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Economic and Agronomic Impacts of Agrivoltaics on Arable Land Use at the Example of the Stuttgart Region*

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Abstract

Photovoltaics and wind energy must be considerably expanded to achieve the targeted climate neutrality in Germany in 2045 which may cause new conflicts. Especially ground-mounted photovoltaic systems, which are often associated with a high land consumption rate, conflict with other land uses such as agriculture. Due to the simultaneous electricity generation and agricultural use, agrivoltaics (AV) systems can increase land use efficiency which is why they are in the political focus. In this study, we go beyond the limited point-wise analyses of previous studies which have focused mainly on the technology itself and potential yield changes of individual crops and provide a spatially explicit analysis of the AV potential. This is done by an in-depth analysis on the example of arable land in the Stuttgart Region, one of the most important conurbations in Germany and Europe. The study focusses on the resulting agronomic effects in the region and the associated agro-economic effects. The analysis is carried out with an integrated land use model that optimises arable land use by maximising gross margins at the farm level. Legal framework conditions such as the regional plan are considered constraints, and existing studies on yield effects under AV are used. The results show that there are synergies through increases in the agricultural gross margins. These synergies could be realized on about 3% of arable land in the study region subject to the underlying assumptions made. With more than 10% of the arable land in the study region used for AV, the average gross margins in arable farming decrease by about 280 € per ha of AV. Farms or areas with a high share of special crops, such as strawberries, demonstrate the highest profitability. On the other hand, regions with a high share of root crops in the crop rotation seem to be less favourable to establish AV. This demonstrates that, the agricultural land use structure must be considered in the holistic assessment of the land use efficiency of AV installations. Our results help policymakers better assess the effects of AV on land use and are useful for identifying priority implementation areas, for instance, in regional or land use plans.

Keywords

agrivoltaics; energy transition; economic optimum; agricultural policy; integrated land use model

1 Introduction

The key objectives of the European Green Deal (EUROPEAN COMMISSION, 2019) are to achieve climate neutrality by 2050 and to make agricultural land use sustainable. According to its Climate Change Act, Germany should be climate neutral by 2045. This calls for a significant increase in the share of renewable energies (UBA, 2021). In order to reduce the dependence on fossil fuel while guaranteeing energy security in the long term, wind and solar energy, must be substantially expanded (PIETRONI et al., 2017). PIETRONI et al. (2017) estimate the required installed capacity for solar energy by 2030 at almost 200 GWp, i.e. nearly a fourfold increase of the installed photovoltaic capacity in 2021 (BUNDESNETZAGENTUR, 2021). This is also in line with a meta-analysis by WIESE et al. (2022).

However, renewable energies such as wind and solar are usually associated with a high spatial impact, especially since the necessary solar capacity can probably not be realised on rooftops alone (NITSCH and MAGOSCH, 2021; SCHINDELE, 2021b). The spatial impact becomes particularly visible in the required

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land consumption of ground-mounted photovoltaic systems which may be in conflict to other sustainability goals (SCHINDELE, 2021a).

The basic idea of agrivoltaics (AV) was already described by GOETZBERGER and ZASTROW (1982). AV is an approach with a high land use efficiency that enables dual use between agricultural production and photovoltaics (PV) (SCHINDELE, 2021a; DUPRAZ et al., 2011). Therefore, the technology can also help to achieve sustainability goals (AGOSTINI et al., 2021). Although there are already many installations worldwide, the technology has hardly played a role in Germany so far (SCHINDELE, 2021a; BÖHM et al., 2022). From a political point of view, however, AV as an innovative form of solar energy is also in focus to achieve the climate goals in Germany (KOALITIONSVERTRAG ZWISCHEN SPD, FDP UND GRÜNE, 2021). AV plants on agricultural land are now funded within the framework of the new EEG 2023 (Renewable Energy Act 2023). Accordingly, simultaneous crop cultivation must take place in the same area or be used by perennial crops as described in the German standard DIN SPEC 91434. According to the EEG 2023 up to 8.2 cents per kWh could be generated from AV systems. The levelized cost of electricity from AV is currently still 40% above those of ground-mounted systems predominantly due to the mounting structures needed for farming operations to continue.[1] AV systems are now also explicitly mentioned in the CAP (Common Agricultural Policy) Direct Payments Ordinance of 26 November 2021 (GAPDZV). In the new CAP period from 2023 onwards, agricultural land under AV receives 85% of the premium for arable land.

Since as described above the agricultural land use under AV is the special feature of this system, the agronomic and economic impacts on agricultural land use must also be considered against the background of the desired expansion of the technology. Given the limited implementation of AV plants today and thus the limited empirical data or practical experience, it is still difficult to assess these impacts. FEUERBACHER et al. (2021) and TROMMSDORFF (2016), analysed the impacts of AV on farm management, but did not consider the landscape level. FEUERBACHER et al. (2022) studied the potential of AV for the whole of Germany, but disregarded the role of spatial planning and adjustments in farmers' crop rotations. Against this background, the purpose of our analysis is to extend the existing economic analyses of AV by examining the potential impacts of AV expansion on agricultural land use and farm income at a landscape level. In this context, we also take into account the level of landscape planning with the corresponding legal restrictions on the construction of AV and address potential impacts on landscape aesthetics.[2] We choose the Stuttgart Region, one of Europe's most economically important conurbations (DISPAN et al., 2021), as an illustrative case study region to foster the transferability to other metropolitan regions in Germany and worldwide. The key research questions are: i) What agronomic and economic effect does the expansion of AV have on arable land use? ii) Which areas are most likely to offer an AV implementation potential from an agricultural perspective.

We used a geodata-based integrated land use model with a spatial resolution at the field plot level. It consisted of the crop growth model Expert-N, the crop rotation model CropRota and the economic land use optimisation model PALUD. As AV is a long-term determination of land use, we also considered impacts of climate change on crop yields by coupling Expert-N and PALUD. Different scenarios to cover the energy demand in the region through AV were considered, assuming a basic profitability of electricity generation through AV. To the best of our knowledge, no study has yet investigated the economic and agronomic impacts of AV simultaneously on agricultural land use by adopting such a spatially highly resolved integrated bioeconomic land use model. The results were used to derive recommendations on how AV can contribute to the transition towards a sustainable energy system while preserving agricultural land use.

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[1] An overview on potential construction costs as well as the operating costs including maintenance and insurance, among other cost positions, can be found in SCHINDELE et al. (2020). They estimated the construction costs at about 672.000 € per hectare or an installed capacity of 0.52 MWp (megawatt-peak). This means that the maximum electrical output is 0.52 MW per hectare.

[2] In addition to the EEG and the CAP, also legal restrictions from the building law are important when AV systems are to be implemented. Under certain circumstances, a building permit for AV plants can be granted as a privileged project in an undesignated outlying area ("Privilegierte Bauvorhaben im Außenbereich") according to Article 35 German Building Code (BauGB) or within the framework of a project-related development plan TROMMSDORFF et al. (2020); VOLLPRECHT et al. (2021). According to § 1 para. 4 BauGB, spatial planning objectives must be considered. In this context, certain uses can be explicitly excluded in defined areas (Article 7 Federal Regional Planning Act).

2 Material and Methods

2.1 Study Area

The Stuttgart Region in the south-west German state Baden-Württemberg consists of the districts of Böblingen, Esslingen, Göppingen, Ludwigsburg, Rems-Murr-Kreis, and the city of Stuttgart.

According to the Integrated Administration and Control System (IACS) 2021, the arable land in the Stuttgart Region amounts to about 72,120 ha. The use of arable land differs significantly between the districts (Table 1). Special crops grown on arable land like vegetables and strawberries comprise a comparatively high share of arable land in Stuttgart and Esslingen, of 10% and 9%, respectively.

The region is characterised by a relatively high average annual solar irradiation of about 1,170 kWh per m² in comparison to other locations in the north of Germany such as Hamburg with values of ca. 1,000 kWh between 1990 and 2021 (DWD Climate Data Center, 2021). Approximately 1,202 full load hours can be achieved in electricity generation through photovoltaics, which means that 1,202 kWh can be generated per installed kWp and year (Feuerbacher et al., 2021).

AV implementation is also subject to legal restrictions and technical limitations, which were accounted for in our study. According to building law, any construction projects have to be aligned with the objectives of regional planning as fixed in the regional plans. The Verband Region Stuttgart as regional planning authority in our study area has therefore provided the current regional plan, which contains, among other things, specifications on green areas and areas for raw material extraction. According to information from the Verband Region Stuttgart (oral information from Ms. Jahnz, 15.03.2021), these are fundamental exclusion criteria for AV. Regional green corridors were not taken into account as a restriction since, in practice, the construction of PV systems can still be permitted within green corridors (see, e.g., Regionalverband Heilbronn-Franken (2020)). According

Table 1. Overview of the amount and use of arable land in the districts of the Stuttgart Region in 2021

Urban / rural District	**Arable land in hectares**	**Crop shares on arable land in the districts in 2021 in %**									
		Forage crops	Grain legumes	Potatoes	Maize	Oil-seeds	Spring Cereals	Winter cereals	Sugar beets	Vegetables and strawberries	Other
Böblingen	14,661	8.5	2.1	1.4	10.6	8.8	19.5	39.4	5.2	1.4	3.0
Esslingen	9,572	8.1	1.6	1.8	22.1	3.1	9.6	41.0	0.3	9.2	3.2
Göppingen	11,955	10.4	1.0	0.2	23.5	7.6	11.1	44.8	0.1	0.2	1.2
Ludwigsburg	23,418	4.9	2.3	1.2	21.5	1.7	9.6	42.9	10.8	2.4	2.8
Rems-Murr-Kreis	11,116	10.5	1.0	1.3	28.8	2.8	6.2	41.7	1.7	3.0	2.9
Stuttgart	1,398	8.0	4.2	1.9	20.6	1.3	12.1	29.6	5.2	10.2	6.9
Stuttgart Region average	**72,120**	**7.9**	**1.8**	**1.2**	**20.8**	**4.5**	**11.4**	**41.8**	**5.0**	**3.0**	**2.7**

Source: own calculation based on data from the Integrated Administration and Control System 2021

Table 2. Areas that are not suitable for the implementation of agrivoltaics

Areas not permitted for AV	**Data source**
Green corridors	Regional plan of Verband Region Stuttgart
Area for the mining of near-surface raw materials	Regional plan of Verband Region Stuttgart
Areas for securing raw material deposits	Regional plan of Verband Region Stuttgart
Nature protection areas	LUBW (2021a)
Biotopes	LUBW (2021a)
Biosphere reserves	LUBW (2021a)
Areal natural monuments	LUBW (2021a)
Water protection areas (Zone I and II)	LUBW (2021a)
Floodplains HQ 100	LUBW (2021a)
Distance to forests (< 30 m)	BKG (2021a)
Average plot slope (> 7 %)	BKG (2021b)

Source: based on LUBW (2021b) and oral information from Ms. Jahnz, 15.03.2021 from the Verband Region Stuttgart as well as oral information from Mr. Schindele, BayWa AG, 15.11.2021 to LUBW (2021b), environmental protection and nature conservation restrictions have been defined based on a catalogue of criteria for the construction of open-space PV systems. In addition, we assumed that AV is not possible on land with an average slope of more than 7% (oral information from Mr. Schindele, BayWa AG, 15.11.2021). After considering all restrictions (Table 2), AV is, in principle, possible on 45,495 ha or 63% of the arable land in the Stuttgart Region, which reflects the total agrivoltaics potential.

2.2 Overview of the Integrated Land Use Model

Figure 1 schematically shows the integrated land use model coupled to CropRota (SCHÖNHART et al., 2011), Expert-N (PRIESACK, 2006), and PALUD (SPONAGEL et al., 2022). All model components are explained in detail below.

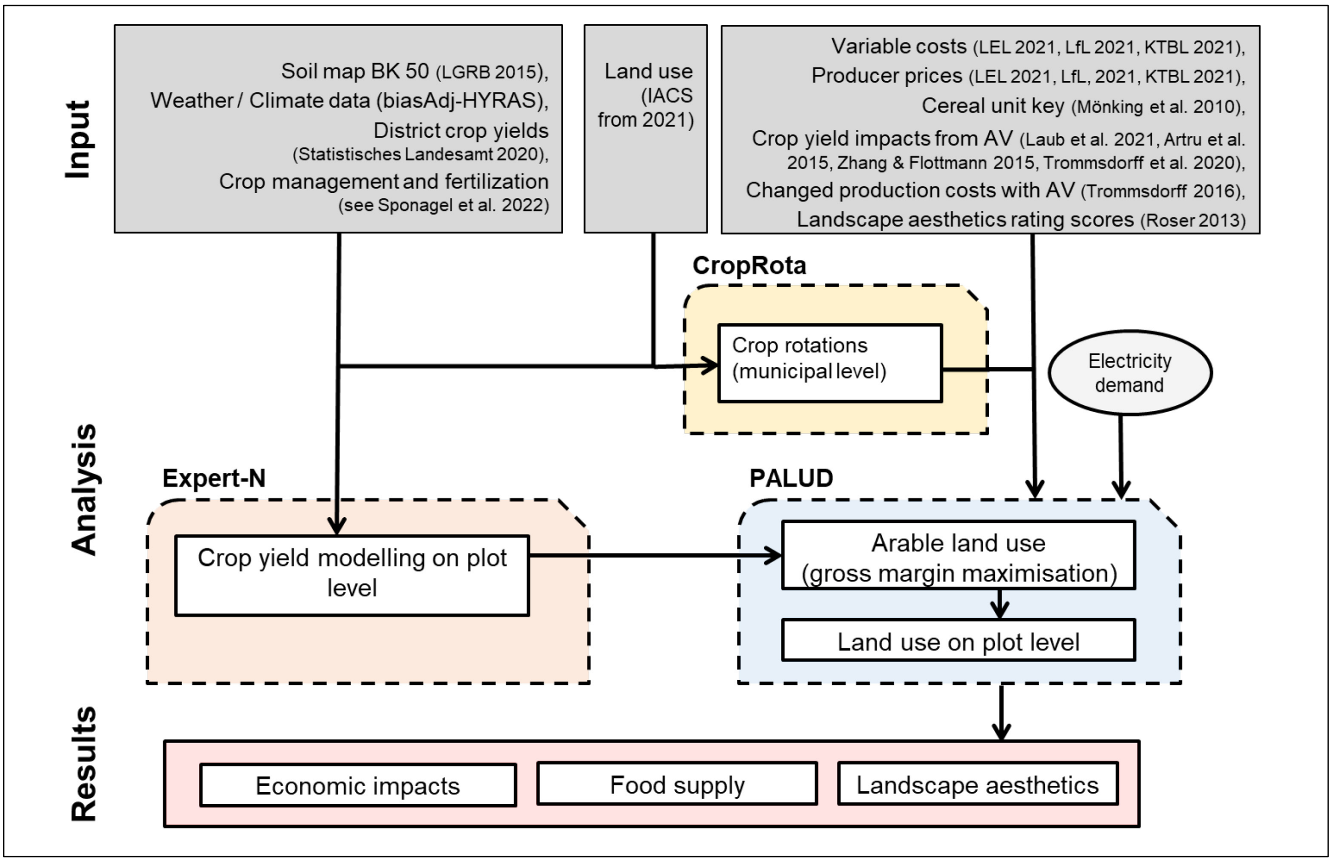
2.3 Crop Yield Simulation with Expert-N

Projections of average yields were simulated for seven selected crops (silage maize, grain maize, sugar beet, potatoes, winter wheat, spring barley, winter oilseed rape) with the biophysical agroecosystem model Expert-N (PRIESACK, 2006) at the field level for the time period 2020 to 2050. The simulated crop yields refer to the water-limited yield potential and it was further assumed that crop pests and weeds are under control by the farmer and do not negatively affect crop yields. These seven crops accounted for more than 75% of the arable land in the Stuttgart Region in 2021 (Table 1). The used climate projections were based on the assumed emission scenario RCP8.5 (business-as-usual). For a more robust prediction of the crop yields, a climate model ensemble of six were used. The average field level yields for the above-mentioned time period were incorporated into the PALUD model as exogenous data. Winter wheat was used to indicate the relative yield of other winter cereals. For all other crops, such as vegetables and strawberries, three yield levels were formed in each case according to the natural soil fertility from soil map 50 (LGRB, 2015). More details on the Expert-N setup may be found in SPONAGEL et al. (2022).

2.4 CropRota

CropRota is a crop rotation model based on linear programming, which was used to derive typical crop rotations based on observed land use and an agronomic expert assessment (SCHÖNHART et al., 2011).

Figure 1. Structure of the integrated land use model



Source: own presentation

With the help of CropRota, three- or four-year crop rotations, incl. special crops, were derived at the level of the 179 municipalities in the Stuttgart Region based on the shares of 24 individual or aggregated crop types in 2021 according to the IACS data. On average, about 15 crop rotations were simulated per municipality. The crop rotations were then integrated into PALUD.

2.5 PALUD

PALUD (SPONAGEL et al., 2022) is an economic geodata-based land use model based on linear programming. In the objective function, land use was optimised at the level of arable plots (n = 76,280) using the sum of the gross margins (GM) of all arable plots under restrictions. The land use of an arable field resulted from the available possible crop rotation options in the respective municipality generated with CropRota and the associated gross margins. Hence, the decision for AV implementation was made on plot level by the model. Based on the explanations in Chapter 2.1, only the suitable areas could be selected for AV, the others could only be used for crop rotations without AV. The margins were calculated using the spatially explicit simulation of yields (see Chapter 2.3) and standard calculation data (LEL, 2021; LFL, 2021; KTBL, 2021). This was done by the model, whereby the fertiliser costs were considered on the basis of the yields and nutrient contents in Annex 7 of the Fertiliser Ordinance. In the case of arable fodder predominantly organic fertilisation was assumed (approx. 30% mineral nitrogen). Arable fodder was valued at € 0.22 per 10 MJ NEL (net energy lactation) based on maize silage (AMI, 2019, 2020, 2021). In addition, based on the GAPDZV, area premiums of € 150 per ha without AV and € 127.50 per hectare with AV were considered. The optimisation of the objective function was subject to the condition that the amount of arable fodder in 2021 in MJ NEL is covered at the municipal level and remains constant. Furthermore, the proportion of set-aside arable land had to remain at least constant at the municipal level compared to the year 2021. In addition, it was assumed that the region's cultivation area for feed grains and clover grass must remain at least at a level of 60% compared to 2021 to cover the needs of livestock farming (BLE, 2020). To allow flexibility in the model with regard to future cultivation, it was assumed that an expansion of an individual crop is possible by 20% at regional and by 25% at municipal level, which is line with (HAß et al., 2020).

The optimisation also takes into account the availability of labour as a constraint in PALUD. Within PALUD we therefore calculated the demand for labour in labour unit per hour using standard calculation data from KTBL (2021) and LFL (2021). We assumed that labour units per hour can be extended only in a limited range by a maximum of 10% in comparison to the calculated labour demand for the observed crop share in 2021.

The aforementioned restrictions, such as the available crop rotations, labour restrictions and the coverage of arable fodder requirements at the municipal level, as well as the possibility of cultivation flexibility, means that PALUD generated a modelled status quo that approximates the observed land use in the reference year 2021. As this is a future perspective taking into account the influence of climate change on crop yields, the modelled status quo also deviated in part from the reference year. For example, the cultivated areas of winter cereals were 15% lower in the region. In contrast, the areas of spring cereals were 14%, of oilseeds 18%, of maize 16% and of root crops 9% higher.

2.6 Assumptions on the AV System and its Impacts on Arable Land Use

In the Federal State of Baden-Württemberg, located in south-west Germany, a pilot AV plant was set up in 2016 in Heggelbach. It was used to investigate the effects of shading from the elevated solar panels on yields of four different crops (TROMMSDORFF et al., 2020). The results from 2017 and 2018 showed that yield quantity reductions are expected, but highly depend on crop type and weather conditions (WESELEK et al., 2021). This result is also confirmed by LAUB et al. (2022) who in a meta analysis investigated the yield effects of crops due to different degrees of shading.

Following this AV pilot plant in Heggelbach (Figure 2), an installed electrical capacity of 0.52 MWp (megawatt-peak) per hectare of AV was assumed as considered in SCHINDELE et al. (2020). The PV modules are elevated and permanently installed with southwest orientation. This allows a clearance height of about 5 m and a clearance width between the support rows of about 19 m with agricultural machinery (SCHINDELE et al., 2020).

This system was developed for arable farming and not, for example, specifically for fruit growing. In this respect, the same cultivation flexibility could be assumed for areas under AV as for areas without

Figure 2. Illustration of the AV pilot plant in Heggelbach (Baden-Württemberg) which served as example for our study

Source: photo taken by Christian Sponagel

AV in PALUD. The AV mounting structure was assumed to reduce the arable area under AV by 8% (Trommsdorff et al., 2020). In addition, the AV system had an impact on the management costs of the usable area under the system (Trommsdorff, 2016). An increase in variable machinery costs of 2% or, in the case of costs for contract machinery, 5% was assumed (Trommsdorff, 2016). In addition, a higher labour effort by 10% was assumed under AV (Feuerbacher et al., 2021). In contrast, the system can offer protection against hail damage to the crops grown underneath, which is why a cost reduction of 10% was assumed for hail insurance (Trommsdorff, 2016). In addition, a 35% reduction in usable solar radiation by the crops under AV was assumed (Trommsdorff et al., 2020). Table 3 provides an overview of the assumed relative yield losses due to AV based on studies by Laub et al. (2022), Artru et al. (2018), Zhang and Flottmann (2015), and Trommsdorff et al. (2020). For sensitivity analysis we also considered 90% of the literature-based yields under AV (Table 3). In addition, we also analysed the impact of assuming that there will be no strawberry cultivation under AV as well as 20% higher and lower producer prices in relation to the assumptions outlined in section 2.2.

2.7 Model Output Indicators

From the PALUD model output, we obtained the marginal gross margin change from agricultural production for one additional MWp installed AV capacity in the Stuttgart Region. This is calculated within GAMS as the marginal value for an equation or shadow price (GAMS, 2023), hence the impact on the objective function if one additional MWp are to be installed. The same solar radiation and cost for grid connection was assumed across all areas in the Stuttgart Region. Hence, the contribution margin from electricity production is identical on all areas and can be left out in the subsequent analysis.

To anticipate food supply in the region, as a secondary objective, the cereal unit was used as a standardised indicator and calculated endogenously in the model (Mönking et al., 2010).

In addition, we observed the distribution of AV arable land plots from the model output regarding potential landscape aesthetic impacts. Therefore, rating scores were obtained from Roser (2013), who developed a state-wide landscape aesthetic rating score map for Baden-Württemberg. The rating methodology is described in Roser (2014) in more detail. In general, the map has a spatial resolution of 100 x 100 m. Based on a survey, each pixel received a rating score between zero (very bad) and ten (very good). Regarding the Stuttgart Region, the scores are relatively low in centre of the region.

2.8 Scenarios for the Development of Agrivoltaics in the Stuttgart Region

Nitsch and Magosch (2021) describe an expansion path for renewable energies to achieve the climate neutrality target of Baden-Württemberg by 2040. The AV development scenarios for the Stuttgart Region were derived from this. The installed capacity, electric energy generated per energy source estimated for

Table 3. Assumed crop yield change percentages as a consequence of shading by the AV system in the basic scenario as well as adjusted yield impacts for sensitivity analysis.

Crop type	Forage crops	Maize	Vegetables	Potatoes	Grain legumes	Oilseeds	C3 Cereals	Sugar beets	Strawberries
Crop yield change under AV (basic)	-5.0%	-48.5%	-9.9%	-33.4%	-43.4%	-20.0%	-32.3%	-30.0%	+15.6%
Crop yield change under AV for sensitivity analysis	-14.5%	-53.7%	-18.9%	-40.1%	-49.1%	-28.0%	-39.1%	-37.0%	+4.0%

Source: based on Laub et al. (2022), Artru et al. (2018), Zhang and Flottmann (2015) and Trommsdorff et al. (2020)

Table 4. Description of the development scenarios for agrivoltaics in the Stuttgart Region

Scenario		Expansion of AV in GWp	AV area in ha	AV share of arable land %	AV share of the PV demand until 2040 in %
0	Modelled status quo	0	0	0	0
1	Low expansion	1	1,923	2.7	12
2	Medium expansion	3	5,769	8.0	36
3	High expansion	5	9,615	13.3	60

Source: own calculation based on NITSCH and MAGOSCH (2021), SCHINDELE et al. (2020) and data from the Integrated Administration and Control System 2021

2020, and electricity consumption were taken from NITSCH and MAGOSCH (2021). According to this, the necessary demand for PV in 2040 is about 38.7 GWp of installed capacity. In 2017, based on STEIDLE (2021), the Stuttgart Region had a share of about 21% of electricity consumption. Transferring the projected expansion demand for PV in Baden-Württemberg to the Stuttgart Region, therefore, results in a demand of just under 8.3 GWp by 2040. This includes all types of PV, including installations on roof surfaces. In 2018, the total installed PV capacity in the Stuttgart Region was around 0.8 GWp, of which almost 99% was on roof surfaces (LUBW, 2022). Based on this, three expansion scenarios for AV were created (Table 4). Scenario 0 represents the modelled status quo. Scenario 1 (“low expansion”) is based on the assumption that 1 GWp is covered by AV, i. e. a share of just under 12% of the PV demand. Scenario 2 (“medium expansion”) assumes that 3 GWp is provided by AV and Scenario 3 (“high expansion”) assumes an AV expansion of 5 GWp. The arable land shares under AV thus vary greatly between 2.7% and 13.3% in the Stuttgart Region.

3 Results

Clear spatial disparities in preferability of AV systems on arable land can be seen in the Stuttgart Region (Table 5). The moderate expansion of AV in Scenario 1 (1 GWp) results in about 33% of the AV area in the district of Ludwigsburg. In relation to the share of arable land, a large proportion of the AV area is also located in the district of Stuttgart, which is characterised by a particularly high share of special crops such as strawberries. Only 1% of the AV area would be established in the district of Göppingen, where hardly any special crops are cultivated. With increasing AV expansion, the area ratios between the districts change simultaneously. In Scenario 3 (5 GWp), only about 21% of the AV areas are implemented in the district of Ludwigsburg. In Stuttgart, only a slight expansion of AV areas can be observed in Scenario 3 compared to Scenario 2 (3 GWp). In contrast, about 21% of the total AV area are in the district of Göppingen.

There are also spatial disparities within the individual districts (Figure 3). For instance, the city of Stuttgart stands out in Scenario 1 with a comparatively high AV area of about 17% of the arable land. While the AV area in Scenario 1 is mainly concentrated in the western part of the region, an increasing areal expansion in the eastern part of the region can be observed in Scenario 3. In contrast, the AV potential is only utilised to a relatively low degree in the district of Ludwigsburg until an AV development of 5 GWp in the Stuttgart Region.

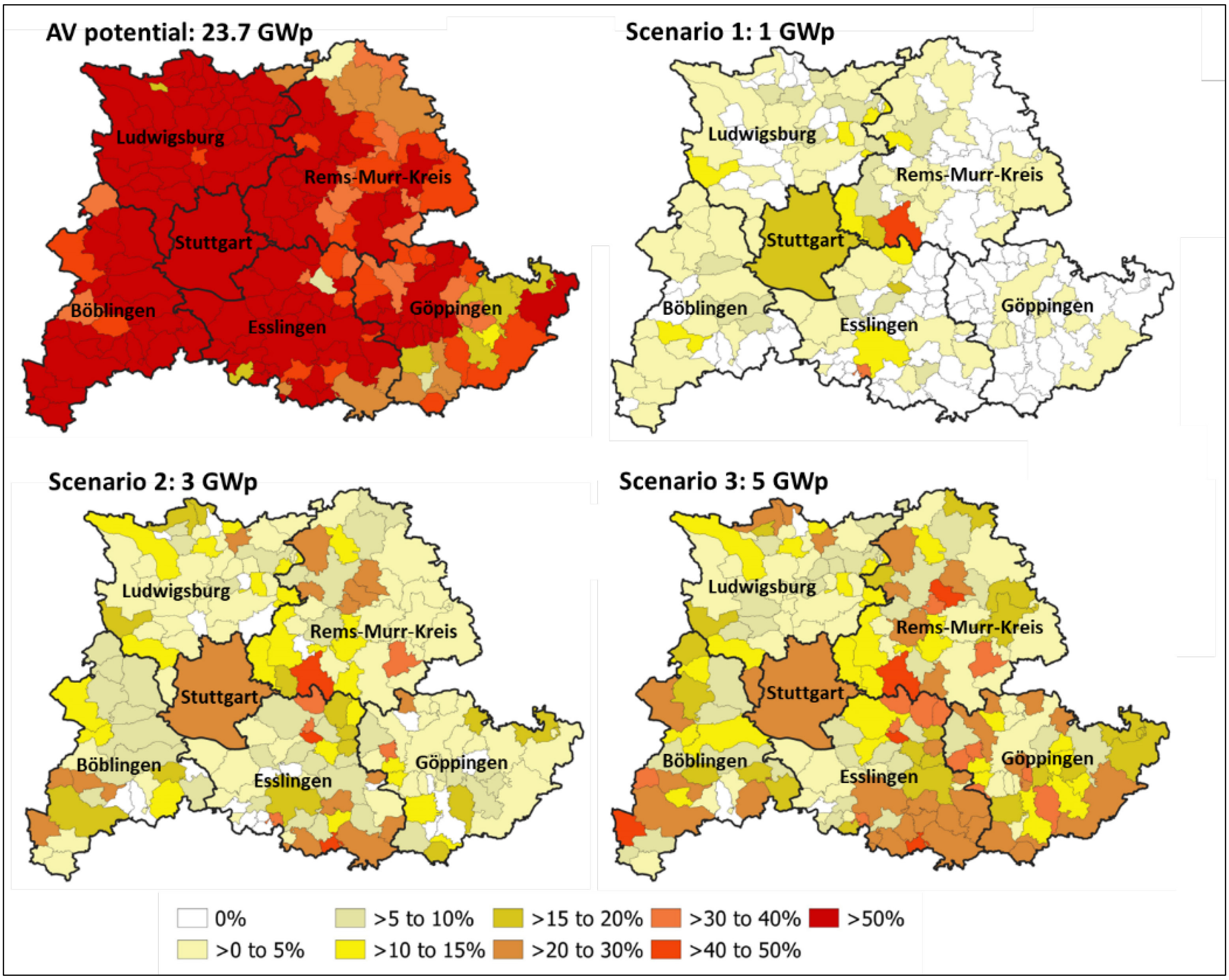
Table 6 provides an overview of the scenarios’ land use under AV systems. In Scenario 1 (1 GWp), strawberries make out almost 30% of the area under

Table 5. Area of agrivoltaics by district and scenario

Urban/ rural district	Arable land under AV system for the Scenarios 1,2 and 3, in hectares			Regional share of the entire AV area for the Scenarios 1,2 and 3, in %		
	1	2	3	1	2	3
Böblingen	308	1,548	2,403	16.0	26.8	25.0
Esslingen	296	891	1,325	15.4	15.4	13.8
Göppingen	18	478	2,014	1.0	8.3	20.9
Ludwigsburg	625	1,385	1,996	32.5	24.0	20.8
Rems-Murr-Kreis	442	1,164	1,548	23.0	20.2	16.1
Stuttgart	235	303	333	12.2	5.3	3.5

Source: own calculation

Figure 3. **Total agrivoltaics potential in percent of arable land (upper left field) as well as the share of arable land used for AV according to own calculations in the individual scenarios by municipality (BKG, 2022)**



Source: own presentation after BKG (2022)

AV. Summer and winter cereals account for another 50% of the area. In this context, it has to be said that most of the respective strawberry crop rotations also include summer and winter cereals. Forage crops and oilseeds are almost not cultivated at all under AV systems. In the medium Scenario 2 (3 GWp), however, the spectrum of cultivation under AV changes. The share of strawberries decreases to about 10%, whereas forage crops account for a high amount of land use at over 50%. In Scenario 2, strawberries alone account for about 586 ha of the AV area, hence ca. 539 ha cultivation area including the 8% area loss under AV. The high share of forage crops can be explained by the relatively low yield reductions assumed. In Scenario 3 (5 GWp), also oilseeds are cultivated on a larger scale with a share of about 7% of the total AV area. In turn, there is a reduction in the share of forage crops, with winter cereals again increasing to a share of about 25%. Potatoes and vegetables are not cultivated under AV in any scenario. Sugar beet also accounts for only a small share in Scenario 3, with about 1.6% of the area under AV.

Looking at the total arable land in the region, there are no changes in the shares of the individual crop types in Scenario 1 compared to the modelled reference. Only in Scenario 3, compared to the modelled reference, are trends of an impact of AV expansion on the cropping spectrum in the region recognisable. The area of winter cereals decreases by 3.3%, whereas the area of summer cereals and maize remain almost constant. Furthermore, the area under sugar beet decreases by about 7%.

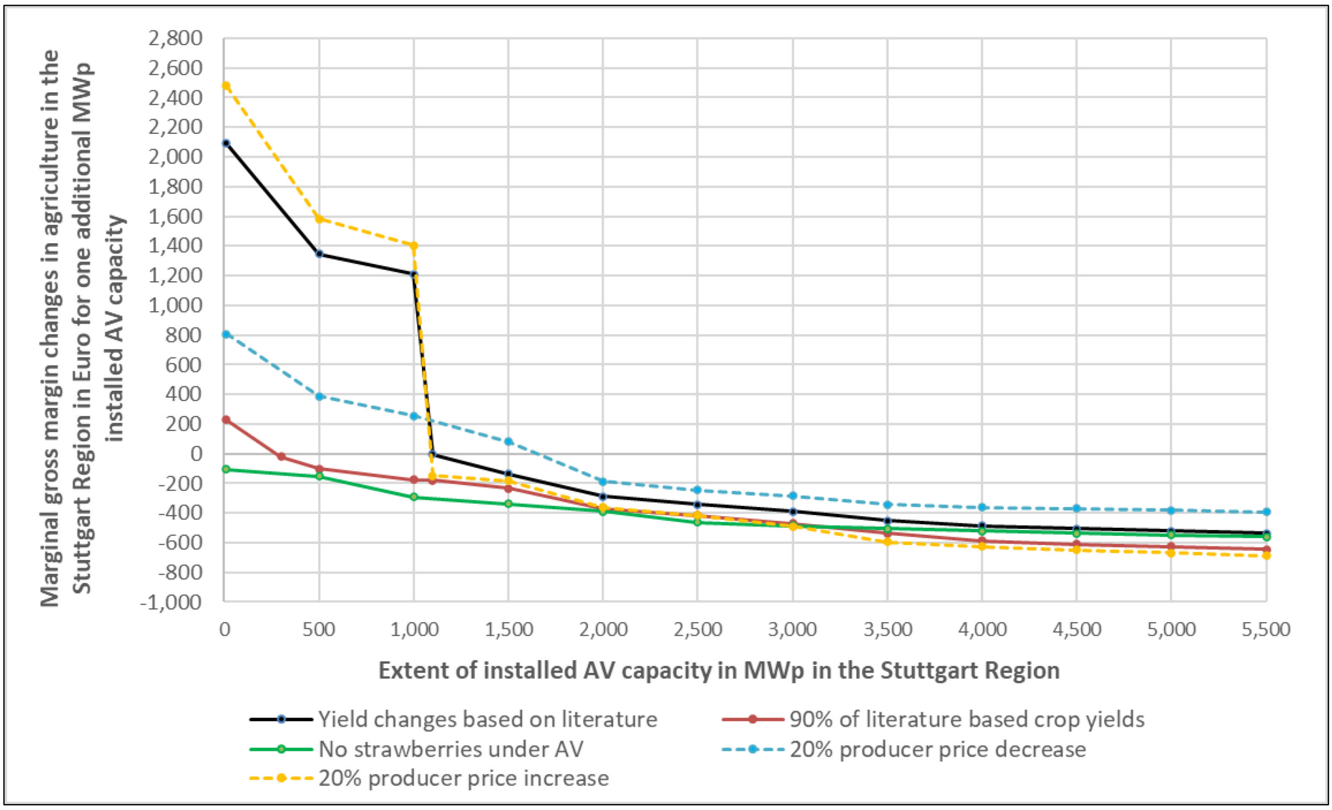
Table 6. Cultivation of crop types under agrivoltaics as well as their proportion of the total area under AV by district and scenario, i. e. the actual cultivated area is only 92% of the figures shown

Urban/ rural district	Cultivations areas of crop types under the AV systems by scenario in hectare								
	Forage crops	**Grain legumes**	**Maize**	**Oil-seeds**	**Spring cereals**	**Straw-berries**	**Other crops**	**Winter cereals**	**Sugar beet**
	Scenario 1								
Böblingen	4	5	0	3	121	82	11	64	18
Esslingen	1	2	44	0	58	95	8	88	0
Göppingen	0	0	2	0	4	5	0	7	0
Ludwigsburg	0	60	34	0	56	159	0	264	51
Rems-Murr-Kreis	0	0	45	0	64	126	1	148	58
Stuttgart	0	0	78	0	0	78	0	78	0
Sum in hectare	5	68	203	3	304	545	20	649	127
Proportion of total AV area	0.3%	3.5%	10.6%	0.2%	16.0%	28.3%	1.1%	33.7%	6.6%
	Scenario 2								
Böblingen	938	5	5	3	336	93	26	112	29
Esslingen	471	4	48	0	109	99	16	145	0
Göppingen	378	0	2	3	38	5	9	43	0
Ludwigsburg	502	84	37	8	76	193	100	334	51
Rems-Murr-Kreis	570	0	30	0	129	119	29	229	58
Stuttgart	46	22	56	0	22	78	0	78	0
Sum in hectare	2,905	116	179	14	710	586	180	941	138
Proportion of total AV area	50.4%	2.0%	3.1%	0.2%	12.3%	10.2%	3.1%	16.3%	2.4%
	Scenario 3								
Böblingen	1,179	5	3	113	468	97	62	440	36
Esslingen	601	5	63	44	194	92	51	275	0
Göppingen	526	0	3	412	236	5	27	805	0
Ludwigsburg	840	71	47	59	129	202	165	419	64
Rems-Murr-Kreis	646	0	24	58	208	112	55	388	57
Stuttgart	46	19	60	0	26	78	26	78	0
Sum in hectare	3,838	100	199	686	1,261	585	386	2,405	158
Proportion of total AV area	39.9%	1.0%	2.1%	7.1%	13.1%	6.1%	4.0%	25%	1.6%

Source: own calculation

Figure 4 shows the marginal changes in the total agricultural gross margins of arable land use in the region depending on the installed electrical capacity of AV. Following the shade-induced yield changes (see Chapter 2.6), positive impacts on the gross margins or marginal yields can be recorded in the region up to an installation of about 1,100 MWp, i.e. between Scenario 1 and 2. This is also true regarding the gross margins in each individual district. Even if positive yield effects only result for strawberries, the average gross margins for the crop rotations under AV are nevertheless higher than without AV within this range. Up to this level of AV expansion, all strawberries in the region are already grown under AV, hence no additional positive gross margin effects can be achieved with further AV expansion. From about 3,500 MWp onwards, the marginal costs of AV increase only slightly and are at about 520 € per MWp or about 270 € per ha at 5,500 MWp. However, there are regional disparities with regard to the economic effects. For example, the additional revenue in relation to the gross margins through AV in Scenario 3 in Stuttgart is, on average, just under 630 € per ha of AV. In contrast, in the district of Göppingen, average costs of about 225 € per ha of AV arise. In the district of Böblingen, the average additional revenue per ha of AV would still be about 12 €. Deviating from the yield assumptions in Chapter 2.6 from the literature (black line in Figure 4), the sensitivity analysis regarding the yield impacts from shading (red line in Figure 4) showed that positive effects on gross margins in the region can only be observed up to a

Figure 4. **Marginal agricultural gross margin changes per MWp of installed AV capacity in the Stuttgart Region**

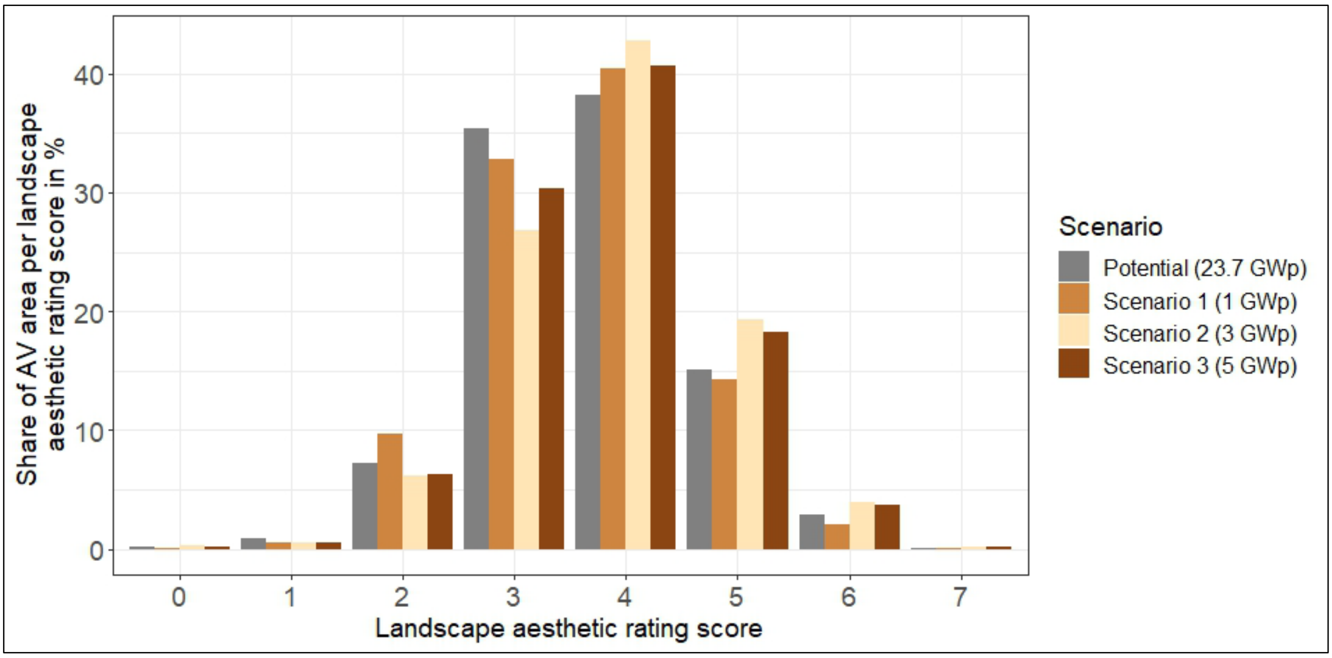


Source: own calculation

total installed capacity of about 300 MWp under these conditions. Consequently, in Scenario 1 the marginal costs are about 240 € per MWp AV. However, it can be observed that the costs converge with a larger expansion of AV. At 5,500 MWp, the costs are about 100 € per MWp apart. Figure 4 also shows that the positive impact from AV implementation is solely dependent from the strawberry cultivation under AV. Assuming that no strawberries are implemented under AV, the marginal costs would be at about 340 € per MWp in Scenario 1 (green line in Figure 4). In addition, raising producer prices first led to higher benefits and with increasing AV implementation up to 5,500 MWp to ca. 150 € higher costs per MWp in comparison to the basic assumptions (black line in Figure 4). In contrast, reduced producer prices led to decreased positive marginal gross margin changes up to AV implementation of about 1,500 MWp. However, the cost remained at a lower level with increasing AV capacity up to 5,500 MWp by about 140 € per MWp in comparison to the basic assumptions.

The expansion of agrivoltaics also reduces the food supply. In Scenario 1 (1 GWp), the food supply measured in cereal units decreases by about 0.7% to about 2.9% in Scenario 3 (5 GWp). In addition to the agronomic and economic impacts of AV in the Stuttgart Region, Figure 5 shows how the AV areas are distributed to landscape aesthetic rating scores by scenario. In general, no arable land plots are suitable for AV in areas with a rating score higher than 7. More than 70% of suitable AV plots are in areas with a medium rating score of three or four and approximately 8% or 3,800 hectares are found with rating scores zero to two. Especially in Scenarios 2 and 3, the share of AV plots in areas with a relatively high rating score above four increases. In contrast, only about 15% of the potential in the areas with low rating values below three is utilised. This is in line with Figure 3, which shows that the AV areas are also shifting to the more rural eastern districts of the region with increasing installed capacity.

Figure 5. The relative proportion of the area covered by AV with respect to their landscape aesthetic rating score levels



Source: own calculation based on ROSER (2013)

4 Discussion

The discussion is structured as follows: first, we will discuss the results of our study and our contribution to the literature on agronomic and economic impacts of agrivoltiacs on arable land. Second, the methodological approach, including model limitations, is discussed. Finally, we focus on the sustainability assessment of AV and its potential contribution to energy supply.

The results generally show that synergy effects between agriculture and renewable energy production are possible depending on the expansion of AV systems on arable land. This is in line with other studies, for instance, DINESH and PEARCE (2016). In contrast, FEUERBACHER et al. (2022) assessed the potential of AV for the whole of Germany and found synergy effects for less than 1% of farms. Yet, this study did not include possible crop rotation adjustments by farmers. In terms of the total gross margin from arable farming in the region, marginal returns can be achieved up to an expansion of AV to about 1,100 MWp of installed capacity. This means that synergy effects between agriculture and electricity generation can be generated up to this point. This would correspond to about 2,100 ha of arable land or approximately 3% of the arable land in the region. An expansion beyond this amount would be accompanied by higher costs on the side of agriculture. In Scenario 3 (5 GWp), the costs range between 200 € and 360 € per ha of AV. However, in relation to the electricity production of the AV system, these gross margin changes in agriculture account for less than 0.1 Euro cents of the electricity production costs per kWh (TROMMSDORFF et al., 2020). According to DIN SPEC 91434, referred to in the EEG 2023, agricultural use under the system is mandatory. This means that from an agricultural perspective, gross margin changes in the observed range are relevant, also regarding the type and extent of individual crop rotation elements under AV systems.

Especially in municipalities with high shares of strawberries, AV can contribute to a particularly high land use efficiency. The positive yield effects for strawberries under AV may even compensate negative yield effects of other crops such as summer cereals in the respective crop rotations from a monetary perspective. Also municipalities with comparatively high average soil qualities, according to LGRB (2015), as shown by the example of Stuttgart, offer a potential for AV. In contrast, for ground-mounted PV, whenever possible particularly suitable agricultural land should not be used according to the Open Space Ordinance (FFÖ-VO). Based on our results, an optimal area for AV can differ from ground-mounted PV. The preference for AV in municipalities or farms with a high share of root crops and maize in the crop rotation may be comparatively lower. In contrast, SCHINDELE et al. (2020) conclude that potato cultivation under

AV systems is economically preferable, which could not be confirmed. Especially in the case of potatoes, even small yield losses can mean a high reduction in revenue. Even in Scenario 3 with a high expansion of AV (almost 13% of arable land), only small effects on the cropping spectrum in the region could be determined.

In this study, the focus was on one specific AV system and only on arable land. Arable land makes out the highest share of the utilised agricultural area (UAA) in the Stuttgart Region with ca. 54%, followed by grassland with a share of ca. 38%. Only approximately 1% of the utilised agricultural area is used for permanent crops, according to the IACS dataset 2021. The EEG 2023 now also explicitly addresses grassland sites and permanent crops as potential areas for AV. However, there have also been concerns about implementing AV on grassland plots from a nature conservation perspective (DIE BUNDESREGIERUNG, 2022). Consequently, grassland sites in areas with a high nature conservation value are excluded from the EEG 2023 according to Article 37 Paragraph 1 Number 3c, for instance, Natura 2000 sites. In the study region almost 30% of grassland sites are located within the Natura 2000 network (based on IACS data and LUBW (2021a)). Taking Natura 2000 as well as the legal restrictions from Table 2 into account, approximately 80% of grassland sites in the Stuttgart Region would not be suitable for the implementation of AV at all. Hence, the total potential for AV on grassland might be limited in comparison to arable land in the study region. This can justify our focus on arable land in this study. Nonetheless, the inclusion of areas other than arable land into our modelling approach might impact the results. This should be considered by future research on the potential of AV in Germany and beyond.

Constant solar irradiation and grid connection costs were assumed irrespective of the location of the fields. Thereby, the profitability of electricity generation did not vary across locations as we focused on a single study area. This aspect can be relevant for a comparison of different regions in a larger spatial framework. However, our results are also transferable to other metropolitan areas with a similar agricultural land use structure to identify regional priority areas for AV.

It can be assumed that the specific plot shape impacts the construction costs of AV and therefore the profitability, for instance the material costs could increase (decrease) if more (less) pillars are necessary. This was neglected in our study due to data limitations (cost changes due to different AV system shapes and land ownership is unknown). Principally, with better data the shape of the AV system could be optimised by aggregation of plots which is a subject for further research. The same holds for possible economies-of-scale which may be realised if plots are aggregated to allow for larger AV systems. In addition, with increasing research and developments the AV construction costs may also change over time (FEUERBACHER et al., 2022). We leave those considerations for future research. Our results provide a starting point with regard to economic and agronomic impacts in areas with different framework conditions.

From statistical reports such as STATISTISCHES LANDESAMT (2020), average crop yields at district level can be obtained. Given the spatial resolution of our model, crop yields at plot level were required. Therefore, we used the Expert-N model to simulate crop yields at plot level. This approach also allowed us to consider long-term yield impacts from climate change as the implementation of AV is also a long-term land use decision.

With regard to the methodological approach, uncertainties regarding the modelling must be mentioned. This concerns the yield simulation with Expert-N, especially as the effects of the intermittent daytime shading by the AV modules on photosynthetic performance are not yet fully known. The effects on yield formation would mainly concern the absolute costs of arable land use under AV. In addition, we did not model the crop yields under AV explicitly. In order to do this with Expert-N, the boundary conditions of the model, especially radiation at stand height and microclimate, would have to be specified accurately. This data was not available for the study, hence further research is needed. Therefore, we have assumed changes in crop yields based on the literature. However, these values are also subject to uncertainties and need to be validated by future field investigations (LAUB et al., 2022). Other shading effects and thus other effects on yields could also occur, for instance, due to a change in the spacing of the modules or their orientation (TROMMSDORFF et al., 2020). In addition, the high sensitivity of the marginal agricultural costs of AV concerning the yield effects of shading was shown. This is mainly due to the influence of the yield effects on the gross margins for strawberries.

The crop rotations from CropRota represent typical crop rotations, which may, however, deviate from reality and thus are subject to uncertainty (SCHÖN-

HART et al., 2011). Further model uncertainties concern restrictions in PALUD such as arable feed restrictions or set-aside areas which may change due to the CAP reform. In addition, producer prices and variable production costs in PALUD are subject to uncertainty. Hence the gross margins can vary, especially for crops such as strawberries, due to farm-specific marketing channels. In this context, the system boundaries of the PALUD model must also be mentioned because the model only represents the supply side and not the demand side. If one assumes, for example, that the demand for crops such as strawberries will decline in the future, then the AV potential with synergy effects between agriculture and electricity generation would also be considerably lower in the model due to a market price drop as well as a corresponding decline of cultivation area. In our model strawberries were extended by a maximum of 3% in Scenario 3 compared to observed land use in 2021. Furthermore, within a municipality, the model may also shift strawberry cultivation areas towards AV-suitable areas, which may not be cultivated by strawberry farms in reality. Therefore, the flexibility in terms of land management is slightly overestimated in PALUD. Furthermore, we made the assumption that labour availability can be increased within a range of 10% in comparison to the reference year 2021. However, this is also subject to uncertainty as well as the crop specific labour demand, which might change in future.

Our study also contributes to a sustainability assessment of electricity production with AV. Thereby we focused on the economic and social dimensions. The economic impacts and effects on landscape aesthetics depend highly on the installed AV capacity. We observed that positive effects on gross agricultural margins and food supply are only possible on a very limited share of arable land, i.e. approximately up to 3%. Nevertheless, AV could contribute to about 13% to the required PV capacity in the Stuttgart Region in 2040. In comparison, SCHINDELE (2021b) estimated in a scenario analysis the potential contribution of AV to the energy supply through photovoltaics to be about 27 % in Germany in 2050. With an increase in area equipped with AV, also a high share of the AV area was in areas with relatively high rating scores for landscape aesthetics in our model. This might not be preferable from a societal point of view. In this context, KETZER et al. (2020) found that the installed amount of AV can affect social acceptance. We used a simplified approach to consider landscape impacts; however, the effects of aggregation or size of individual AV plants are also relevant regarding the agricultural landscape's aesthetic and recreational value (KETZER et al., 2020). In addition, a more holistic sustainability assessment of AV systems would need to consider also impacts on biodiversity and greenhouse gas emissions, for instance, by a life cycle assessment approach.

5 Conclusions and Outlook

The economic and agronomic impacts of AV and consequently the economic viability for the installation is highly dependent on the structure and type of land use, especially the predominantly cultivated crop type. Our study revealed spatial disparities regarding the economic viability of agrivoltaics implementation from the agricultural perspective. In general, AV can offer a potential for the Stuttgart Region or similarly structured regions against the background of synergy effects and presumably higher acceptance of agriculture. Our study therefore demonstrates the effects of AV on agriculture to political decision-makers. It can help to identify priority areas for AV, considering also regional energy and food self-sufficiency or ecological parameters. The results are expected to be useful to inform spatial planning, which is deemed an important contribution since commonly AV is not considered explicitly in regional planning in Baden-Württemberg. This can be seen, for example, in the fact that the current planning maps for promoting the expansion of renewable energies in Baden-Württemberg only include areas for wind energy and ground-mounted PV (MLW, 2022). As a highlight of our study, we found that areas earmarked for ground-mounted PV might not be optimal for AV, thus might not be a good proxy to consider AV in spatial planning.

We recommend that AV first be implemented in crop rotations where synergy effects between agriculture and electricity production are expected. In our study this was the case for strawberry cultivation. As our study focused on arable land, similar analyses are necessary for other agricultural land uses, such as permanent crops like apple trees or hops. For this purpose, recent studies on the shading impacts of AV on fruit yields from apple trees might be useful to consider AV on these areas in our model, for instance, JUILLION et al. (2022). Before implementing AV on arable land without positive impacts on agriculture the feasibility and economic impacts on other agricultural land use types should first be examined from an economic point of view. It is possible that other agricultural land uses like permanent crops are even more economically advantageous from an agricultural point of view, so that in this case implementation on arable land should initially be given secondary priority. However, fruit growing in Baden-Württemberg, for example, is highly spatially concentrated (LEL, 2015), so this must also be weighed against the background of the respective regional conditions.

In addition, social acceptance also plays a role in the expansion of AV. This includes effects of AV on landscape aesthetics (KETZER et al., 2020) that should be considered in more detail in subsequent studies.

Another future field of research is the analysis of the contribution of agrivoltaics to increasing the resilience of cropping systems in the context of climate change since, for example, yields of winter wheat under AV tend to be quite stable even in dry years (TROMMSDORFF et al., 2020). Furthermore, AMADUCCI et al. (2018) showed a positive impact of AV on the stability of rainfed maize yields. In the future, the aspect of resilience to climate change could also be analysed by coupling PALUD with a crop growth model that is able to account for the impacts of AV (microclimatic and shading effects) on crop yields during different weather conditions. Hence, more research is needed to better understand the biophysical processes in a cropped AV system to make more reliable assessments of plant growth, soil development and energy gain by AV.

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