Renewable Energy 263 (2026) 125494

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

The techno-economic potentials of agrivoltaic installations in Austria

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ARTICLE INFO

Keywords:
Techno-economic potentials
Agrivoltaics
Agricultural production
Climate change
Simulation framework
Austria

ABSTRACT

Austria's goal of reaching netzero emissions by 2040 requires an up to tenfold expansion of solar photovoltaics. Besides roof-top installations, the development of ground mounted photovoltaics will be required, possibly creating conflicts with agricultural production. Here, we assess how the deployment of agrivoltaic installations can reduce the land-use competition between agriculture and electricity generation in Austria — and under which conditions such systems are profitable. For that purpose, we simulate electricity generation of agrivoltaic installations, and the reduction in agricultural output due to shading under past and future climate. Profits from electricity generation are significantly higher than those from agriculture, therefore making agrivoltaic schemes less profitable than stand-alone solar PV systems, even under the current regulatory scheme which grants higher subsidies to agrivoltaic systems. For attaining $90\,\mathrm{TW\,h\,y^{-1}}$ of electricity generation from solar PV on cropland, an upper bound in all climate neutrality scenarios, an amount of 5%–16% of total crop area is required. The required areas and the simulated reduction in the yield imply that the loss in Austrian crop production would reach 2%–6%. Only agrivoltaic systems are capable of achieving production losses at the lower end of the observed range. Climate change adaptation effects of agrivoltaic systems are minor.

1. Introduction

Solar photovoltaics (PV) is a key technology to shift to renewable energy sources (RES), required to meet the objectives of the Paris Climate Agreement and of European and Austrian climate targets. Recent growth has been rapid, reaching $600\,\mathrm{GW_p}$ of deployment in 2024 alone [1]. Due to its extraordinary growth, power from PV is expected to provide one-quarter of the electricity required globally in 2050 [2].

The European Union (EU) set the goal of meeting at least 45 % of its final energy consumption from wind and PV energy by 2030. To achieve this, the EU has implemented the Renewable Energy Directive III, to promote the uptake of renewable energy sources [3]. In Austria, the "Erneuerbare Ausbau Gesetz" (Renewable Expansion Act) [4] set the target to attain an additional production of $11\,\mathrm{TW\,h\,y^{-1}}$ from PV by 2030, starting in 2020. However, depending on the availability of low-carbon imports from outside of Austria, these goals seem to be insufficient when considering the target of achieving climate neutrality by 2040: in total between $16\,\mathrm{TW\,h\,y^{-1}}$ to $100\,\mathrm{TW\,h\,y^{-1}}$ of solar PV generation are necessary to reach the goal of net zero carbon emissions [5].

Comparable to global growth, the expansion of PV has been very rapid in last years in Austria, increasing from about 340 MW in 2020 to 9.300 MW in 2024 [6]. While this expansion has taken place to an extent of 85% on roof-tops, ground mounted PV plants have also been installed. In the future, it is expected that in total not more than $16\,\mathrm{TW\,h\,y^{-1}}$ can be installed on rooftops [7], implying that in particular for scenarios requiring higher quantities of solar PV generation, ground mounted PV plants will have to be expanded strongly.

This potentially leads to land use competition between agriculture, biodiversity [8] and electricity generation [9]. Consequently, PV solutions that reduce the amount of required land, are becoming more important. The co-location of solar PV and agricultural activities by utilization of agrivoltaics (APV) is one potential solution: the land continues to be used primarily for agricultural production, i.e. food, feed, fibre, and fuels, but as a secondary function, electricity is produced from APV [10]. Furthermore, APV systems are considered to promote less intensive farming practices compared to conventional agriculture [11], as the areas between rows and around the mounting system are not used for agricultural production, thus providing potentially biodiverse habitats [12]. Furthermore, APV systems may serve as

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https://doi.org/10.1016/j.renene.2026.125494
Received 13 November 2025; Received in revised form 23 February 2026; Accepted 24 February 2026
Available online 2 March 2026

climate change adaptation mechanism, because additional shading can potentially protect crops against heat stress [13].

These advantages have been considered by policy makers in Austria as PV systems without agricultural co-utilization receive 25% lower tariffs [14] than APV systems. An assessment of this policy on the profitability of APV systems for the whole of Austria, and an assessment of the potentials for electricity generation and agricultural production from APV systems is, however, still lacking.

Analysing the co-benefits and trade-offs between electricity and agricultural production on a national scale requires an integrated analysis. While the simulation of PV electricity generation is well-established, the agronomic effects of APV projects, such as implications for agricultural management and practices [15], crop selection, and microclimatic changes [16], including the effects of PV modules on ground shading [17], are still being investigated. Therefore, there is still considerable uncertainty associated with APV systems.

Frequently, impacts on agricultural yields are estimated by averaging ratios that transform irradiation reductions into yield reductions, or assume that the APV system has only a negligible or no effect on crops [12]. Such approaches require refinement taking into account heterogeneity regarding among others, cropping systems and biophysical location factors, e.g. soil quality, climate. Most of the literature on APV is focused on electricity generation and the siting of the PV panels [18], while few studies combine both electrical and agricultural analysis (e.g. [19] and [20]), yet often with very simplistic, linear irradiation assumptions on plant growth impacts or as conceptual reviews. Recent case study based papers also explore the dimensions of energy generation and crop yield, but additionally include meteorological, social and environmental aspects [21,22]. Social aspects discussed include issues regarding acceptability, with vertical APV systems being seen as preferable [21] but extend to energy and water security. Corresponding results show improvements in both aspects. Water security in APV systems may be improved due to a reduction in evaporative water loss, additionally harvested rainwater from panel run-off can help cover irrigation needs. Possible further benefits include increased climate change resilience [22]. Also, economic analyses have been performed and APV was found especially profitable for low value crops [23]. However, a detailed, combined simulation of APV and a country level analysis of the potential of APV systems, determining electricity generation and impacts on crop productivity at high spatial and temporal resolution in a consistent modelling framework, is not available so far.

We address this research gap by presenting, for the first time, a spatially explicit simulation framework that consistently estimates large-scale agrivoltaic (APV) potentials while jointly accounting for electricity generation and agricultural output. The framework integrates profitability assessments for both solar PV generation and agricultural production, enabling a systematic analysis of the economic incentives faced by farmers at the national scale. Moreover, we evaluate APV potentials under both current and future climate conditions, thereby assessing the role of APV systems as an adaptation strategy to climate change. Beyond closing this research gap, our results provide policy-relevant insights into how existing feed-in regimes shape privately optimal investment decisions for APV systems, particularly in comparison with conventional PV installations on agricultural land. Our work is tailored to the Austrian situation, but results can be very well applied to facilities under similar conditions in Central Europe and beyond.

2. Material and methods

2.1. Simulation framework

To be able to jointly analyse APV installations in terms of electricity output and impact on crop growth, we developed a modularized APV simulation framework using established software products where possible, i.e. for crop growth and PV electricity generation simulation, and developed our own software, where necessary, i.e. for the selection of suitable APV sites and for deriving ground shading from APV systems. In particular, to identify suitable areas for APV expansion and estimate both crop as well as electricity output, we developed software that allows to spatially explicitly select suitable areas based on user defined criteria, simulate the electricity generation of systems using *PVlib*, version 0.9.1 [24], estimate the reduction of irradiation, i.e. the surface downwelling shortwave flux in air, on crops, with our own python based software, and simulate the output of the agricultural yield with the bio-physical process model EPIC v.1102 (Environmental Policy Integrated Climate model) [25]. In more detail, EPIC simulates crop yields and agri-environmental impacts by site specific conditions and management practices. Our framework is freely available (GPL licence)[1] and is implemented primarily in `Python 3.14` with a direct link to *PVlib* and EPIC. Fig. 1 shows an overview of the simulation framework, and the input data which is described in more detail below. Final outputs were analysed in R-Studio 2.24.12.0, R Version 4.2, and figures were plotted using ggplot 3.4.2.

Area selection We select areas based on the type of agricultural land-use, using the EU Common Agricultural Policy's (CAP) Integrated Administration and Control System (IACS) [26]. IACS data has been used to develop the gridded cropland data in EPIC and to classify areas suitable for the use of APV. Here, we focus on arable areas and do not consider areas with permanent crops such as wine, hops, or fruit trees. Furthermore, we exclude grassland from our simulations as this land-use type can be mainly found in alpine areas and is mostly situated at a considerable distance from existing electrical infrastructure. We further filter the respective crop growing areas by defining a minimum area (1ha of connected cropland independent of ownership), minimum compactness (0.22 according to the Schwartzberg compactness index), maximum average slope (20°), and maximum altitude (1950 m above sea level) using a 50 meter digital height model (DHM) [27].

Electricity generation We simulate electricity generation from PV modules per hectare based on the open-source Python library *PVlib*, version 0.9.1 [24]. The calculations of electricity generation in *PVlib* is mainly based on two reports by the Sandia National Laboratories. The conversion of solar irradiance to DC power output is covered in [28], while the conversion from DC to AC is discussed in [29]. To reduce computational load, calculations are performed for 10,000 randomly generated points over Austria, taking into account the specified type of panels, the number of panels, and the orientation, i.e. azimuth and zenith. We use daily or subdaily global horizontal irradiation (GHI) data from a climate simulation on a 1 km grid (see data below), upsampled to hourly values. We implemented the algorithm proposed in Liu et al. [30] to determine the ratio between daily and hourly values, using the sunset azimuth and the sun azimuth vector as inputs. GHI values are split into direct normal irradiation (DNI) and diffuse horizontal irradiation (DHI) values in order to apply correction factors to the irradiation values due to terrain-based shadow effects. These calculations are based on the ERBS [31] model implemented in *pvlib*.

For each simulated point, we also determine the time when the sun is above the horizon. For that purpose, 30 horizon angles are calculated from the DHM utilizing the *grass GIS* `r.horizon` function, and setting the DNI values to zero if the sun zenith angle is below the corresponding horizon angle. During these periods, the sun is not visible from the perspective of the PV panels. Furthermore, the DHI value is reduced by the calculated *skyviewfactor* (svf) [32], using all the values of the horizon angle.

Shading due to PV panels We determine the reduction of irradiation caused by the shade from the PV panels on ground and modify the input of climate data to the *EPIC* model which is used for crop growth simulation. For the purpose of determining shading, we resample daily

[1] https://github.com/inwe-boku/renSpatial

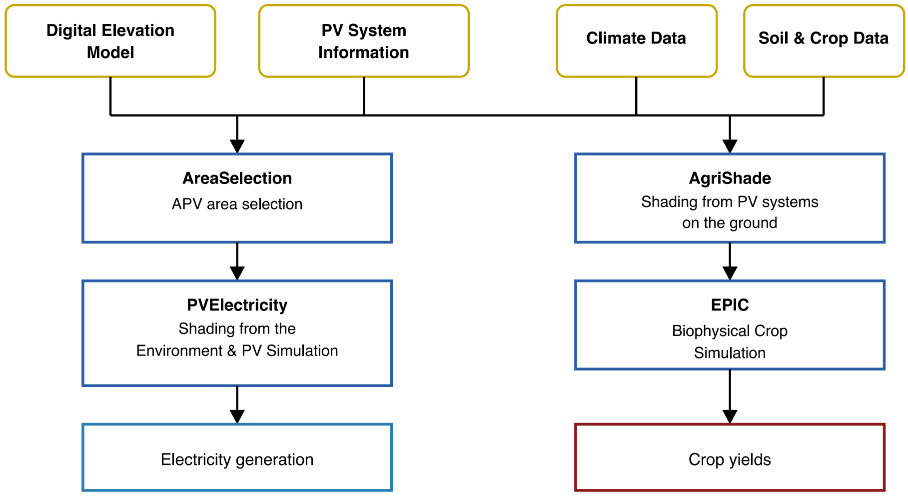

Fig. 1. Overview of the simulation framework.

to hourly irradiation values (GHI) and split GHI data into DNI and DHI components. The DNI values are reduced on the basis of a relative daily shading factor, which is calculated from the average shadowcast on the ground (shadow footprint) by the PV panels on an hourly basis from the sun azimuth and zenith angle values and the specified geometric layout of the APV system (see Table 1). DHI values are reduced by the *skyviewfactor*, calculated for the whole APV installation. Ultimately, the hourly irradiation values of DNI and DHI are combined to hourly GHI values and aggregated to daily GHI values, which are used in *EPIC* to simulate crop growth.

Crop growth simulation We use EPIC to simulate key environmental processes and plant growth at the plot level with daily time steps and a spatial resolution of 1 km×1 km. The modelling framework covers all grid cells containing cropland, amounting to approximately 36 500 cells across Austria. EPIC represents a wide range of environmental processes, including climate impacts, nutrient flows through water and air pathways, soil carbon sequestration, and soil erosion and sediment transport. Crop growth is simulated based on the interaction of environmental conditions and management practices, such as crop rotations, resulting in annual outputs of biomass and crop yields [33]. Impacts of agrivoltaic systems (APV) are incorporated through reductions in incoming solar irradiation, as described above. A set of representative crops is included in the simulations (Table A.5). EPIC has been widely applied and validated in the Austrian context [33].

Climate data The simulation of PV system output relies on the temporal upscaling of daily solar irradiation data from a bias-corrected iteration of the `ICHEC RCP4.5` scenario (`CCCA ÖKS 15` climate model from [34]) for two periods: 1981 to 2020 (current) and 2031 to 2070 (future). For the *EPIC* simulations, the same climate data is used, including additional variables: daily minimum and maximum temperatures, average humidity, average wind speed, and total precipitation. The climate simulations are available on a 1 km grid.

APV systems In this paper we assess two different APV systems and two baseline scenarios. The two baseline scenarios are used as a reference and include (1) agricultural production without any PV system and (2) a ground-mounted PV system without any agricultural production (GM-PV). The results of these simulations are then compared to those obtained from simulations with an APV system. The most important parameters of the GM-PV and APV systems are shown in Table 1. The first APV scenario is based on an overhead stilted APV system (S-APV) and is very similar to a demonstration system used in Germany [35]. It consists of 573.5 $\mathrm{k}W_\mathrm{p}\,\mathrm{ha}^{-1}$ of installed power on south facing panels at an installation height of approximately 10 m, while the loss of land due to installations amounts to 8 % [36]. The clearance height of the S-APV system is assumed to be 4.5 m, which is higher than the typical maximum machinery height in Europe at below 4 m. The second APV scenario is based on a vertical bifacial system (VB-APV), with a row distance of 10 m and 2 bifacial panels on top of each other. The lower bound of the panels is at a height of 0.8 m facing east–west. Bifacial modules were chosen for this setup in order to achieve adequate power generation throughout the day as opposed to being largely limited to the morning or evening hours. The loss of area due to installations is about 12 %, mainly due to the safety distance for machines to the panels. An overview of the most important parameters of the different systems is shown in Table 1. Detailed links to data sheets can be found in the appendix A.7.

Spatial resolution of simulation framework Most data for site selection is mainly based on vector data or on spatially highly resolved raster data, i.e. DHM at 50 meter. The size of the chosen potential agricultural sites is at least 1ha and potential APV systems are associated with those locations. Climate data is available on a 1 km grid and used for EPIC simulations at that resolution. EPIC output is uniformly assigned to all potential APV sites within the 1 km grid. For PV electricity generation, we randomly simulate output for 10,000 Austrian locations, also based on the 1 km climate data. This output is used as reference for the output of potential APV sites in proximity, using a nearest neighbour assignment.

2.2. Analysis of costs and revenues

Profitability of different systems We assess the overall profits from the four different systems by determining the revenues and variable and annualized investment costs of the PV systems, and add the gross margins achieved in agricultural production, as described in detail below. The design of the PV systems is optimized to agricultural production in terms of machinery sizes. Hence, investments to maintain agricultural activities are not considered, as these are assumed to be independent from the installation of PV systems on a farm, at least in the short to mid term.

Overall profitability of the combined electricity generation and crop production $\pi_{s,i}$ for system s and location i are given by the sum of the profits from electricity generation $\pi^e_{s,i}$ and the gross margins from agricultural production $g_{s,i}$. These variables are calculated per hectare, and afterwards the profit is scaled according to the available area a at each location. Note that $\pi^e_{s,i} = 0$ for systems with agricultural production only.

$$\pi_{s,i} = a(\pi^e_{s,i} + g_{s,i}) \tag{1}$$

Profits $\pi^e_{s,i}$ from electricity generation are determined by multiplying the electricity output $o^{\mathrm{PV}}_{s,i}$ of system s at location i, as determined

Table 1
Parameters of (A)PV systems.

System	PV Panels			Orientation		Height		Distance (m)	Area loss (%)
	Type	Number (per ha)	Capacity ($\mathrm{kW_p}$ per ha)	Azimuth	Zenith	Clearance (m)	Slant (m)		
S-APV	Standard	2048	573.5	180°	35°	10	0.85	–	8
VB-APV	Bifacial	840	348.8	[90°,270°]	90°	0.8	1.2	10	12
GM-PV	Standard	2500	1000	180°	35°	1	0.85	–	100

Table 2
Costs per $\mathrm{kW_p}$ power and annual costs per hectare for each of the three systems.

	Cost scenario	Costs (€ per $\mathrm{kW_p}$)	Annualized costs (€ per ha)
S-APV	**low**	987	57,901
	mid	1111	53,918
	high	1234	59,888
VB-APV	**low**	550	14,556
	mid	619	16,382
	high	688	18,208
GM-PV	**low**	458	33,915
	mid	515	36,470
	high	572	40,585

with the simulation framework described in Section 2.1, with the feed-in tariff p^e and deducting annualized investment costs I_s, where $r = 5\%$ is the interest rate and $n = 25$ is the investment period in years, and operating costs opex_s, which are assumed to be 1% of I_s:

$$\pi^e_{s,i} = o^{pv}_{s,i} p^e - I_s \frac{1-(1+r)^{-n}}{r} - \mathrm{opex}_s \tag{2}$$

Ground-mounted PV installations rely on income from auctioned feed-in tariffs. We assessed a wide range of values for p^e: 0.05 €/(kW h), 0.075 €/(kW h) and 0.1 €/(kW h). This range covers recent auction results, as PV has achieved feed-in tariffs of 0.07 €/(kW h) to 0.085 €/(kW h) in 2025 [37]. For GM-PV, these tariffs are reduced by 25%, to represent current regulation in Austria [14].

System costs I_s for the three PV systems are based on the numbers presented in [38] and are reported in Table 2. In two other scenarios, we assume 20% lower and 20% higher cost in a sensitivity analysis.

Total gross margins $g_{s,i}$ are calculated by summing up gross margins per hectare $g^c_{s,i,c}$ for all individual crop rotations c and weighting them by their area share $s_{i,c}$:

$$g_{s,i} = \sum_c s_{i,c} g^c_{s,i,c} \tag{3}$$

Gross margins from agricultural production Agricultural gross margins $g^c_{s,i,c}$ measure the short-run profitability of a specific crop rotation by subtracting variable costs from gross output. We calculated gross margins of agricultural production on a per hectare basis by determining the difference between gross revenues and variable production costs, and adding area fixed agricultural subsidies s_s. The former are determined by multiplying crop production per hectare $o^c_{s,i,c}$, as simulated by our simulation framework, with crop prices $p^c_{i,c}$, the latter are variable costs of agricultural production $c_{s,i,c}$ per hectare.

$$g_{s,i,c} = o^c_{s,i,c} p^c_{i,c} - c_{s,i,c} + s_s \tag{4}$$

The prices of crops are differentiated spatially for eight major production regions, which classify Austria's agricultural production along bio-physical and farm structural criteria (see Fig. B.6). Area fixed agricultural subsidies are 207€/ha in Austria [39]. Standard systems are exempt from agricultural subsidies, while subsidies for areas with Agri-PV systems are reduced by the area loss implied by the installation of the modules (see Table 1).

Variable costs include costs for seeds, fertilizer, plant protection, machinery costs, and also insurance. Gross margins were estimated using the simulated crop yields of *EPIC* and the crop prices and variable crop production costs published by [40]. The database provides expenses such as seeds, fertilizer, pesticides, machinery-related costs, and insurance, but does not take into account labour costs. It is a typical assumption for Austrian farming systems with a high share of family labour supply. Fixed costs – such as for land, buildings, machinery, or family labour – are excluded since gross margins are assumed to cover these fixed costs on a farm. Fixed area subsidies for agricultural production are included in the assessment, but we do not account for environmental payments, as these are unknown and most likely only marginally increase gross margins, as they are designed to recover additional costs by farmers.

We determine gross margins not for single crops but for typical crop rotations in the main agricultural regions, shown in Fig. B.6. The crop rotations have been modelled from observed IACS crop land use data with the CropRota model [41] and enter the EPIC model as one of several management characteristics of a gridcell. Consequently, we model realistic management of crop lands, where different crops are planted in rotations on the same piece of land over successive seasons. By varying the types of crops grown, farmers can improve soil fertility, nutrient efficiency, reduce the risk of crop-specific pests and diseases, and adapt to marketing risks.

3. Results

3.1. PV electrical yield

On average in Austria, GM-PV systems generate 1173 MW h ha^{-1}, stilted S-APV system 684 MW h ha^{-1}, and the VB-APV system 373 MW h ha^{-1} of electricity. The evaluation of the electricity generation in the eight major agricultural production zones (see Table 3) shows some variation. The differences between systems result from different peak capacities installed, but also from varying angles of the systems. In contrast, the varying results for the same system between regions can be explained by the differences in irradiation and in orography. Clearly, the Southern regions in Austria show higher productivity, with the exception of "Hochalpen", which is a mountainous regions where shading of agricultural areas plays an important role. Fig. B.7 shows a detailed analysis of a municipality in an alpine environment in Austria, illustrating the effect of shading due to orography. The exact location has a major influence on generated electricity, particularly if there are hills or mountains to the south, east and west. This is especially the case for the east and west facing VB-APV. The wide spread in productivity within a single region confirms that an accurate estimate of PV electrical output requires simulations for individual locations.

3.2. Profits from combined agricultural and electricity production

PV generation with GM-PV systems are more profitable than Agri-PV systems even though feed-in tariffs for those systems are lower than for Agri-PV systems (Fig. 2). Even more pronounced is the difference to agricultural production alone: gross margins from agricultural production without PV generation are an order of magnitude lower than for electricity generation, at least when compared to GM-PV and at mid to high feed-in tariffs. Our analysis indicates that the VB-APV system

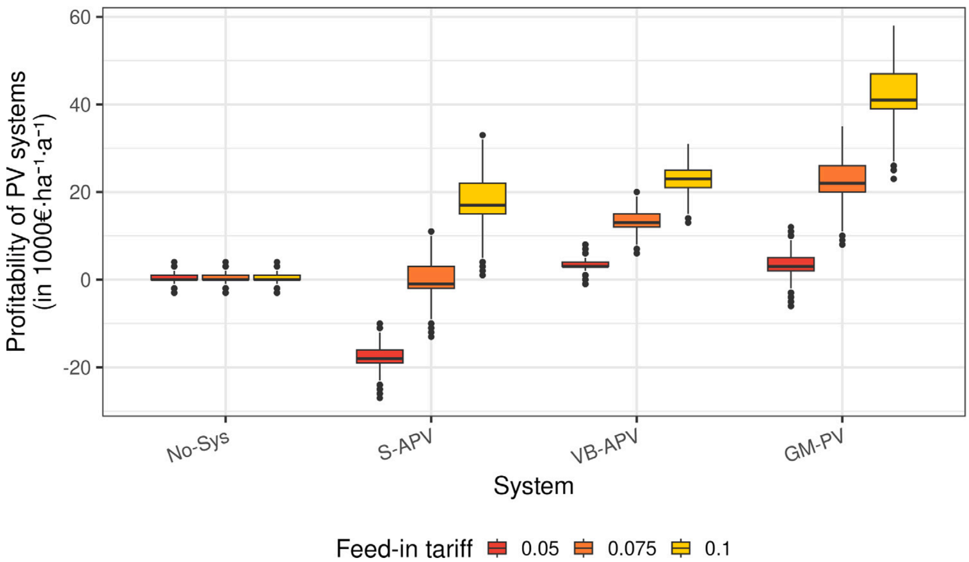

Fig. 2. Overall profitability of PV systems per hectare, as determined by the sum of average profits of PV electricity generation and gross margins from agricultural production combined, for mid solar PV system cost scenarios, for all Austrian municipalities. No-Sys: agricultural production only. S-APV: stilted Agri-PV system with agricultural production, VB-APV: Vertical Agri-PV system with agricultural production, GM-PV: solar PV installation without combined agricultural production.

Table 3
PV generation for both APV systems and the GM-PV system per agricultural main production area in $\mathrm{MW\,h\,ha^{-1}\,y^{-1}}$ sorted by productivity of GM-PV.

Region	GM-PV	S-APV	VB-APV
Kärntner Becken	1353.5	777.2	423.8
Südöstliches Flach- und Hügelland	1346.6	772.0	421.0
Alpenostrand	1290.0	747.3	407.5
Nordöstliches Flach- und Hügelland	1278.5	734.6	400.6
Alpenvorland	1206.0	692.7	377.8
Wald- und Mühlviertel	1200.5	689.6	376.0
Voralpen	1151.2	690.5	376.6
Hochalpen	1145.5	712.3	388.4

is more profitable than S-APV, as a result of the significantly higher installation costs of the latter. S-APV only generates positive profits at all locations at the highest simulated feed-in tariff.

On average, the VB-APV system yields a profit ratio compared to agricultural production alone ranging from 10:1 to 50:1 depending on electrical yield, feed-in tariff and VB-APV system cost, while the S-APV system has a wider range of ratios. Under some parameter settings and for some locations, agricultural production alone can become more profitable, while at higher feed-in tariffs, low PV costs, and at some locations a profit ratio of 60:1 is attained. For GM-PV systems, the profits can be even higher compared to the ones from agricultural production with a ratio of up to 100:1.

There is also a trade-off between electricity generation potential and chosen system (see Fig. 3). The GM-PV system allows much more total generation, compared to S-APV and VB-APV, which has the lowest total generation potential due to the lower packing density of the Agri-PV systems. The curves linking total production to profitability show spatial variation in production conditions and confirm the findings that GM-PV outperforms S-APV and VB-APV systems in terms of profitability.

3.3. Impact of agrivoltaics on agricultural yields

Fig. 4 shows the distribution of yields per municipality and climate period relative to a baseline scenario without any PV installation of the 6 main crops produced in Austria, as determined by their share in total area. All simulated crops show reduced yields from PV installations due to loss of area and reduced radiation. The median of the relative production indicates a loss of at most 30%, but single locations may experience even higher losses. Note that the constant area reduction is assumed to be 12 % for VB-APV systems and 8 % for S-APV.

Clover grass and temporary grassland is less affected by shading of the panels than maize, wheat or barley, but variability between production regions is high. APV systems in the future scenario show fewer relative yield losses than in the current period for most simulated crops in most regions and for both simulated APV systems. This indicates that APV may be a potential measure of adaptation in agriculture reducing heat and drought stress from shading. However, despite the existence of statistically significant differences in the medians, the absolute adaptation effect is limited to lower than 5 percentage points for the 6 major crops.

Although the estimated area loss is higher in the VB-APV scenario, it shows lower yield losses compared to the S-APV system due to lower impacts from shading on crop growth. According to our model results, the impact of irradiation on crops is about twice as high for the S-APV system, with higher yield losses for specific crops like maize, rape seed or soybean and generally lower losses for roughage feed crops (e.g. grass clover).

3.4. Gross margins from agricultural production

Average gross margin losses range from 27.2 % to 39.2 % for VB-APV and 37.4 % to 39.3 % for S-APV in the current period (see Table A.6), depending on the region. Losses in the main production areas *Alpenvorland*, *Südöstliches Flach- und Hügelland* and *Wald- und Mühlviertel* are the lowest. Note that the gross margin losses are higher than those for yield losses, resulting from yield-independent cultivation costs such as soil mechanization.

We also calculated gross margins for full crop rotations. Fig. 5 shows the mean annual gross margins per hectare of the top six crop rotations (by acreage) in Austria. In general, the gross margins without Agri-PV systems range from almost zero to $1200\,€\,\mathrm{ha^{-1}\,y^{-1}}$. The yield losses of the APV simulations (see Fig. 4) have effects on the gross margins, causing even negative gross margins for some crop rotations. In all simulations, gross margins in the future are higher compared to the current period (past), independent of the installed system: this indicates that under the chosen climate scenario, crop productivity increases on average. This, however, is only true on average, single years can show significant decreases in productivity.

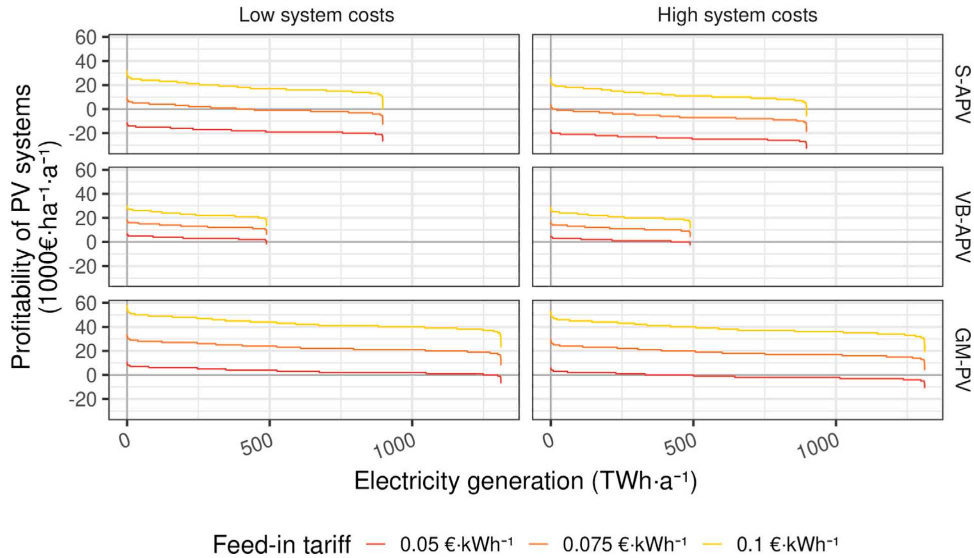

Fig. 3. Overall profitability of PV systems per hectare of the three PV systems, as determined by the sum of average profits of PV electricity generation and gross margins from agricultural production combined. The *x*-axis shows the cumulative sum of the electricity generation sorted in a decreasing order by our profitability indicator, representing combined profits from electricity generation and the gross margins from agricultural production for all PV systems, high and low system costs and the three feed-in tariffs.

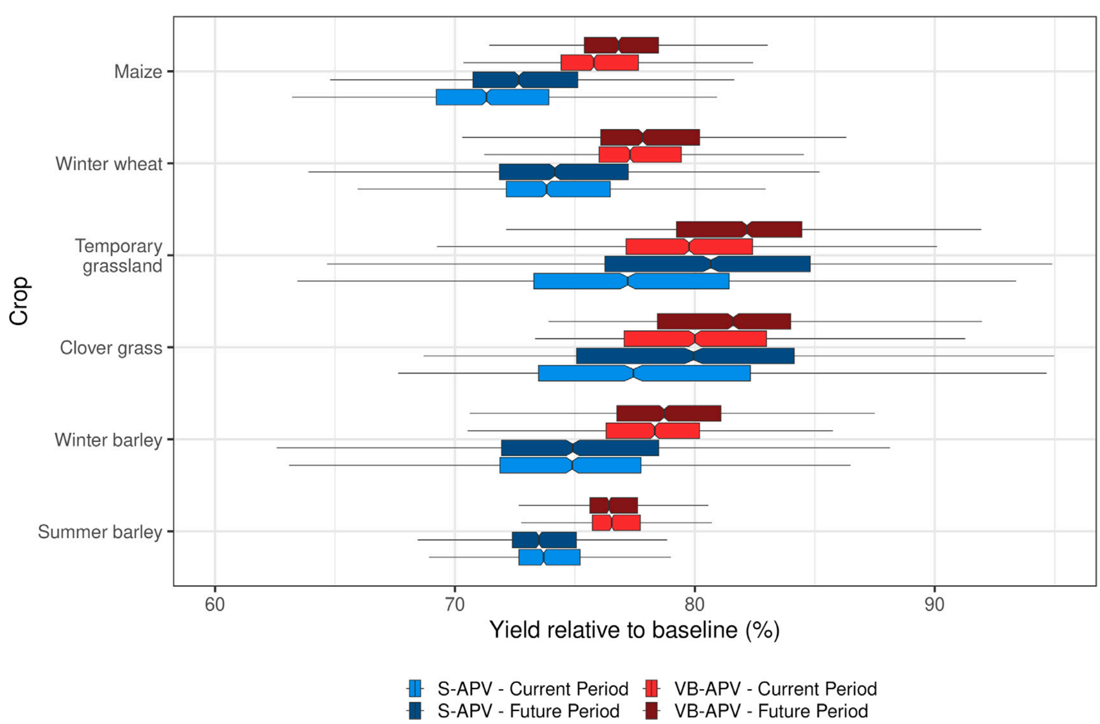

Fig. 4. Agricultural yields relative to agricultural production without PV for the top 6 crops in terms of area share in Austria, ordered by area share (top highest share). The boxplot shows results for all municipalities for the average yield in two climate simulations (current and future). The results are averaged over all years for the respective period. The notches of the box plots indicate the 95 % confidence interval of the median value. Non-overlapping notches indicate that the true medians are statistically different at the given confidence interval.

3.5. Austrian PV expansion goals and impacts on crop production

We also determined the land requirements and the loss in agricultural production for near-term and long-term solar PV expansion goals. Until 2030, the Austrian government has the goal of an expansion of 11 TWh. About 7 TWh have been achieved so far. If all of the remaining 4 TWh would be installed on crop land, between 0.24% (GM-PV) and 0.66% (VB-APV) of all crop land would be required to satisfy the goal, with the exclusive installation of S-APV requiring 0.35% of crop land. This analysis is based on the assumption that locations are developed sequentially, starting with those offering the highest electricity generation potential (see Table 4). Under this expansion, total agricultural output – measured as the change in production volumes across all crops – declines by 0.07% for S-APV, 0.08% for VB-APV, and 0.24% for GM-PV. These results indicate that the two Agri-PV systems, despite requiring different amounts of land, lead to very similar reductions in

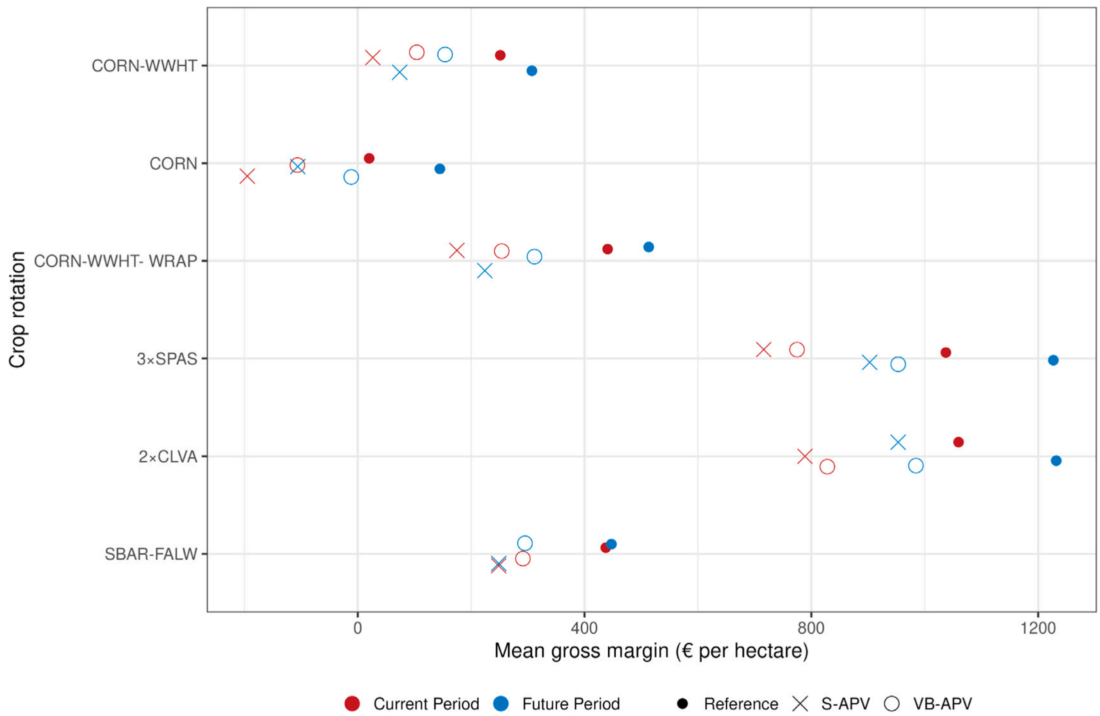

Fig. 5. Mean gross margins from agricultural production for the top 5 crop rotations for each main production region in Austria, for both APV systems and baseline (reference) conditions and for the current and future climate period.

Table 4
Share of areas and share of losses in crop production required to reach Austrian PV expansion goals, current climate period.

	GM-PV	S-APV	VB-APV
2030 goal: Plus 4 TWh on crop land			
Share in agricultural area (%)	0.24	0.35	0.66
Loss in agricultural production (%)	0.24	0.07	0.08
Upper bound of expansion for climate neutrality: Plus 90 TWh on crop land			
Share in agricultural area (%)	5.35	8.36	15.80
Loss in agricultural production (%)	5.65	1.66	1.95

agricultural output. In contrast, GM-PV, while deployed on a smaller agricultural area, results in productivity losses that are approximately three times higher.

The upper bound of PV expansion found in any long-term climate neutrality scenario is 100 TWh. Assuming that 90% are built on crop land, 5.35% to 15.80% of Austrian crop land would be required, causing a decrease in agricultural output of 1.66% (S-APV), 1.95% (VB-APV) and 5.65% (GM-PV) on average. As illustration the spatial distribution of VB-APV systems is shown in Fig. B.8.

4. Discussion

Previous field experiments and simulations show results consistent with our simulations. [36] shows a decline of crop yield during a normal climatological year for winter wheat of 18 %, 17 % for potatoes and 5 % for grass and clover, excluding land loss under an overhead demonstration site in Germany, while during a very hot and dry year, yields increased below the panels. Our simulations show a decline of 19 % for winter wheat, 23 % for potatoes and 15 % for grass and clover on average. Other field experiments show significant losses for maize of up to minus 50 % [42] in comparison to only 14 % to 22 % from our simulations and 15 % for winter wheat [43]. In [43] an overall 73 % to 83 % of relative yield for a series of crops is additionally simulated.

Furthermore, our PV electricity generation simulation varies between 1.11 MWh/kW/year and 1.35 MWh/kW/year, depending on location and system configuration. This is well in line with estimates in the Global Solar Atlas [44], where Southern regions consistently show potentials of over 1.30 MWh/kW/year, while Northern regions fall below 1.20 MWh/kW/year.

With some exceptions, our simulation results therefore align well with experiments. Still, there are significant limitations in our large-scale analysis. First, we only consider the reduction in solar irradiation and do not include other effects such as possible changes in wind speed and direction or the influence of precipitation blockage and run-off from APV systems. Similarly, the temperature effects below and between APV systems have not been modelled or modified, as the literature shows [45] that mean daily air temperatures are similar under direct sunlight and under the shade of PV panels. Third, there may be effects on soil temperature and moisture which we did not simulate. According to [46] agrivoltaic systems generally result in reduced soil temperatures and increased soil moisture contents, which is beneficial with respect to water conservation and the avoidance of crop-stress. Evapotranspiration in APV systems is generally reduced due to higher ambient humidity, particularly when combined with reduced temperatures and decreased solar radiation. Other micrometeorological variables such as air temperature are more variable and highly site dependent. The exclusion of these factors may explain the existing differences to experimental results. A more detailed analysis is therefore necessary to fully account for these effects and to improve simulation quality.

Impacts of shading on crop growth seem to affect maize, barley, and wheat more than temporary grassland, but spatial variation is considerable — between and within production regions. Furthermore, overall impacts will depend on the crop rotations, where these single

Table A.5
List of simulated crops.

Shortname	Nomenclature	English
ALFA	Medicago sativa	Alfalfa
BARL	Hordeum vulgare	Winter barley
CLVA	Trifolium	Clover grass
CLVR	Trifolium pratense	Red clover
CORN	Zea mays	Maize
CRRT	(-)	Vegetables
CSIL	Zea mays (silage)	Maize (silage)
DWHT	Triticum durum	Durum wheat
FABN	Vicia faba	Faba bean
FALW	Novale	Fallow
FPEA	Pisum sativum	Pea
CRSG	Sorghum bicolor	Sorghum
OATS	Avena sativa	Oats
POTA	Solanum tuberosum	Potatoes
SBAR	Hordeum volgare	Summer barley
SGBT	Beta vulgaris	Sugar beet
SOYB	Glycine max	Soybean
SPAS	Partum	Fieldmeadow
SUNF	Helianthus annuus	Sunflower
TRIT	Tritico secale	Triticale
WRAP	Brassica napus	Winter rapeseed
WRYE	Secale cereale	Winter rye
WWHT	Triticum aestivum	Winter wheat

Table A.6
Relative gross margin losses for each main production region, period, and APV system.

Region	Period	Gross margin loss	
		VB-APV (%)	S-APV (%)
Voralpen	Current	31.3	41.3
	Future	28.6	37.0
Hochalpen	Current	32.0	41.8
	Future	27.1	34.2
Kärntner Becken	Current	32.7	43.3
	Future	33.0	43.6
Südöstliches Flach- und Hügelland	Current	27.2	37.4
	Future	30.8	42.2
Alpenostrand	Current	31.5	41.0
	Future	28.4	36.2
Alpenvorland	Current	27.9	38.5
	Future	30.4	31.3
Wald- und Mühlviertel	Current	30.2	39.3
	Future	36.3	49.1
Nordöstliches Flach- und Hügelland	Current	31.8	44.2
	Future	35.3	48.4

Table A.7
Assumed panels and inverters for the systems. The detailed technical assumptions can be found in the pvlib data repository [47].

System	Panel model	Inverter model
S-APV	Aleo Solar S79y280	PV Powered PVP2000EVR 240V
VB-APV	LG Electronics Inc LG410N2W A5	ABB PVI 5000 OUTD US 240V
GM-PV	LG Electronics Inc LG410N2W A5	ABB PVI 5000 OUTD US 240V

crops occur in different combinations. The choice of optimal crops to be combined with Agri-PV schemes therefore depends on individual climate and soil conditions and crop rotations, and cannot be reduced to the choice of specific crops.

We identify minor climate change adaptation effects of Agri-PV installations. It is, however, possible that more pronounced effects may be observed if a future climate with higher temperatures is assumed, since we used the moderate RCP 4.5 scenario. In RCP 4.5 global greenhouse gas emissions peak in 2040. For later periods in the century and under higher emission scenarios, the adaptation effect of APV may therefore be more pronounced. This is in line with studies discussing the contribution of APV systems in achieving the Sustainable Development Goals set forth by the UN. Well designed APV systems may support food security (SDG 2) as well as mitigate the impacts of climate change (SDG 13) [22]. Beyond this, they contribute in reaching many SDGs, but directly positively impact the goal of ensuring access to affordable, reliable, sustainable and modern energy (SDG 7) [48]. There may, however, be trade-offs to consider when it comes to local biodiversity (SDG 15), which can be alleviated through biodiversity-sensitive land management approaches [49].

Furthermore, we studied a limited number of systems. A further reduction in land demand for PV would be possible if tracking solar PV systems are used, but those have not been studied in detail to reduce complexity in determining ground shading.

A further simplification is our assumption on average prices and costs for silage maize and temporary grassland yields. These are, in fact, traded to a low degree in Austria, but are used primarily on farm. Therefore, our market price assumptions may not take into account the value added from livestock production on the farm, which can vary widely depending on the region, climate, soil, slope, and size of the farm. Also, possible increases in costs – APV systems may aggravate soil management and increase labour demand – or damage risks of the PV modules have not been included and are subject to further research. However, we assumed efficient designs for APV systems that likely limit such effects. Innovations in autonomous mechanization (e.g. field robots) may lower risks further in the future.

We expect large variation for all these factors due to different system designs, farm equipment and labour skills that require further research. Gross margins are used for agricultural business planning to compare revenues and costs of production alternatives. Substantial differences in family labour demand and costs for fixed assets need to be taken into account when farmers decide for a production system. While our method simplifies farming systems from a business level, it is appropriate to compare production alternatives at a national scale.

Furthermore, we did not include grid connection costs in our analysis. Costs of connecting to the next grid connection point, however, accrue to the project developer. They may therefore alter profitability of projects and will move optimal deployment patterns for solar PV closer to grid connection points, often in proximity to settlements. Restricted data availability on grid connection points limits the potential to assess those costs on a national scale, but nevertheless this should be considered to be an important future research direction.

Our economic analysis of the PV electrical output and the analysis of gross margins from agricultural production demonstrate that profits from electricity generation can be significantly higher by one to two orders of magnitude than gross margins from agriculture. This is confirmed by land markets in Europe and also in Austria, where rates for leased land are considerably lower for agricultural uses compared to PV installations [50].

5. Conclusions

We estimated, for the first time, the potential of Agri-PV systems on crop land in Austria, including estimates of impacts on crop yields, and their economic viability taking into account current regulatory rules.

We find a significant potential for all Agri-PV systems, allowing for the achievement of solar PV generation levels in line with all available climate neutrality scenarios on crop land alone, incurring a volume loss in agricultural output of only close to 2%. PV systems on crop land without combined agricultural production need less agricultural areas, but losses in agricultural output triple.

Overall, APV systems can be operated profitably on crop land under current feed-in tariffs. Vertical systems outperform overhead systems in terms of profitability, but have lower total electricity generation potential. However, APV systems are not competitive and are outperformed by stand-alone PV installations, although the latter receive reduced feed-in tariffs and no agricultural subsidies. An adaptation of the corresponding tariff structure may therefore be necessary to allow

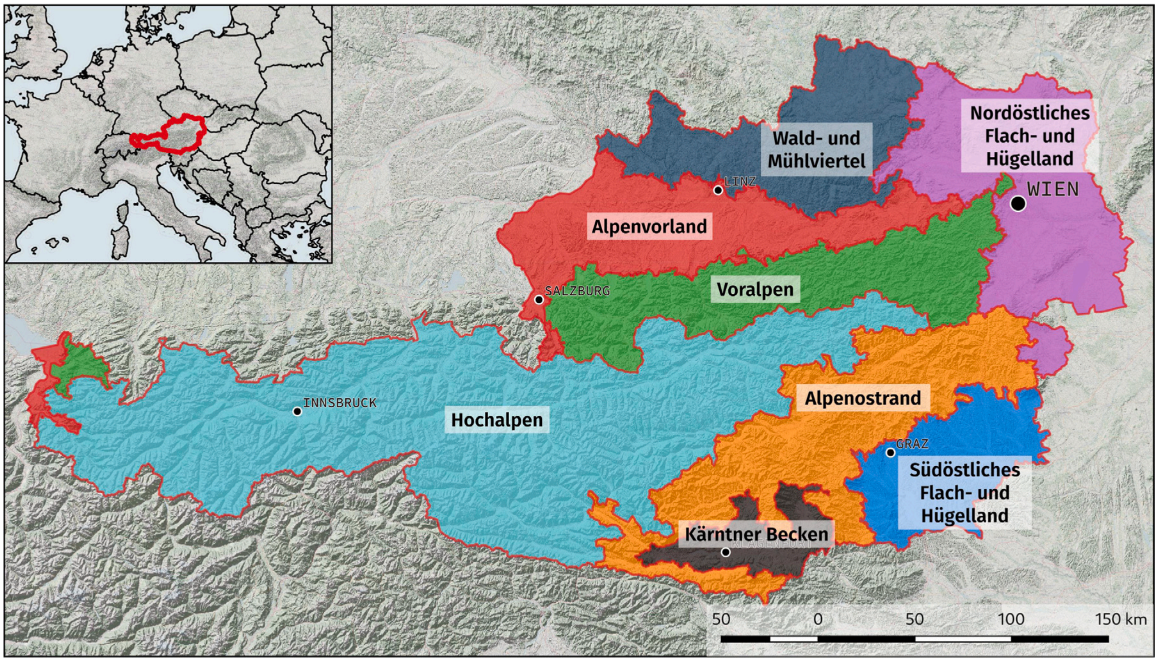

Fig. B.6. Agricultural main production regions of Austria.

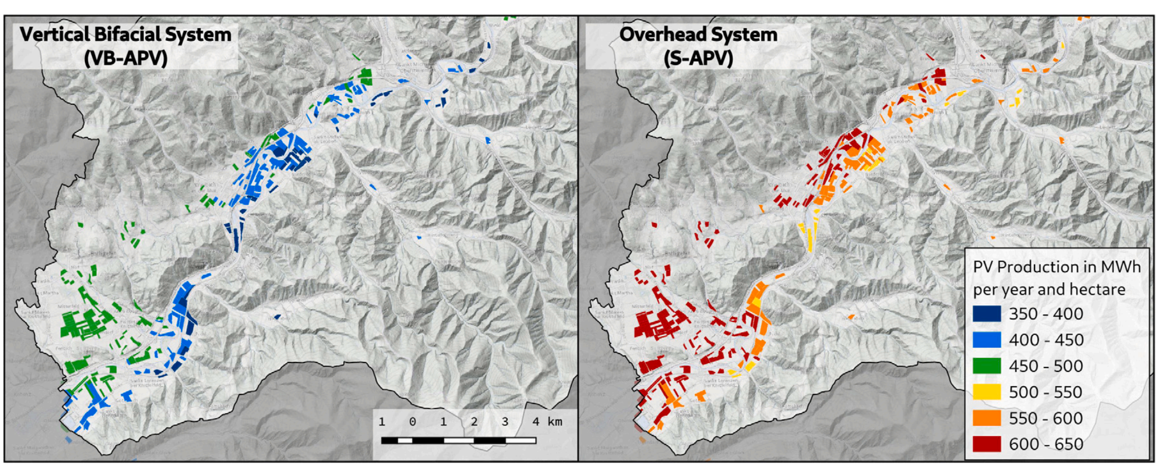

Fig. B.7. Electricity generation per field for an exemplary alpine municipality (St. Stefan ob Leoben in Styria)

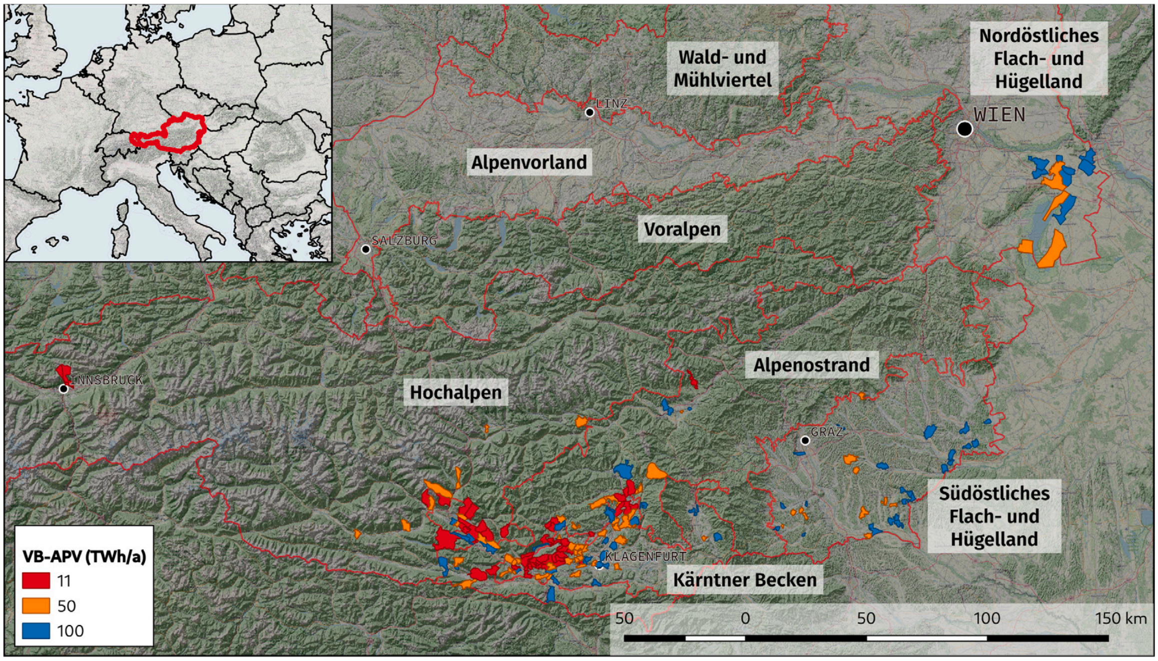

Fig. B.8. Municipalities sorted according to profitability. Red: municipalities required to reach the $11\,\mathrm{TW\,h\,y^{-1}}$ goal for 2030. Orange: municipalities required to reach $50\,\mathrm{TW\,h\,y^{-1}}$, and blue municipalities additionally required to reach $100\,\mathrm{TW\,h\,y^{-1}}$ utilizing the VB-APV system.

for increased uptake of APV systems on crop land. We did not analyse systems on grass land in this context, however, which show higher complexity due to on-site livestock management potentials.

While we have identified optimal areas for APV systems in terms of maximizing on-farm profits, we did not account for distances to the power grid, which is a main determinant for making solar PV installations viable. We recommend further research into this direction, although data availability is currently restricted. Also, subsequent research should focus on a broader understanding of production costs, including impacts on labour productivity and variable costs. Furthermore, impacts of PV and APV systems on biodiversity warrant further research, since biodiversity conservation is a major societal concern besides climate change and food security.

CRediT authorship contribution statement

Christian Mikovits: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Isabelle Grabner:** Writing – review & editing. **Alexander Bauer:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Theresa Kern:** Writing – review & editing, Project administration, Conceptualization. **Iris Kral:** Writing – review & editing, Conceptualization. **Thomas Schauppenlehner:** Writing – review & editing, Conceptualization. **Erwin Schmid:** Writing – review & editing, Software, Methodology, Data curation, Conceptualization. **Martin Schönhart:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Johannes Schmidt:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Christian Mikovits reports financial support was provided by Austrian Climate and Energy Fund. Theresa Kern reports financial support was provided by Austrian Climate and Energy Fund. Iris Kral reports financial support was provided by Austrian Climate and Energy Fund. Christian Mikovits reports financial support was provided by Austrian Academy of Sciences. Isabelle Grabner reports financial support was provided by Austrian Research Promotion Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the Austrian Climate Research Program (Climate & Energy Fund Austria), projects "CROSS-SEC", grant number FO999924987, and project "PA^{3}C^3", grant number KR19AC0K17594, and by OeAW (Austrian Academy of Sciences), project "BioPV", grant number ESS22-23-BioPV.

Appendix A. Additional tables

See Tables A.5–A.7.

Appendix B. Additional figures

See Figs. B.6–B.8.

Data availability

The resulting data of this analysis will be provided in an open repository upon acceptance of the manuscript.

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