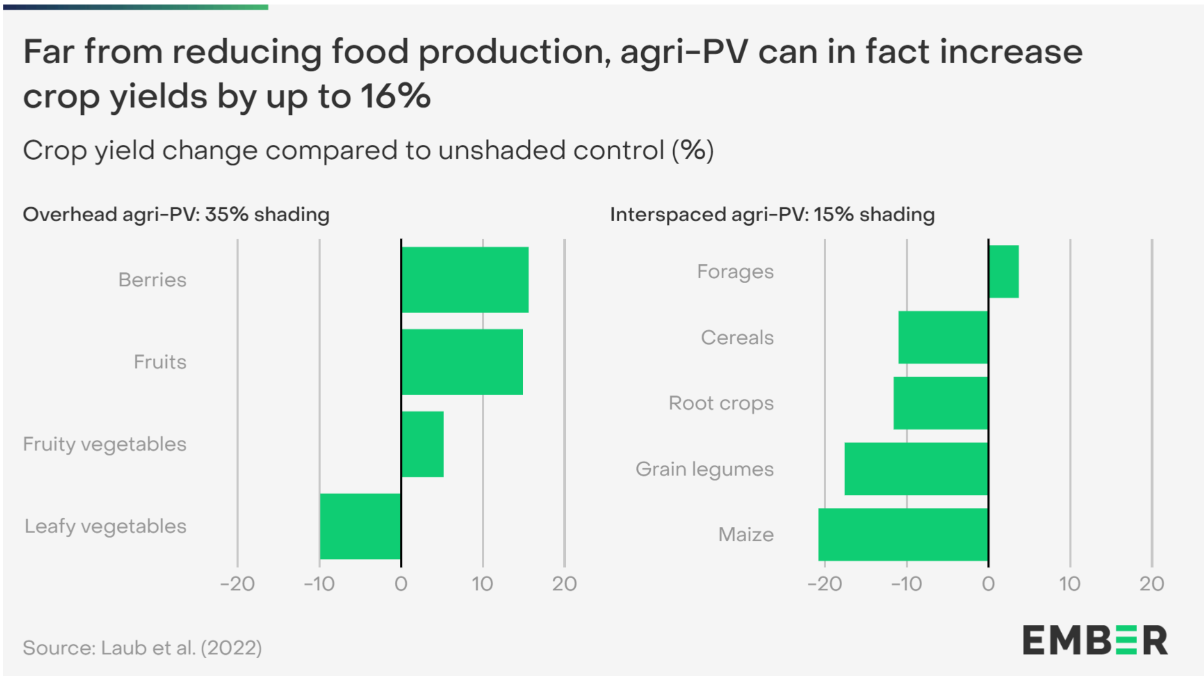
Agri-PV also brings electricity system benefits, enabling more solar power to be delivered into the grid at higher prices. The agri-PV solar panels are frequently east-west-oriented as opposed to south-facing like much of the traditional solar. As a result, their daily electricity generation profile is wider, with a lower midday peak and greater efficiency during cooler times of the day. This makes grid balancing easier, reducing curtailment and increasing capture rates (prices received for electricity). Vertical agri-PV systems have the added benefit of fully utilising the bifacial features of modern solar panels - reaching comparable capacity factors to traditional ground-mounted solar farms despite an east-west orientation.

In countries where legislative frameworks for agri-PV have been introduced, it has resulted in rapid deployment of new agri-PV projects. In Germany, France, Italy and the Netherlands, regulations allow the shared use of land for agriculture and electricity production without the loss of farming subsidies. This has led to over 200 agri-PV projects already being installed across Europe. Agri-PV is also gaining momentum in Australia, India, China, Canada and the USA.

Agri-PV can increase crop yields by up to 16% and drive farmers' profits

While solar energy and farming are often seen as incompatible, agri-PV systems can in fact increase crop yields for certain types of plants. This varies depending on the location, type of crop and weather conditions. Metastudies such as Laub et. al. show that crop yields for berries or fruits can increase by 15-16% under 35% shade, compared to an unshaded reference. This makes them a perfect fit for overhead agri-PV systems.

Crops such as cereals (e.g. wheat, rye, oats), maize and root vegetables, are more sensitive to shading. With 15% shading, cereals will decrease in yield by 11%, root crops by 12%, maize by over 20%. Forages (mostly grasses) can increase by 4%. All of these crops can be combined with interspaced agri-PV - a row-to-row spacing of around 10 metres limits the shading in these systems to between 10% and 20% (depending on location and panel height), guaranteeing at least 80% crop yields compared to a reference.



The benefits to crops of agri-PV have already been demonstrated in several projects. For instance, the APV-RESOLA project in Germany revealed that in 2018, potato, celery and winter wheat cultivated using the agri-PV system outperformed the reference yields. Celery showed the highest yield increase, achieving a 12% gain compared to the reference. In regions with high solar radiation, such as Spain, leafy vegetables (lettuce) that would normally suffer from shading, did not show signs of reduced yields and in one case increased yields were achieved. A pilot project with a 1 GW capacity is now also planned in Poland, while in Czechia, a pilot project focused on assessing the effects of agri-PV is already underway.

AGV Litomyšl - one of the first agri-PV projects in Central Europe

While most agri-PV projects have been installed in Western Europe, in Czechia, Školky Litomyšl is implementing a power plant above vegetable and berry crops with an expected output of up to 6 MWp over 7 hectares. The project is testing the cultivation of fruits, such as raspberries, under horizontally placed photovoltaic panels that partially transmit solar radiation. Results from the project can provide evidence for other Central European countries that are still lacking agri-PV legislation.

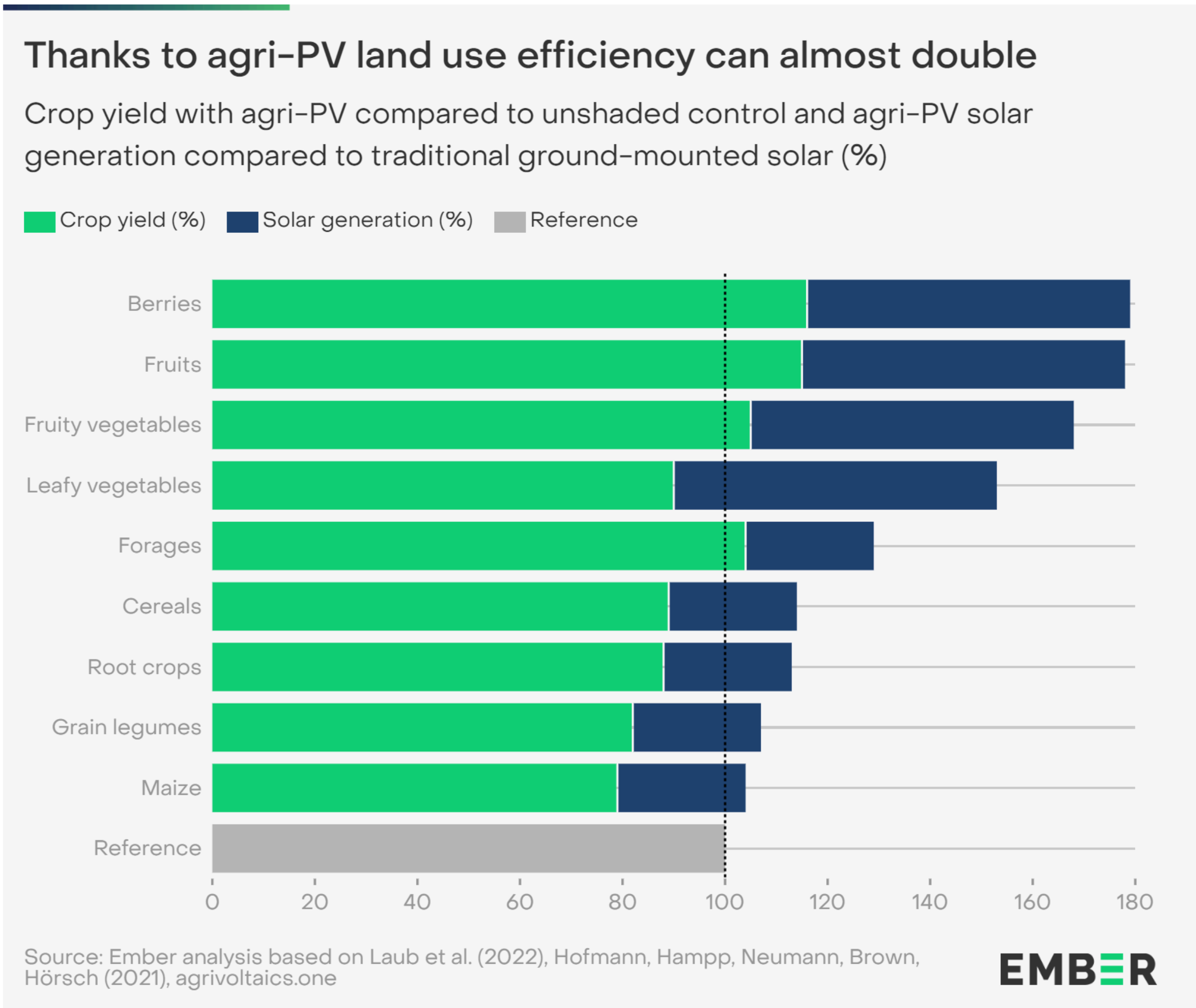
Even with the most shade-sensitive crops, the returns from electricity generation significantly outweigh any loss in crop yields.

A project in Poland shows that annual revenues from 1 hectare of agri-PV can be 12 to 15 times higher (€20,000 to €26,000) than from wheat crops alone (€1700). An annual profit of €1268 to €7300 per hectare is possible from electricity sales, depending on the electricity price (average 2023 auction price - average wholesale 2023 price adjusted for capture rate). Traditional wheat production (without agri-PV) is estimated to be generating net losses of €97/ha in 2024. Subsidies should still be applicable to land covered with agri-PV as, while electricity production might be more profitable than agriculture, it is critical to preserve farming activities on agricultural land to both ensure food security and support farming communities.

The above calculations are dependent on future electricity price assumptions, but the minimum value using Polish renewables auction prices can be treated as conservative - it is achievable within the current legal framework and stabilises revenues for investors for a fifteen year period. The financing costs and final profits for each project will be dependent on the business and ownership model.

It is important to note that the capital expenditure for agri-PV projects is higher than for traditional ground-mounted solar farms, especially with regards to the mounting system. An estimate of the levelized cost of electricity (LCoE) over a twenty year period shows that overhead agri-PV with 2.1 to 4 metres clearance height can be around 40% higher than for ground-mounted PV, for interspaced agri-PV this is around 11%. Both types of agri-PV are much cheaper (40-50%) than rooftop solar.

The combined production of food and electricity means that the efficiency of land use is significantly increased compared to the use of land purely for farming or energy purposes. This efficiency is measured as a sum of solar electricity generation compared to a traditional ground-mounted solar farm plus the crop yield compared to an unshaded reference. Depending on crop type, the results can reach 170-180% for berries, fruits and fruity vegetables and 110-130% for root vegetables, cereals and forages. Even the least shade tolerant crop, maize, reaches 104% land use efficiency, showing that agri-PV will be more productive than the traditional approach of separating ground-mounted solar and farming.



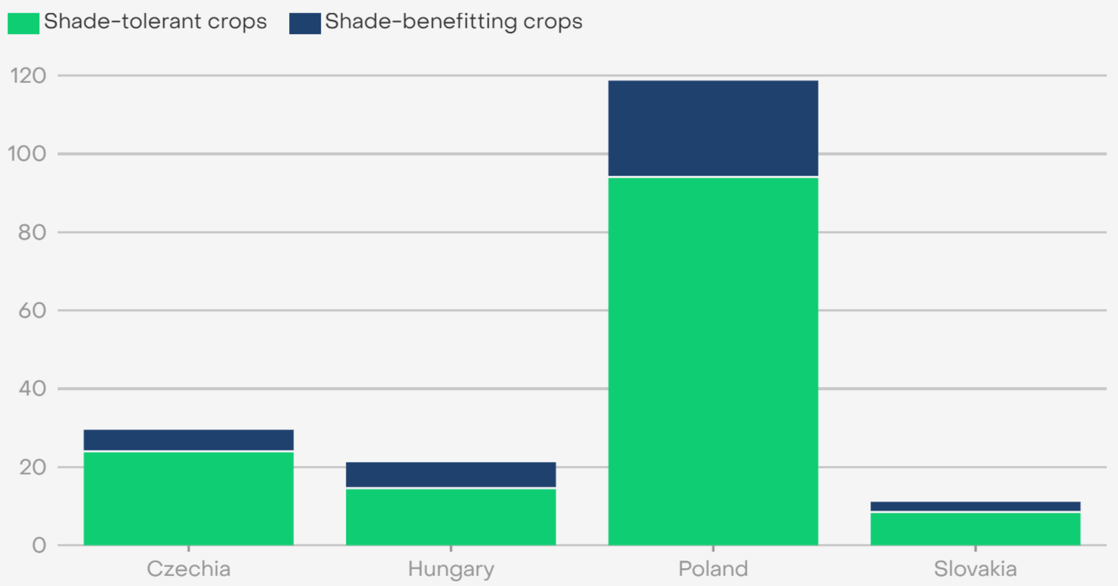
Solar generation from agri-PV varies depending on multiple parameters - height, row spacing, tilt, geographic location, panel orientation, transparency, bifaciality ratio and tracking. The relative generation compared to a traditional solar farm ranges from 25% for interspaced agri-PV to 63% for overhead agri-PV. The lower solar generation is predominantly due to the fact that less solar capacity can be installed per hectare. Typically, capacity of 1 MW per hectare is assumed for traditional solar farms compared with 0.3 MW/ha to 0.7 MW/ha for agri-PV, as indicated by Fraunhofer ISE and confirmed by shading analysis. Capacity factors were calculated using atlite for each analysed country, assuming bifacial east-west vertical panels for interspaced agri-PV and a 15 degrees tilted east-west overhead system. All assumptions are provided in the Methodology section of this report.

Central Europe could almost triple its current renewable electricity generation with agri-PV

Central Europe has substantial untapped agri-PV potential. Ember's spatial analysis indicates that Czechia, Hungary, Poland and Slovakia could deploy 180 GW of agri-PV, 39 GW above shade-benefitting crops such as berries and 141 GW of vertical solar panels placed between cereals.

The additional solar capacity could produce 191 TWh of clean electricity annually. This is equivalent to 68% of current electricity demand in Czechia, Hungary, Poland and Slovakia and almost three times their combined renewable electricity generation (73 TWh).

The agri-PV potential of Central European countries can reach 180 GW, with 39 GW above shade-benefitting crops



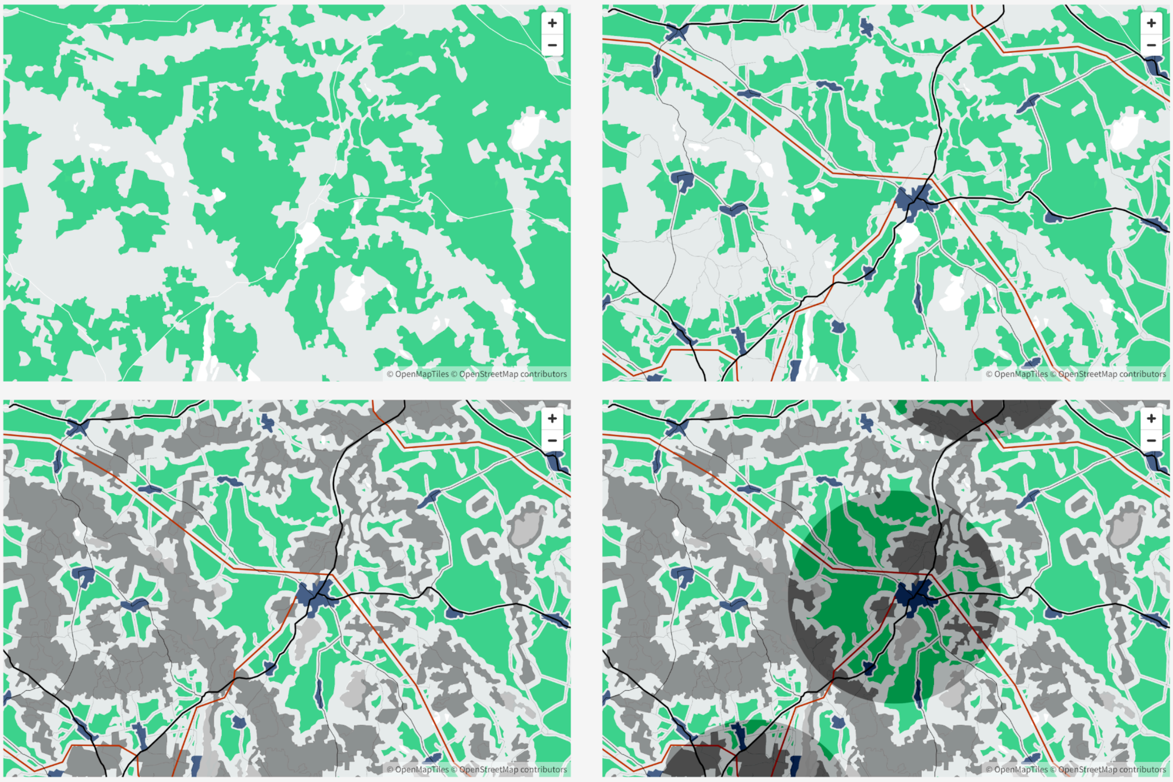
Source: Ember spatial analysis using GLAES and Laub et al. (2022), agrivoltaics.one, Ryberg, Robinius, Stolten (2018)
Shade-tolerant crops include cereals, shade-benefitting crops include fruits, berries and forages

EMBER

The calculated agri-PV potential incorporates important spatial planning considerations - such as buffer zones around roads, railways, power lines, buildings, forests, bodies of water and natural protection areas. It also prioritises areas within five kilometres of a grid connection point - a high to medium-voltage substation - a distance suggested by solar project developers for medium sized projects. This analysis builds on the report authors' previous work and uses the GLAES tool following a methodology first introduced by Ryberg, Robinius and Stolten in 2018, later adopted by the European Commission, and modified to account for the special case of agri-PV. All spatial constraints and data sources are detailed in the Methodology section of the report.

The potential of agri-PV is calculated by considering multiple spatial constraints and crop shading tolerance

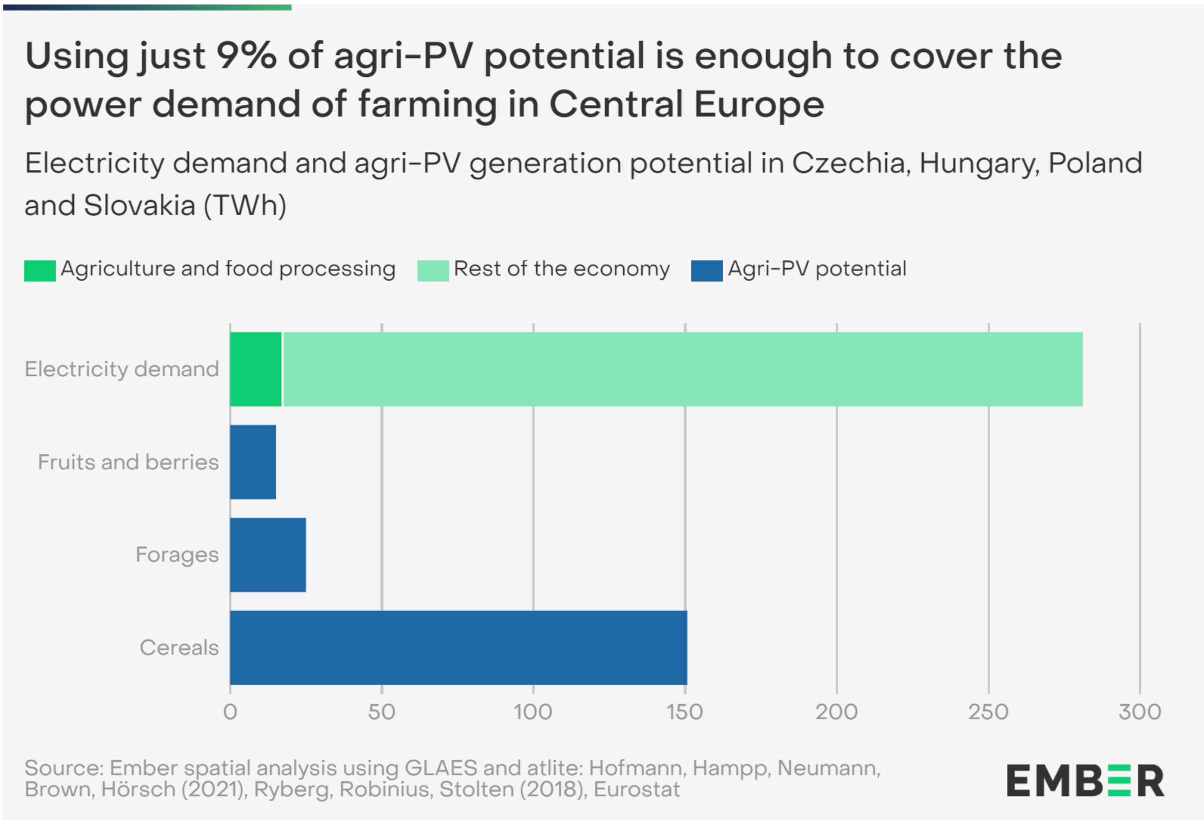
Agri-PV is deployed on arable land with buffers around roads, power lines, settlements, forests or water, and in close proximity to grid connection point



Source: Ember

EMBER

The calculated potential of agri-PV is over ten times higher than the current electricity demand from agriculture and food processing (17 TWh) in the analysed countries. This means that unlocking just 9% of the agri-PV potential is enough to cover the farming sector's entire electricity needs. Overhead agri-PV above fruits and berries alone could generate 15 TWh - covering 87% of that demand.



The agriculture and food processing sectors are typically not the biggest consumers of electricity - combined, they were responsible for 6% of total 2022 electricity demand in Central Europe. Agriculture uses vast amounts of oil and gas, but around 55% of energy inputs come from indirect sources, and are therefore underreported. The sector and its supply chains are already being electrified, with electric tractors being introduced and electrolysis proposed for fertiliser production, making the case for agri-PV even stronger.

Electrification of agriculture will bring additional benefits - stabilising fertiliser prices and lowering dependence on imported fossil fuels. Those factors have proven to be major risks for food security, translating directly into a surge in food prices and the cost of living since 2021.

Legislation is key to harnessing agri-PV's potential and benefits

The lack of an EU-harmonised definition of agri-PV means that Member States are responsible for defining the concept and introducing relevant legislation. This legislation needs to ensure that agricultural land retains its characteristics following any installation of agri-PV systems so that it remains eligible for agricultural subsidies under the Common Agricultural Policy.

Facilitating the deployment of agri-PV will require efficient spatial planning and simplification of permitting and grid connection procedures. It is also important that erosion and damage of the soil is avoided and the dismantling of the PV systems is done without any permanent damage to the land.

In Europe, countries with the highest number of agri-pv projects are Germany, France, Italy and the Netherlands. Germany introduced the first technical standard providing clear guidelines for defining specific agrivoltaic systems already in 2021. In the subsequent legislative modifications, agri-PV was also supported economically. Projects were made eligible for guaranteed grid access and feed-in tariffs provided by the Renewable Energies Act (EEG) and, in certain cases, agri-PV projects can receive a technology bonus for each kWh. According to the recent survey, more than 70 % of farmers in Germany are now willing to implement the technology.

Overview of agri-PV definitions

Country	Definition	Reference
France	Photovoltaic installations compatible with the exercise of an agricultural activity. An installation will only be recognised as agrivoltaic if it offers at least one of services: improvement of agronomic potential and impact, adaptation to climate change, protection against climatic hazards, improvement of animal welfare.	Decree No. 2024-318
Germany	Agri-PV is a multifunctional land use configuration on one and the same agricultural land area where solar power generation is integrated into an agricultural activity.	DIN SPEC 91434 , DLR
Italy	Agrivoltaic system - adopts solutions aimed at preserving the continuity of agricultural and pastoral farming activities, on installation site. Advanced agrivoltaic system - innovative integrative solutions with the assembly of the PV (with rotation and monitoring systems).	Official guidelines
Netherlands	No legal definition but municipalities allow the projects that can serve as the protection for the crops. As long as the area for the agricultural function does not change, the installation of solar panels has no consequences for agricultural rights.	JRC
Czechia	Agrivoltaics is "building for agriculture" – possibility to place on "agricultural areas" in zoning plans.	Regulation 334/1992 Call
Slovakia	no legal definition or official guidelines	
Poland	no legal definition or official guidelines	
Hungary	no legal definition or official guidelines	

EMBER

The recently approved regulation in Czechia shows that the necessary regulatory changes are achievable in Central Europe. The Czech approach to agri-PV serves as a good example of how to facilitate projects while avoiding both negative impacts on stakeholders and increased bureaucracy. The definition of agri-PV, as approved in May 2024, ensures that it will not be necessary to remove land from the agricultural land fund to facilitate solar electricity generation. It is also now possible to permit an agri-PV system as a construction for agriculture that can be placed on agricultural land without changing the spatial plan. Unfortunately, Czechia's current legislation excludes agri-PV systems in between cereals or grasses, cutting the potential agri-PV capacity by 96% and missing out on 21 TWh of clean electricity.

To ensure the best outcome for agri-PV projects, the process of legislative changes needs to be accompanied by close cooperation with the farmer and ministries and by utilising years of experience from countries with successful agri-PV farms. Typically, legislators aim to ensure a minimum relative crop yield, while also introducing constraints on the design of the solar installation. But, as highlighted by Dupraz (2023), these two requirements are not always aligned, and often do not account for different crop types or provide guidance on the relative crop yield measurements.

Regulatory requirements of agri-PV projects

Feature	Min. relative crop yield	Max. lost area	Min. clearance height	Supported types of crops
France	90 %	10 %	to allow normal operation	not specified
Germany	66 %	10 % in overhead installations, 15 % in vertical installations	2,10 m	not specified
Italy	60 %	30 %	2,10 m	not specified
Netherlands	not specified	not specified	not specified	not specified, most of the projects focus on the berry crops
Czechia	not specified	draft of secondary legislation suggests: 5 % for horizonal type, 20 % for vertical type	2,1 m	wineyards, hopyards, orchards, tree nursery, crops in containers

EMBER

Ultimately, agri-PV legislation should prioritise and incentivise continued food production, allowing farmers to reap the benefits of agri-PV systems for their crops and financial conditions.

Conclusion

Agri-PV is a win-win solution that needs to be unlocked

The many benefits of agri-PV are being acknowledged across Europe. Countries like Czechia, Hungary, Poland and Slovakia can utilise agri-PV to reach their 2030 renewable electricity targets and support farming communities in the process.

Agri-PV can be an important enabler of the recently updated EU 2030 renewables target and national targets set in the revised NECPs, addressing challenges faced by ground-mounted solar: social acceptance, land availability, grid connection, balancing and reduced capture prices. At the same time, agri-PV is a response to the 2024 farmers' protests, allowing farmers to participate in and directly benefit from the energy transition.

Agri-PV needs to be unlocked by legislation to secure access to CAP subsidies for farmers that generate electricity. This is especially important in Central Europe. Despite the vast agri-PV potential, out of the over 200 projects across Europe, only three are located in Central and Eastern European countries. There is no doubt that tapping into that potential would bring benefits for both food and energy security. Governments in Hungary, Poland and Slovakia should join Czechia by introducing regulations that enable agri-PV.

Key recommendations

The following recommendations can provide guidance for governments looking to introduce agri-PV legislation, or, as in the case of Czechia, expand it to encompass multiple types of agri-PV systems.

1. **Benefits for farmers should be central**
   The economic benefits and the security of property and investments for farmers should be central to efforts promoting agri-PV, alongside raising public awareness and acceptance. Most importantly, farmers that take advantage of agri-PV still need to be supported by the Common Agricultural Policy subsidies.
2. **All types of agri-PV need to be included in the legislation**
   Excluding interspaced agri-PV from regulations significantly lowers the potential, despite evidence showing that negative impacts on crop yields can be limited. At the same time, agricultural land needs to be preserved for food production - e.g. through minimum crop yield requirements and their robust monitoring.
3. **Research and Development (R&D) needs to be supported**
   R&D programmes, along with pilot projects, are vital to overcoming technical challenges in the agri-PV sector. They should simultaneously take into consideration energy production, crop yield and biodiversity.
4. **Agri-PV targets should be set within CAP**
   Agri-PV should be assigned specific capacity targets and financial support within the individual Member States' CAP Strategic Plans.
5. **Investment subsidies are necessary to include farmers in the energy transition**
   With agri-PV in early stages of development across Central Europe, governments should consider CAPEX subsidies to lower entry barriers for farmers.

Supporting Materials

Country results

Detailed results of agri-PV potential mapping for each of the analysed countries are presented below. The methodology behind these results, as well as data sources, are described in the following section.

Capacity (GW)	Arable land				Fruits and berries	Pastures	Shade benefit (Fruits and berries + pastures)	Shade tolerance (Arable land)	**Total**
	Wheat	Barley	Oats	Rye					
Czechia	15.9	6.5	0.9	0.6	1.1	4.3	5.5	24.0	29.5
Hungary	10.9	3.0	0.3	0.4	3.4	3.3	6.6	14.6	21.2
Poland	44.8	12.7	18.5	18.1	11.4	13.3	24.6	94.1	118.8
Slovakia	5.9	2.2	0.2	0.2	0.2	2.4	2.6	8.5	11.1
Total	77.5	24.4	20.0	19.3	16.1	23.3	39	141	180

Generation (TWh)	Arable land				Fruits and berries	Pastures	Shade benefit (Fruits and berries + pastures)	Shade tolerance (Arable land)	**Total**
	Wheat	Barley	Oats	Rye					
Czechia	17.2	7.1	1.0	0.7	1.1	4.7	5.8	26.0	31.8
Hungary	12.8	3.5	0.4	0.4	3.5	3.8	7.3	17.0	24.3
Poland	46.8	13.3	19.3	18.9	10.3	13.9	24.2	98.3	122.6
Slovakia	6.4	2.4	0.3	0.2	0.2	2.6	2.8	9.3	12.1
Total	83.3	26.3	20.9	20.3	15.1	25.0	40.1	150.7	190.8

Methodology

Solar parameters for land use efficiency calculations

For the purpose of the calculations, the design of the agri-PV systems was chosen in such a way that meets the shading requirements of different crop types, as well as the standard regulatory requirements. As described in the main report after Laub et. al., crop yields for berries or fruits achieve their best performance under 30-35% shade. The overhead agri-PV system was chosen to meet those shading values in Central European latitudes. Shading analysis was performed using the agrivolatics.one tool from KU Leuven. An east-west orientation with a typical tilt angle of 15 degrees was chosen to provide both good shading conditions for crops, as well as to widen the generation profile to improve power system balancing and increase solar capture prices. The clearance height of three metres was chosen to accommodate both berries and small fruit trees. The transparency ratio was set to 22%, according to the recent product parameters of module producer Bisol. The row-to-row distance was then optimised to meet 35% shading level, as well as match the typical 0.7 MW/ha capacity to land ratio as indicated by Fraunhofer ISE.

Some countries require a minimum of 70-90% crop yield compared to a reference within their agri-PV legislative framework. For main crops like cereals, this is only possible with shading of 25% and less, which in turn translates to a ground coverage ratio (GCR) below 20% in traditional PV systems. Since the shading in vertical agri-PV panels varies significantly depending on the location - from 10%, through 15% to 20% for designs with around 10% GCR, the calculations assume a 10 metre row-to-row spacing. This resulted in a 0.25 MW capacity per hectare. This could be viewed as conservative, but it allows for the use of farming machinery such as combine headers. For most crops, this design guarantees a minimum of 80% crop yields compared to a reference

Solar generation was calculated by multiplying the capacity by the capacity factors calculated using atlite for each analysed country, using the same PV system designs (tilt, azimuth, bifacial factor).

All the parameters used in the shading and solar generation calculations are presented in the table below.

	Interspaced	Overhead
Latitude	52.0°	52.0°
Longitude	19.0°	19.0°
Azimuth	90°	90°
Tilt angle	90°	15°
Height/clearance	1m	3m
Array width	1m	2m
Row-to-row distance	10m	4m
Configuration	Shed	Dome
Tracking	No	No
Shade factor of mounting system	Moderate	Moderate
Transparency	0%	22%
Bifacial factor	90%	0%
DC/AC factor	1.25	1.25
Module length	1m	1.1
Module width	2m	2m
Module capacity	500Wp	410 Wp
Number of rows	10	10
Row width	20m	20m
Capacity per ha	0.25 MW/ha	0.726 MW/ha
Shading	10% +/-3.06%	36% +/-1.46%
Capacity factor (PL)	11.9%	10.4%

Spatial potential mapping

The potential of agri-PV was calculated using the GLAES tool, following a methodology first introduced by Ryberg, Robinius and Stolten in 2018 and later adopted, among others, by the European Commission. This particular report builds on the author's previous work on ground-mounted solar potential mapping from 2021.

Spatial data on arable land, pastures, fruit and berry plantations in the analysed countries was sourced from the European Commission's Corine Land Cover dataset (2018 edition). Several exclusions were then applied to account for buffer zones around roads, railways, power lines, buildings, forests, bodies of water and natural protection areas. A maximum elevation and slope was also set. While the author's previous analysis and the recent European Commission report limited land used for ground-mounted solar to only low quality soil areas, no exclusions were applied to soil classes in the case of this report. Agri-PV combines agriculture and electricity generation, and should, therefore, also be applicable to good quality soil areas, opening up more potential. A full list of exclusion parameters is provided below (after Ryberg, Robinius and Stolten, with Ember modifications following Instrat, JRC and others).

	Constraint		Excludes		Data Source
Social and Political					
	Settlements		below	100 m	CLC
	Roads				
		Main	below	200 m	OpenStreetMap
		Secondary, tertiary and unclassified	below	100 m	OpenStreetMap
	Airports		below	5100 m	CLC
	Railways		below	100 m	OpenStreetMap
	Power Lines (> 110kV)		below	200 m	OpenStreetMap
Physical					
	Slope		above	10°	EU-DEM
	Water bodies		below	300 m	CLC
	Woodlands		below	300 m	CLC
	Wetlands		below	1000 m	CLC
	Elevation		above	1200 m	EU-DEM
	Aspect		above	3 °N	EU-DEM
Conservation					
	Protected areas: habitats, birds areas, reserves, national parks, Natura 2000		below	500 m	WDPA
Technical Economic					
	Connection Distance		above	5 km	OpenStreetMap

After applying all exclusions, the programme limited the land available for agri-PV to areas within five kilometres of a grid connection point - a high-voltage to medium-voltage substation (based on OpenStreetMap data) - with the distance suggested by solar project developers for medium sized projects. In some studies, a 10 km distance is suggested for larger solar farms (> 10-20 MW), but at the moment these are far less frequent among European agri-PV projects. An exception was made for Slovakia because of the low quality of grid data and therefore extremely high exclusions resulting from the grid proximity criterion. The share of arable land available for agri-PV in Slovakia was an average of the results for other countries, then adjusted for Slovakia's overall smaller share of arable land in the country's total land area compared to the Central European average.

The resulting area was translated into installed capacity using values consistent with the other calculations present in the report - namely 0.3 MW/ha for interspaced agri-PV on arable land and pastures and 0.7 MW/ha for overhead agri-PV over fruits and berries. The results for arable land were further disaggregated based on the share of arable land occupied by different main crops - in particular wheat, barley, oats and rye (Eurostat 2020 data).

Agri-PV profits per hectare

The report provides a simplified calculation of the revenues, costs and profits of an interspaced agri-PV system between wheat crops in Poland. Values are provided per hectare. As used in other places in the report, due to the row spacing the capacity is around 0.3 MW/ha, translating into 261 MWh/ha of annual electricity generation in a vertical bifacial east-west design (the reasoning behind these parameters is described in the first Methodology subchapter), and resulting in below 15% shading and a 11% yield (revenue) loss for wheat.

Revenues from electricity generation are calculated based on two price scenarios:

1. Using the average 2023 wholesale electricity price for Poland - 111.7 EUR/MWh (via Montel), multiplied by the capture rate 0.89 - Ember's hour-by-hour estimate of the value of solar generation compared to the baseload price over the whole day, yielding 99.3 EUR/MWh. It is worth noting that in the case of east-west facing agri-PV, the capture rate could potentially be higher.
2. Using the 2023 renewables auction results for solar - with an average bid price of 76.2 EUR/MWh, guaranteed for a period of 15 years.

Costs were based on Fraunhofer ISE levelised cost of electricity estimates - 60 EUR/MWh, with 79.1% of that attributed to CAPEX and the rest being OPEX. Consistent agri-PV CAPEX data was only available for 2020, so the CAPEX values were adjusted to 2023 using the average increase of capital expenditure for ground-mounted solar between 2020 and 2023 in Poland - 21%. This resulted in an LCOE value of 70.2 EUR/MWh.

Annual profits per hectare were calculated as the difference between revenues and costs. Depending on the price scenario, the annual revenues varied between 19900 and 25932 EUR/ha, annual costs were 18346 EUR/MWh. **It needs to be noted that the comparison of LCOE with electricity prices is simplified.** No discounting was applied to revenues as no detail was available on the discounting (or lack of it) in the agri-PV LCOE. The end result will therefore vary depending on the discount factor (which also varies by country) or the future electricity price assumptions. Furthermore, the LCOE was provided for a 20 year period, while auctions have a 15-year price guarantee and predictions of electricity prices in the late 2030s come with major uncertainties. The results will also vary depending on the ownership model and therefore the financing costs, or potential profit sharing schemes between farmers, land owners and solar investors.

As a comparison, the revenues and costs of traditional wheat production (without agri-PV) were used. According to estimates by the Greater-Poland Agricultural Chamber, revenues from 2024 winter wheat are estimated at 1715 EUR/ha, with costs at 1812 EUR/ha, resulting in a net loss of 97 EUR/ha. This includes only basic direct subsidies (116 EUR/ha), with significant revenues possible from other CAP subsidies. However, a major portion of these subsidies should still be applicable to agri-PV systems.

(EUR/ha/year)	**Agri-PV with wheat**	**Wheat only**
Solar revenues	19900-25932	
Wheat revenues	1526	1715
Solar costs	18346	
Wheat costs	1812	1812
Solar profits	1554-7586	
Wheat profits	-286	-97
Total	**1268-7300**	**-97**

Acknowledgements

The authors would like to thank several Ember colleagues for their valuable contributions and comments, including Sarah Brown, Ali Candlin, Reynaldo Dizon, Dave Jones, Richard Black and others. We would also like to extend our gratitude to our partners: SolarPower Europe, Polish Photovoltaics Association, Modern Energy Union and Czech Solar Association. We appreciate Jiří Bím's valuable insight into Czech agrivoltaic legislation and the insightful comments from Adrianna Wrona from the Green Economy Institute.

Photo credit: title picture - SolarPower Europe, Školka Litomyšl picture - Kristýna Čermáková