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Agrivoltaics increases public acceptance of solar energy production on agricultural land

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Abstract

Competition for land is a key challenge for decarbonized energy transitions. Open-space solar energy farms are gaining in importance but have large land requirements and displace agricultural production. Agrivoltaics offers a compromise, integrating solar panels into existing farming operations. However, adoption of Agrivoltaics remains limited, as it has lower energy output per hectare and higher installation costs than open-space solar. Here, we compare public attitudes towards Agrivoltaics and open-space solar in Germany, using experimental data from a nationally representative sample. Participants were shown three images of a landscape that only differed in terms of land use, namely an agricultural field without solar, an Agrivoltaics system, and an open-space solar system, together with some technical information. While both solar systems have perceived negative impacts on landscape attractiveness, the impacts are less negative for Agrivoltaics. In comparison to their regular electricity bill, 44% of the participants expressed their willingness to pay more for electricity from Agrivoltaics, compared to 29% for electricity from open-space solar. We also find a higher monetary willingness to pay for Agrivoltaics. These results hold across different agricultural systems, implying that Agrivoltaics could play an important role for socially-acceptable energy transitions. More widespread Agrivoltaics adoption may depend on targeted policy support.

Keywords: Agrivoltaics, Renewable energies, Social acceptance, Contingent valuation, Willingness to pay

JEL Codes: J38, O13, Q15, Q4

1. Introduction

Land is a critical resource required to meet food and energy needs of a growing world population. Since global land availability is finite, strategies leading to highly land-efficient food and energy production are required for sustainable futures (Slätmo, 2017). In this context, Agrivoltaics (AV), which are systems that combine solar energy generation with agricultural production on the same set of land, can potentially play an important role (Feuerbacher et al., 2022)[1].

In AV systems, solar panels are installed on sections of agricultural land, either mounted on stilts or arranged in rows with vertical alignment, to enable continued agricultural production beneath or around the solar panels (Trommsdorff et al., 2021). AV systems tend to reduce agricultural output per unit of land but can also create synergies in some situations, for example, when solar panels offer protection for crops against extreme weather, such as intense radiation or hailstorms (Gorjian et al., 2022; Wagner et al., 2024). Overall, AV systems offer the potential to produce energy and food more efficiently in a combined system, in comparison to the more common approach of taking land parcels completely out of agricultural production for open-space (OS) solar projects[2]. Several countries around the world strive to promote the expansion of AV systems, including France, the USA, China, Japan, South Korea, and Germany (Trommsdorff et al., 2021; BMWK, 2023). At present, however, the construction of AV systems is costly and less profitable than OS, meaning that actual AV adoption is limited (Feuerbacher et al., 2022). Wider AV adoption might require government financial incentives.

More generally, widespread use of solar systems on agricultural land – including both AV and OS – represents significant changes in the agricultural landscape (Biró-Varga et al., 2024). Public acceptance of such landscape changes is critical for implementation but, so far, remains poorly understood (Pascaris et al., 2022). Most citizens consume electricity and depend on agricultural production for food, and many also enjoy the recreational effects of agricultural landscapes (van Zanten et al., 2016; Choi et al., 2024).

Compared to OS, AV projects could lead to greater acceptance, as they maintain agricultural production on the same field and may lead to less drastic landscape impacts (Trommsdorff et al., 2021). But empirical evidence is lacking. Here, we address this research gap by pursuing two key questions. First, are AV systems viewed more favorably by the general public than OS systems? Second, do public perceptions differ between AV in different agricultural production

1 Agrivoltaics is sometimes also referred to as 'Agri-PV' or 'Aglectric'.

2 Energy production from agricultural land is often also associated with biofuels, such as bioethanol from grain or biodiesel from oil crops. Here, we do not look at biofuels, rarely used to produce electricity. It should be noted, however, that the per-hectare energy output from biofuels is several dimensions lower than the energy output from AV and OS solar systems, even in temperate climates with limited sunshine (Turnley et al., 2024).

systems? In analyzing public attitudes, we explicitly consider current limitations of AV systems, such as lower energy efficiency and higher costs, to provide a realistic assessment.

Our study focuses on Germany, a densely populated country where land competition is a key challenge that needs to be solved to decarbonize energy systems (Schlemminger et al., 2024). We have collected nationally representative data with observations from 1,893 individuals to investigate public preferences measured in terms of willingness to pay (WTP) for electricity supply from AV or OS systems. To our knowledge, this study is the first to compare public acceptance of converting agricultural land into AV or OS solar systems, not only in Germany but in any country. Results may be relevant for research and policy-making. A more favorable evaluation of AV compared to OS systems would suggest that increased funding for developing and implementing AV technology is justified.

The remainder of this article is structured as follows. Section 2 provides a short review of the literature on design and characteristics of AV systems and on acceptance research related to renewable energy. Section 3 describes the study design and the methods of data analysis. In section 4, the empirical results are presented, while section 5 discusses the main findings in context and derives research and policy implications.

2. Literature Review

2.1 Agrivoltaics

The most important criterion for AV systems is the dual use of land for agricultural and solar electricity production (Schindele et al., 2020). The EU's Common Agricultural Policy guidelines for AV, for example, state that a total of 85% of an AV area must remain available for agricultural use (BMEL, 2021). AV system configuration can differ considerably by type of agricultural production. In systems for special crops such as horticulture or viticulture, the solar panels are usually constructed on stilts to allow crops to grow underneath. While such a stilted design is also possible for grain crops, vertical bifacial systems are often preferred; these are erected in rows between the crops and require little space due to their narrow design (Gorjian et al., 2022). AV is also possible on permanent grassland. However, in order to classify as AV on grassland, a wider spacing of the solar panels than in OS systems is required to meet the dual-use criterion and allow for grazing or mowing in-between the rows (Wagner et al., 2024).

AV systems usually produce a lower yield than pure agricultural land and a lower electricity output than OS solar systems. Lower agricultural yield results from the construction of the solar panels and the associated farming restrictions; depending on technical details, reduced solar radiation due to shadow cast may also play a role. However, as mentioned, AV systems can also provide agronomic benefits for the crops in some situations. For example, stilted systems protect fruits from hailstorms and extreme solar radiation, while vertical systems can reduce crop damage caused by storms (Schindele et al., 2020). Lower electricity output results from different designs in AV and OS systems: while OS systems are typically installed with a hectare output of one megawatt or more, the output of current AV systems ranges anywhere between 100 and 800 kilowatt hours per hectare (ISE, 2022). More complex designs of AV systems and the lower energy output per hectare increase the costs per kilowatt hour compared to OS systems. As a result, AV systems are currently economically less attractive than OS systems despite the additional yield from agricultural production (Trommsdorff et al., 2021; Feuerbacher et al., 2022). However, economies of scale could make AV systems more attractive in the future and deliver a higher overall economic output through optimized integration of agricultural and energy production. Furthermore, against the background of rising global demand for food and biomass, maintaining fertile agricultural land for production could be viewed as a social benefit of AV systems, an aspect that is not always fully reflected in market prices (Cousse, 2021; Schindele et al., 2020).

2.2 Public acceptance of large-scale solar projects

There is a relatively broad body of literature dealing with the public acceptance of renewable energy-related infrastructure. Earlier studies focus on the acceptance of wind farms (Rand

and Hoen, 2017), whereas research on the acceptance of solar projects has only increased more recently (Carlisle et al., 2015; Liebe and Dobers, 2019; Cousse, 2021).

Existing studies suggest that accepting large-scale solar projects is more generally associated with personal attitudes toward renewable energies. Personal attitudes, in turn, are shaped by individual knowledge of the current climatic effects of electricity production, environmental beliefs, familiarity with and interest in environmental technologies, and perceptions of technology developer incentives (Carlisle et al., 2015; Liebe and Dobers, 2019; Donald et al., 2022; Campos et al., 2023). Furthermore, landscape aesthetics, especially for projects near the individual's home, are a frequently mentioned concern, as outlined in a recent social media analysis of large-scale OS solar projects (Roddis et al., 2020). The size of a project also determines its aesthetics and, therefore, its acceptance. Cousse (2021) revealed that the acceptance of OS solar projects is often higher than that of wind energy projects but falls with increasing size.

The literature on the social acceptance of AV systems is very limited. One of the first studies by Pascaris et al. (2022) found generally positive acceptance of AV systems in two states of the USA. A study examining the in-field user experience of AV systems in the Netherlands concluded that participants perceived a negative impact on landscape experience but that the landscape's future value and use value increased due to AV installation (Biró-Varga et al., 2024).

3. Material and Methods

3.1 Online survey

An online survey was conducted among adult German residents in March 2024. The study received ethical approval from the Center for Development Research Ethics Committee at the University of Bonn. Due to quota sampling, the data reflect the German adult population in terms of age, sex, education, income, and state of residency. A three-stage pre-test preceded the final survey. Three weeks before the final survey, the questionnaire was initially presented to 21 participants from the researchers' scientific and non-scientific networks, including experts in AV and OS systems and farming. The participants provided feedback on the questionnaire and the empirical data obtained. This feedback was used to improve the questionnaire. Subsequently, in the second pre-test stage, the panel provider recruited 165 participants who completed the questionnaire in full. In the third pre-test stage, 390 persons participated to investigate any undesirable patterns in the questionnaire design and WTP behavior. The pre-test participants were not part of the final study sample.

In the final survey, a total of 2,415 complete questionnaires were collected. After a rigorous data-cleaning process, 1,893 participants remained. As conscious reading in the information part of the questionnaire was required, participants who did not correctly answer at least two out of three comprehension questions were excluded. Furthermore, observations of participants with a survey time below 50% of the median time ('speeders') were also excluded.

3.2 Experimental approach

Measuring and comparing public attitudes towards large-scale solar projects on agricultural land in quantitative ways requires the pricing of inherent preferences. Since market prices for electricity do not capture relevant non-marketed aspects, we employ a stated preferences experimental approach, namely the contingent valuation method (CVM), a common tool in the empirical economics literature (Choi et al., 2024).

The main objective of our study is to provide an overview of the public acceptance of AV in comparison to OS solar. More specifically, we estimate people's WTP as a price premium for AV and OS systems on their annual electricity bill and use these WTP values as proxies of acceptance. Both systems are compared to pure agricultural production land and people's current electricity bill. As the experiment uses scenarios and stated preferences, some hypothetical bias is possible. It should also be mentioned that our survey targets the adult population as a whole, not only household decision-makers concerning electricity supply. Therefore, the estimated monetary WTP values should not be overinterpreted. Nevertheless, potential biases refer to both AV and OS, meaning that comparing between the two systems can still lead to meaningful insights.

Depending on the concrete situation, CVM studies can use different designs, such as open-ended questions, bidding games, payment cards, or dichotomous choices. While dichotomous choice is the most commonly used design, it has been shown to be subject to a starting point bias and relies on relatively strong assumptions (Hanemann, 1984). We employ the payment card (PC) method, offering participants a range of payment options that increase in value with progressively larger intervals. Based on our pre-test results, the PC intervals were adjusted to minimize potential centering bias. The highest amount was open-ended to capture WTP beyond the fixed values. Additionally, the PC used in our experiment included an opt-out option, allowing participants to make a zero-payment choice (Figure 1). While this approach is not subject to the starting point bias, it may be affected by a range, centering, and endpoint bias (Cameron and Huppert, 1989). Nevertheless, the PC design is useful in our context. A certain range bias was even intended because we expect not all respondents to be very familiar with the exact costs of their current annual electricity supply.

0€	5€	10€	15€	20€	25€	30€	40€	50€	75€	100€	150€	200€	250€ or more

Fig. 1: Payment card design

The participants in our study do not face any consequences for their payment decisions. Therefore, before asking for their WTP, we informed them about the annual average electricity costs for a three-person household in Germany between 2019-2021 to provide a realistic frame for their answers. Furthermore, we implemented a cheap talk script using the example of Carlsson et al. (2005) to encourage honest and realistic responses. Additionally, we followed Bishop and Heberlein (1979) and implemented a dichotomous choice-like question before the PC valuation, asking participants first to state their general WTP attitude with a 'yes/no' question format.

3.3 Questionnaire design

The questionnaire used in our survey was divided into three parts. First, participants responded to questions concerning their socioeconomic background and whether or not they had heard of AV before, were interested in renewable energies, and had invested in renewable energy projects outside of stock market investments.

Second, participants received information in text form about the advantages and disadvantages of AV and OS solar systems on agricultural land concerning the loss of arable land for agricultural production and the possible CO2 savings. As part of this information, we emphasized the need for more solar on agricultural land to decarbonize the energy supply. We pointed out that AV systems vary in how they are used (providing crop farming, pasture grazing, and viticulture as examples) and, therefore, vary in how they are built. Following the advice of several pre-test participants, the usual procedure for leasing land from the farmer to a solar project developer and the distribution of revenues (agricultural products and electricity) between farmer and project developer was briefly explained. Three comprehension questions were then asked to test the respondents' attention span.

Third, the CVM experiment was implemented, following the study design by Zhang and Wu (2012) and guidelines of the NOAA (1993) panel. In a between-subject design, participants were randomly assigned to one of the three AV scenarios: (1) crop farming with vertical bifacial solar panels on a grain field; (2) grassland for cattle grazing (pasture) with ground-mounted modules (and wider row spacing than for OS solar; (3) high-stilt solar in viticulture.

The AV systems were visualized with edited images and compared to baseline agricultural land and OS systems (Figure 2). The baseline agricultural land without solar modules was presented first, followed by the edited images with AV and OS systems. Important attributes of the various alternatives in terms of land requirements, solar electricity output per hectare, and CO2 emissions saved through solar (in comparison to the German average emissions per kilowatt hour of electricity) were also explained, as shown in Figure 2. Furthermore, it was pointed out that the yields in AV systems are lower than on pure agricultural land and that no agricultural production takes place on the OS field. The exact description was adapted to each scenario, as the yield losses in grain, pasture, and viticulture differ (ISE, 2022). In addition, reference was made to the agronomic advantages of AV for each specific scenario (e.g., wind protection for grain crops and hailstorm protection for viticulture) (Schindele et al., 2020).

Study participants first answered the ‘yes/no’ question about whether they would be willing to pay an additional amount on their annual electricity bill to support the respective AV or OS project shown. Participants who answered ‘yes’ were then directed to the payment card and could enter an amount between 5€ and 250€-and more per year (separately for the AV and OS scenarios) or choose the opt-out of 0€. Participants who answered ‘no’ had the option to state an additional amount on the PC whether they would be willing to pay for preventing the respective project, or indicate again that their WTP is 0€.

In addition to the WTP questions, the perceived landscape impacts of each solar project were surveyed in terms of various environmental and social attributes. For the choice of relevant attributes, we followed Biró-Varga et al. (2024), looking at landscape attractiveness, access, wildlife, recreational value, and multifunctionality, among others. Respondents were asked to assess the AV and OS scenarios for each attribute compared to agricultural land without solar, using a Likert scale from 1-‘much worse’ to 5-‘much better’.

Grain Scenario	Pasture Scenario	Viticulture Scenario
		
Baseline without solar Agriculture: On the whole field Solar power: None Land use solar: None CO_2 savings: None	**Baseline without solar** Agriculture: On the whole field Solar power: None Land use solar: None CO_2 savings: None	**Baseline without solar** Agriculture: On the whole field Solar power: None Land use solar: None CO_2 savings: None
		
Agrivoltaic system Agriculture: Restricted Solar power: 400 kWp* CO_2 savings**: 180 to per ha/a*** Land use solar: 2.5 hectares compared to 1-hectare OS solar	**Agrivoltaic system** Agriculture: Restricted Solar power: 700 kWp* CO_2 savings**: 315 to per ha/a*** Land use solar: 1.4 hectares compared to 1-hectare OS solar	**Agrivoltaic system** Agriculture: Restricted Solar power: 625 kWp* CO_2 savings**: 280 to per ha/a*** Land use solar: 1.6 hectares compared to 1-hectare OS solar
		
Open-space solar Agriculture: None Solar power: 1.000 kWp* Co_2 savings**: 450 to per ha/a*** Land use solar: 1 hectare compared to 2.5 hectares AV	**Open-space solar** Agriculture: None Solar power: 1.000 kWp* Co_2 savings**: 450 to per ha/a*** Land use solar: 1 hectare compared to 1.4 hectares AV	**Open space-solar** Agriculture: None Solar power: 1.000 kWp* Co_2 savings**: 450 to per ha/a*** Land use solar: 1 hectare compared to 1.6 hectares AV

Fig. 2: Scenarios used in experiment with edited images and information provided. *Kilowatt peak installed per hectare based on existing examples according to (ISE, 2022); **Based on the average CO_2 emissions per kilowatt hour (434g) for the average German electricity supply in 2022 and approximated life-cycle emissions from solar power of 60g per kilowatt hour produced (UBA, 2023, 2024); ***Calculated per hectare and year estimating an annual production of 1,000 kilowatt hours produced per installed kilowatt peak. *Photo credit and permission to modify: Grain scenario based on picture material from Next2Sun and Wienenergie/Christian Hofer; Grassland (pasture) scenario pictures free to access and modify under commons creative licenses; Viticulture scenario Photographer: Bob Jones (Published under creative commons license), EcoWind/A10 Gemeinde Steiermark Agri-PV Anlage Haidegg, and Wienenergie/Christian Hofer*

3.4 Statistical analysis

Descriptive analysis

We use descriptive statistics for responses by study participants on their assessment of the different scenarios (e.g., landscape impacts) and compare mean values for the two solar systems (AV and OS) using t-tests, Kruskal-Wallis tests, and, if significant, Dunn-post-hoc tests for pairwise comparison.

WTP for the two solar systems is evaluated and compared regarding expected distributions. The expected distributions of participants obtaining a negative WTP (project 'preventers'), a WTP equal to zero, and a WTP >0€ are expressed by the frequency of the respective payment decisions divided by the number of participants (Tian et al., 2011). For participants willing to pay a premium >0€, the expected WTP is denoted as:

$$E(WTP)_{positive} = \sum_{i=1}^{n} A_i P_i \quad (1)$$

where A_i is the bid amount, the individual selected from the PC, and P_i represents the frequency of the bid amount options. The number of bid amount options (13 options in the present study) is represented by n.

Using the minimal legal WTP model (ML), the average WTP can be derived as a mean value from the individual responses (Tian et al., 2011):

$$ML - WTP_{positive} = \sum_{i=1}^{H} A_i P_i \quad (2)$$

where H represents the overall number of responses but only including responses greater than zero. In addition to the mean, we also calculate the median WTP.

As PC studies use intervals, the ML model may underestimate WTP since the participants' true point valuation probably lies somewhere in the interval. Accordingly, an approximate method assigns the interval's midpoint as the true valuation (IM). Equation (3) represents the mean WTP using the IM approximation (Tian et al., 2011):

$$IM - WTP_{positive} = \sum_{i=0}^{H-1} \frac{A_i + A_{i+1}}{2} * P_i + \frac{A_H + A_T}{2} * P_H \quad (3)$$

where A_H marks the highest PC value and A_T the truncated (upper limit) value.

Equations (2) and (3) only consider participants stating a positive WTP. As a large number of zero WTP responses is expected, a spike model is calculated additionally to refine the results of the mean WTP estimation. Using the ML model as example, the refined $ML - WTP_{non-negative}$ can be obtained by $ML - WTP_{positive}$ times the percentage of positive WTP observations relative to the total number of non-negative WTP observations (Zhang and Wu, 2012).

Since participants in our study had an opt-out option, although they had initially indicated a WTP, participants with a (no/0€) statement were classified as 'true zeros', whereas the (yes/0€) observations were classified as 'opt-outs'. In the ML model, the opt-outs are valued at 0€, while in the IM model, the center of the interval 0-5€ (2.5€) is assumed as the true value.

Regression analysis of WTP

The analysis described above provides an intuitive overview of the general distribution of stated WTP among study participants. However, individual WTP is determined by a range of socioeconomic factors, including income, gender, education, and place of residence, as well as personal interest and familiarity with the technologies analyzed (Dribek and Voltaire, 2017; Cameron and Huppert, 1989). We use interval regression (IR) with a maximum likelihood estimator to model WTP while controlling for socioeconomic factors (Cameron and Huppert, 1989). We run models for AV and OS across all agricultural land-use types and also separately for the grain production, pasture, and viticulture scenarios. In interval settings like ours, the IR method is preferred over standard models, such as OLS or Tobit (Dribek and Voltaire, 2017).

Following Sajise et al. (2021), the valuation function for the IR model to calculate the true individual WTP is specified as:

$$logWTP_{i_{non-negative\,\&\,non-true\,zero}} = X'\beta_i + \varepsilon_i \tag{4}$$

where WTP_i is the true WTP for respondent i, X'_i is a vector of socioeconomic variables, β is the associated vector of coefficients, and ε_i the random error term. WTP values are transformed into their natural logarithm to avoid negative values and to account for the right-skewed nature of their distribution (Cameron and Huppert, 1989). Then, assuming a lognormal distribution of valuations (Dribek and Voltaire, 2017), median and mean WTP are calculated as follows:

$$MedianWTP_{non-negative\,\&\,non-true\,zero} = \exp(\beta_0 + \beta X'_i) \tag{5}$$

$$MeanWTP_{non-negative\,\&\,non-true\,zero} = \exp(\beta_0 + \beta X'_i + \sigma^2/2) \tag{6}$$

where σ^2 is an unbiased estimator of the true population error variance (Dribek and Voltaire, 2017). For each scenario, the models are estimated without 'preventers' (negative WTP) and 'true zeros'. Calculating with the total sample is not feasible, as the preventers exhibit a negative WTP for the solar systems, which violates the IR model assumptions (Dribek and Voltaire, 2017). Including participants reporting a 'true zero' WTP in the interval regression would also bias the regression results and the average WTP due to increased variance.

In addition to the IR models, we estimate probit models to explain the first decision-stage binary 'yes/no' decision for a positive WTP for AV and OS, using the following specification:

$$Pr(y_i = 1|x_i) = \Phi(\frac{x_i'\beta}{\sigma}) \tag{7}$$

where $y_i = 1$ indicates the initial willingness of participants to pay a premium for the respective scenario, $\Phi(.)$ denotes the standard normal cumulative density function, X_i' is the vector of explanatory variables, and β/σ marks the parameters to be estimated. The probit model facilitates the analysis of participants excluded under the specifications of the IR model, adding a comprehensive analysis of the factors influencing WTP decisions.

4. Results

4.1 Descriptive results

Table 1 shows descriptive statistics for the overall sample and the three mutually exclusive subsamples for the grain, pasture, and viticulture scenarios in comparison to the total German population. Our sample is representative of the German adult population; only agricultural workers are slightly overrepresented compared to the German census (BMEL, 2023). Due to the randomized scenario allocation, the subsample mean values hardly differ from each other. Table 1 also shows that just over one-third of the participants (36%) had heard about AV systems prior to the study.

Figure 3 presents the responses to the initial question of whether participants were willing to pay a price premium on their annual electricity bill to support AV and OS systems. Figure 4 presents the distributions of the different bid amounts for both systems, only including observations from participants with a 'yes' response to the initial question. For these illustrations, observations from the three scenarios (grain, pasture, viticulture) are combined. Figure 3 shows that more people are willing to pay a premium for electricity from AV (44%) than for electricity from OS (29%). Yet, the bid amount distributions for AV and OS are fairly similar (Figure 4). For both systems, the highest frequencies are observed for payment bids of 5€, 10€, 50€, and 100€.

Table 1: Sample description by scenario compared to the German census

Variable/Scenario	Grain n=669 (35.3)	Pasture n=602 (31.8)	Viticulture n=622 (32.9)	Overall sample n=1,893	Germany (reference)
Age					
18-29	102 (15.3)	99 (16.5)	100 (16.2)	301 (15.9)	18%
30-39	86 (12.9)	95 (15.8)	94 (15.1)	275 (14.5)	17%
40-49	89 (13.3)	95 (15.8)	98 (15.8)	282 (14.9)	16%
50-59	165 (24.7)	107 (17.7)	147 (23.6)	419 (22.1)	21%
>60	227 (33.9)	206 (34.2)	183 (29.4)	616 (32.5)	28%
Sex					
Male	333 (49.7)	275 (45.7)	306 (48.7)	914 (48.3)	50%
Female	336 (50.2)	327 (54.3)	316 (50.3)	979 (51.7)	50%
Diverse	-	-	-	-	n.a.
Education					
No qualification/SNVQ [a]	197 (29.5)	171 (28.4)	150 (24.1)	521 (27.5)	30%
Secondary school VQ [b]	215 (32.1)	182 (30.2)	211 (33.9)	608 (32.1)	31%
High school (Abitur)	257 (38.4)	246 (40.9)	261 (42.0)	761 (40.4)	39%
Income					
<1,500 €	89 (13.3)	65 (10.8)	87 (14.0)	241 (12.7)	13%
1,501-3,000 €	238 (35.6)	213 (35.4)	192 (30.9)	643 (34.0)	33%
3,001-4,500 €	199 (29.8)	194 (32.2)	207 (33.3)	600 (31.7)	31%
>4,501 €	143 (21.4)	130 (21.6)	136 (21.9)	409 (21.6)	23%
Residence					
Big city (>100,000)	228 (34.1)	189 (31.4)	183 (29.4)	600 (31.7)	77%
City (20,000-100,000)	161 (24.1)	148 (24.6)	152 (24.4)	461 (24.4)	
Small city (<20,000)	130 (19.4)	131 (21.7)	131 (21.1)	392 (20.7)	
Village	143 (21.4)	127 (21.1)	144 (23.2)	414 (21.8)	23%
Rural single residence	7 (1.0)	7 (1.2)	12 (1.9)	26 (1.4)	
Employment in agriculture					
Yes	18 (2.7)	20 (3.3)	22 (3.5)	60 (3.2)	2%
No	651 (97.3)	582 (96.7)	600 (96.5)	1833 (96.8)	98%
Heard of AV before					
Yes	232 (34.7)	216 (35.9)	236 (37.9)	684 (36.1)	-
Not sure	115 (17.2)	97 (16.1)	89 (14.3)	301 (15.9)	-
No	322 (48.1)	289 (48.0)	297 (47.8)	908 (48.0)	-

Total numbers of respondents with percentage share of respondents per category in parentheses; [a] SNVQ= secondary school non-vocational qualification, corresponds to German “Hauptschulabschluss”; [b] VQ= vocational qualification, corresponds to “Realschulabschluss”; n-a.= not available; information about federal state distribution of participants in comparison to the German census is shown Appendix Table A1.

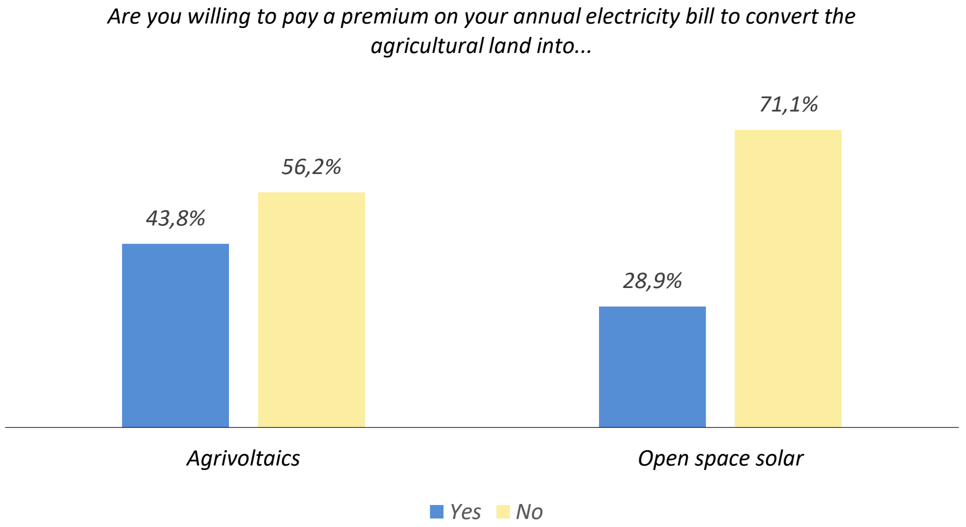

Fig. 3: Share of participants initially willing to pay more for electricity from AV and OS systems

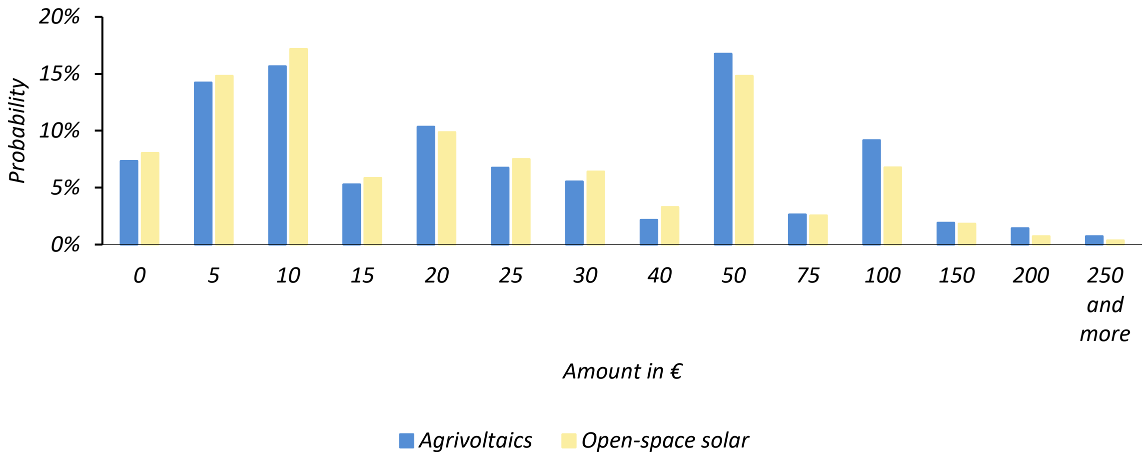

Fig. 4: Distribution of WTP bids for AV and OS systems. Only observations with a 'yes' response to the initial WTP question are included.

Table 2 presents descriptive results for the WTP calculations. As can be seen, the WTP is quite consistent across the different scenarios. Column (1) depicts the results of the initial WTP question ('yes/no'), and columns (2) to (5) depict descriptive WTP results in terms of mean and median WTP. In column (2), the minimal legal (ML) WTP is calculated for a stated WTP of 5€ or more (equation 2). In column (3), the ML model is combined with a spike model, including zero responses but excluding 'preventers'. Columns (4) and (5) calculate the mean and median WTP according to the interval-midpoint (IM) method (equation 3). Preventers are analyzed in column (6).

Table 2: Comparison of mean and median WTP per scenario and share of participants willing to pay for preventing solar systems

Scenario	(1) Initial WTP yes/no	(2) Mean (median) WTP ML positive non-zero responses	(3) Mean (median) WTP ML spike model w/o preventers	(4) Mean (median) WTP IM positive non-zero responses	(5) Mean (median) WTP IM spike model w/o preventers	(6) Share of preventers n(%) and mean WTP ML [a]
Overall AV n=1,893	830 (43.8%)/ 1,063 (56.2%)	39.36€ (25€) n=769	16.46€ (0€) n=1,839	48.16€ (27.5€) n=769	20.22€ (0€) n=1,839	54 (2.9%)/0.60€
Grain AV n=669	312 (46.6%)/ 357 (53.4%)	37.59€ (20€) n=293	16.79€ (0€) n=656	46.20€ (22.5€) n=293	20.70€ (0€) n=656	13 (3.6%)/0.53€ n=669
Pasture AV n=602	256 (42.5%)/ 346 (57.5%)	43.13€ (25€) n=232	17.28€ (0€) n=579	52.22€ (27.5€) n=232	21.03€ (0€) n=579	23 (6.6%)/0.71€ n=602
Viticulture AV n=622	262 (42.1%)/ 360 (57.9%)	37.91€ (25€) n=244	15.32€ (0€) n=604	46.66€ (27.5€) n=244	18.92€ (0€) n=604	18 (5.0%)/0.54€ n=622
Overall OS n=1,893	547 (28.9%)/ 1,346 (71.1%)	34.39€ (20€) n=503	9.60€ (0€) n=1,803	41.81€ (22.5€) n=503	11.73€ (0€) n=1,803	90 (4.8%)/1.21€
Grain OS n=669	210 (31.4%)/ 459 (68.6%)	32.20€ (20€) n=193	9.56€ (0€) n=650	39.46€ (22.5€) n=193	11.78€ (0€) n=650	19 (4.1%)/1.53€ n=669
Pasture OS n=602	175 (29.1%)/ 427 (70.9%)	39.27€ (25€) n=158	10.89 (0€) n=570	47.93€ (27.5€) n=158	13.36€ (0€) n=570	32 (7.5%)/1.16€ n=602
Viticulture OS n=622	162 (26.1%)/ 460 (73.9%)	32.11€ (20€) n=152	8.37€ (0€) n=583	38.45€ (22.5€) n=152	10.07€ (0€) n=583	39 (8.5%)/0.90€ n=622

Mean (median) WTP; ML= minimal legal average (median) of the chosen PC values; non-zero responses apply only to participants that stated positive WTP; spike model= (mean of WTP >0€*(N>0€/N); w/o preventers= participants with a negative WTP were excluded; IM= interval midpoint using the midpoint between the payment points, assuming that the interval's midpoint marks the "real" amount; [a] share and average WTP calculated based on the number of participants initially unwilling to pay for AV or OS.

The descriptive analysis demonstrates a higher acceptance and WTP for the AV than for the OS system. The average WTP for AV is highest in the pasture scenario and somewhat lower in the grain and viticulture scenarios, with certain differences according to the calculation method. For OS, the highest WTP is observed in the pasture and the lowest in the viticulture scenario. On average, using the IM spike model (column 5 of Table 2), we observe a mean premium of 20.22€ for electricity from AV and of 11.73€ for electricity from OS systems.

Column (6) of Table 2 shows that around 2.9% of the participants, initially unwilling to pay any premium, were willing to pay at least 5€ to prevent AV systems, resulting in an average WTP of 0.60€ for prevention. For the OS system, the proportion of preventers is 4.8%, and the average WTP for prevention is 1.21€.

4.2 WTP regression results

The interval regressions with socioeconomic factors explaining WTP for AV and OS are shown in Table 3. These models combine the observations from all three scenarios (grain, pasture, viticulture) except for participants stating a negative (e.g., a WTP to prevent the respective system) or a true zero WTP. Separate models for each scenario are provided in Appendix Tables A2 and A3. However, as the scenario dummy variables in Table 3 are not statistically significant, we conclude that the type of agricultural production is not a major factor driving people's WTP. Significant socioeconomic drivers are income and education. As one would expect, people's WTP for AV and OS is positively associated with income and levels of school education. Unsurprisingly, people who stated that they are interested in renewable energies have a higher WTP for AV and OS than people who are not interested in related technologies. Investment in renewable energy also increases the WTP, although the coefficient is only significant for AV systems. Interestingly, people in urban areas (city dwellers) have a significantly higher WTP for AV systems on agricultural land than people in rural areas. This association also reveals a positive coefficient for OS systems but is not statistically significant.

Table 3: Interval regression models for WTP

	WTP for AV (Respondents WTP= 'yes')			WTP for OS (Respondents WTP= 'yes')		
	Coeff.	SE	CI (95%)	Coeff.	SE	CI (95%)
1,501-2,999 [a]	0.25*	0.14	-0.02/0.52	0.28	0.18	-0.06/0.63
3,000-4.499 [a]	0.38***	0.14	0.10/0.65	0.24	0.18	-0.10/0.59
>4,500 [a]	0.49***	0.15	0.20/0.77	0.54**	0.18	0.17/0.90
Secondary school VQ [b]	0.11	0.11	-0.10/0.33	0.19	0.13	-0.08/0.45
High school (Abitur) [b]	0.40***	0.11	0.18/0.61	0.27**	0.14	0.01/0.55
Age	0.00	0.00	-0.00/0.01	0.00	0.00	-0.01/0.01
Female	-0.07	0.08	-0.22/0.09	-0.10	0.09	-0.28/0.08
City dweller	0.27***	0.10	0.08/0.46	0.18	0.12	-0.06/0.42
Small interest in renewable energy [c]	0.32*	0.17	-0.03/0.66	0.88***	0.26	0.38/1.38
Medium interest in renewables [c]	0.38**	0.16	0.05/0.69	1.00***	0.24	0.53/1.48
Strong interest in renewables [c]	0.61***	0.17	0.28/0.94	1.17***	0.25	0.69/1.65
Invested in renewables	0.18*	0.11	-0.02/0.39	0.16	0.12	-0.08/0.40
Aware of AV (not sure) [d]	0.11	0.11	-0.11/0.32	-0.02	0.13	-0.28/0.24
Aware of AV (yes) [d]	0.07	0.09	-0.10/0.24	0.09	0.10	-0.12/0.29
Pasture scenario [e]	-0.03	0.09	-0.21/0.15	-0.05	0.11	-0.26/0.16
Viticulture scenario [e]	-0.09	0.10	-0.27/0.10	-0.04	0.11	-0.26/0.18
Constant	1.93***	0.26	1.41/2.45	1.44***	0.35	0.75/2.13
Sigma	1.05	0.03	1.00/1.11	1.01	0.03	0.95/1.08
BIC			4181.22			2726.07
N			830			547

Regression coefficients shown with standard errors (SE) and 95% confidence intervals (CI 95%). Only participants who initially responded with 'yes' to the WTP question were included in the estimation. * denotes a statistical significance level of 10%; ** denotes a statistical significance level of 5%; *** denotes a statistical significance level of 1%. [a] Reported monthly household income in € (base category <=1,500); [b] VQ= vocational qualification according to the German school system (base category= no qualification/secondary school without VQ); [c] Base category is 'no interest' in renewable energies (combined 'strongly disagree' and 'disagree' statements). [d] Base category is 'not heard before' about AV; [e] Base category is grain scenario.

Based on these interval regressions, Table 4 shows the estimated mean and median WTP for AV and OS. Controlling for socioeconomic factors and excluding preventer and true zero observations reduces the WTP gap between the models, which is expected, as a higher proportion of participants initially voted 'yes' in the AV scenario, a difference not accounted for in the model. However, the WTP for AV remains higher with 46.02€, whereas for OS, it is 39.05€. We observe some differences between the scenarios, even though these differences are relatively small and statistically insignificant for the overall model (Table 3): for both AV and OS, the highest WTP is observed in the pasture scenarios.

Table 4: Mean WTP per scenario calculated based on interval regressions

	AV				OS			
Scenario	Overall AV	Grain AV	Pasture AV	Viticulture AV	Overall OS	Grain OS	Pasture OS	Viticulture OS
Mean (median) WTP for participants initially stating WTP= 'yes'	46.02€ (23.78€) n=830	44.23€ (24.20€) n=312	50.66€ (27.60€) n=256	43.70€ (24.72€) n=262	39.05 (21.41€) n=547	37.54€ (21.72€) n=210	44.15€ (24.30€) n=175	35.74€ (21.75€) n=162

Estimates based on interval regression models and variables shown in Table 3 and calculated for specific scenarios, as outlined in the corresponding table for the overall models. Scenario-specific regression outputs are provided in Appendix Tables A2 and A3.

As explained, we also use probit models to analyze factors explaining whether or not respondents have a positive WTP for AV and OS ('yes/no' question). The results of these two probit models are shown in Table 5. While education is just a marginally significant WTP predictor for AV and not for OS systems, for both solar systems, the likelihood of observing a positive WTP decreases with age. We see a negative association, meaning that older people have a lower WTP than younger ones. Furthermore, WTP increases with people's interest in renewable energies. Living in a city is also associated with a higher likelihood of a positive WTP for both systems. Having heard of AV increases the probability of a positive WTP for AV, whereas the coefficient for OS is not statistically significant.

4.3 Perceived landscape impacts

Participants' evaluations of the landscape impacts of AV and OS in terms of various social and environmental attributes are shown in Table 6. As explained, both solar systems were compared with pure agricultural land. The answers were recorded with a Likert scale, ranging from 1-'much worse' to 5-'much better', implying that a ranking of 3 is equivalent to the neutral 'no change'. In Table 6, we also show tests for mean value comparisons between the impacts of AV and OS (column 1, upper and lower Table part). A plus sign in column (1) indicates a significantly better rating for the respective system, a minus sign indicates a significantly worse rating. In columns (2) to (4) of Table 6, we compare the three agricultural scenarios.

AV systems are rated significantly more positively than OS systems in terms of all social and environmental attributes. However, except for the multifunctionality of the landscape, the regional function, and farmers' integration into energy production, participants rated AV systems below the neutral value of 3, suggesting that AV has negative perceived landscape impacts. For OS, the perceived negative impacts are even stronger.

Table 5: Probit models for positive WTP

	Positive WTP for AV ('yes/no')			**Positive WTP for OS ('yes/no')**		
Variable	Coeff.	SE	CI (95%)	Coeff.	SE	CI (95%)
1,501-2,999 [a]	0.05	0.10	-0.15/0.25	0.13	0.11	-0.09/0.35
3,000-4.499 [a]	0.16	0.11	-0.04/0.37	0.25**	0.11	0.03/0.48
>4,500 [a]	0.20*	0.11	-0.03/0.42	0.18	0.12	-0.06/0.42
Secondary school VQ [b]	-0.05	0.08	-0.21/0.11	-0.03	0.09	-0.20/0.15
High school (Abitur) [b]	0.16*	0.08	-0.01/0.32	0.12	0.09	-0.06/0.29
Age	-0.01***	0.00	-0.01/-0.00	-0.01***	0.00	-0.01/-0.00
Gender (female=1)	0.10	0.06	-0.03/0.22	-0.02	0.07	-0.15/0.11
City dweller	0.28***	0.07	0.13/0.42	0.34***	0.08	0.18/0.50
Small interest in renewable energy [c]	0.12	0.11	-0.09/0.34	0.32**	0.13	0.06/0.57
Medium interest in renewables [c]	0.69***	0.11	0.48/0.90	0.80***	0.13	0.56/1.05
Strong interest in renewables [c]	0.96***	0.12	0.73/1.19	1.02***	0.14	0.76/1.29
Invested in renewables	-0.06	0.09	-0.24/0.12	-0.00	0.09	-0.19/0.18
Aware of AV (not sure) [d]	0.03	0.09	-0.14/0.20	0.09	0.09	-0.09/0.27
Aware of AV (yes) [d]	0.15**	0.07	0.01/0.28	0.12	0.07	-0.02/0.27
Pasture scenario [e]	0.13	0.07	-0.01/0.28	0.08	0.08	-0.07/0.24
Viticulture scenario [e]	-0.03	0.08	-0.17/0.12	-0.12	0.08	-0.27/0.04
Constant	-0.84***	0.19	-1.21/-0.46	-1.46***	0.21	-1.88/-1.05
BIC			2469.07			2203.03
N			1893			1893

Probit coefficients shown with standard errors (SE) and 95% confidence intervals (CI 95%). Marginal effects are provided in Appendix Table A4. * denotes a statistical significance level of 10%; ** denotes a statistical significance level of 5%; *** denotes a statistical significance level of 1%. [a] Reported monthly household income in € (base category <=1,500); [b] VQ= vocational qualification according to the German school system (base category= no qualification/secondary school without VQ); [c] Base category is 'no interest' in renewable energies (combined 'strongly disagree' and 'disagree' statements). [d] Base category is 'not heard before' about AV; [e] Base category is grain scenario.

Table 6: Comparison of the landscape impact of Agrivoltaics and open-space solar

Landscape attributes	(1) Overall	(2) Grain	(3) Pasture	(4) Viticulture
AV				
Access	2.71*** (+)	2.69[c]	2.68[c]	2.77[ab]
Attractiveness	2.46*** (+)	2.47	2.45	2.45
Multifunctionality	3.08*** (+)	3.08	3.04	3.13
Regional function	3.22*** (+)	3.17	3.22	3.28
Farmer integration	3.85*** (+)	3.87	3.80	3.87
Tranquility	2.72*** (+)	2.74[b]	2.66[ac]	2.75[b]
Wildlife	2.58*** (+)	2.56[C]	2.54[C]	2.66[AB]
Recreation	2.51*** (+)	2.51	2.49	2.54
OS				
Access	2.29*** (-)	2.25	2.32	2.30
Attractiveness	2.10*** (-)	2.08	2.11	2.09
Multifunctionality	2.48*** (-)	2.41	2.54	2.49
Regional function	2.64*** (-)	2.65	2.70	2.58
Farmer integration	3.20*** (-)	3.19	3.26	3.15
Tranquility	2.36*** (-)	2.35	2.38	2.35
Wildlife	2.22*** (-)	2.21	2.21	2.23
Recreation	2.20*** (-)	2.19	2.19	2.22

Notes: Measured on a five-point Likert scale: How do you perceive the landscape compared to the previous situation without solar plants? 1- 'much worse', 2- 'worse', 3- 'no change', 4- 'better', 5- 'much better'. *** significant t-test on a 1% level between AV and OS overall; (+)= in favor of; (-)= not in favor of comparing AV and OS systems; [abc] significant Kruskal-Wallis and Dunn post-hoc test within a 10% confidence interval compared to the respective group (capital letters mark significance within a 5% confidence interval) – [a] grain, [b] pasture, [c] viticulture; t-test and Kruskal-Wallis test statistics and effect sizes for significant post-hoc results are provided in Appendix Table A5.

5. Discussion and conclusion

5.1 Main findings and policy implications

The public acceptance of solar energy is a widely-researched topic (Oerlemans et al., 2016), and studies on various aspects of AV are evolving (Schindele et al., 2020; Trommsdorff et al., 2021; Pascaris et al., 2022; Wagner et al., 2024). However, we are not aware of previous studies comparing AV with OS solar projects on agricultural land in terms of public acceptance, and this in spite of researchers and other stakeholders often mentioning enhanced public acceptance as a possible advantage of AV over OS projects (Schindele et al., 2020; Trommsdorff et al., 2021; Pascaris et al., 2022; Rodríguez-Segura et al., 2023; Jürkenbeck and Schulze, 2024). We have addressed this research gap in our study.

In our nationally representative online survey and experiment among German residents, we indeed find higher acceptance rates for AV than for OS systems. More positive attitudes towards AV hold in spite of the fact that we informed study participants about the larger area requirements, the lower CO2 saving potential per hectare, and the higher installation costs for AV in comparison to OS systems. Our results support previous research showing general positive public attitudes towards AV in the USA and Germany (Pascaris et al., 2022; Jürkenbeck and Schulze, 2024) and extend those results by comparing with alternative OS systems and with scenarios where the agricultural land is maintained without any solar energy production.

Around 44% of the study participants are willing to pay a premium for electricity derived from AV systems (29% for electricity from OS systems). The additional mean WTP for AV on the annual electricity bill with respect to zero responses is 20€ (12€ for OS) in the IM spike model. Fewer than 5% of the participants are willing to pay for preventing AV or OS projects, indicating widespread positive or at least neutral attitudes towards solar energy production on agricultural land. This is in line with an earlier study showing higher acceptance of large-scale solar projects in comparison to wind energy projects in rural Germany (Liebe and Dobers, 2019). However, we cannot rule out that the absence of an alternative investment option for energy production – omitted from our study due to its complexity to integrate into the experiment– may have discouraged some participants from expressing a WTP for prevention. Considerable research potential exists to evaluate energy production on agricultural land in comparison to renewable energy projects that do not require agricultural land.

Like Biró-Varga et al. (2024), we find that large-scale solar projects on agricultural land are perceived as having negative impacts on landscape attractiveness and wildlife and recreational value. However, we show that AV is perceived as having less negative landscape impacts than OS. Overall, our results suggest that better communication to explain the need for large-scale solar projects to support successful energy transitions is important to improve acceptance, as was also pointed out by Böhm and Tietz (2022). More than half of our study participants had not heard about AV before, so there is considerable potential to increase awareness and emphasize the dual-use aspect of this new land-use type.

Furthermore, communication efforts should ensure early involvement of rural communities in the vicinity of planned AV or OS projects concerning aesthetic, environmental, and socioeconomic impacts (Roddis et al., 2018). We find lower support for AV and OS from rural residents in comparison to urban people, which likely reflects a 'not in my backyard' (NIMBY) effect. Rural residents are more affected by solar projects on agricultural land in their daily routines (Bosley and Bosley, 1988). OS projects are sometimes implemented by paying compensation to communities (BMJ, 2024). This might also be useful and important for increasing the acceptance of AV projects. The positive effects of economic incentives for municipalities to enhance the acceptance of renewable energy projects are well-researched (Stadelmann-Steffen and Dermont, 2021; Campos et al., 2023; Trandafir et al., 2023).

However, economic incentives are only one aspect. Communication at local levels may also involve signposts along AV fields, explaining the dual-use aspect of the systems to interested persons using the agricultural area for hiking and recreation. Existing studies show that personal experience with renewable energies and increased knowledge enhance the acceptance of related projects (Liebe and Dobers, 2019; Lucas et al., 2021; Chodkowska-Miszczuk et al., 2022). Furthermore, AV systems may offer new marketing opportunities for food products as well. Using the example of apples, Jürkenbeck and Schulze (2024) show that food products from AV systems generate a higher value for some consumers.

Beyond personal attitudes towards renewable energies, we also find that age significantly predicts AV and OS acceptance. Younger study participants have a higher WTP for AV and OS systems than older participants. A possible explanation is that younger people tend to be more concerned about climate change (Corner et al., 2015), making them more willing to support decarbonized energy transitions.

We did not find major differences in terms of AV acceptance between the three agricultural scenarios: grain production, pasture, and viticulture. Even though we observe the highest WTP for electricity from AV in the pasture scenario, WTP differences between the scenarios are small and mostly not statistically significant. This is an important finding, as successful energy transitions require electricity generation that is decentralized and widespread (Bogdanov et al., 2021). Geographic regions are often specialized in terms of their agricultural production due to varying soil and climate conditions (Rendon et al., 2020). Especially for regions with high agricultural production potential, AV systems are a useful alternative to OS for producing solar energy while maintaining agricultural production (Schindele et al., 2020). AV systems should remain open to technology innovations, as vertical bifacial systems are suitable for crop farming, whereas stilted solar panels are needed in horticultural systems (Gorjian et al., 2022).

While many study participants stated that they are willing to pay more for electricity from AV systems, an interesting question is also why many others are not. We reckon that the relatively high electricity prices in Germany may play some role here. Electricity prices in Germany are above the European Union average (Eurostat, 2024), and study participants may not be willing or feel economically unable to pay even more for electricity from AV systems. Similar studies in other countries with lower electricity prices could possibly provide interesting additional insights. Furthermore, relatively high opt-out rates may be attributed to the non-market nature of the scenarios evaluated (agricultural fields). In such studies, WTP levels are often relatively low (Zhang and Wu, 2012). People not involved in agriculture may be interested in maintaining healthy agricultural lands for emotional reasons (Wang et al., 2022; Franceschinis et al., 2023), but as this is not associated with immediate monetary benefits for the individual, the WTP may be limited for some fractions of society.

While we find more positive public attitudes towards AV than OS, actual AV adoption levels are still very low due to high initial investment costs and limited profitability in comparison to OS (Schindele et al., 2020). Therefore, AV systems require further development to be easily integrated into existing farming schemes and enable double land-use income (Trommsdorff et al., 2021). Some government support could facilitate this process, and our results suggest that related subsidies would be socially acceptable and justified.

Eventually, farmers, as landowners, need to be willing to adopt AV systems. Profitability constraints often prevail in the current situation, but a general openness among many farmers to adopt AV exists (Wagner et al., 2024). Farmers in the European Union also benefit from the fact that, in contrast to OS systems, AV fields retain their arable status and thus remain eligible for subsidies if 85% of the original area is retained for farming purposes (BMEL, 2021). However, AV must also be economically profitable for project investors and developers (Schindele et al., 2020). Appropriate conditions for successful upscaling need to be developed.

5.2 Study limitations

A mean WTP, measured as a price premium on the annual electricity bill of 20€ applied to almost 40 million German households, would imply a large potential to support AV systems through public subsidies. However, our concrete numerical estimates should be interpreted with some caution, as study participants responded to hypothetical scenarios without real-life consequences, which may lead to an overestimated WTP (Carlsson et al., 2005). For this reason, we focus our interpretation mostly on general attitudes and on the comparison between AV and OS, as a potential bias would affect both systems in identical ways.

The choice of the concrete images used in our study may also influence the results. We tried to reduce potential bias by randomly assigning participants to various scenarios with different images and found no significant deviations between the scenarios. However, images are never a perfect substitute for experiencing landscape impacts in the real world. Finally, we should mention that we deliberately refrained from trying to evaluate specific technical attributes of AV systems. AV systems are currently subject to dynamic technical developments, which are difficult to capture and compare in experiments with laypersons without increasing the study complexity and, thus, possibly overburdening participants.

5.3 Conclusion

Agricultural land is finite. Therefore, using land efficiently is important from agricultural and broader public perspectives. Large-scale renewable energy production requires land, sometimes displacing agricultural production and thus causing potential tradeoffs. Our study demonstrates that AV systems are more acceptable by society than OS systems despite being less cost-effective due to lower electricity generation and greater land consumption per unit of power output. On average, people's WTP for electricity from AV is significantly higher than their WTP for electricity from OS solar systems. AV systems are also perceived to have less negative landscape impacts than OS systems. AV may become more efficient in the future through technological advancements. Our results suggest that AV can be a socially acceptable ingredient in decarbonized energy transitions, but may require public financial incentives for more widespread adoption.

However, in spite of being more acceptable than OS systems on agricultural land, AV systems are also perceived as having negative impacts on landscape attractiveness. Improved communication and awareness-building may help to further increase public acceptance. More widespread AV adoption requires a comprehensive strategy that actively addresses local stakeholder concerns.

Finally, we draw some broader conclusions for policy practices concerning solar energy systems on agricultural land. From a public perspective, AV is equally acceptable across various types of agricultural production systems, including grain crops, pastureland, and horticultural production. This means that further technological developments in various types of AV systems are useful and important. While OS systems may be preferred in regions with lower agricultural potential, where production losses through conversion to OS are small, AV systems may be preferred in regions with good soil and production conditions. In any case, AV systems should be seen as complements to OS systems, not as substitutes.

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Appendix

Appendix Table A1: Sample distribution over Germany's federal states compared to census data

Variable/Scenario	Grain n=669 (35.3)	Pasture n=602 (31.8)	Horticulture n=622 (32.9)	Sample ovr. n=1,893	Germany (Reference)
Federal state					
Schleswig-Holstein	31 (4.6)	17 (2.8)	26 (4.2)	74 (3.9)	4%
Hamburg	12 (1.8)	16 (2.6)	13 (2.1)	41 (2.2)	2%
Niedersachsen	71 (10.6)	61 (10.1)	63 (10.1)	195 (10.3)	10%
Bremen	7 (1.1)	6 (1.0)	3 (0.5)	16 (0.9)	1%
Nordrhein-Westfalen	151 (22.6)	141 (23.4)	126 (20.3)	418 (22.1)	22%
Hessen	36 (5.4)	47 (7.8)	53 (8.5)	136 (7.2)	7%
Rheinland-Pfalz	33 (4.9)	26 (4.3)	42 (6.7)	101 (5.3)	5%
Baden-Württemberg	87 (13.0)	78 (13.0)	76 (12.2)	241 (12.7)	13%
Bayern	110 (16.4)	100 (16.6)	93 (14.9)	303 (16.0)	16%
Saarland	5 (0.8)	6 (1.0)	10 (1.6)	21 (1.1)	1%
Berlin	29 (4.3)	19 (3.2)	23 (3.7)	71 (3.8)	4%
Brandenburg	12 (1.8)	16 (2.7)	23 (3.7)	51 (2.7)	3%
Mecklenburg-Vorpommern	11 (1.7)	11 (1.8)	13 (2.1)	35 (1.8)	2%
Sachsen	41 (6.1)	27 (4.5)	29 (4.7)	97 (5.1)	5%
Sachsen-Anhalt	15 (2.2)	15 (2.5)	16 (2.6)	46 (2.4)	2%
Thüringen	18 (2.7)	16 (2.7)	13 (2.1)	47 (2.5)	3%

Total numbers of respondents, share of respondents per category in parenthesis.

Appendix Table A2: Interval regression results grain and pasture

	AV Grain (Respondents WTP= 'yes')			OS Grain (Respondents WTP= 'yes')				AV Pasture (Respondents WTP= 'yes')			OS Pasture (Respondents WTP= 'yes')		
Variable	**Coeff.**	**SE**	**Ci95**	**Coeff.**	**SE**	**Ci95**	**Variable**	**Coeff.**	**SE**	**Ci95**	**Coeff.**	**SE**	**Ci95**
1,501-2,999[1]	0.16	0.21	-0.25/0.57	0.40	0.25	-0.08/0.88	1,501-2,999	-0.18	0.32	-0.80/0.45	-0.44	0.42	-1.26/0.38
3,000-4.499	0.29	0.21	-0.13/0.71	0.21	0.25	-0.27/0.7	3,000-4.499	0.00	0.32	-0.63/0.63	-0.38	0.42	-1.20/0.45
>4,500	0.28	0.23	-0.17/0.73	0.26	0.26	-0.25/0.77	>4,500	0.14	0.33	-0.49/0.78	0.13	0.43	-0.72/0.98
Secondary school VQ[2]	-0.07	0.18	-0.41/0.28	0.34*	0.21	-0.06/0.75	Secondary school VQ2	0.56**	0.22	0.13/0.99	0.48*	0.27	-0.04/1.01
High school (Abitur)	0.32*	0.17	-0.02/0.65	0.53**	0.22	0.11/0.96	High school (Abitur)	0.61***	0.22	0.18/1.03	0.48*	0.26	-0.04/1.00
Age	0.00	0.00	-0.01/0.01	0.00	0.01	-0.01/0.01	Age	0.00	0.00	-0.01/0.01	0.00	0.01	-0.01/0.01
Female	-0.18	0.13	-0.43/0.08	-0.18	0.15	-0.48/0.12	Female	0.21	0.14	-0.07/0.49	0.07	0.17	-0.26/0.39
City dweller	0.14	0.17	-0.19/0.46	-0.09	0.19	-0.46/0.29	City dweller	0.38**	0.18	0.03/0.74	0.66***	0.23	0.2/1.11
Int_RE Part/Part[3]	0.10	0.28	-0.46/0.65	0.35	0.49	-0.61/1.3	Int_RE Part/Part	0.40	0.32	-0.23/1.04	1.40***	0.46	0.5/2.29
Int_RE Rather agree	0.27	0.26	-0.24/0.78	0.70	0.46	-0.2/1.6	Int_RE Rather agree	0.31	0.30	-0.29/0.91	1.44***	0.45	0.57/2.31
Int_RE Tot. Agree	0.44	0.27	-0.09/0.96	0.92*	0.47	0/1.85	Int_RE Tot. Agree	0.75**	0.33	0.11/1.39	1.67***	0.45	0.8/2.55
Investor	0.08	0.19	-0.29/0.45	0.10	0.21	-0.31/0.5	Investor	-0.07	0.19	-0.45/0.31	-0.14	0.22	-0.58/0.30
AWAR_AV (not sure)[4]	-0.13	0.18	-0.49/0.22	-0.22	0.22	-0.64/0.21	AWAR_AV (not sure)	0.23	0.21	-0.19/0.64	0.04	0.25	-0.46/0.53
AWAR_AV (Yes)	-0.03	0.14	-0.31/0.24	-0.04	0.17	-0.37/0.29	AWAR_AV (Yes)	0.25	0.17	-0.08/0.57	0.16	0.19	-0.22/0.53
Constant	2.54***	0.41	1.74/3.33	1.79***	0.59	0.63/2.95	Constant	1.67***	0.48	0.74/2.60	0.92	0.63	-0.32/2.16
Sigma	1.06	0.05	0.98/1.15	1.012	0.05	0.91/1.12	Sigma	1.08	0.05	0.98/1.19	1.04	0.06	0.93/1.17
BIC	1579.75			1052.63			BIC	1323.21		1323.21	914.12		
N	312			210			N	256		256	175		

Only participants who initially responded with 'yes' to the WTP question were included in the estimation. * denotes a statistical significance level of 10%; ** denotes a statistical significance level of 5%; ***denotes a statistical significance level of 1%.

[1]Reported monthly household income in € (base category= <1,500); [2]VQ= vocational qualification according to the German school system (base category= no qualification/secondary school without VQ; [3]Int_RE means reported Interest in renewable energies (base category merged out of categories = totally disagree and disagree); [4]AWAR_AV means awareness of Agrivoltaics (base category= Not heard yet).

Appendix Table A3: Interval regression results viticulture

	AV Viticulture (Respondents WTP= 'yes')			OS Viticulture (Respondents WTP= 'yes')		
Variable	**Coeff.**	**SE**	**Ci95**	**Coeff.**	**SE**	**Ci95**
1,501-2,999[1]	0.68***	0.23	0.22/1.13	0.6*	0.31	-0.01/1.21
3,000-4.499	0.68***	0.23	0.24/1.12	0.59**	0.30	0/10.18
>4,500	0.93***	0.24	0.47/1.4	1.16***	0.32	0.54/1.79
Secondary school VQ[2]	0.00	0.20	-0.38/0.39	-0.27	0.22	-0.71/0.17
High school (Abitur)	0.37*	0.20	-0.01/0.76	-0.04	0.23	-0.48/0.41
Age	0.00	0.00	0.00/0.01	0.00	0.00	-0.01/0.01
Female	-0.17	0.13	-0.43/0.09	-0.18	0.15	-0.47/0.11
City dweller	0.28	0.16	-0.04/0.6	-0.05	0.22	-0.47/0.37
Int_RE Part/Part[3]	0.23*	0.32	-0.4/0.86	0.95**	0.38	0.21/1.70
Int_RE Rather agree	0.40	0.3	-0.19/0.98	1.00***	0.35	0.32/1.69
Int_RE Tot. Agree	0.54*	0.31	-0.06/1.15	0.91***	0.35	0.22/1.59
Investor	0.47***	0.17	0.14/0.79	0.45**	0.20	0.07/0.83
AWAR_AV (not sure)[4]	0.26	0.19	-0.10/0.63	0.11	0.20	-0.28/0.50
AWAR_AV (Yes)	0.09	0.15	-0.2/0.38	0.23	0.16	-0.10/0.55
Constant	1.43***	0.47	0.52/2.35	1.31**	0.60	0.12/2.49
Sigma	0.98	0.05	0.89/1.07	0.86	0.05	-0.26/-0.03
BIC	1318.42			818.16		
N	262			162		

Only participants who initially responded with 'yes' to the WTP question were included in the estimation. * denotes a statistical significance level of 10%; ** denotes a statistical significance level of 5%; ***denotes a statistical significance level of 1%. [1]Reported monthly household income in € (base category= <1,500); [2]VQ= vocational qualification according to the German school system (base category= no qualification/secondary school without VQ; [3]Int_RE means reported Interest in renewable energies (base category merged out of categories = totally disagree and disagree); [4]AWAR_AV means awareness of Agrivoltaics (base category= Not heard yet).

Appendix Table A4: Marginal effects of variables included in the probit models

AV

Outcome	Income	Education	Age	Gender	Rural	Interest RE	Investor	AV heard of	Scenario
Yes[1]	0.0252 (2.12**)	0.0322 (2.18**)	-0.0026 (-3.66***)	0.0265 (1.2)	0.1003 (3.91***)	0.1328 (11.6***)	-0.0246 (-0.76)	0.0243 (1.97**)	-0.0066 (-0.5)

OS

Outcome	Income	Education	Age	Gender	Rural	Interest RE	Investor	AV heard of	Scenario
Yes[1]	0.0161 (1.46)	0.0214 (1.55)	-0.0018 (-2.67***)	-0.0084 (-0.41)	0.1044 (4.26***)	0.1110 (9.99***)	-0.0087 (-0.3)	0.0191 (1.68)	-0.0189 (-1.53)

Notes: The values in brackets are the z-test values of the corresponding coefficients. [1]Base Outcome= No; *denotes a statistical significance level of 10%; **denotes a statistical significance level of 5%; *** denotes a statistical significance level of 1%.

Appendix Table A5: Test statistics and effect sizes for T-Tests comparing differences between AV and OS system assessment and Kruskal-Wallis Test and Dunn Post-hoc test concerning perceived landscape impacts between the scenarios.

Landscape Access			
AV	μ= 2.71	**OS**	μ= 2.29
T-test	t-statistics=-21.4580	Pr(T < t) = 0.0000 & Pr(|T| > |t|) = 0.0000	
Kruskal-Wallis AV	Probability=0.0953 (n=1,893)	χ2=4.701 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.68/2.69 (-0.16)	-	
Grain vs. Viti	2.68/2.77* (-2.06)	0.06	
Pasture vs. Viti	2.69/2.77* (-1.95)	0.05	
Kruskal-Wallis OS	Probability=0.3895 (n=1,893)	χ2=1.886 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.32/2.25 (1.37)	-	
Grain vs. Viti	2.32/2.30 (0.33)	-	
Pasture vs. Viti	2.25/2.30 (-1.04)	-	
Landscape Attractivity			
AV	μ= 2.46	**OS**	μ= 2.10
T-test	t-statistics= -18.6125	Pr(T < t) = 0.0000 & Pr(|T| > |t|) = 0.0000	
Kruskal-Wallis AV	Probability=0.7684 (n=1,893)	χ2=0.527 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.45/2.47 (-0.77)	-	
Grain vs. Viti	2.45/2.45 (-0.42)	-	
Pasture vs. Viti	2.47/2.45 (0.35)	-	
Kruskal-Wallis OS	Probability=0.9483 (n=1,893)	χ2=0.106 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.11/2.08 (0.34)	-	
Grain vs. Viti	2.11/2.09 (0.13)	-	
Pasture vs. Viti	2.25/2.30 (-0.21)	-	
Landscape Multifunctionality			
AV	μ= 3.08	**OS**	μ= 2.48
T-test	t-statistics= -21.2483	Pr(T < t) = 0.0000 & Pr(|T| > |t|) = 0.0000	
Kruskal-Wallis AV	Probability=0. 4298 (n=1,893)	χ2=1.689 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	3.04/3.07 (-0.72)	-	
Grain vs. Viti	3.04/3.13 (-1.35)	-	
Pasture vs. Viti	3.07/3.13 (-0.66)	-	
Kruskal-Wallis OS	Probability=0.1374 (n=1,893)	χ2=3.969 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.54/2.41 (0.34)	-	
Grain vs. Viti	2.54/2.49 (0.13)	-	
Pasture vs. Viti	2.25/2.49 (-0.21)	-	

Landscape Stability			
AV	μ= 3.22	**OS**	μ= 2.64
T-test	t-statistics= -22.6573	Pr(T < t) = 0.0000 & Pr(|T| > |t|) = 0.0000	
Kruskal-Wallis AV	Probability=0.2757 (n=1,893)	χ2=2.577 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	3.22/3.17 (0.93)	-	
Grain vs. Viti	3.22/3.28 (-0.70)	-	
Pasture vs. Viti	3.17/3.28 (-1.66)	-	
Kruskal-Wallis OS	Probability=0.2406 (n=1,893)	χ2=2.850 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.70/2.65 (0.73)	-	
Grain vs. Viti	2.70/2.58 (1.73)	-	
Pasture vs. Viti	2.65/2.58 (1.04)	-	
Farmer Involvement			
AV	μ= 3.85	**OS**	μ= 3.20
T-test	t-statistics= -25.7708	Pr(T < t) = 0.0000 & Pr(|T| > |t|) = 0.0000	
Kruskal-Wallis AV	Probability=0.4334 (n=1,893)	χ2=1.672 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	3.80/3.87 (-1.25)	-	
Grain vs. Viti	3.80/3.87 (-1.20)	-	
Pasture vs. Viti	3.87/3.87 (0.03)	-	
Kruskal-Wallis OS	Probability=0.2514 (n=1,893)	χ2=2.762 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	3.26/3.19 (1.10)	-	
Grain vs. Viti	3.26/3.15 (1.71)	-	
Pasture vs. Viti	3.19/3.15 (0.65)	-	
Landscape Tranquility			
AV	μ= 2.72	**OS**	μ= 2.36
T-test	t-statistics= -18.0077	Pr(T < t) = 0.0000 & Pr(|T| > |t|) = 0.0000	
Kruskal-Wallis AV	Probability=0.0973 (n=1,893)	χ2=4.661 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.66/2.74* (-1.73)	0.05	
Grain vs. Viti	2.66/2.75* (-2.18)	0.06	
Pasture vs. Viti	2.74/2.75 (-0.49)	-	
Kruskal-Wallis OS	Probability=0.8987 (n=1,893)	χ2=0.214 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.38/2.35 (0.48)	-	
Grain vs. Viti	2.38/2.35 (0.17)	-	
Pasture vs. Viti	2.35/2.35 (-0.31)	-	
Potential for Wildlife			
AV	μ= 2.58	**OS**	μ= 2.22

T-test	t-statistics= -18.3365	Pr(T < t) = 0.0000 & Pr(|T| > |t|) = 0.0000	
Kruskal-Wallis AV	Probability=0.0364 (n=1,893)	χ2=6.629 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.54/2.56 (-0.15)	-	
Grain vs. Viti	2.54/2.66** (-2.40)	0.07	
Pasture vs. Viti	2.56/2.66** (-2.32)	0.07	
Kruskal-Wallis OS	Probability=0.8557 (n=1,893)	χ2=0.312 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.21/2.21 (0.10)	-	
Grain vs. Viti	2.21/2.22 (-0.44)	-	
Pasture vs. Viti	2.21/2.22 (-0.55)	-	
Recreational value			
AV	μ= 2.51	**OS**	μ= 2.19
T-test	t-statistics= -16.9991	Pr(T < t) = 0.0000 & Pr(|T| > |t|) = 0.0000	
Kruskal-Wallis AV	Probability= 0.4145 (n=1,893)	χ2=1.761 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.49/2.51 (-0.73)	-	
Grain vs. Viti	2.49/2.54 (-1.41)	-	
Pasture vs. Viti	2.51/2.54 (-0.71)	-	
Kruskal-Wallis OS	Probability=0.7123 (n=1,893)	χ2=0.678 with 2 degrees of freedom	
	μ (z)	**r**	
Grain vs. Pasture	2.19/2.19 (-0.03)	-	
Grain vs. Viti	2.19/2.21 (-0.75)	-	
Pasture vs. Viti	2.19/2.21 (-0.74)	-	

Based on the question: “Please evaluate how the solar system shown affects the landscape.” – Assessment on a five-point Likert-scale from 1- Much worse to 5- Much better, with a neutral midpoint; Grain= Grain scenario; Viti= Viticulture scenario; μ= Mean values of the variables for the respective group; z= z-statistic group-wise comparison; r= Wilcoxon Effect Size ($Z/\sqrt{N}$); *, **, and *** indicate significant differences in mean at the 10%, 5%, and 1%, levels; All Dunn Post-Hoc test were calculated using Benjamini-Hochberg correction.