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Preserving agricultural land with agrivoltaic – But at what cost? An economic analysis of different agrivoltaic systems in Germany

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ABSTRACT

Agrivoltaic systems have been advocated for their potential to reduce land use conflicts, as they enable the combined production of food and electricity on the same land. This paper determines the additional costs of agrivoltaic systems over conventional ground-mounted photovoltaic facilities on farmland and relates the extra cost to the amount of land saved, yielding an estimate of the costs of preserving farmland with agrivoltaics. The analysis is based upon extensive data collection from project developers as a basis of the cost calculations for various agrivoltaic and ground-mounted photovoltaic systems and system sizes. Net returns from farming under the agrivoltaic systems are credited against the costs of these systems. The levelized costs of electricity generation (LCOE) of agrivoltaic systems are significantly higher than those of ground-mounted photovoltaic systems. Depending on the agrivoltaic system type and scale, the additional costs range from 4 % to 148 % of the LCOE of ground-mounted photovoltaic systems. Agricultural production usually has little impact on overall profitability of the AV systems examined. When relating the additional costs of the agrivoltaic systems to the saved farmland area, the annual costs of preserving one hectare of land range between €8000 and €26,000 per ha and year for medium-sized, low-mounted agrivoltaic systems and between €42,000 and €75,000 per ha and year for high-mounted agrivoltaic systems. This is many times over the potential net returns from agricultural production on the land area saved. Given these findings, the meaningfulness of financial support for agrivoltaics, as offered by the German government, must be called into question.

1. Introduction

Following the Paris Agreement on climate change, the expansion of renewable energy has become a central policy objective worldwide (United Nations Framework Convention on Climate Change (UNFCCC), 2023). Among the available technologies, photovoltaic systems (PV), especially ground-mounted systems, have gained momentum due to their scalability and declining cost over time (Hassan et al., 2024; Kost et al., 2024). With a 70 % share of planned energy generation capacity from renewable sources, photovoltaics clearly dominates the expansion targets for renewable energies in Europe. Germany is among the drivers of this development (International Energy Agency IEA, 2025). However, the increasing deployment of close-spaced ground-mounted PV (subsequently GM PV) has given rise to concerns about land use conflicts, as agricultural land is a scarce and contested resource (Sacchelli et al., 2016). Increasing demands for land across sectors such as energy production, food production, urban development, and nature conservation have fuelled the debate, highlighting the need for solutions that are more efficient in terms of land use (Böhm, 2023; Osterburg et al., 2023).

Agrivoltaic (AV) systems have been advocated as a means of mitigating land use conflicts by enabling the simultaneous use of farmland for both electricity and food production (Amaducci et al., 2018; Böhm,

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2023; Schallenberg-Rodriguez et al., 2023). By integrating solar energy generation with agricultural practices, AV aligns closely with two Sustainable Development Goals: Zero Hunger (SDG 2) and Affordable and Clean Energy (SDG 7). In response, several governments have introduced financial incentives to support AV deployment. In Germany, this is reflected in the Renewable Energy Sources Act (EEG 2023), which grants AV systems with a minimum height of 2.1 m an additional bonus of €cent 1.2 per kWh in addition to the feed-in tariff (Bundesministerium der Justiz BMJ 2024). Compared to GM PV, agrivoltaic systems produce lower energy yields per hectare, but the underlying idea is that these losses can be offset by agricultural production on the same land (Schindele et al., 2020; Böhm, 2024). Furthermore, agricultural production can be influenced by the PV systems themselves, for example through shading effects, which may have positive or negative impacts on crop yields (Laub et al., 2022). These trade-offs lead to the central research question of this paper: At what cost is agricultural land preserved through AV systems compared to conventional GM PV? Furthermore, the paper aims to identify AV systems that are most favourable in this regard and to explore the factors that influence the outcome.

Previous studies have examined the technical feasibility and agronomic effects of AV systems, including their potential to improve microclimatic conditions (Elamri et al., 2018; Meier-Grüll et al., 2024), and to what extend they may serve as climatic adaption strategy (Aroca-Delgado et al., 2018; Wydra et al., 2023; Chopdar et al., 2025). Other studies have focused on the synergistic use of AV mounting structures for insect nets (Gadhiya et al., 2024). The literature also describes the potential of AV to power innovative precision agriculture systems (Bhadra et al., 2024).

Various studies show that dual land use for electricity and food production can significantly increase land use efficiency (Giri et al., 2022). Gadhiya et al. (2024) indicate an increase of up to 197 %, which is confirmed by Trommsdorff et al. (2021) for dry years.

Studies assessing the economic implications of AV systems, have focussed on pilot projects or specific AV configurations (Schindele et al., 2020; Agostini et al., 2021; Alam et al., 2023). This limits comparability. Moreover, the societal cost of preserving farmland through AV, expressed as the additional cost per hectare relative to GM PV, have been addressed but not systematically assessed across different system types and agricultural uses (Amaducci et al., 2018; Weselek et al., 2019; Feuerbacher et al., 2021; Trommsdorff et al., 2021).

Against this background, the objective of this paper is to determine the costs of farmland preservation for different AV systems and different agricultural land uses. To this end, the levelized cost of electricity (LCOE) of four AV system types and conventional close-spaced GM PV across three major agricultural land uses (arable land, grassland, and apple orchards) are calculated. The additional costs of AV systems are then related to the preserved farmland, yielding the annual preservation price per hectare. For a comprehensive assessment the analysis accounts for the agricultural returns under AV systems and examines the sensitivity of the results to key assumptions, such as interest rates and distances to the grid connection point. The literature is supplemented by systematically analysing four different AV systems, each in various system sizes, covering the three most important agricultural production systems in Germany: arable farming (11,657,000 ha in 2022 in Germany), grassland (4733,000 ha), and permanent crops (63,000 ha), of which apple cultivation accounts for around 50 % (Bundesministerium für Ernährung und Landwirtschaft BMEL 2024a, 2024b). Although the area under apples is relatively small, the synergy potential with AV is expected to be very high (Trommsdorff et al., 2023).

The scientific contribution of this study lies in its systematic and comparative analysis of a range of AV systems of different sizes under various agricultural land uses, based on recent data, while assessing the sensitivity of the results to the underlying assumptions. In terms of social impact, the results of this study contribute to the objectification of the political debate on land use conflicts in connection with photovoltaics on farmland.

The remainder of the paper is structured as follows: Section 2 outlines the methodology and data sources. Section 3 presents the results, including cost structures, LCOE comparisons, and preservation prices. Section 4 discusses the implications for policy and practice and makes recommendations for future research and policy design.

2. Methodology and data

Despite the widespread discussion of agrivoltaic concepts, there were only around 20 pilot plants in Germany at the beginning of 2024 (Fraunhofer Institute for Solar Energy Systems ISE (Fraunhofer ISE) 2024a), leaving an insufficient database for any meaningful comparative economic analysis. Given the paucity of data, it was necessary to conduct an ex-ante data collection and cost calculation for different PV systems and locations. Accordingly, the first step of the methodology involved data collection for different AV systems.

In Germany, AV is defined by DinSpec 91434, distinguishing between high-mounted (from 2.1 m) and low-mounted systems (*Deutsches Institut für Normung e.V.* (DIN), 2021). This preliminary industry standard stipulates that a minimum of 85 % (ground-level) or 90 % (high-mounted) of the system area must stay in agricultural production (see Table 2).

The capital expenditure (CAPEX) includes the costs of modules, inverters, mounting system, cabling within the system, installation costs, fencing, transformers, a potential substation, land acquisition, biodiversity measures, approval costs, structural engineering reports, environmental reports, project planning and construction supervision.

Operational expenses (OPEX) include system monitoring and operation (monitoring, reporting, inspection, maintenance), remote control capability, security monitoring, insurance, commercial administration, legal advice, biodiversity conservation measures, grassland maintenance, cleaning costs, repairs to inverters and miscellaneous costs.

Fig. 1 visualises the methodological approach adopted in this study. First, a literature review was conducted and data on CAPEX and OPEX of AV and GM PV was collected from project planners. Second, the LCOE and the profitability of the different AV systems were calculated without consideration of agricultural production. Third, the net return from agricultural production was determined, and deducted from the LCOE (as a kind of credit) in the fourth step. Finally, the differences in LCOE between the AV systems and a conventional GM PV system were compared with the land area saved in order to obtain estimates of the costs associated with this type of land preservation.

For this analysis, the most common AV systems were selected based on the literature review and current market observations, with conventional GM PV systems serving as a reference (see Table 1 and Table 2). As indicated in Table 1, the AV systems differ considerably in their design and technical characteristics. To ensure realistic technical and economic assumptions for the various PV systems, a data collection protocol was developed following Böhm et al. (2022) and Trommsdorff et al. (2023). This protocol contained predefined fields for technical design parameters (e.g. power density and annual yield differences) and CAPEX and OPEX components. Project planners and developers were asked to complete this file based on their experience. The collected responses were processed to validate and refine assumptions derived from the literature, following the interactive approach described by Kekeya (2016). In total, 44 project planners and developers of AV and GM PV projects in Germany were contacted. Feedback from 20 respondents was subsequently discussed and validated to inform the system specifications used in the analysis.

The total cost of GM PV systems has declined by approximately 12 % annually over the past twelve years (Fraunhofer Institute for Solar Energy Systems ISE (Fraunhofer ISE) 2024b). To ensure comparability across system types, all assumptions were standardised to reflect conditions as of August 2023. In order to account for economies of scale, system sizes of 1, 2, 5, 10, 20, 40 and 80 ha were considered. For

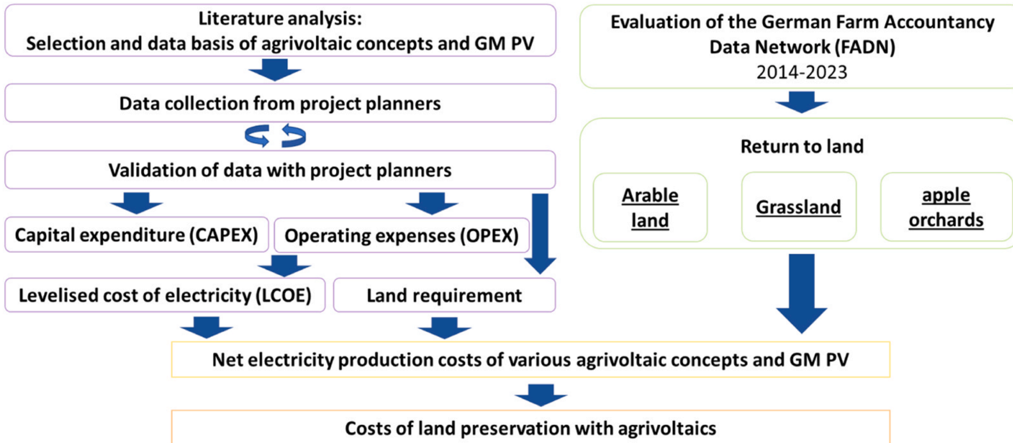


Fig. 1. Workflow for calculating the cost of land preservation.

simplicity, the 2-hectare system is referred to as a small-scale plant, the 10-hectare plant as a medium-scale, and the 40-hectare system as a large-scale. All additional data and calculation results are provided in the Appendix Table 1–17. Since PV projects are highly site-specific – particularly with respect to the distance to the grid connection point – assumptions were made to enhance the generalisability of the results. Specifically, a business model was assumed in which a farmer or landowner acts as both investor and operator of the system. All calculations are exclusive of taxes. The opportunity costs of land use are captured by the concept of 'return to land,' which represents the net profit attributable to land as a factor of production. It is calculated by deducting all costs – including opportunity costs for capital and labour, but excluding ground rent – from total revenue. The resulting figure indicates the amount available to remunerate land and thus reflects its economic value in agricultural production. The study is based on an analysis of long-term average return to land at farm level. These returns are calculated using data from the German Farm Accountancy Data Network (FADN). In economic terms, this indicator can be interpreted as the maximum willingness to pay for land, derived from agricultural profit after accounting for all other costs. For the AV_{apple} system, it is assumed that the reference GM PV installation would be located on arable land.

An annual performance degradation rate of 0.4 % was assumed for all PV systems, based on previous research (JinKo Solar, 2024; Longi, 2024). In addition, annual increases in maintenance costs were set at 1.3 %, following (Böhm et al., 2022).

It was assumed that 3 % of the electricity generated by PV systems cannot be sold at a positive price due to periods of negative electricity prices on the energy exchange. For $AV_{vertical}$ systems, this share was reduced to 2 %, reflecting their more favourable feed-in profile with generation peaks in the morning and afternoon. Although this assumption relates to the revenue, it is incorporated into the cost calculation because the LCOE is based on the amount of electricity that can be sold

Table 1
Characteristics of the AV systems investigated.

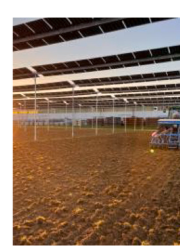
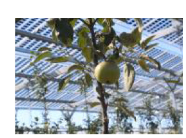
System	GM PV	$AV_{vertical}$	$AV_{tracking}$	$AV_{2.1\ m}$	$AV_{>4\ m}$	AV_{apple}
Distance to ground	Close	0.8 m	variable	> 2.1 m	> 4 m	> 2.5 m
Module direction	30° and south oriented	90° and east-west oriented (frameless modules)	Single axis tracked and east-west oriented	30° and south oriented	Single axis tracked and east-west oriented	30° and east oriented and 30° and west oriented (module transparency 50 %)
Distance between the rows	2.5 m	10 m	10 m	Farming under and between the modules (agriculture only possible with special machinery)	10 m	Adjusted to apple orchards
Pictures	 © fabersam - picabay.com	 © Next2Sun	 © ÖKO-HAUS GmbH	 © SUNfarming	 © Krinner Carport GmbH	 © Fraunhofer ISE
Descrip-tion	Economically optimised ground-mounted PV system; grazing with sheep is possible	PV system with vertical oriented frameless modules; suitable for crops and grassland with a maximum crop height of approx. 1 m.	PV system with tracked modules; suitable for crops and grassland with a maximum crop height of approx. 1 m.	PV system that have been optimised for the feed-in tariff bonus for systems with a minimum height of 2.1 m; suitable for a wide range of crops, but with limited machinery working width.	PV system which is optimised for arable farming with normal-sized maschinery but limited in working width. The modules are tracked and the structure is secured; suitable for a wide range of crops	PV system which is optimised for apple production with semi transparent modules, it can replace hail net systems

Table 2
Detailed assumptions of the systems under consideration, derived from the data survey and DinSpec 91434.

System	GM PV	$AV_{vertical}$	$AV_{tracking}$	$AV_{2.1\ m}$	$AV_{>4\ m}$	AV_{apple}
Power density [MWp/ha]	1.1	0.4	0.7	1	0.5	0.82
Annual yield differences per kWh/kWp	100 %	100 %	120 %	100 %	120 %	90 %
Remaining usable area of agricultural land according to DinSpec 91434	0 %	85 %	85 %	90 %	90 %	100 %

at a positive price. Consequently, a decrease in marketable kilowatt hours increases the calculated LCOE. The analysis focuses on LCOE rather than actual market revenues, so potential additional revenues from direct marketing via spot markets were not considered.

The investment requirement for the cable route to the grid feed-in point is estimated at €120,000 per kilometre for each system. A typical distance of 2.5 km to the grid connection was assumed; however, both the cost and the distance can vary significantly in real projects.

Although the revenue does not directly affect the LCOE, it does have an effect on the potential financing. In terms of revenue, it was assumed that PV systems with a capacity of less than 20 MWp would receive a fixed feed-in tariff for 20 years under the EEG. In contrast, larger systems generally sell electricity through Power Purchase Agreements (PPA). Based on the collected data, it was assumed that the equity shares for systems under 20 MWp is 25 %; for larger systems it is 40 %, as banks usually require a higher equity contribution due to increased price risk associated with PPAs. The assumed equity interest rate is 5 %, while the debt interest rate is 4.68 %, based on conditions provided by *Rentenbank*, the German Government's development bank for agriculture and rural areas (Rentenbank, 2023).

The levelized cost of electricity (LCOE) reflects the average unit cost of electricity generated over the entire lifetime of a system, independent of the timing of electricity production. (Böhm et al., 2022; Chalgynbayeva et al., 2024).

$$LCOE_{PV} = \frac{CAPEX_{aa} + OPEX_{area}}{y} \tag{1}$$

with
$LCOE_{PV}$ = levelized cost of electricity of PV [€/kWh]
$CAPEX_{aa}$ = amortisation of the investment requirement incl. grid connection per hectare [€/ha/year]
y = average annual electricity yield over the lifetime of the system [kWh/ha/year]
$OPEX_{area}$ = Average annual operating expenses per area including repair reserves and opportunity costs for land usage [€/ha/year]
with

$$OPEX_{area} = OPEX * c \tag{2}$$

c = installed capacity per hectare [kWp/ha]

$$OPEX = a_{OM} + a_R + a_G + a_C + a_i + a_M + \frac{oc}{c} \tag{3}$$

with
a_{OM} = average operation and maintenance [€/kWp/year]
a_R = repair reserves for inverters [€/kWp/year]

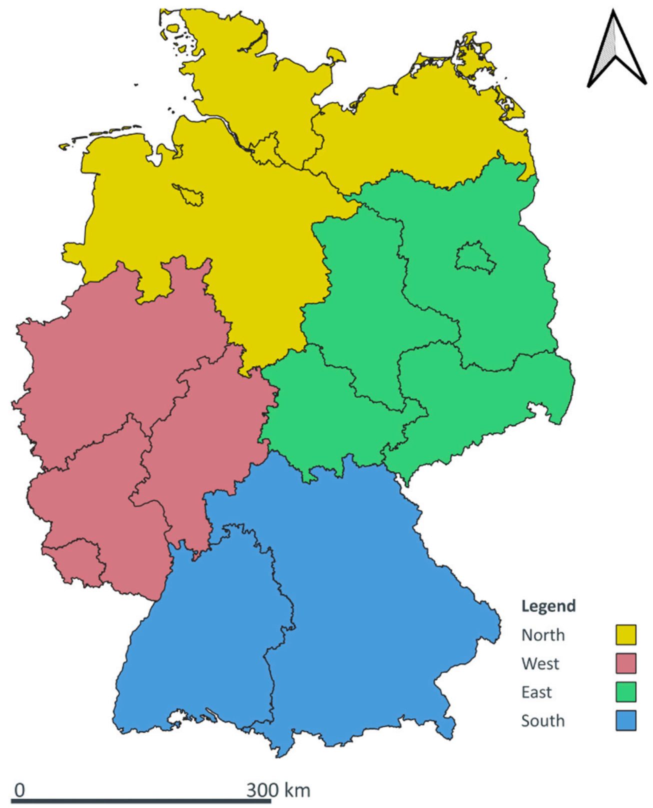


Fig. 2. Adapted soil climatic zones of Germany according to Freier et al. (2010).

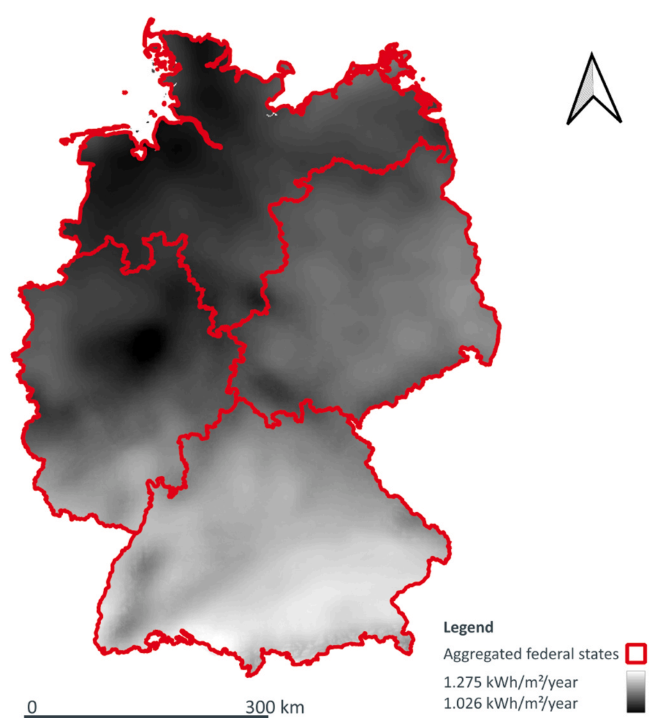


Fig. 3. Mean global horizontal irradiation [kWh/m²/year] from 2014 to 2023 for Germany.

a_G = grassland and bush care [€/kWp/year]
a_C = average cleaning costs per year [€/kWp/year]
a_i = costs for insurances [€/kWp/year]
a_M = commercial management, direct marketing/trader and remote monitoring costs [€/kWp/year]
oc = opportunity costs for land usage = the loss of return to land for agricultural land [€/ha/year]

$$CAPEX_{aa} = CAPEX * c * af \tag{4}$$

with
CAPEX = investment requirement including grid connection [€/kWp]
af= annuity factor see appendix 1

$$CAPEX = C_{PV} + C_i + C_M + C_B + C_{BOS} + C_G \tag{5}$$

with
C_{PV} =costs for PV modules [€/kWp]
C_i = costs for inverter [€/kWp]
C_M = costs for mounting structures [€/kWp]
C_B = mounting costs [€/kWp]
C_{BOS} = costs for other hardware like cable, remote control, environmental assessments, legal assistance [€/kWp]
C_G = cost for the grid connection [€/kWp]

$$C_G = C_{ST} + \frac{C_C * d}{c} \tag{6}$$

C_{ST} = costs for transformer and substation [€/kWp]
C_C = costs for cable to the grid connection point [€/km]
d = distance to the grid connection point [km]

Given the annual variability in the profitability of both PV systems and agricultural production, this study employs the ten-year average (2014–2023) of global horizontal irradiation and agricultural returns to land. These averages are calculated for four climatic zones as defined by Freier et al. (2010), following the methodology of Duden and Offermann (2020) (see Fig. 2). For this period, Germany's general climatic conditions include an average annual temperature of 10 °C and average precipitation of 722 mm (Federal Statistical Office (Destatis), 2023).

To estimate electricity yields, the study utilised average global solar radiation data provided by the German Weather Service (DWD) for the four soil climate zones over the period 2014–2023. The annual sums of global radiation were derived from 1 × 1 km grid data available through the Open Climate Data Centre. These spatial datasets were intersected with the study regions using the QGis software (Fig. 3).

According to Solargis (2021), the estimated mean electricity yield in the first year of operation is 1067 kWh/kWp/year for the north region, 1076 kWh/kWp/year for the western region, 1087 kWh/kWp/year for the eastern region and 1171 kWh/kWp/year for the southern region.

The calculation of the net returns to land using data from the German Farm Accountancy Data Network (FADN) follows the methodology outlined by Hansen et al. (2021).

$$R_{AG} = \frac{FP + LR - W - II}{l} \tag{7}$$

with
R_{AG} = Net return to land of agricultural production [€/ha/year]
FP = farm profit (corrected for extraordinary and out-of-period payments) [€/farm/year]
LR = land rent [€/farm/year]
W = imputed wages for family workers [€/farm/year]
II = imputed interest for own capital (excluding land) [€/farm/year]
l = agricultural land per farm [ha/farm].

For arable farming, the German FADN dataset comprises between 1479 and 1856 farms per year. In the case of grassland, specialised dairy farms and specialised forage farms with a grassland share exceeding 80 % were selected, resulting in a sample of 695–921 farms annually. For apple production, farms classified as specialised fruit farms or mixed permanent crop farms with more than 80 % of agricultural land dedicated to apples were included, yielding a sample size of 27–101 farms. Due to the presence of only one or two apple farms in the western and eastern region, data from these areas were excluded from the analysis.

In apple cultivations, AV systems (AV_{apple}) can substitute for traditional hail protection nets, potentially reducing investment and maintenance. Annual cost savings from replacing hail nets are estimated to average around €1800 € per hectare (Iglesias and Alegre, 2006; Bahlo et al., 2013; Porsch et al., 2018; Rogna et al., 2019; Trommsdorff et al., 2023).

AV installations may lead to increased operational costs due to reduced working widths and slower machinery speeds, which can affect overall production efficiency. The potential need to adapt agricultural machinery, such as adjusting sprayer or spreader working width or accommodating a minimum clearance height of 2.1 m, may lead to increased production costs and could reduce the overall profitability of agricultural production. However, due to the high degree of uncertainty and the limited availability of empirical data on these specific cost impacts, this study assumes that AV systems do not incur additional agricultural production costs. The potential influence of AV on agricultural profitability is further explored through a sensitivity analysis.

To enable a meaningful comparison of the profitability and LCOE of AV systems versus GM PV systems, the return to land from agricultural production must be accounted for. Therefore, the agricultural net return to land is incorporated as 'agricultural benefit' (AB) in the calculation the $LCOE_{PV}$.

$$AB = \frac{R_{AG}}{y} \tag{8}$$

AB = agricultural benefit [€/kWh]

$$LCOE_{net} = LCOE_{PV} - AB \tag{9}$$

with:
$LCOE_{net}$ = levelized cost of electricity (net) [€/kWh]

For apple production, the cost saving of the substitution of hail nets is considered.[1]

$$LCOE_{net,\ AVapple} = LCOE_{PV} - \frac{R_{AG} + h}{y} \tag{10}$$

with:
$LCOE_{net,AVapple}$ = levelized cost of electricity (net) for apple production [€/kWh]
h = hail net costs [€/ha/year]

The preservation price for agricultural land per unit of electricity produced [€/kWh] ($AV_{premium}$) is computed as difference of the levelized cost of electricity production under GM PV and AV.

$$AV_{premium} = LCOE_{net;GMPV} - LCOE_{net;AV} \tag{11}$$

with:
$AV_{premium}$ = cost difference between GM PV and AV[€/kWh]
$LCOE_{net;GM\ PV}$ = $LCOE_{net}$ of GM PV[€/kWh]
$LCOE_{net;AV}$ = $LCOE_{net}$ of AV[€/kWh]

The preservation price is calculated to reflect the additional costs associated with maintaining land availability for agricultural use under AV systems. Following the terminology of Schindele et al. (2020), this value is referred to as a preservation price rather than a cost. The annual preservation price per hectare of agricultural land [€/ha/year], denoted as APP, is determined by assuming an AV system that generates the same annual electricity output as one hectare of GM PV.

The required AV system area is derived from the ratio of energy yields per hectare, expressed as $\left(\frac{y_{GM\ PV}}{y_{AV}}\right)$. The additional cost (AD) of

[1] In Germany, the use of hail nets is widespread in southern Germany, particularly in new orchards.

Table 3
CAPEX and OPEX of different PV-concepts and system sizes.

	System	GM PV	$AV_{vertical}$	$AV_{tracking}$	$AV_{2.1\ m}$	$AV_{>4\ m}$	AV_{apple}
CAPEX with grid connection [€/kWp]	2 ha	811	1269	1159	923	1658	1586
	10 ha	549	779	776	637	1230	1362
	40 ha	565*	607	801*	658*	1102	1419*
OPEX with repairs, with-out land rent [€/kWp/year]	2 ha	16.9	17.2	19.3	19.1	18.1	16.8
	10 ha	11.4	10.8	12.8	13.0	12.0	11.7
	40 ha	8.9	8.6	9.7	10.3	9.7	10.0

* From 25 MWp, a substation is also included, resulting in higher CAPEX.

Table 4
Average annual return to land of arable land, grassland and apple orchards according to the German FADN 2014-2023.

Location (soil climatic region)	north	west	east	south
Return to arable land [€/ha/year]	367	376	286	362
Return to grassland [€/ha/year]	366	124	62	-11
Return to land under apple orchards [€/ha/year]	2549	N/A	N/A	-9

producing the same electricity with AV is calculated as:

$$AD = AV_{premium} * y_{GM\ PV}$$

This cost is then related to the area effectively preserved for agricultural production, which is the difference between the one hectare fully occupied by GM PV and the fraction of a hectare occupied by AV. The resulting formula for the annual preservation price (APP) is:

$$APP = \frac{AD}{1 - \left(\frac{y_{GM\ PV}}{y_{AV}} * \left(1 - s_{ag}\right)\right)} \tag{12}$$

or after rearranging:

$$APP = \frac{AV_{premium} * y_{GM\ PV} * y_{AV}}{y_{AV} - \left(y_{GM\ PV} * \left(1 - s_{ag}\right)\right)} \tag{13}$$

with:

APP = annual preservation price for agricultural land [€/hectare/year]

s_{ag} = share of area usable for agriculture under AV [%]

If the denominator in the preservation price formula is positive, which represents the typical case, the APP reflects the cost of preserving one hectare of agricultural land. If the denominator equals zero, both AV and GM systems exhibit identical area efficiency, meaning that no land is effectively preserved and the preservation price becomes undefined. If the denominator is negative, the AV system is less area-efficient than GM PV, indicating that it occupies more agricultural land per unit of electricity produced and, consequently, no land is preserved.

3. Results and Sensitivity Analysis

3.1. Descriptive Results

Table 3 shows a summary of the total investment requirements (CAPEX) and operating expenses (OPEX) by system size, based on prices in August 2023 and annualised over a 25-year project lifetime. A breakdown of these costs is presented in Appendix Table 1–13. For systems with peak capacity above 25 MWp, a substation was assumed to be necessary for grid connection. This requirement results in higher investment costs for certain system sizes, particularly compared to the 10 ha and 40 ha configurations.

Table 4 displays the average returns to land from agricultural production. These values vary considerably across years and regions, with some regions even showing negative returns. Such negative values result from quasi-fixed production factors and the inclusion of imputed cost such as remuneration for equity capital and family labour. It should be noted that farm-specific returns to land can deviate substantially from the mean, depending on individual production conditions and farm structures.

The high land use efficiency of AV systems becomes evident when comparing the area required to generate the same amount of electricity as conventional GM PV systems. To match the annual electricity output of one hectare of GM PV, the $AV_{vertical}$ system requires a total facility area of 2.72 ha facility area, yet only 0.41 ha farmland are effectively removed from agricultural use. The $AV_{tracking}$ system performs even better in this regard, requiring 1.31 ha of facility area while occupying

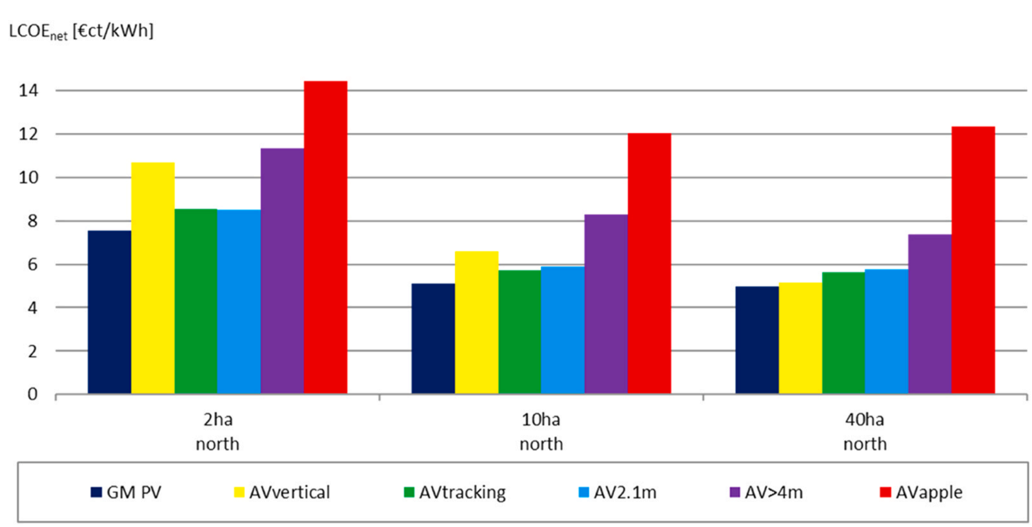


Fig. 4. $LCOE_{net}$ of different AV systems and facility sizes on arable land / apple orchards in the northern region. Remark: Other regions show similar results, see Appendix Tables 14 and 15.

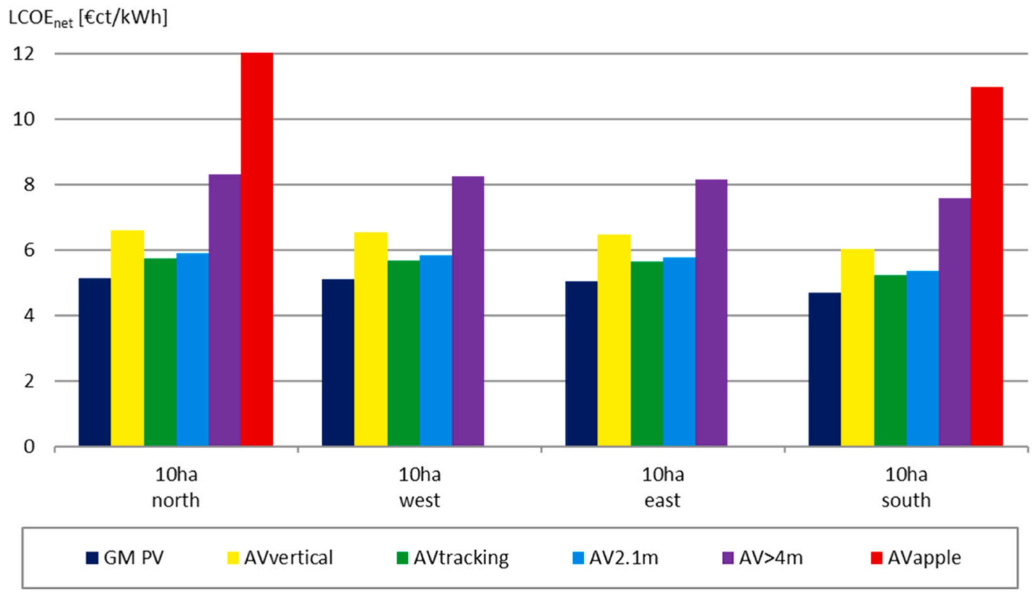


Fig. 5. $LCOE_{net}$ of different AV systems in the four regions for 10 ha facilities on arable land / apple orchards. *No data for apple production in west and east available (see Table 3).

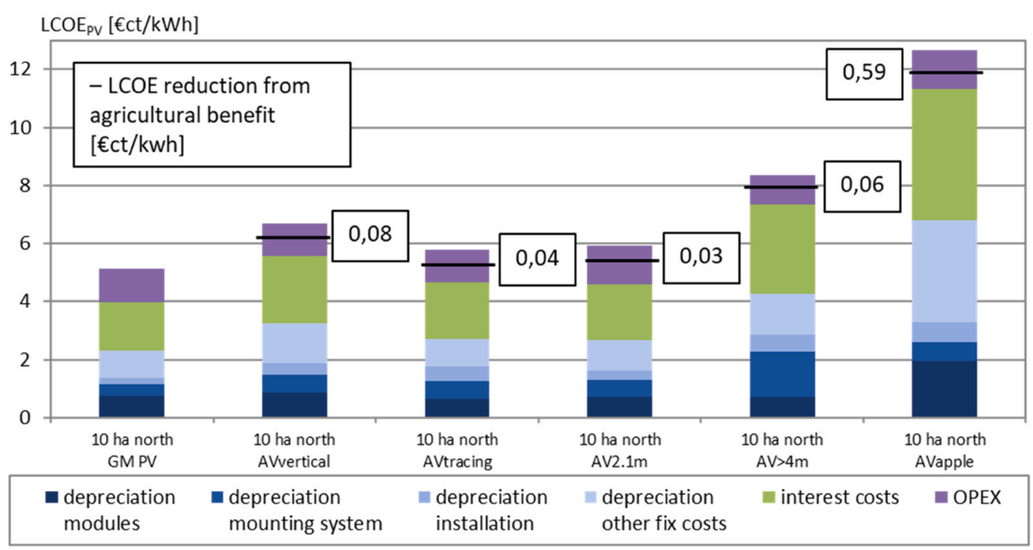


Fig. 6. LCOE components, assuming medium size system (10 ha). The reduction in LCOE due to the agricultural benefit from crop production is illustrated. Remark: The share of interest costs is presented in an aggregated form.

just 0.2 ha of farmland. The $AV_{2.1\ m}$ demonstrates the highest land use efficiency, producing the same electricity on 1.1 ha with only 0.11 ha of farmland lost. For the $AV_{>4\ m}$ systems, the corresponding figures are 1.83 ha of facility area and 0.18 ha of farmland loss. Overall, the results highlight the potential of AV systems to mitigate land use conflicts by significantly reducing the effective loss of agricultural land.

3.2. Levelized cost of electricity

The levelized cost of electricity (LCOE) varies depending on system size and location. For GM PV systems, the LCOE ranges from €cent 4.54 per kWh for the large-scale installations in the south to €cent 7.55 per kWh for the small-scale systems in the north. Detailed $LCOE_{net}$ results for all systems are provided in Appendix Tables 14 and 15.

Even when agricultural returns are considered, AV systems generally exhibit higher $LCOE_{net}$ values than GM PV. For $AV_{vertical}$, $LCOE_{net}$ is 4–42 % higher than GM PV. For $AV_{tracking}$, the increase ranges from 12 % to 13 %, while $AV_{2.1\ m}$ systems show a 13–16 % increase. Electricity generation in $AV_{>4\ m}$ system is 48 % and 62 % more expensive than in GM PV. The highest cost occur in AV_{apple} systems, where $LCOE_{net}$ is 91–248 % above GM PV.

Fig. 4 demonstrates that the systems benefit from economies of scale. In smaller installations, the $LCOE_{net}$ of the $AV_{vertical}$ system is higher than that of $AV_{2.1\ m}$ and $AV_{tracking}$, primarily due to its lower energy yield per unit of installed capacity. However, in larger facilities, this relationship reverses, as $AV_{vertical}$ benefits more from economies of scale.

Table 5
Annual preservation price (APP) for arable land, grassland and apple orchards of different AV systems in the northern region, depending on system size.

System [€/hectare/ year]	Annual preservation price for crop land (1 ha / **10 ha** / 40 ha systems)	Annual preservation price for grassland (1 ha / **10 ha** / 40 ha systems)	Annual preservation price for apple orchards (1 ha / **10 ha** / 40 ha systems)
$AV_{vertical}$	57,521 / **26,841** / 3201	57,523 / **26,843** / 3202	-
$AV_{tracking}$	13,567 / **8072** / 8514	13,569 / **8074** / 8516	-
$AV_{2.1\ m}$	11,950 / **9186** / 9463	11,951 / **9188** / 9465	-
$AV_{>4\ m}$	50,465 / **42,082** / 31,721	50,467 / **42,084** / 31,723	-
AV_{apple}	-	-	74,444 / **74,994** / 79,707

Remark: All APP results are presented in Appendix Table 15 and 16.

The main reason for this greater economy of scale lies in the assumption that, with an area of 40 ha, $AV_{tracking}$ requires a substation due to the system's very high output, whereas $AV_{vertical}$ does not. Consequently, the fixed costs associated with grid connection increase less for $AV_{vertical}$ at larger scales, reinforcing its cost competitiveness.

Fig. 5 displays the costs of electricity production for the medium-sized 10 ha facilities by region. As one would expect, the southern region exhibits the lowest LCOE due to higher levels of global radiation. The difference between the northern and southern regions is consistent across all system types, with LCOE values in the north being 9 % higher on average.

Fig. 6 provides a detailed breakdown of the $LCOE_{net}$ structure for a medium-sized system in the northern region. Comprehensive results for all regions and system sizes are provided in Appendix Tables 14 and 15. After depreciation, interest represents the largest cost component, accounting for 32–37 % of the $LCOE_{net}$, depending on system type. The modules account for the largest share of depreciation, ranging from 8 % to 15 %. Operating expenses (OPEX) represent 10–23 % of $LCOE_{net}$. The most significant variation between systems occurs in the proportion of the cost of mounting systems, which ranges from 5 % to 19 %.

Fig. 6 illustrates the impact of agricultural benefits on the $LCOE_{PV}$ for medium sized systems. Arable farming under $AV_{vertical}$ can reduce the LCOE by up to 1.5 %. In contrast, grassland use provides a smaller benefit due to its comparatively low returns. The AV_{apple} system delivers the most significant cost-saving effect in the northern region, where high agricultural return to land leads to a reduction in $LCOE_{net}$ of up to 4.6 % (see Table 3). Overall, the effect of agricultural production on the LCOE remains modest.

When evaluating the cost of preserving agricultural land by substituting a GM PV system with an AV system, it becomes evident that even small differences in LCOE can result in substantial cost per hectare due to the high electricity yields per hectare. Table 5 displays the annual preservation prices (APP) for the various AV systems, differentiated by system size and type of agricultural land use. The results in Table 5 apply to the northern region; differences to the other regions are negligible.

The computed APP values vary significantly by system size. For example, $AV_{vertical}$ offers the lowest APP for large-scale systems (40 ha), whereas $AV_{tracking}$ and $AV_{2.1\ m}$ are more cost-effective for medium sized systems (10 ha).

Table 5 also indicates that the annual preservation price substantially exceeds the agricultural returns to land (see Table 4). Even the lowest preservation price remains significantly higher than achievable returns to land. Differences between arable and grassland systems are minor, as are regional variations between north and south, which are detailed in Appendix Tables 16 and 17.

3.3. Sensitivity analysis

A series of sensitivity analyses were conducted to examine the impact of variations in key assumptions. As illustrated in Fig. 6, interest costs are a major driver of LCOE. When the interest rate increases from 4,8–10 %, the APP increases up to €5600 per hectare for the $AV_{2.1\ m}$ and €45,000 per hectare for AV_{apple}, despite concurrent increases in GM PV costs. This effect is primarily due to the higher capital intensity of AV systems, which amplifies the impact of financing costs.

Another sensitivity analysis aimed at determining the threshold interest rates required to bring the APP down to zero. The break-even interest rates for the different AV systems are as follows: 4.3 % for the $AV_{vertical}$ system, 3.4 % for $AV_{tracking}$ system, 3.2 % for $AV_{2.1\ m}$, and 0.7 % for $AV_{>4\ m}$. Notably, AV_{apple} would require a negative interest rate of −1.9 % to achieve an APP of zero.

To investigate the effect of varying distances to the grid connection point, the distance was increased from 2,5 km to 10 km. For $AV_{vertical}$, the APP of the large-scale system in the northern region rises from €3200 to €7700 per hectare per year, while the APP of the small-scale system increases markedly from €57,500 to €148,200 per hectare per year. For $AV_{tracking}$, the corresponding values increase from €8500 to €9100 (for large-scale systems) and from €13,600 to €25,600 (for small-scale systems) per hectare per year, respectively. These results highlight the significant influence of both system size and cost structure: the smaller the system, the more pronounced the impact of the grid connection distance on the cost of land preservation.

To further investigate the influence of agricultural productivity, a sensitivity analysis was conducted for medium-sized systems. Specifically, the analysis determined the agricultural return to land required to reduce the APP to zero. For $AV_{vertical}$, $AV_{tracking}$ and $AV_{2.1\ m}$, the necessary agricultural values to offset the higher LCOE lie between €6000 and €8500 per hectare per year. The resulting LCOE reductions amount to 11 % for $AV_{tracking}$ and up to 23 % for $AV_{vertical}$. In contrast, the high-elevation $AV_{>4\ m}$ system would require an agricultural return to land of €21,000 per hectare and year to achieve cost parity, corresponding to a 39 % reduction of LCOE. For AV_{apple}, the required return to land rises to €52,000 per hectare per year, equating to a 59 % LCOE reduction. These figures underscore the substantial increase in agricultural output needed to neutralise the APP, particularly for highly adapted systems such as AV_{apple}. While such increases may be theoretically achievable with high-value crops, they are unlikely to be realised through conventional arable farming or grassland use, especially given the farming constraints imposed by systems like $AV_{2.1\ m}$.

Overall, the analysis indicates that agricultural productivity plays only a marginal secondary role in determining the profitability of AV systems, while capital and energy-related factors exert a more dominant influence. The findings presented are consistent across all system sizes examined. Detailed input data are provided in Appendix Table 1–13, and the corresponding calculation results are presented in Appendix Table 14–17.

4. Discussion

This paper aimed to quantify the price associated with preserving farmland by deploying AV systems instead of conventional close-spaced GM PV installations. To achieve this, the study calculated the LCOE for various AV configurations and compared them with LCOE of conventional GM PV systems. The additional costs associated with AV systems were then related to the amount of agricultural land preserved, providing an estimate of the preservation cost per hectare. The cost assessment also accounted for the agricultural return to land generated under the AV systems, which was credited against the total system costs.

When the additional costs of AV systems are related to the preserved farmland area, the annual costs of conserving one hectare ranges from €8000 to €26,000 for medium-sized, low-mounted AV systems and from €42,000 to €75,000 for high-mounted AV systems. These estimates are consistent with previous findings, such as €9052 per ha and year reported by Schindele et al. (2020) and €13,852 per ha per year observed by Feuerbacher et al. (2022). The notably higher LCOE associated with AV_{apple} is also confirmed by Trommsdorff et al. (2023), who report a 58 % increase compared to GM PV. Overall, these cost estimates significantly exceed the potential returns to land from the preserved land, highlighting that farming contributes little to the profitability of AV systems.

Zeddies et al. (2025) found an increasing societal willingness to pay for electricity from AV systems. According to the LCOE analysis, the bonus of €cent 1.2 per kWh provided by the EEG is sufficient to offset the extra costs of medium-sized, low-mounted systems, particularly $AV_{tracking}$, $AV_{vertical}$ and $AV_{2.1\ m}$, thus creating a financial incentive for their deployment. However, the bonus does not bridge the cost gap for high-mounted systems such as $AV_{>4\ m}$ and AV_{apple}, which remain financially uncompetitive. Given the high costs associated with farm land preservation through AV systems, the economic justification for the EEG bonus must be called into question. Ultimately, this bonus is financed by electricity consumers and taxpayers. From a welfare economics perspective, such a subsidy would only be justified if the societal value attributed to the preserved land exceeds the actual cost of its preservation. Based on the cost estimates derived in this study, this condition is unlikely to be met. While it is conceivable that the societal value of preserved farmland, particularly as a strategic reserve or ecological buffer, may exceed its current market value, it is doubtful that this value will exceed the high preservation costs identified in this analysis. Under the assumptions made in this study, a spatial separation of land use, i.e., conventional GM PV installation alongside independent agriculture production, emerges as the economically efficient alternative. If AV systems are to be promoted for political or strategic reasons, their deployment should be limited to locations where exceptionally high returns to land from agricultural production can be expected, ideally sufficient to offset the implicit cost of land preservation. In this context, a competitive tendering scheme would likely be more effective than a fixed bonus in identifying and supporting the most cost-effective AV projects.

In light of the high cost associated with farmland preservation through AV systems, it is essential to consider alternative, more cost-effective strategies for safeguarding agricultural land for food production. As noted by Böhm (2023) and Osterburg et al. (2023), 8.7 % of Germany`s arable land is currently used for cultivating feedstock for biogas plants to generate electricity and heat, and an additional 3.1 % for rapeseed as biodiesel feedstock. However, the energy yield per hectare of GM PV or AV exceeds that of biogas crops by more than 20 times (Böhm, 2024). Redirecting land use from energy crops to GM PV could therefore free up substantial areas for food production, at a significantly lower cost than AV deployment.

Three methodological caveats should be acknowledged when interpreting the results. First, the cost structure of PV systems is highly project-specific and subject to considerable uncertainty, particularly in the case of AV, which remains at an early stage of market penetration. Most AV systems have been implemented only at small scale whereas small-scale GM PV installations are rare due to their limited economic viability. Consequently, the cost data obtained from project developers may contain inaccuracies, especially regarding differentiation by system size.

Second, there is uncertainty regarding the impact of system orientation, such as tracking or vertical alignment, on the electricity yield, which can vary by geographic location. The potential for improved grid feed-in profiles (e.g. higher generation in the morning and evening hours with $AV_{vertical}$) was acknowledged and incorporated into the analysis. This temporal shift in electricity generation can enhance profitability, as spot market prices tend to be higher during these periods. However, the benefit depends heavily on market conditions. As a result, AV systems with favourable generation profiles may achieve higher market revenues, thereby enhancing overall profitability. This potential should be examined more closely in future research.

Third, AV can influence both agricultural yields and production costs. Yield effects primarily result from the shading caused by of the PV installations; these can be either positive or negative depending on weather conditions, plant species and variety, geographic location and the specific AV system design (Laub et al., 2022; Pataczek et al., 2023). The literature is divided on the yield effects of AV. Some studies indicate yield increases, while others have found yield depressions (Laub et al., 2022; Pataczek et al., 2023; Fraunhofer Institute for Solar Energy Systems ISE (Fraunhofer ISE) 2024a) Due to this uncertainty, the calculations in the present study assumed that AV systems would not affect agricultural yields. Once a clearer picture emerges, future research could refine the economic assessment of AV systems accordingly.

Beyond economic considerations, AV systems are increasingly discussed as a tool for enhancing climate resilience in agriculture. Farms in Germany face growing yield and income volatility due to weather-related risks (Duden and Offermann, 2020). AV systems offer a potential pathway for income diversification and may help stabilise crop yields (Touil et al., 2021; Laub et al., 2022). Particularly in dryer regions, the shading effect of the modules can have positive effects on both the level and stability of agricultural yield (Randle-Boggis et al., 2021).

Further research is needed to evaluate the costs-effectiveness of AV systems in comparison to alternative climate resilience strategies for agriculture. In addition, the impact of reduced working width and lower operating speed, particularly relevant for arable and grassland farming, on agricultural production costs warrants closer examination. This is especially true for AV systems with a minimum hight of 2.1 m, which often require the use of specialised machinery.

Another promising area or future research is the integration of PV systems with biodiversity and nature conservation measures. Initial findings suggest that meaningful ecological synergies can be achieved with relatively low financial input (Zaplata and Dullau, 2022; Schneider et al., 2023).

5. Conclusion

This study provides a systematic comparison of LCOE and land use implications for AV and GM PV systems in Germany. It combines technical and economic perspectives and uses real cost data from project developers to ensure a high degree of practical relevance. The analysis confirms that, compared to conventional GM PV, AV systems offer an opportunity to preserve farmland by enabling simultaneous electricity generation and agricultural production. However, this benefit comes at a significant cost: LCOE for AV systems are between 4 % and 148 % higher than for GM PV, with AV_{apple} showing the largest cost differential. Agricultural production is a marginal contributor to overall profitability. When the additional costs of the agrivoltaic systems are related to the saved agricultural land, the annual cost of maintaining one hectare of land ranges from €8000 to €26,000 per hectare per year for medium-sized, low-mounted agrivoltaic systems, and from €42,000 to €75,000 per hectare per year for high-mounted agrivoltaic systems. This is many times the potential net return from agricultural production on the land saved. These findings cast doubt on the cost-effectiveness of AV as a land management strategy and call into question the German government's subsidisation of its deployment. Concerning AV's contribution to the Sustainable Development Goals, this article has led to the sobering realisation that there is a clear trade-off between the goals of Zero Hunger (SDG 2) and Affordable and Clean Energy (SDG 7). Although AV can serve both goals simultaneously, the goal of Zero Hunger (through the preservation of farmland) is achieved at the expense of a much-reduced affordability of clean energy.

Ethics approval

Compliance with Ethical Standards is assured.

Authors' contribution

All authors contributed to the study's conception and design. The material preparation, data collection and analysis were mainly done by Jonas Böhm. The first draft of the manuscript was written by Jonas Böhm and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

CRediT authorship contribution statement

Jonas Böhm: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Thomas de Witte:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Frank Offermann:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Uwe Latacz-Lohmann:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used COPILOT and DeepL for language editing. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of Competing Interest

The authors have no relevant financial or non-financial interests to disclose.

Appendix 1

$$af = \frac{(1+i_{calc})^N * ((1+i_{calc})-1)}{(1+i_{calc})^N - 1} \quad (1)$$

af = annuity factor according to Mußhoff and Hirschauer (2020)
i_{calc} = calculation interest rate [%]
N = operating life [years].

$$i_{calc} = \quad i_{eq} * sh_{eq} + \quad i_{de} * sh_{de} \quad (2)$$

sh_{eq} = share of equity [%]
sh_{de} = Debt capital share [%]
i_{eq} = equity interest rate [%]
i_{de} = debt interest rate [%]

Appendix Table 1
Investment requirements and OPEX of different PV systems and seven system sizes

	system Power density [MWp/ha]	GM PV 1.1	$AV_{vertical}$ 0.4	$AV_{tracking}$ 0.7	$AV_{2.1\ m}$ 1	AV_{apple} 0.82	$AV_{>4\ m}$ 0.5
Investment requirements without cabling to the grid* [€/kWp]	1 hectare	815	1019	1141	967	1473	1365
	2 ha	675	894	945	773	1403	1269
	5 ha	592	786	817	675	1356	1185
	10 ha	522	704	734	607	1325	1137
	20 ha	487	635	679	566	1298	1087
	40 ha	558	588	790	651	1410	1061
	80 ha	499	680	702	587	1342	1147
OPEX with repair reserves and without land rent** [€/kWp/year]	1 hectare	20.9	20.5	23.8	23.8	21.8	20.3
	2 ha	16.9	16.5	20.0	19,8	18.2	17.4
	5 ha	12.7	12.1	15.2	15.0	14.2	13.2
	10 ha	11.4	10.4	13.2	13.5	11.5	10.3
	20 ha	10.0	9.3	11.4	11.8	11.5	10.3
	40 ha	8.9	8.3	10.0	10.7	10.6	9.3
	80 ha	7.8	7.5	8.6	9.4	9.8	8.6

*The investment requirements include the costs for the modules, the inverters, the mounting system, the cabling within the system, the installation costs, the fencing, the transformers, from 25 MWp also a substation, land acquisition, biodiversity measures, approval costs, structural engineering reports, environmental reports, project planning and construction supervision.
**The operational expenditures (OPEX) include monitoring and operation of the system (monitoring, reporting, inspection, maintenance), remote controllability, safety monitoring, insurance, commercial management, legal advice, biodiversity measures, grassland maintenance, cleaning costs, repair reserves for inverter, other costs.

Appendix Table 2
Investment requirements (CAPEX) of seven system sizes of **GM PV** separated between components. According to the data collected in this study

component costs in €/kWp System size in hectare	PV modules	Inverter	Mounting structure and foundation	cabeling	Mounting	Infrastructure (fencing)	Transformer	Substation	Permission costs (without expert assessments)	Expert assessments (structural engineering reports, environmental assessmetns, etc.)	Project planning, site acquisition and construction supervision
1	202.50	45.00	115.40	31.74	85.00	21.50	171.67	0.00	71.23	20.00	50.98
2	194.25	43.00	108.07	29.23	73.33	19.50	121.75	0.00	49.14	7.00	29.68
5	187.50	39.33	101.45	27.03	68.00	18.00	93.25	0.00	36.14	3.00	18.38
10	180.00	36.33	94.62	24.01	56.67	16.50	71.00	0.00	27.48	1.80	13.64
20	175.00	34.67	91.43	21.01	51.67	15.50	64.25	0.00	21.25	1.60	11.06
40	172.00	33.33	87.60	20.28	45.00	12.50	59.50	102.27	14.63	1.20	9.61
80	168.50	32.00	83.93	19.32	41.67	11.50	54.25	68.18	10.16	0.90	8.26

Appendix Table 3
Investment requirements (CAPEX) of seven system sizes of **$AV_{vertical}$** separated between components. According to the data collected in this study

component costs in €/kWp System size in hectare	PV modules	Inverter	Mounting structure and foundation	cabeling	Mounting	Infrastructure (fencing)	Transformer	Substation	Permission costs (without expert assessments)	Expert assessments (structural engineering reports, environmental assessmetns, etc.)	Project planning, site acquisition and construction supervision
1	260.00	56.64	181.94	54.20	158.99	15.39	140.00	0.00	75.43	21.18	43.39
2	230.00	54.07	171.53	53.96	131.42	10.74	110.00	0.00	79.94	11.39	32.01
5	228.00	51.65	158.67	53.64	108.99	6.67	65.00	0.00	73.41	6.09	27.17
10	215.00	50.08	149.59	48.39	95.97	4.66	45.00	0.00	65.22	4.27	20.51
20	200.00	48.59	141.03	43.15	84.82	3.25	37.00	0.00	53.89	4.06	15.38
40	195.00	47.15	132.97	42.91	74.98	2.27	33.00	0.00	40.55	3.33	12.79
80	190.00	45.71	125.36	42.67	66.07	1.58	25.00	140.63	28.38	2.51	9.11

Appendix Table 4
Investment requirements (CAPEX) of seven system sizes of **$AV_{tracking}$** separated between components. According to the data collected in this study

component costs in €/kWp System size in hectare	PV modules	Inverter	Mounting structure and foundation	cabeling	Mounting	Infrastructure (fencing)	Transformer	Substation	Permission costs (without expert assessments)	Expert assessments (structural engineering reports, environmental assessmetns, etc.)	Project planning, site acquisition and construction supervision
1	202.24	37.66	248.60	26.34	224.98	55.10	228.11	0.00	47.59	40.12	30.20
2	199.43	37.07	209.19	23.31	198.83	48.80	138.81	0.00	40.32	30.60	18.70
5	192.26	31.63	190.27	30.15	169.25	44.41	87.17	0.00	31.20	26.43	14.42
10	185.66	28.80	176.79	19.39	150.72	41.06	67.72	0.00	27.56	24.31	11.58
20	179.08	25.99	168.82	17.97	133.13	38.37	58.76	0.00	23.98	22.78	9.91
40	175.03	24.68	157.84	17.11	123.04	33.84	50.86	160.71	19.47	21.23	6.36
80	173.50	22.88	152.34	15.82	112.03	31.96	43.77	107.14	17.53	19.82	5.41

Appendix Table 5
Investment requirements (CAPEX) of seven system sizes of **$AV_{2.1\ m}$** separated between components. According to the data collected in this study

component costs in €/kWp System size in hectare	PV modules	Inverter	Mounting structure and foundation	cabeling	Mounting	Infrastructure (fencing)	Transformer	Substation	Permission costs (without expert assessments)	Expert assessments (structural engineering reports, environmental assessmetns, etc.)	Project planning, site acquisition and construction supervision
1	192.37	40.10	169.97	34.92	111.37	33.52	235.22	0.00	46.67	18.08	67.40
2	187.21	37.93	155.97	32.16	94.85	29.01	126.64	0.00	38.33	8.92	48.92
5	181.13	34.58	144.66	29.94	84.70	25.37	95.82	0.00	26.67	5.37	37.70
10	175.58	31.17	137.65	28.20	76.30	23.79	71.82	0.00	21.67	3.72	30.31
20	170.09	29.45	131.49	26.48	69.52	22.61	66.19	0.00	16.67	3.29	24.13
40	166.01	28.00	125.47	25.81	64.83	20.17	63.74	112.50	12.00	3.05	23.13
80	162.00	26.85	122.60	25.16	59.93	19.44	56.83	75.00	10.67	2.31	21.95

Appendix Table 6
Investment requirements (CAPEX) of seven system sizes of **AV_{apple}** separated between components. According to the data collected in this study

component costs in €/kWp System size in hectare	PV modules	Inverter	Mounting structure and foundation	cabeling	Mounting	Infrastructure (fencing)	Transformer	Substation	Permission costs (without expert assessments)	Expert assessments (structural engineering reports, environmental assessmetns, etc.)	Project planning, site acquisition and construction supervision
1	376.66	25.32	164.40	17.34	233.99	33.31	166.29	0.00	56.00	240.77	52.74
2	434.70	31.55	148.19	15.31	176.55	29.42	166.66	0.00	56.00	226.82	12.07
5	430.72	31.10	144.72	13.88	162.81	26.67	154.64	0.00	56.00	218.15	11.57
10	427.76	30.78	142.23	12.89	153.74	24.77	147.83	0.00	56.00	212.06	11.28
20	424.86	30.46	139.84	11.97	145.67	23.00	142.51	0.00	56.00	206.34	11.03
40	422.00	30.15	137.56	11.11	138.48	21.35	138.36	137.20	56.00	200.97	10.84
80	419.18	29.85	135.38	10.32	132.08	19.83	135.11	91.46	56.00	195.93	10.68

Appendix Table 7
Investment requirements (CAPEX) of seven system sizes of **$AV_{>4\ m}$** separated between components. According to the data collected in this study

component costs in €/kWp System size in hectare	PV modules	Inverter	Mounting structure and foundation	cabeling	Mounting	Infrastructure (fencing)	Transformer	Substation	Permission costs (without expert assessments)	Expert assessments (structural engineering reports, environmental assessmetns, etc.)	Project planning, site acquisition and construction supervision
1	210.00	70.00	496.00	42.00	185.00	92.00	140.00	0.00	44.89	59.86	46.45
2	210.00	70.00	476.00	41.00	175.00	64.00	110.00	0.00	42.15	56.20	37.67
5	210.00	65.00	464.00	41.00	170.00	40.00	65.00	0.00	38.77	51.70	28.57
10	205.00	65.00	460.00	41.00	170.00	28.00	45.00	0.00	36.40	48.54	23.17
20	200.00	60.00	458.00	40.00	165.00	20.00	37.00	0.00	34.18	45.57	18.80
40	200.00	60.00	457.00	40.00	165.00	14.00	33.00	0.00	32.09	42.79	15.25
80	200.00	60.00	456.50	40.00	160.00	9.00	25.00	112.50	30.13	40.17	12.37

Appendix Table 8
OPEX of seven system sizes of **GM PV** separated between components. According to the data collected in this study

Different OPEX costs in €/kWp/year System size in hectare	Operation and Mantainance	Repair reserves for inverters	cleaning costs	remote monetoring control	safty monitoring	insurences	commercial managment / trading costs	lecal advice	Costs for biodiversity measures	grassland maintenance under the modules	grassland maintenance between the module rows	wood care	other costs
1	6.00	1.80	1.00	0.80	0.80	1.10	0.80	4.00	0.50	1.85	0.92	0.92	0.38
2	5.00	1.72	0.70	0.64	0.64	1.10	0.64	3.00	0.50	1.35	0.67	0.67	0.30
5	4.50	1.57	0.40	0.51	0.51	1.00	0.51	1.00	0.50	0.99	0.49	0.49	0.25
10	4.40	1.45	0.40	0.44	0.44	1.00	0.44	0.44	0.50	0.80	0.40	0.40	0.25
20	3.80	1.39	0.40	0.38	0.38	0.90	0.38	0.38	0.50	0.65	0.33	0.33	0.20
40	3.28	1.33	0.30	0.33	0.33	0.90	0.33	0.33	0.50	0.53	0.27	0.27	0.18
80	2.83	1.28	0.30	0.28	0.28	0.80	0.28	0.28	0.50	0.43	0.22	0.22	0.15

Appendix Table 9
OPEX of seven system sizes of **$AV_{vertical}$** separated between components. According to the data collected in this study

Different OPEX costs in €/kWp/year System size in hectare	Operation and Mantainance	Repair reserves for inverters	cleaning costs	remote monetoring control	safty monitoring	insurences	commercial managment / trading costs	lecal advice	Costs for biodiversity measures	grassland maintenance under the modules	grassland maintenance between the module rows	wood care	other costs
1	8.00	2.27	1.00	0.80	0.80	1.00	0.80	4.00	0.00	1.85	0.00	0.92	0.00
2	6.38	2.16	0.70	0.64	0.64	1.00	0.64	3.00	0.00	1.35	0.00	0.67	0.00
5	5.11	2.07	0.40	0.51	0.51	1.00	0.51	1.00	0.00	0.99	0.00	0.49	0.00
10	4.40	2.00	0.40	0.44	0.44	1.00	0.44	0.44	0.00	0.80	0.00	0.40	0.00
20	3.80	1.94	0.40	0.38	0.38	1.00	0.38	0.38	0.00	0.65	0.00	0.33	0.00
40	3.28	1.89	0.30	0.33	0.33	1.00	0.33	0.33	0.00	0.53	0.00	0.27	0.00
80	2.83	1.83	0.30	0.28	0.28	1.00	0.28	0.28	0.00	0.43	0.00	0.22	0.00

Appendix Table 10
OPEX of seven system sizes of **$AV_{tracking}$** separated between components. According to the data collected in this study

Different OPEX costs in €/kWp/year System size in hectare	Operation and Mantainance	Repair reserves for inverters	cleaning costs	remote monetoring control	safty monitoring	insurences	commercial managment / trading costs	lecal advice	Costs for biodiversity measures	grassland maintenance under the modules	grassland maintenance between the module rows	wood care	other costs
1	8.65	1.51	1.00	0.79	0.79	1.10	0.79	4.00	0.00	1.84	0.00	0.92	1.50
2	7.92	1.48	0.70	0.64	0.64	1.10	0.64	3.00	0.00	1.34	0.00	0.67	1.20
5	6.93	1.27	0.40	0.53	0.53	1.00	0.53	1.00	0.00	1.04	0.00	0.49	1.00
10	6.12	1.15	0.40	0.46	0.46	1.00	0.46	0.44	0.00	0.86	0.00	0.40	1.00
20	5.35	1.04	0.40	0.40	0.40	0.90	0.40	0.38	0.00	0.71	0.00	0.33	0.80
40	4.61	0.99	0.30	0.35	0.35	0.90	0.35	0.33	0.00	0.58	0.00	0.27	0.70
80	3.90	0.92	0.30	0.31	0.31	0.80	0.31	0.28	0.00	0.48	0.00	0.22	0.60

Appendix Table 11
OPEX of seven system sizes of $\mathbf{AV_{2.1\ m}}$ separated between components. According to the data collected in this study

Different OPEX costs in €/kWp/year System size in hectare	Operation and Mantainance	Repair reserves for inverters	cleaning costs	remote monetoring control	safty monitoring	insurences	commercial managment / trading costs	lecal advice	Costs for biodiversity measures	grassland maintenance under the modules	grassland maintenance between the module rows	wood care	other costs
1	6.48	1.60	1.00	0.69	0.69	1.10	0.94	4.00	2.75	1.84	0.00	0.92	0.75
2	5.45	1.52	0.70	0.56	0.56	1.10	0.76	3.00	2.75	1.34	0.00	0.67	0.60
5	4.77	1.38	0.40	0.46	0.46	1.00	0.61	1.00	2.25	1.02	0.00	0.51	0.50
10	4.36	1.25	0.40	0.41	0.41	1.00	0.51	0.44	2.25	0.93	0.00	0.46	0.50
20	3.79	1.18	0.40	0.36	0.36	0.95	0.41	0.38	1.75	0.85	0.00	0.43	0.40
40	3.27	1.12	0.30	0.32	0.32	0.90	0.37	0.33	1.75	0.79	0.00	0.40	0.35
80	2.91	1.07	0.30	0.28	0.28	0.80	0.33	0.28	1.25	0.74	0.00	0.37	0.30

Appendix Table 12
OPEX of seven system sizes of $\mathbf{AV_{apple}}$ separated between components. According to the data collected in this study

Different OPEX costs in €/kWp/year System size in hectare	Operation and Mantainance	Repair reserves for inverters	cleaning costs	remote monetoring control	safty monitoring	insurences	commercial managment / trading costs	lecal advice	Costs for biodiversity measures	grassland maintenance under the modules	grassland maintenance between the module rows	wood care	other costs
1	7.95	1.01	1.00	0.79	0.79	3.60	0.79	4.00	0.00	0.00	0.00	0.00	0.00
2	6.36	1.26	0.70	0.64	0.64	3.60	0.64	3.00	0.00	0.00	0.00	0.00	0.00
5	5.30	1.24	0.40	0.53	0.53	3.60	0.53	1.00	0.00	0.00	0.00	0.00	0.00
10	4.62	1.23	0.40	0.46	0.46	3.60	0.46	0.44	0.00	0.00	0.00	0.00	0.00
20	4.03	1.22	0.40	0.40	0.40	3.60	0.40	0.38	0.00	0.00	0.00	0.00	0.00
40	3.51	1.21	0.30	0.35	0.35	3.60	0.35	0.33	0.00	0.00	0.00	0.00	0.00
80	3.06	1.19	0.30	0.31	0.31	3.60	0.31	0.28	0.00	0.00	0.00	0.00	0.00

Appendix Table 13
OPEX of seven system sizes of $\mathbf{AV_{>4\ m}}$ separated between components. According to the data collected in this study

Different OPEX costs in €/kWp/year System size in hectare	Operation and Mantainance	Repair reserves for inverters	cleaning costs	remote monetoring control	safty monitoring	insurences	commercial managment / trading costs	lecal advice	Costs for biodiversity measures	grassland maintenance under the modules	grassland maintenance between the module rows	wood care	other costs
1	7.95	1.01	1.00	0.75	0.75	1.00	0.75	4.00	0.00	1.70	0.00	0.92	0.00
2	6.36	1.26	0.70	0.66	0.66	1.00	0.66	3.00	0.00	1.40	0.00	0.67	0.00
5	5.30	1.24	0.40	0.55	0.55	1.00	0.55	1.00	0.00	1.09	0.00	0.51	0.00
10	4.62	1.23	0.40	0.48	0.48	1.00	0.48	0.44	0.00	0.90	0.00	0.46	0.00
20	4.03	1.22	0.40	0.42	0.42	1.00	0.42	0.38	0.00	0.74	0.00	0.43	0.00
40	3.51	1.21	0.30	0.36	0.36	1.00	0.36	0.33	0.00	0.61	0.00	0.40	0.00
80	3.06	1.19	0.30	0.32	0.32	1.00	0.32	0.28	0.00	0.50	0.00	0.37	0.00

Appendix Table 14

Results $LCOE_{net}$ crop land and apple production. 'North', 'east', 'west' and 'south' describe the locations of the systems according to the assumptions made in the study

[€cent/ kWh]	1 ha north	2 ha north	5 ha north	10 ha north	20 ha north	40 ha north	80 ha north	1 ha west	2 ha west	5 ha west	10 ha west	20 ha west	40 ha west	80 ha west	1 ha east	2 ha east	5 ha east	10 ha east	20 ha east	40 ha east	80 ha east	1 ha south	2 ha south	5 ha south	10 ha south	20 ha south	40 ha south	80 ha south
GM PV	9.91	7.55	5.96	5.13	4.66	4.98	4.43	9.83	7.49	5.91	5.09	4.62	4.94	4.39	9.72	7.40	5.84	5.03	4.57	4.89	4.34	9.03	6.88	5.43	4.67	4.25	4.54	4.04
AVvertical	14.63	10.69	7.89	6.60	5.73	5.16	5.66	14.50	10.60	7.82	6.54	5.69	5.12	5.61	14.35	10.49	7.74	6.47	5.63	5.06	5.55	13.33	9.74	7.19	6.01	5.23	4.70	5.16
AV tracking	11.27	8.56	6.65	5.73	5.13	5.62	4.95	11.18	8.48	6.59	5.68	5.09	5.57	4.90	11.06	8.40	6.53	5.62	5.04	5.51	4.85	10.27	7.80	6.06	5.22	4.68	5.12	4.51
AV2.1 m	11.36	8.53	6.73	5.89	5.33	5.76	5.15	11.26	8.46	6.68	5.84	5.29	5.71	5.11	11.15	8.37	6.61	5.78	5.23	5.66	5.05	10.35	7.77	6.13	5.36	4.86	5.25	4.69
AVapple	16.78	14.42	12.76	12.05	11.59	12.34	11.69															15.29	13.14	11.63	10.98	10.56	11.25	10.65
AV> 4 m	14.09	11.35	9.19	8.30	7.69	7.38	7.73	13.98	11.26	9.11	8.23	7.62	7.31	7.66	13.83	11.14	9.02	8.15	7.54	7.24	7.58	12.84	10.35	8.37	7.57	7.00	6.72	7.04

Appendix Table 15

Results $LCOE_{net}$ grassland land and apple production. 'North', 'east', 'west' and 'south' describe the locations of the systems according to the assumptions made in the study

[€cent/kWh]	1 ha north	2 ha north	5 ha north	10 ha north	20 ha north	40 ha north	80 ha north	1 ha west	2 ha west	5 ha west	10 ha west	20 ha west	40 ha west	80 ha west	1 ha east	2 ha east	5 ha east	10 ha east	20 ha east	40 ha east	80 ha east	1 ha south	2 ha south	5 ha south	10 ha south	20 ha south	40 ha south	80 ha south
GM PV	9.91	7.55	5.96	5.13	4.66	4.98	4.43	9.81	7.46	5.88	5.07	4.60	4.92	4.37	9.70	7.38	5.82	5.01	4.55	4.87	4.32	9.00	6.85	5.40	4.64	4.21	4.51	4.00
AVvertical	14.63	10.69	7.89	6.60	5.73	5.16	5.66	14.50	10.59	7.81	6.53	5.68	5.11	5.60	14.35	10.48	7.73	6.46	5.62	5.05	5.54	13.31	9.73	7.17	6.00	5.21	4.69	5.14
AVtracking	11.27	8.56	6.65	5.73	5.13	5.62	4.95	11.18	8.48	6.59	5.68	5.08	5.57	4.90	11.06	8.39	6.52	5.62	5.03	5.51	4.85	10.27	7.79	6.05	5.21	4.67	5.11	4.50
AV2.1 m	11.36	8.53	6.73	5.89	5.33	5.76	5.15	11.26	8.46	6.67	5.83	5.28	5.71	5.10	11.14	8.37	6.60	5.77	5.23	5.65	5.05	10.34	7.77	6.13	5.36	4.85	5.25	4.69
AVapple	16.78	14.42	12.76	12.05	11.59	12.34	11.69															15.29	13.14	11.63	10.98	10.56	11.25	10.65
AV> 4 m	14.09	11.35	9.19	8.30	7.69	7.38	7.73	13.97	11.26	9.11	8.23	7.62	7.31	7.66	13.83	11.14	9.02	8.15	7.54	7.24	7.58	12.84	10.34	8.37	7.56	7.00	6.72	7.04

Appendix Table 16

Results APP crop land and apple production. 'North', 'east', 'west' and 'south' describe the locations of the systems according to the assumptions made in the study

[€/ha/year]	1 ha north	2 ha north	5 ha north	10 ha north	20 ha north	40 ha north	80 ha north	1 ha west	2 ha west	5 ha west	10 ha west	20 ha west	40 ha west	80 ha west	1 ha east	2 ha east	5 ha east	10 ha east	20 ha east	40 ha east	80 ha east	1 ha south	2 ha south	5 ha south	10 ha south	20 ha south	40 ha south	80 ha south
AV vertical	86,314	57,521	35,355	26,841	19,663	3201	22,522	86,305	57,513	35,346	26,833	19,655	3192	22,513	86,395	57,603	35,436	26,923	19,745	3282	22,603	86,319	57,527	35,360	26,846	19,668	3206	22,527
AV tracking	18,354	13,567	9339	8072	6351	8514	6941	18,346	13,559	9331	8064	6343	8506	6933	18,436	13,649	9421	8154	6432	8596	7023	18,359	13,572	9345	8077	6356	8519	6946
AV 2,1 m	17,578	11,950	9436	9186	8164	9463	8756	17,570	11,942	9428	9178	8156	9455	8748	17,659	12,031	9517	9268	8245	9545	8838	17,583	11,955	9441	9191	8169	9468	8761
AV apple	74,387	74,444	73,696	74,994	75,036	79,707	78,641															74,392	74,449	73,701	74,999	75,041	79,712	78,646
AV > 4 m	55,465	50,465	42,899	42,082	40,140	31,721	43,735	55,456	50,457	42,891	42,074	40,132	31,713	43,727	55,546	50,547	42,981	42,164	40,222	31,803	43,816	55,470	50,470	42,904	42,087	40,146	31,726	43,740

Appendix Table 17
Results APP grassland land and apple production. 'North', 'east', 'west' and 'south' describe the locations of the systems according to the assumptions made in the study

[€/ha/year]	1 ha north	2 ha north	5 ha north	10 ha north	20 ha north	40 ha north	80 ha north	1 ha west	2 ha west	5 ha west	10 ha west	20 ha west	40 ha west	80 ha west	1 ha east	2 ha east	5 ha east	10 ha east	20 ha east	40 ha east	80 ha east	1 ha south	2 ha south	5 ha south	10 ha south	20 ha south	40 ha south	80 ha south
AV vertical	86,315	57,523	35,356	26,843	19,665	3202	22,523	86,557	57,765	35,598	27,084	19,906	3444	22,765	86,619	57,826	35,660	27,146	19,968	3506	22,827	86,692	57,900	35,733	27,220	20,042	3579	22,900
AV tracking	18,356	13,569	9341	8074	6352	8516	6942	18,597	13,810	9583	8315	6594	8757	7184	18,659	13,872	9644	8377	6656	8819	7246	18,733	13,946	9718	8451	6730	8893	7320
AV 2,1 m	17,579	11,951	9437	9188	8165	9465	8758	17,821	12,193	9679	9429	8407	9706	8999	17,883	12,255	9741	9491	8469	9768	9061	17,957	12,328	9815	9565	8542	9842	9135
AV apple	74,389	74,446	73,697	74,996	75,038	79,709	78,643															74,766	74,823	74,074	75,373	75,415	80,086	79,020
AV > 4 m	55,466	50,467	42,901	42,084	40,142	31,723	43,736	55,708	50,708	43,142	42,325	40,384	31,964	43,978	55,770	50,770	43,204	42,387	40,445	32,026	44,040	55,843	50,844	43,278	42,461	40,519	32,100	44,113

Data availability

A preliminary version of this article was published as part of a dissertation (https://doi.org/10.38071/2025-00605-2) and was presented in part at the AgriVoltaics World Conference 2025. The datasets generated and/or analysed as part of the current study can be found in the article or in the appendix to the article.

References

Agostini, A., Colauzzi, M., Amaducci, S., 2021. Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment. Appl. Energy 281, 116102. https://doi.org/10.1016/j.apenergy.2020.116102.

Alam, H., Alam, M.A., Butt, N.Z., 2023. Techno Economic Modeling for Agrivoltaics: Can Agrivoltaics Be More Profitable Than Ground Mounted PV? IEEE J. Photovolt. 13 (1), 174–186. https://doi.org/10.1109/JPHOTOV.2022.3215087.

Amaducci, S., Yin, X., Colauzzi, M., 2018. Agrivoltaic systems to optimise land use for electric energy production. Appl. Energy 220, 545–561. https://doi.org/10.1016/j.apenergy.2018.03.081.

Aroca-Delgado, R., Pérez-Alonso, J., Callejón-Ferre, Á., Velázquez-Martí, B., 2018. Compatibility between Crops and Solar Panels: An Overview from Shading Systems (en). Sustainability 10 (3), 743. https://doi.org/10.3390/su10030743.

Bahlo, J., Hilbers, J., Görgens, M., Holthusen, H., Clever, M., 2013. Vorernteführungen 2013. Mittel Des. Obstbau Des. alten Landes (OVR) 68, 10.

Bhadra, S., Pruseth, A., Behera, S., Giri, N.C., 2024. Design of Automated Agrivoltaic Smart Drip Irrigation and Techno-Economic Assessment. In: Sahoo, D.K., Das, A., Kumar Panda, P. (Eds.), 2nd International Conference on Signal Processing, Communication, Power and Embedded System: SCOPES 2024: 19-21 December 2024; conference location: Paralakhemundi Campus, Centurion University of Technology and Management, Odisha., India. IEEE, Piscataway, NJ, pp. 1–6. https://doi.org/10.1109/SCOPES64467.2024.10991166.

Böhm, J., 2024. Key Advantages of Agrivoltaic Systems in Germany – A Comparison of the Electricity Yield of Different Systems. Agric. Conf. Proc. 2. https://doi.org/10.52825/agripv.v2i.986.

Böhm, J., de Witte, T., Plaas, E., 2022. PV-Freiflächenanlagen: Rahmenbedingungen und Wirtschaftlichkeit (de). Berichte über Landwirtschaft -. Zeitschrift für Agrarpolitik und Landwirtschaft, Aktuelle Beiträge. https://doi.org/10.12767/buel.v100i2.421.

Böhm, J., 2023. Vergleich der Flächenenergieerträge verschiedener erneuerbarer Energien auf landwirtschaftlichen Flächen – für Strom, Wärme und Verkehr (de). Ber. üBer. Landwirtsch. Z. F. üR. Agrarpolit. und Landwirtsch. Aktuelle Beiträge. https://doi.org/10.12767/BUEL.V101I1.462.

Bundesministerium der Justiz (BMJ), 2024. Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG 2023): Erneuerbare-Energien-Gesetz vom 21. Juli 2014 (BGBl. I S. 1066), das zuletzt durch Artikel 1 des Gesetzes vom 8. Mai 2024 (BGBl. 2024 I Nr. 151) geändert worden ist", 127 pp. ⟨https://www.gesetze-im-internet.de/eeg_2014/EEG_2023.pdf⟩.

Bundesministerium für Ernährung und Landwirtschaft (BMEL), 2024a. 47. Landwirtschaftlich genutzte Fläche nach Kulturarten. ⟨https://www.bmel-statistik.de/landwirtschaft/tabellen-zur-landwirtschaft⟩ (accessed 12 April 2024).

Bundesministerium für Ernährung und Landwirtschaft (BMEL), 2024b. Betriebe mit Verkaufsanbau von Baumobst nach Größenklassen der Baumobstfläche. ⟨https://www.bmel-statistik.de/landwirtschaft/tabellen-zur-landwirtschaft⟩ (accessed 12 April 2024).

Chalgynbayeva, A., Balogh, P., Szőllősi, L., Gabnai, Z., Apáti, F., Sipos, M., Bai, A., 2024. The Economic Potential of Agrivoltaic Systems in Apple Cultivation—A Hungarian Case Study. Sustainability 16 (6), 2325. https://doi.org/10.3390/su16062325.

Chopdar, R.K., Sengar, N., Giri, N.C., 2025. Agrivoltaic Systems for Enhancing Sustainability in Hot Arid and Semi-arid Climates (en) 2025 ed. Springer Nature Singapore In: Vadhera, S., Kumar, R., Dewan, A. (Eds.). In: Advances in Green Energy Technologies: Proceedings of ICGEST 2023, 1st ed. 2. Imprint Springer, Singapore, pp. 107–119 2025 ed. Springer Nature Singapore. https://doi.org/10.1007/978-981-96-0861-4_8.

Destatis, 2023. Hitze und Trockenheit. ⟨https://www.destatis.de/DE/Themen/Querschnitt/Hitze/_inhalt.html⟩ (accessed 20 October 2025).

DIN, 2021. Din Spec 91434: Agri-Photovoltaik-Anlagen - Anforderungen an die landwirtschaftliche Hauptnutzung, 26 pp. ⟨https://www.beuth.de/de/technische-regel/din-spec-91434/337886742⟩ (accessed 20 April 2021).

Duden, C., Offermann, F., 2020. Income Risk of German Farms and its Drivers. Ger. J. Agric. Econ. (GJAE) 69 (2). https://doi.org/10.30430/69.2020.2.85-107.

Elamri, Y., Cheviron, B., Lopez, J.-M., Dejean, C., Belaud, G., 2018. Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces. Agric. Water Manag. 208, 440–453. https://doi.org/10.1016/j.agwat.2018.07.001.

Feuerbacher, A., Herrmann, T., Neuenfeldt, S., Laub, M., Gocht, A., 2022. Estimating the economics and adoption potential of agrivoltaics in Germany using a farm-level bottom-up approach. Renew. Sustain. Energy Rev. 168, 112784. https://doi.org/10.1016/j.rser.2022.112784.

Feuerbacher, A., Laub, M., Högy, P., Lippert, C., Pataczek, L., Schindele, S., Wieck, C., Zikeli, S., 2021. An analytical framework to estimate the economics and adoption potential of dual land-use systems: The case of agrivoltaics. Agric. Syst. 192, 103193. https://doi.org/10.1016/j.agsy.2021.103193.

Fraunhofer Institute for Solar Energy Systems ISE (Fraunhofer ISE), 2024a. Agric. Oppor. Agric. Energy Transit. A Guidel. Ger. 76. ⟨https://www.ise.fraunhofer.de/de/veroeff

entlichungen/studien/agri-photovoltaik-chance-fuer-landwirtschaft-und-energiewende.html⟩ (accessed 11 April 2024).
Fraunhofer Institute for Solar Energy Systems ISE (Fraunhofer ISE), 2024b. Photovoltaics Report. ⟨https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/photovoltaics-report.html⟩ (accessed 29 July 2024).
Freier, B., Sellmann, J., Schwarz, J., Jahn, M., Moll, E., Gutsche, V., Zornbach, W., 2010. Netz Vergleichsbetriebe Pflanzenschutz – Jahresbericht 2009 (de). Berichte aus dem Julius Kühn-Institut. Berichte aus dem Julius Kühn-InstitutNetz Vergleichsbetriebe Pflanzenschutz: Jahresbericht: Analyse der Ergebnisse der Jahre … bis … = Network of reference farms for plant protection; annual report: analysis of results of 156. https://doi.org/10.5073/20140925-155743.
Gadhiya, G., Patel, U., Chauhan, P., Giri, N.C., Yin, G.-Z., Khargotra, R., 2024. Development of agrivoltaic insect net house to enhance sustainable energy-food production: A techno-economic assessment. Results Eng. 24, 103228. https://doi.org/10.1016/j.rineng.2024.103228.
Giri, N.C., Mohanty, R.C., Shaw, R.N., Poonia, S., Bajaj, M., Belkhier, Y., 2022. Agriphotovoltaic System to Improve Land Productivity and Revenue of Farmer Sep. 23-25, 2022 In: Soon, T.K., Balas, V.E., Das, S. (Eds.), 2022 IEEE Global Conference on Computing, Power and Communication Technologies (GlobConPT): India Habitat Centre, Lodhi Road, New Delhi, India. IEEE, Piscataway, NJ, pp. 1–5 Sep. 23-25, 2022. https://doi.org/10.1109/GlobConPT57482.2022.9938338.
Hansen, H., Forstner, B., de Witte, T., Neuenfeldt, S., Tergast, H., Tietz, A., 2021. Steigen Bodenpreise und ökonomische Nachhaltigkeit landwirtschaftlicher Betriebe: Bericht im. Auftragt des BMEL.
Hassan, Q., Viktor, P.J., Al-Musawi, T., Mahmood Ali, B., Algburi, S., Alzoubi, H.M., Khudhair Al-Jiboory, A., Zuhair Sameen, A., Salman, H.M., Jaszczur, M., 2024. The renewable energy role in the global energy Transformations. Renew. Energy Focus 48, 100545. https://doi.org/10.1016/j.ref.2024.100545.
Iglesias, I., Alegre, S., 2006. The effect of anti-hail nets on fruit protection, radiation, temperature, quality and probability of Mondial Gala apples. JAH 08 (02), 91–100. https://doi.org/10.37855/jah.2006.v08i02.22.
International Energy Agency (IEA), 2025. Renewables 2025: Analysis and forecasts to 2030. https://iea.blob.core.windows.net/assets/76ad6eac-2aa6-4c55-9a55-b8dc0dba9f9e/Renewables2025.pdf.
JinKo Solar, 2024. Tiger Neo N-Type 614-635 Watt: Bifaziales Modul mit Doppelglas. Datenblatt, 4 pp. ⟨https://jinkosolar.eu/de/downloads-de/datenblaetter-tiger-neo/⟩.
Kekeya, J., 2016. Analysing qualitative data using an iterative process. Contemp. PNG Stud. 24, 86–94. https://doi.org/10.3316/informit.220284691031027.
Kost, C., Müller, P., Sepulveda Schweiger, J., Fluri, V., Thomsen, J., 2024. Levelized Cost of Electricity - Renewable Energy Technologies. Fraunhofer Institute for Solar Energy Systems ISE (Fraunhofer ISE). ⟨https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html⟩ (accessed 1 July 2021).
Laub, M., Pataczek, L., Feuerbacher, A., Zikeli, S., Högy, P., 2022. Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis. Agron. Sustain. Dev. 42 (3). https://doi.org/10.1007/s13593-022-00783-7.
Longi, 2024. Hi-MO7 585–620 M: Datenblatt, 2 pp. ⟨https://www.longi.com/en/download/?categoryId=28⟩.
Meier-Grüll, M., Jedmowski, C., Hoelscher, K., Müller, C., Raumann, L., Pieters, B., Gerber, A., Trommsdorff, M., Berwind, M., Muller, O., 2024. Agri-Horti-PV Research System in North Rhine-Westphalia Including PV Trackers and Integrated Rainwater Harvesting. Agric. Conf. Proc. 1. https://doi.org/10.52825/agripv.v1i.632.
Mußhoff, O., Hirschauer, N., 2020. Modernes Agrarmanagement: Betriebswirtschaftliche Analyse- und Planungsverfahren (ger), 5., überarbeitete und erweiterte Auflage ed. Verlag Franz Vahlen, München. Verlag Franz Vahlen München.(ISBN) 9783800662265.
Osterburg, B., Ackermann, A., Böhm, J., Bösch, M., Dauber, J., Witte, T., de, Elsasser, P., Erasmi, S., Gocht, A., Hansen, H., Heidecke, C., Klimek, S., Krämer, C., Kuhnert, H., Moldovan, A., Nieberg, H., Pahmeyer, C., Plaas, E., Rock, J., Röder, N., Söder, M., Tetteh, G., Tiemeyer, B., Tietz, A., Wegmann, J., Zinnbauer, M., 2023. Flächennutzung und Flächennutzungsansprüche in Deutschland. Thünen Work. 224. https://doi.org/10.3220/WP1697436258000.
Pataczek, L., Weselek, A., Bauerle, A., Högy, P., Lewandowski, I., Zikeli, S., Schweiger, A., 2023. Agrivoltaics mitigate drought effects in winter wheat (eng). Physiol. Plant. 175 (6), e14081. https://doi.org/10.1111/ppl.14081.
Porsch, A., Gandorfer, M., Bitsch, V., 2018. Strategies to manage hail risk in apple production. AFR 78 (5), 532–550. https://doi.org/10.1108/AFR-07-2017-0062.
Randle-Boggis, R.J., Lara, E., Onyango, J., Temu, E.J., Hartley, S.E., Agrivoltaics in East Africa: Opportunities and challenges. AGRIVOLTAICS2020 CONFERENCE: Launching Agrivoltaics World-wide. https://doi.org/10.1063/5.0055470.
Rentenbank, 2023. Konditionenrundschreiben Nr. 17 / 2023: Terms and Conditions Circular No. 17 / 2023.
Rogna, M., Schamel, G., Weissensteiner, A., 2019. Modeling the Switch from Hail Insurance to Anti-Hail Nets. SSRN J. https://doi.org/10.2139/ssrn.3424071.
Sacchelli, S., Garegnani, G., Geri, F., Grilli, G., Paletto, A., Zambelli, P., Ciolli, M., Vettorato, D., 2016. Trade-off between photovoltaic systems installation and agricultural practices on arable lands: An environmental and socio-economic impact analysis for Italy. Land Use Policy 56, 90–99. https://doi.org/10.1016/j.landusepol.2016.04.024.
Schallenberg-Rodriguez, J., Rodrigo-Bello, J.-J., Del Río-Gamero, B., 2023. Agrivoltaic: How much electricity could photovoltaic greenhouses supply? Energy Rep. 9, 5420–5431. https://doi.org/10.1016/j.egyr.2023.04.374.
Schindele, S., Trommsdorff, M., Schlaak, A., Obergfell, T., Bopp, G., Reise, C., Braun, C., Weselek, A., Bauerle, A., Högy, P., Goetzberger, A., Weber, E., 2020. Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications. Appl. Energy 265. https://doi.org/10.1016/j.apenergy.2020.114737.
Schneider, A.-K., Klabunde, F., Buck, L., Ohlhoff, M., Reis, L., Olvermann, M., Kauffeld, S., Engel, B., Glatzel, G., Schröder, B., Frerichs, L., 2023. Drawing transformation pathways for making use of joint effects of food and energy production with biodiversity agriphotovoltaics and electrified agricultural machinery (eng). J. Environ. Manag. 335, 117539. https://doi.org/10.1016/j.jenvman.2023.117539.
Solargis, 2021. Global Solar Atlas - Methodology. ⟨https://globalsolaratlas.info/support/methodology⟩ (accessed 11 January 2021).
Touil, S., Richa, A., Fizir, M., Bingwa, B., 2021. Shading effect of photovoltaic panels on horticulture crops production: a mini review (En;en). Rev. Environ. Sci. Biotechnol. 20 (2), 281–296. https://doi.org/10.1007/s11157-021-09572-2.
Trommsdorff, M., Hopf, M., Hörnle, O., Berwind, M., Schindele, S., Wydra, K., 2023. Can synergies in agriculture through an integration of solar energy reduce the cost of agrivoltaics? An economic analysis in apple farming. Appl. Energy 350, 121619. https://doi.org/10.1016/j.apenergy.2023.121619.
Trommsdorff, M., Kang, J., Reise, C., Schindele, S., Bopp, G., Ehmann, A., Weselek, A., Högy, P., Obergfell, T., 2021. Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany. Renew. Sustain. Energy Rev. 140, 110694. https://doi.org/10.1016/j.rser.2020.110694.
United Nations Framework Convention on Climate Change (UNFCCC), 2023. Outcome of the first global stocktake.: Proposal by the President. Draft decision -/CMA.5. https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf.
Weselek, A., Ehmann, A., Zikeli, S., Lewandowski, I., Schindele, S., Högy, P., 2019. Agrophotovoltaic systems: applications, challenges, and opportunities. A review. Agron. Sustain. Dev. 39 (4). https://doi.org/10.1007/s13593-019-0581-3.
Wydra, K., Vollmer, V., Busch, C., Prichta, S., 2023. Agrivoltaic: Solar Radiation for Clean Energy and Sustainable Agriculture with Positive Impact on Nature. https://doi.org/10.5772/intechopen.111728.
Zaplata, M.K., Dullau, S., 2022. Applying Ecological Succession Theory to Birds in Solar Parks: An Approach to Address Protection and Planning. Land 11 (5), 718. https://doi.org/10.3390/land11050718.
Zeddies, H.H., Parlasca, M., Qaim, M., 2025. Agrivoltaics increases public acceptance of solar energy production on agricultural land. Land Use Policy 156, 107604. https://doi.org/10.1016/j.landusepol.2025.107604.