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An analytical framework to estimate the economics and adoption potential of dual land-use systems: The case of agrivoltaics

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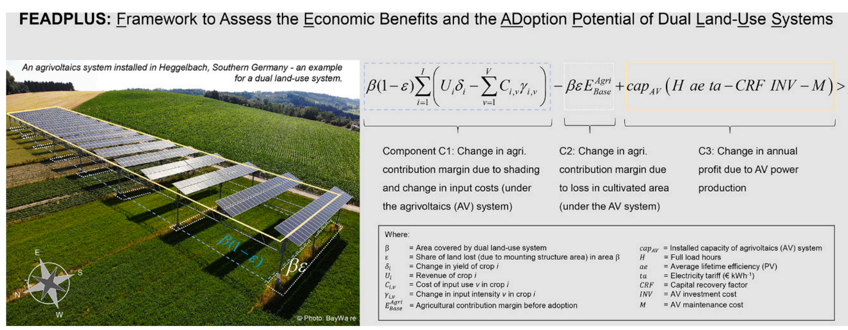
HIGHLIGHTS

- Dual land-use systems, like agrivoltaics, allow for high land-use efficiency and are becoming increasingly relevant
- We report a novel analytical Framework to assess the economic benefits and the adoption potential of dual land-use systems (FEADPLUS)
- The framework allows for a analysis of farm-specific synergies and trade-offs determining agrivoltaic profitability
- Profitability is most dependent on photovoltaic parameters, but farm specific effects may tip the scale towards adoption
- The framework meets researchers' demands for a simple tool to analyze dual land-use systems at various scales and allows for many extensions

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Dual land-use systems allow for a high land-use efficiency and are becoming increasingly relevant amid the rising scarcity of land. Agrivoltaics is a prominent example, yet there are farming system-specific trade-offs when simultaneously producing agricultural output and photovoltaic power.
OBJECTIVE: Our objective is to report a novel analytical Framework to assess the Economic benefits and the ADoption Potential of dual Land-Use Systems (FEADPLUS). The framework is developed with the goal of enabling a straightforward application in large farm-level datasets.
METHODS: FEADPLUS is grounded in neoclassical economic theory and applied to the case of agrivoltaics. An annualized profitability condition is derived and decomposed to identify the main components determining the agrivoltaic systems' economic viability, allowing for a comprehensive analysis of farm-specific synergies and trade-offs. Modifications enable calculation of the break-even electricity tariff and the relative change in

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agricultural contribution margin below the agrivoltaic system. The framework's functionality is demonstrated using data for cereal and vegetable farming systems on the Filder Plain, Southern Germany.
RESULTS AND CONCLUSIONS: We show that farm-specific characteristics explain differences in the adoption potential under equal solar radiations. Cereal and vegetable farms could adopt agrivoltaics at a tariff of 8.63 and 9.00 EUR-cents kWh^{-1}, respectively. Yet, the agricultural contribution margins from land cultivated below the agrivoltaics system decline by 40.3% and 73.9%, respectively. The decline is due to shading effects on crop yields, higher machinery and labor costs, and the foregone agricultural contribution margins from area lost due to the agrivoltaics mounting structure. In the presence of such trade-offs, the adoption of agrivoltaics is more profitable for farms growing low-value crops, such as cereals, than high-value crops like vegetables. Our sensitivity analyses show that this may change if there are synergies, e.g., positive shading effects on yield. Moreover, they indicate that agricultural contribution margins in some scenarios, which could incentivize farmers to abandon farming below the agrivoltaics system. This highlights the need for policymakers to put adequate safeguards in place.
SIGNIFICANCE: Dual land-use systems are still understudied, but their high land-use efficiency becomes increasingly relevant in light of the mounting pressures on land. FEADPLUS is the first framework that allows estimation of economic benefits and adoption potential across farming systems and specific technology setups under different policy designs. To this end, it meets researchers' demands for a simple tool and allows for many extensions, e.g., incorporation of stochastics or aspects of (dynamic) optimization and economies of scale.

1. Introduction

Land provides important habitat for wildlife and is the main production input to feed a growing global population. It is not only needed to sustain agricultural production, it also needs to meet many other demands of mankind, e.g., land for settlements, transportation infrastructure, disaster prevention and leisure activities. Dual land-use systems are characterized by high degrees of land-use efficiency since they allow for the combined use of land for agricultural production and other desired, land-intensive, outputs.[1] Agrivoltaics (AV; also referred to as agrophotovoltaics or Agri-PV) is one such dual land-use system, which lately has received increased attention and interest (e.g., Amaducci et al., 2018; Parkinson and Hunt, 2020). The transformation of energy systems towards clean energy sources has been accompanied by adverse impacts on biodiversity, landscape aesthetics and changes in land cover and use (Allison et al., 2014; Hernandez et al., 2014). More generally, the food-energy nexus is expected to increase the scarcity of land for food production as more land is needed for energy generation (Tilman et al., 2009). This is reflected in the "food vs. fuel" debates, which center on the question about the primary purpose of land-use. While this debate has mostly involved criticisms of biofuels, the focus increasingly is shifted towards other renewable energy sources, such as wind and photovoltaics (PV). For example, a recent study found the highest potential of PV to be on areas, currently used as cropland (Adeh et al., 2019).

Against this background, AV is a promising dual land-use system that can mitigate these trade-offs (Dinesh and Pearce, 2016; Dupraz et al., 2011; Götzberger and Zastrow, 1982; Miao and Khanna, 2020). AV allows for a simultaneous production of agricultural output and PV power on the same area. It therefore has a substantially higher land-use efficiency than conventional ground-mounted PV systems. However, recent research shows that the levelized cost of energy of AV can be about 38% higher compared to ground-mounted PV (Schindele et al., 2020). Firstly, the installation of the PV panels in AV systems is usually associated with higher cost (e.g., due to the mounted steel structure to elevate the panels). Secondly, the installed AV system can also lead to changes in crop yields due to the reduction in photosynthetically active radiation and to higher production cost (e.g., more labor requirement of agricultural operations). In some farming systems, these additional costs might be offset by cost-saving synergies or increases in yields of (shade-loving) crops. In other farming systems, adoption is only economically feasible if AV systems benefit from higher tariffs than ground-mounted PV. Past studies focused on the potential of AV at either single crop or farm-level (Barron-Gafford et al., 2019; Dinesh and Pearce, 2016; Schindele et al., 2020) or studied the potential of AV at the regional level, neglecting the heterogeneity of farming systems (Sacchelli et al., 2016). However, both the farming system-specific differences in AV's opportunity cost and the solar radiation based regional differences in AV electricity yield determine the economic feasibility and therefore the adoption of AV.

The objective of this study is to develop and report an analytical Framework to assess the Economic benefits and the ADoption Potential of dual Land-Use Systems (FEADPLUS), which accounts for the heterogeneity of farm-level, spatial and technological determinants. Using representative data from agricultural landholdings, FEADPLUS can be applied to quantitatively assess the potential of dual land-use systems at varying degrees of policy support and considering various technology designs. The framework is developed using the example of AV, but may also be applied to other dual land-use systems. The paper is structured as follows: In the subsequent section we report the development of the analytical framework, FEADPLUS, highlighting the framework's main assumptions and components. In Section 3, we apply the framework to assess the adoption potential of AV across two hypothetical typical farm types representative for the Filder Plain in Southern Germany. Section 4 discusses the main merits of the framework, possible modifications and limitations, and ends with concluding remarks.

2. The analytical framework FEADPLUS

The analytical framework FEADPLUS assumes that the farmer, landowner and investor are one entity. Yet, it can be modified to accommodate other investor and ownership settings. FEADPLUS is grounded in neoclassical economic theory. Farmers maximize their profit by choosing the agricultural production system returning the most favorable expected average yearly net benefit.[2] Hence, profit maximizing farmers will adopt a dual land-use system when this increases their profit. In the following, we will use AV as an example of a dual land-use system. The situation with or without adoption of AV is

[1] It should be noted, that there is (yet) no formal definition of dual land-use systems. In the following, it is defined as land-use systems that allow for the combined production of agricultural outputs and a secondary, non-agricultural output. Other examples for dual land-use systems comprise the simultaneous production of agricultural output and use of the land for other renewable energies (e.g., wind farms), recreational uses (e.g., maize labyrinths, open air concerts) and disaster prevention measures (e.g., flood control).

[2] In reality, profit maximization behavior is not (always) the case, e.g., due to bounded rationality or because farmers maximize utility, which, beyond profits, also depends on further utility components (e.g., utility of being a farmer) that are not reflected in monetary terms (see for instance Simon (1990) or Kliebenstein et al. (1980)).

captured by the subscripts "AV" or "Base", respectively. The annual contribution margins from agriculture are termed E^{Agri} and the additional annualized farm profit from the PV power sold is termed, E^{PV}.

A contribution margin is computed as the difference between sales revenue from goods sold (or stored) and the variable cost incurred to produce these goods. Fixed costs, such as machinery or buildings, are not included. Eq. (1) shows that in order to adopt AV, the annual profit from PV and the new agricultural contribution margin combined have to be larger than the base agricultural contribution margin.

$$E_{AV}^{Agri} + E_{AV}^{PV} - E_{Base}^{Agri} > 0 \tag{1}$$

2.1. Changes in farmers' agricultural income

The farmers' contribution margin from agricultural operations is the sum of the contribution margins from all agricultural activities performed. In the following, our point of departure is the assumption that the AV system is installed within a cropping system on arable land. Principally, FEADPLUS can also be used when AV systems are installed within other agricultural systems (e.g., horticulture, livestock husbandry). In a usual farming system, a farmer cultivates crop i (from a population I of cultivated field crops) with yield y_i, which can be sold to the market at producer price p_i. A farmer thus generates a contribution margin per unit of land, e_i, as follows:

$$e_i = p_i y_i - \sum_{v=1}^{V} x_{i,v} p_v \tag{2}$$

where $x_{i,v}$ is the quantity of input v for V different inputs (e.g., production factors such as machinery and labor, and related intermediate inputs like diesel) and p_v is the respective unit price (the farm's family labor can be valued with its opportunity cost[3]). At low AV adoption levels within an economy, it is unreasonable to expect any substantial changes in market prices of outputs and inputs. In such a context, output and input prices are assumed to remain unaffected, which allows to rewrite the contribution margin as the difference in crop specific revenue, u_i, and the sum of input cost, $c_{i,v}$. Both are expressed per unit of land (e.g., hectare).

$$e_i = u_i - \sum_{v=1}^{V} c_{i,v} \tag{3}$$

The total annual agricultural contribution margin from all crop producing activities, E^{Agri}, is the sum of cultivated area per crop in the base situation, a_i, times the crop specific contribution margin, e_i, per unit of area. At the farm-level, E^{Agri} can thus be expressed as the sum of contribution margins from each crop. The contribution margin of each crop is the individual revenue U_i, of each crop i, minus the sum of the input costs$C_{i,v}$ of each input v for that crop:

$$E_{Base}^{Agri} = \sum_{i=1}^{I} e_i a_i = \sum_{i=1}^{I} \left(U_i - \sum_{v=1}^{V} C_{i,v} \right) \tag{4}$$

The installation of an AV plant has implications for a farmer's total production area, crop yields and field management. The mounting structure reduces the production area within the AV system, which is denoted by parameter ε (describing the share of the area covered by the AV plant's mounting structure, which is lost for agricultural production). Other dual land-use systems will likely also involve some loss of production area ε. In the AV case, the crop-specific contribution margins, e_i, are affected by the reduction in solar radiation (shading), changing the crop yields grown within the AV system. The relative change in crop yields is captured by δ_i. Reductions in photosynthetically active radiation may lower the yield of some crops, e.g., cereals such as maize, which is a C4 plant and thus particularly susceptible to shading. Yet, it may hardly impact or even increase the yield of some other crops, e.g., potatoes (Schulz et al., 2019), blueberries (Rotundo et al., 1998) or apples (Lopez et al., 2018). The mounting structure of an AV plant requires changes in the field management and input intensity (Weselek et al., 2019), resulting in potentially higher production costs described by the relative change $\gamma_{i,v}$. Depending on the country and farming system context, labor inputs may be treated as variable costs and thus are affected by the AV adoption. If the opportunity costs of family labor were zero ($p_{labor} = 0$), it would not be considered an input cost affecting AV profitability.

Since farmers usually rotate the crops grown on their fields over the years, it is not straightforward to estimate the share of crop production area cultivated within the AV system. With ambiguous impacts on crop yields, farmers are incentivized to optimize their system to minimize the potential crop yield reductions and to maximize the potential crop yield increases from shading. Incorporating such a behavior requires in-depth knowledge about a farming system, as a number of factors constrain farmers' flexibility of adjusting the crop rotation (Castellazzi et al., 2008). For the sake of simplicity, the framework therefore abstracts from this aspect and assumes that the relative share of crop production area within the AV system is equal across all crops cultivated. Furthermore, it is assumed that the AV design leads to evenly distributed shading of crops, as for instance the case in Schindele et al. (2020). A farmer with total crop area A adopts an AV system on area A_{AV}, such that share $\beta = A_{AV}/A$ of each cultivated crop area is grown within the AV system (i.e., β applies to all crops equally). To correct A_{AV} and β for the lost land due to the mounting structure that carries the AV plant, it is multiplied by $(1 - \varepsilon)$. The share under the previous agricultural system is the remainder $(1 - \beta)$, and the total arable land is reduced by $\beta\varepsilon$. All the above presented AV parameters of agronomic relevance enter the computation of the crop-specific contribution margins with AV adoption $\widetilde{e}_i$, which after some simple re-arrangement (see Appendix A) can be expressed as follows:

$$\widetilde{e}_i = \mathrm{e}_i + \beta(1-\varepsilon)\left(u_i \delta_i - \sum_{v=1}^{V} c_{i,v}\gamma_{i,v} \right) - \beta\varepsilon\ \mathrm{e}_i \tag{5}$$

Since $E_{AV}^{Agri} = \sum_{i=1}^{I} a_i \widetilde{e}_i$, the total annual contribution margin from agriculture with AV adoption is expressed as:

$$E_{AV}^{Agri} = E_{Base}^{Agri} + \beta(1-\varepsilon)\sum_{i=1}^{I} a_i \left(u_i \delta_i - \sum_{v=1}^{V} c_{i,v}\gamma_{i,v} \right) - \beta\varepsilon E_{Base}^{Agri} \tag{6}$$

At the total farm-level, the above can be modified such that only data on total crop specific revenue, U_i and the sum of crop specific input costs $C_{i,\ v}$ are needed:

$$\begin{gathered} E_{AV}^{Agri} = E_{Base}^{Agri} + \beta(1-\varepsilon)\sum_{i=1}^{I} \left(U_i \delta_i - \sum_{v=1}^{V} C_{i,v}\gamma_{i,v} \right) - \beta\varepsilon E_{Base}^{Agri} \\ \Leftrightarrow \\ E_{AV}^{Agri} = E_{Base}^{Agri} + \Delta E_{AV}^{Agri} \end{gathered} \tag{7}$$

The second term in eq. (7) starting with $\beta(1 - \varepsilon)$ describes the change in total agricultural contribution margin due to the AV impacts on shading and production cost. The third term, $\beta\varepsilon E_{Base}^{Agri}$, describes the reduction in contribution margin due to the loss in cultivated land. Together, they determine the difference in agricultural contribution margin due to AV adoption, ΔE_{AV}^{Agri}. Making use of the definition in eq. (7), adoption condition (1) can be expressed as:

$$E_{Base}^{Agri} + \Delta E_{AV}^{Agri} + E_{AV}^{PV} - E_{Base}^{Agri} > 0 \Leftrightarrow \Delta E_{AV}^{Agri} + E_{AV}^{PV} > 0 \tag{8}$$

This shows that the adoption potential of AV is dependent on the balance of two main factors: The change of the contribution margins

[3] In some context, like Germany, family farm labor is usually not treated as a variable cost in contribution margin calculations. Our later empirical example for instance only considers hired labor as variable labor cost.

from agriculture due to AV adoption and the additional farm income from the AV plant.

2.2. Income from the operation of the agrivoltaics (AV) power plant

The AV plant is operated over the horizon of the system's expected lifetime (LT). During this lifetime, the AV system results in annual income from the sale of electricity and cost for operation and maintenance. In addition, one needs to account for the cost for the upfront AV investment, INV, which includes the discounted disposal costs at the end of the lifetime. This upfront cost can be transformed into an annuity using the capital recover factor $CRF = r/[1-(1+r)^{-LT}]$, which is based on LT and the farmer's discount rate r.

The annual profit from the PV plant, E^{PV}_{AV}, is thus:

$$E^{PV}_{AV} = cap_{AV}(H[l,s]\ ae\ ta - CRF\ INV[cap_{AV}] - M[cap_{AV}]) \tag{9}$$

where cap_{AV} denotes the installed peak generation capacity (usually in kWp or MWp), H denotes the average annual full-load hours,[4] which is a function of solar radiation at location, l, and plant setup, s (reflecting the plant's angle and azimuth, density of modules, module type, etc.). To calculate the electricity revenue, we further require the electricity tariff, ta (e.g., in Euro-cents per kWh), at which the farmer can sell the power to the national grid[5] and the average lifetime efficiency of PV modules, ae. The latter is computed $ae = 1 - rmeLT/2$, where rme is the reduction in module efficiency per year.

Both, the upfront AV investment and maintenance are a function of the installed capacity, since with increasing capacity lower unit costs are to be expected, which would result in economies of scale. $INV[cap_{AV}]$ stands for the disposal cost corrected upfront investment per unit of installed capacity. $M[cap_{AV}]$ includes the annual cost for maintenance and any miscellaneous annual expenditures (e.g., insurance, administration), also expressed per unit of installed capacity. These economies of scale are also likely to diminish with increasing capacity, which for the example of $INV[cap_{AV}]$ would imply $\partial INV[cap_{AV}]/\partial cap_{AV} < 0$ and $\partial^2 INV[cap_{AV}]/\partial cap^2_{AV} > 0$.

2.3. Profitability condition for the adoption of AV

Relying on the above assumptions we combine eqs. (7) to (9) to obtain the following profitability condition for the case of an AV adoption:

$$\Delta E^{Agri}_{AV} + E^{PV}_{AV} > 0$$
$$\Leftrightarrow$$
$$\beta(1-\varepsilon)\sum_{i=1}^{I}\left(U_i\delta_i - \sum_{v=1}^{V} C_{i,v}\gamma_{i,v}\right) - \beta\varepsilon E^{Agri}_{Base} + cap_{AV}(H\ ae\ ta - CRF\ INV - M) > 0 \tag{10}$$

Note, henceforth for brevity $H[l,s] = H$, $INV[cap_{AV}] = INV$ and $M[cap_{AV}] = M$.

Eq. (10) enables us to identify the main parameters and components that determine the AV adoption decision of a farmer. Component C1, $\beta(1-\varepsilon)\sum_i\left(U_i\delta_i - \sum_v C_{i,v}\gamma_{i,v}\right)$, describes the change in agricultural contribution margin due to shading and higher input costs. Component C2, $-\beta\varepsilon E^{Agri}_{Base}$, captures the change in agricultural contribution margin due to the loss in cultivated area. Finally, component C3, $cap_{AV}(H\ ae\ ta - CRF\ INV - M)$, comprises the change in annual farm profit due to AV power production. The components are also visualized in Fig. 1 using the example of an AV system installed in Southern Germany, where the PV modules are erected above the cultivated land (as in our later application).

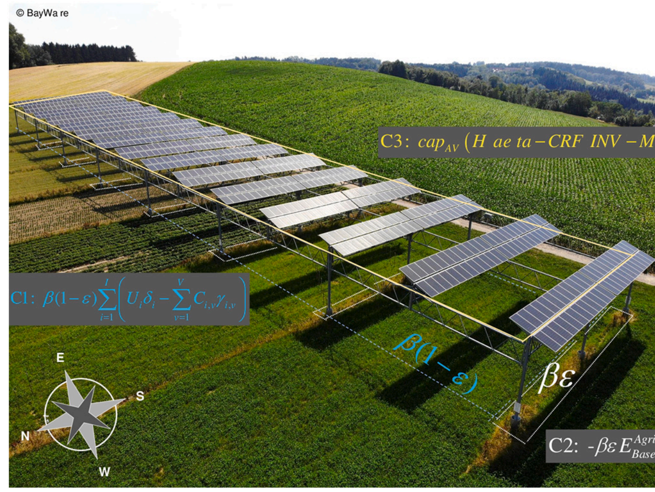

Fig. 1. An agrivoltaic plant in Heggelbach, Southern Germany. The yellow area shows the photovoltaic component and total area shaded. The dashed blue area is the shaded area available for cultivation net of the land loss. The dotted white area shows the land lost due to the mounting structure.

The magnitude and signs of the first two components are subject to farming system characteristics, as most parameters involved, such as U_i, δ_i, C_i and γ_i are specific to the cultivated crop and the production system. The discount rate, r, which determines the CRF, could be treated as farm specific parameter.[6] A region-specific determinant is H, which is mostly dependent on the solar radiation in the farmer's location, the configuration of the plant and the average lifetime efficiency of the modules. Both prices for agricultural outputs and inputs are (usually) beyond the control of farmers and are determined at the national (or global) level. Similarly, the unit cost for the AV investment, INV, the maintenance cost, M, and the tariff received for the generated electricity, ta, are independent from the farming system. A certain share of the cost of construction and maintenance services may be subject to regional differences (e.g., due to regional wage differentials or differences in regulations). The largest part of the investment cost consists of solar modules, converters, and steel, in which case prices are largely regionally invariant. In absolute terms, the size of the AV plant's capacity determines the electricity revenue, the investment expenditure and annual maintenance cost. It also influences the share of area within the AV system,β, and thus the potential agronomic costs or benefits. Technology advancements affect the AV profitability through changes in module efficiency, ae, and cost reductions in the upfront investment and maintenance (e.g., through longevity of modules). The policy and market environment affect AV adoption directly through setting a tariff for AV electricity and, potentially, by defining upper limits for AV plant sizes, delimiting cap_{AV}.

The framework and its profitability condition can also be used to analyze the adoption potential of a ground-mounted PV system, which is the special case when $\varepsilon = 1$. In that case, component C1 is zero, as no agricultural activities are possible within the ground-mounted PV system and component C2 represents the total agricultural contribution margin foregone on the ground-mounted PV system area. Of course, the investment and maintenance cost parameters would need to reflect the lower costs of the ground-mounted PV technology.

The profitability condition (10) can also be rearranged to isolate ta, which yields the break-even electricity tariff:

[4] See also Appendix C for a detailed documentation on how the full-load hours are calculated for the empirical example.

[5] We do not account for the possibility of own consumption of the generated AV power.

[6] The discount rate applied by the farmer may also positively correlate with the size of the AV system relative to the farmer's overall landholding or assets.

$$ta > \frac{-\beta(1-\varepsilon)\sum_{i=1}^{I}\left(U_i\delta_i - \sum_{v=1}^{V} C_{i,v}\gamma_{i,v}\right) + \beta\varepsilon E_{Base}^{Agri} + cap_{AV}(CRF\ INV + M)}{cap_{AV}\ H\ ae} \tag{11}$$

Eq. (11) describes at which electricity tariff an AV investment becomes worthwhile for a farmer given the predefined farming system, generation capacity and (per unit) investment cost. Calculating the break-even electricity tariff allows us to estimate the cumulative adoption of AV across a sample or population of farms, ultimately resulting in an aggregated AV electricity supply curve. The break-even electricity tariff is similar to computing the levelized cost of electricity, which is usually applied to calculate the profitability of PV systems. We can show this by expanding the fraction with the inverse of the capital recovery factor, *CRF*, which is the present value annuity factor (*PVAF*). The corresponding equation for the levelized cost of electricity for an AV system is provided in Appendix B.

2.4. Implications for the agricultural system and data requirements

The first two components in the profitability condition in eq. (10) capture how the adoption of a dual land-use system affects the underlying agricultural system. Depending on the farming system and agro-climatic context, there might be either trade-offs or synergies between the agricultural and the second land-use (e.g., PV power production).

Component C1 can be both, positive or negative, depending on the shade effect on crop yield and the possible changes in production costs. Ceteris paribus, the adoption potential of AV decreases with declining yields, $\delta_i < 0$. The opposite effect is true, if AV results in higher yields, $\delta_i > 0$. The same relationship exists with relative increases in costs, $\gamma_{i,\ v}$, which could also interact with δ_i, for example in the case of lower fertilization rates due to lower attainable yields. Component C2 is negative, when the adoption of AV results in land area lost (within the dual land-use system), i.e., $\varepsilon > 0$. In that case, component C2 is negative for all crops as long as the crop-specific contribution margin before adoption is positive.

The framework's requirement in terms of farm-level data are quite moderate. Since the effect of shading on crop yields varies strongly, data on the farm's revenue and cost from growing the respective arable crops is needed. While crop-specific revenue data is often available, data on input costs at the crop level may be missing. Then, information on total variable input cost can be used instead, $C_v = \sum_{i=1}^{I} C_{i,v}$, which requires to assume that changes in input costs, $\gamma_{i,\ v}$, are not crop specific, but uniform, i.e., $\gamma_{i,\ v} = \gamma_v$. We then rewrite eq. (10) as:

$$\beta(1-\varepsilon)\left(\sum_{i=1}^{I} U_i\delta_i - \sum_{v=1}^{V}\gamma_v C_v\right) - \beta\varepsilon E_{Base}^{Agri} + cap_{AV}(H\ ae\ ta - CRF\ INV - M) > 0 \tag{12}$$

Data on the remaining agronomic parameters, such as shade-induced changes in yield or input cost changes, depend on the specific design of the AV system and are derived from the literature or expert judgements. Ex-post the adoption of an AV system, it is of interest whether farming is still economically worthwhile. Using component C1, which describes the absolute change in the total contribution margin within the dual land-use system (net of the loss in cultivated land, denoted by ε), we can calculate the relative change in the base contribution margin, $perchgE_{AV}^{Agri}$, for the same share of total area, $\beta(1-\varepsilon)$, as follows:

$$perchgE_{AV}^{Agri} = \frac{\beta(1-\varepsilon)\sum_{i=1}^{I}\left(U_i\delta_i - \sum_{v=1}^{V} C_{i,v}\gamma_{i,v}\right)}{\beta(1-\varepsilon)E_{Base}^{Agri}} \tag{13}$$

Note: $\beta(1-\varepsilon)$ can obviously be cancelled out, but it emphasizes that only the $\beta(1-\varepsilon)$ share of the farm's total contribution margin is directly affected by the AV adoption.

3. Application to typical farming systems of the Filder plain (southern Germany)

We demonstrate the potential of FEADPLUS using the example of two hypothetical farm types: a vegetable and a cereal farm. The farm sizes and crop rotations are typical examples of farming systems found on the Filder Plain, a natural region in Southern Germany and part of the Stuttgart metropolitan region. The typical soils in this region are silt loams of the soil type Luvisols (Baxter, 2007), which usually have a depth of two meters and deeper, and a high soil fertility. An example of such a soil can be found on the Heidfeldhof, an experimental station of the University of Hohenheim, which has a pH of 5.9 and 1.22% of organic carbon (Kunz et al., 2016). Due to the fertile soils, both horticultural activities and cereal farming are practiced in the area.

3.1. Farming system data

We assume that each farm type cultivates a total area of 30 ha, which is the average farm size for the "Esslingen" district (Statistisches Landesamt Baden-Württemberg, 2021) wherein most of the Filder Plain is located. To keep the demonstration of the framework simple, each farm has a crop rotation of only three crops, each covering a third of the total area. The two farm types differ in profitability and cost structures, and the changes in crop yields (δ_i) vary as the crops cultivated show different susceptibility towards shading (Table 1). Only variable costs, such as (hired) labor, machinery inputs (fuel, lubricants) and other inputs (fertilizer, pesticides, etc.) are accounted for. This excludes the farmers' own (family) labor, as it is common practice for agricultural contribution margin computations in Germany. Both farms are characterized by a conventional crop production system based on crop budget data from KTBL (2020). The plot sizes of both farms are assumed to equal 2 ha being located 4 km away from the farm. A medium yield level and soil quality as well as a mechanization level based on a 102-kW tractor is assumed. The input specific cost changes, γ_i, due to the adoption of AV (Table 1) are based on assumptions and judgements of farmers cultivating land beneath the Heggelbach research AV plant (Schindele et al., 2020).

The vegetable farm is a labor-intensive system producing mostly high-value crops rotating between iceberg lettuce, winter wheat and cabbage. Iceberg lettuce is cultivated in 1.2 m wide beds, harvested manually and sold as fresh market produce. Cabbage is cultivated for processing and sold after storage. In contrast, the cereal farm grows a rotation of summer barley, winter wheat and grain maize. All cereals are sown after seedbed preparation with a rotary harrow in a reduced tillage system (KTBL, 2020).

3.2. Agrivoltaics system data

The AV system simulated in the following is based on the Heggelbach research AV plant (Schindele et al., 2020). This design is characterized by an annual average reduction in solar radiation (RSR) below the AV system of about 40% (Trommsdorff et al., 2021). The corresponding yield changes at this level of shading as shown in Table 1 are based on empirical estimates of yield responses at different levels of RSR. Elamri et al. (2018) and Marrou et al. (2013) report yield changes for lettuce at RSR between 23% and 50% in temperate regions. On average, this fits the RSR of our AV system and we consider the mean of their reported changes in yield of 15% as a reasonable proxy for lettuce and cabbage. In a similar fashion, based on Ding and Su (2010), we estimate the reductions in maize yield at 39%. For winter wheat and summer barley we assume a yield reduction of 25% based on Zhao et al. (2019), who for a RSR of 44% report a 29% reduction in wheat yields. Of course, the estimates for changes in cost and yield are associated with a high uncertainty, as either data is scarce or because estimates are taken from different agro-climates. We address this by performing a sensitivity analysis over a wide span of variation in these parameters. The AV

Table 1
Characteristics of the two (simplified) farm types found in the Filder Plain region. The two farms differ in their structure, but their total landholding is assumed to be identical.

		Vegetable Farm			Cereal Farm		
Parameter	Unit	Iceberg lettuce[a]	Winter wheat	Cabbage	Summer barley	Winter wheat	Grain maize
Yield	kg ha^{-1}	30,000	7890	90,000	5920	7890	9770
Area	ha	10	10	10	10	10	10
Price	EUR kg^{-1}	0.760	0.150	0.180	0.180	0.150	0.165
Revenue	EUR ha^{-1}	22,800	1184	16,200	1066	1184	1612
Costs	EUR ha^{-1}	15,325	726	6349	549	726	920
Input cost	EUR ha^{-1}	7658	530	2519	367	530	496
Machinery cost	EUR ha^{-1}	1079	196	1853	182	196	424
Labor cost	EUR ha^{-1}	6587	0	1977	0	0	0
Contribution margin	EUR ha^{-1}	7475	457	9851	517	457	692
Expected yield changes δ_i	%	−15	−25	−15	−25	−25	−39
Cost changes by input type γ_v							
Input cost	%	0	0	0	0	0	0
Machinery cost	%	5	5	5	5	5	5
Labor cost	%	10	10	10	10	10	10

Note: Data is based on crop budget data from the KTBL (2020) database. The expected yield changes are based on Elamri et al. (2018), Marrou et al. (2013), Zhao et al. (2019) and Ding and Su (2010). More details are provided in the main text. The input specific cost changes are informed by the authors' assumptions and expert judgements.

[a] Yield and price for iceberg lettuce is measured in pieces and was converted to kilograms assuming 0.5 kg piece^{-1}.

system parameters, e.g., the size, setup and costs of the AV plant, as well as the discount rate *r* are identical for both example farms (Table 2). The AV investment costs comprise all up-front capital expenditures including the cost of planning, permits and installation. Since the cost of maintenance, solar panels and other components are likely to change in the future, we also vary them in the sensitivity analysis below.

3.3. Results

We applied the FEADPLUS framework using the General Algebraic Modeling System (GAMS) software (Brooke et al., 1988), though, it can be easily implemented using other software, e.g., R (R Core Team, 2020), which is an open source and freely available software.[7] Applying the profitability condition from equation (10), the results for the two farm types are presented in Table 3 for an electricity tariff, *ta,* of 8, 9 and 10 EUR-cents kWh^{-1}. The agronomic components are constant across all three scenarios and the photovoltaic component is constant across the farm type. The vegetable farm suffers from a high decline in agricultural contribution margin. While the relative decline in vegetable yield is much lower than for the cereals, this result is explained by the high output value and contribution margin per hectare. In the cereal farm, the higher reductions in crop yield are offset by the relatively low level of contribution margin of cereals. Consequently, the net benefit from AV system is lower for the vegetable farm compared to the cereal farm. For

Table 2
Parameters of the agrivoltaic (AV) system at a size of 1040 kWp covering an area of 2 ha (Schindele et al., 2020).

	Variable	Unit	Variable value
Total farm area owned[a]	A	ha	30
Area for AV system[b]	A_{AV}	ha	2
AV capacity per AV system area[c]		kW$_p$ ha^{-1}	520
AV capacity	cap_{AV}	kW$_p$	1040
Share of total area within AV system	$\beta = A_{AV}/A$	%	6.7
Share of area lost within AV system[c]	ε	%	8.0
Annual full-load hours[d]	$H\ (l,\ s)$	kWh kW$_p^{-1}$ year^{-1}	1202
Expected lifetime of AV system[c]	LT	years	25
Annual reduction in module efficiency[c]	rme	% year^{-1}	0.25
Average PV lifetime efficiency[c]	ae	%	96.9
Farmer's discount rate[c]	r	%	4.1
Capital recovery factor	CRF	%	6.5
AV investment costs[c]	INV	EUR kWp^{-1}	1294
Annual AV maintenance costs[c]	M	EUR kWp^{-1} year^{-1}	16

[a] Statistisches Landesamt Baden-Württemberg (2021).

[b] Authors' assumptions.

[c] Data based on Schindele et al. (2020)

[d] See calculation in Appendix C.

Table 3
Components of the change in contribution margin (CM) in a) total absolute values and b) per hectare at an electricity tariff of 8, 9, and 10 EUR-cents kWh^{-1}. The break-even tariff is 9.00 and 8.63 EUR-cents kWh^{-1} for the vegetable and cereal farm, respectively.

Variable	Vegetable farm			Cereal farm		
Tariff in EUR-cents kWh^{-1}	8	9	10	8	9	10
a) Annual total change in CM, in EUR year^{-1}						
Component C1 - Shading and change in input cost	−4391	−4391	−4391	−755	−755	−755
Component C2 - Loss in cultivated area	−948	−948	−948	−89	−89	−89
Component C3 - AV power production	−6976	5316	17,429	−6996	5316	17,429
Sum C1-C3	−12,135	−23	12,090	−7640	4472	16,585
b) Annual change in CM per hectare under AV, in EUR year^{-1}ha^{-1}						
Component C1	−2195	−2195	−2195	−378	−378	−378
Component C2	−474	−474	−474	−44	−44	−44
Component C3	−3398	2658	8714	−3398	2658	8714
Sum C1-C3	−6068	−11	6045	−3820	2236	8293

[7] In the following, we only used R and the *ggplot2* package (Wickham, 2016) to visualize the results.

both farm types AV is not profitable at a tariff of 8 EUR-cents kWh^{-1}. For the cereal farm it becomes profitable at a tariff of 8.63 EUR-cents kWh^{-1}, while the vegetable farm has a break-even tariff of 9.00 EUR-cents kWh^{-1}. Calculating the relative change in the agricultural contribution margin beneath the AV system, see eq. (13), the contribution margin below the AV system would decline by 40.3% and 73.9% for the vegetable farm and for the cereal farm, respectively. This shows that the relative change in agricultural contribution margin (which is lower for the vegetable farm) is a weak predictor for the economic viability of AV adoption.

3.4. Sensitivity analysis

We test the sensitivity of the break-even electricity tariff (eq. (11)) with regard to variations in agronomic and photovoltaic parameters between −30% and +30%.

The main agronomic parameters of interest are the effects of AV on the relative crop yield $(1 + \delta)$ and cost level $(1 + \gamma)$, which are multiplied with the X percentage change variation in parameters, $(1 + X)$. For example, a −30% variation in the yield effect multiplied by $(1 + \delta)$, with $\delta = -20\%$, results in a relative yield level of 0.56, which is equivalent to a yield loss of −44%. Similarly, a positive variation of 30% multiplied by $(1 + \delta)$, with $\delta = -20\%$, is equivalent to an actual yield gain of 4%. Moreover, we investigate the impacts of changes in contribution margins by equivalent percentage changes in the revenue and cost. The photovoltaic parameters considered in the sensitivity analysis are the annual full-load hours H (due to changes in solar radiation or system losses), the up-front investment cost and the annual maintenance cost. Each sensitivity analysis scenario is conducted varying only one parameter at a time, while leaving the rest of the parameters at their initial values, as defined in Tables 1 and 2. We report the break-even tariff and, in case of the changes in the agronomic parameters, also the relative changes in agricultural contribution margin below the AV system (which does not change, when only photovoltaic parameters are varied).

We find that variations in the full-load hours (or solar radiation) and investment cost have the largest impact on the break-even tariff (Fig. 2b). Despite the differences in break-even tariff between the farms, their change in break-even tariff develops in parallel with changes of solar radiation and investment cost. With 30% less full-load hours, the break-even tariff is 12.86 EUR-cent kWh^{-1} for the vegetable farm and 12.33 EUR-cent kWh^{-1} for the cereal farm. With 30% more full-load hours it drops to 6.93 EUR-cent kWh^{-1} for the vegetable farm and 6.64 EUR-cent kWh^{-1} for the cereal farm.

In comparison, the sensitivity to shade-induced yield changes is lower than changes in solar radiation (Fig. 2a), but the vegetable farm is much more sensitive to variations in yield changes. For example, the difference in break-even tariff between a reduction of $(1 + \delta)$ by 30% and a 30% increase of $(1 + \delta)$ is 1.03 EUR-cent kWh^{-1} for the vegetable farm but only 0.08 EUR-cent kWh^{-1} for the cereal farm. Thus, due to their different margin and cost structures, the vegetable farm shows a higher sensitivity to changes in δ than the cereal farm. The vegetable farm, which has higher input cost than the cereal farm (Table 1), also reacts stronger to changes in $(1 + \gamma)$ than the cereal farm (Fig. 2a). The break-even tariffs are almost equal for both farm types once the cost change decreases by 30% compared to the baseline.

Changes in the contribution margin (due to price changes) and maintenance cost generally have a moderate impact on the break-even tariff. The differences between break-even tariffs of the two farms slightly converges with decreasing levels of the contribution margin. Changes in maintenance cost impact both farm types by the same absolute degree.

A relevant result is also how the agricultural contribution margin changes below the AV system, as shown in Fig. 3. At the base choice of parameters (%-change = 0), we already observe a strong reduction of the agricultural contribution margin of 40.3% and 73.9% for the vegetable and cereal farm, respectively. At higher declines in yield (or higher increases in cost) the contribution margin can turn negative for the cereal farms for the range of changes covered in the sensitivity analysis (and at even higher changes, the same would apply for the vegetable farm). This could incentivize the farmer to abandon the cultivation of the area below the AV system. In the European Union, farmers would probably still farm the land as long as the direct payment per hectare of the Common Agricultural Policy offsets the potentially negative

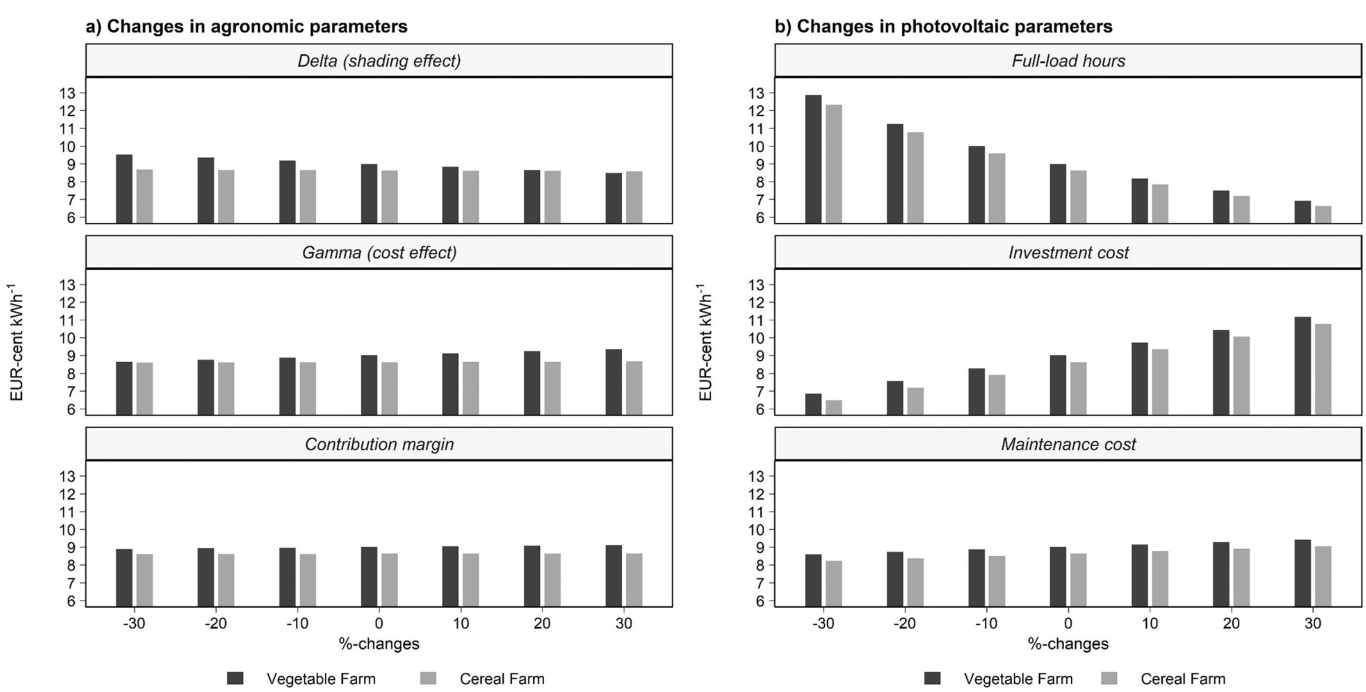

Fig. 2. Sensitivity of main agronomic and photovoltaic parameters on the break-even electricity tariff of two farm types in the Filder Plain region (see Table 1 for differences in profitability and cost structure).

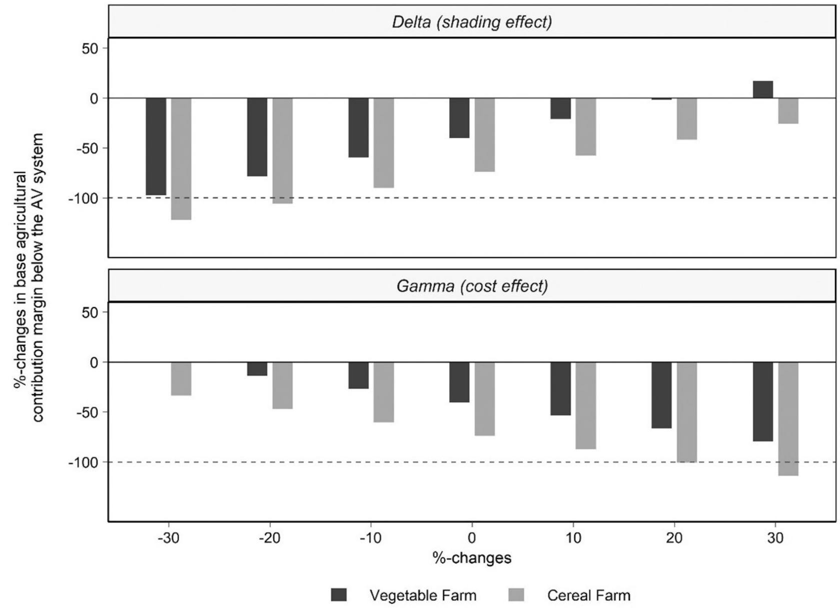

Fig. 3. Relative changes of the agricultural contribution margin for the cultivated area below the AV system. Bars below the dotted horizontal line indicate that the absolute reduction in the agricultural contribution margin exceeds the base agricultural contribution margin.

contribution margin. The sensitivity analysis also shows for very high increases in shade-induced yield changes that, at least for the vegetable farm, the agricultural contribution margin would turn positive.

4. Discussion

Using the example of AV, we demonstrated the functionality of the FEADPLUS framework to assess and estimate the economics and the adoption potential of dual land-use systems. The framework captures both the likely trade-offs and synergies that could arise from the adoption of an AV system. The example calculations show that the threshold at which farmers adopt AV is not only dependent on the solar radiation. Also, the cost and revenue structure of a farm as well as the trade-offs and synergies of agricultural production have to be accounted for when assessing the AV adoption potential.

The trade-offs and synergies are determined by the changes in yields (δ) and input costs (γ) within the first component of the profitability condition in eq. (10). These depend on the farming system, i.e., what type and variety of crops farmers cultivate in what kind of production system. In most arable cropping systems in temperate regions, as illustrated by our analysis of farm types on the Filder Plain, AV may lead to trade-offs due to shade-induced yield declines ($\delta < 0$) and increases in input intensities ($\gamma > 0$) (Weselek et al., 2019). However, in different contexts, AV may offer synergies in these dimensions. In arid and semi-arid climatic regions characterized by water scarcity and high solar radiation, AV may reduce the water input due to reduced evapotranspiration in the shade or because it is combined with rainwater harvesting, possibly resulting in lower input costs (Trommsdorff et al., 2021) and positive yield changes (Marrou et al., 2013). Moreover, the shading may mitigate adverse impacts on labor productivity, which would otherwise occur due to climate change-induced heat stress (Willockx et al., 2020). There are also potential cost synergies in case of fruit production such as berries and apples, where the AV mounting structure could reduce input costs for hail nets or plastic foil. These crops may also be shade-tolerant, which means that component C1 could be positive overall, as yields only decrease slightly (or even increase) and input costs decline. This was corroborated by our sensitivity analysis for the vegetable farm and a +30% relative increase in the yield level. Yet, for some crops, like apples, there may also be reductions in fruit quality (do Amarante et al., 2011).

The results show that variations in the agronomic parameters may flip the relative suitability for AV between different farming systems. Systems relying on high-value crops, i.e., the vegetable farm, are much more sensitive to the yield and cost changes. The case of the vegetable farm shows that an AV system with a lower density of PV modules could at least benefit on the agronomic side, as a lower reduction in photosynthetically active radiation would lead to lower reductions in yield. Yet, there is a potential trade-off with the investment cost, as there may be fixed costs for the mounting structure per area, which then has to be allocated to a lower annual electricity production. On the other hand, systems with low production values may allow for a lower adoption cost of APV. However, there is a risk of negative agricultural contribution margins, as our analysis shows (Fig. 3). In such a case, depending on other factors (e.g., whether the farmer receives direct payments per area cultivated), a profit maximizing farmer may abandon farming on the area beneath the AV system. This would strongly undermine the actual rationale for policymakers to support such systems, while of course an option value is left, as the farmer may re-cultivate the land at any time (unlike in case of ground-mounted PV systems). A focus should be put on farming systems that allow for synergies, but here more research is needed, whether it concerns knowledge about the yield changes of relevant crops due to various levels of shading or the cost of AV systems within different agricultural systems (e.g., for arable land, grassland or specialty crop systems).

A general finding of our study is that the agronomic influence on the economic performance of AV systems is small compared to the influence of the PV component, at least for arable farming, where per hectare contribution margins are relatively low. Yet, this may change in the case of higher value crops which benefit from shading by increasing yield by up to 30%, as was observed in some studies for berries (Makus, 2010; Rotundo et al., 1998). However, the total potential in terms of land area for such crops may be rather limited. Furthermore, future reductions in the price of PV generated electricity may substantially increase the relative importance of the agronomic components in determining the economic feasibility of AV. Future increases in module efficiency would reduce the mounting structure's cost share and allow for higher electricity generation without increasing the level of shade.

Applying FEADPLUS, we can assess the profitability of AV within a one-year horizon, by annualizing all changes in the agricultural and photovoltaic contribution margins. This makes the framework easily applicable to large farm-level datasets, such as the FADN (Farm Accountancy Data Network) database of the European Commission. Various research questions related to the adoption potential of AV across regions and farming systems can be addressed applying FEADPLUS. For instance, it could be used to estimate the cumulative electricity supply from AV systems at varying degrees of policy support (e.g., different electricity tariffs paid for AV above the current ground-mounted PV cost), to estimate the reduction in agricultural supply at given levels of AV adoption or to identify the most cost-efficient farm types or regions. The framework can be extended to account for advances in technology through improved AV system designs or future changes in relative prices between the agricultural and energy market. Also, stochastics can be incorporated to account for the uncertainty in agronomic and technology parameters or economies of scale in the AV system designs or agricultural operations.

Dual land-use systems are an emerging field and policies are needed to provide the necessary support and regulatory framework. In that context, FEADPLUS may serve as a tool to analyze policy scenarios and future technological developments of different dual land-use systems. Specifically, FEADPLUS can be used to identify the minimum policy support necessary to reach a certain adoption level in a given region or farming system. Furthermore, it can be used as an evaluation tool to analyze appropriate policy support (e.g., subsidies or feed-in-tariffs in case of AV systems) for projects that may otherwise be economically unviable. This also enables one to address the problem of additionality (which may be a prerequisite for the eligibility to receive policy support), as one can calculate systematically where the threshold between incentive and windfall gain may be situated for different farming systems and regions. In addition, the framework can support the understanding in which farming systems the adoption of a dual land-use system may create unintended consequences. For example, farmers are incentivized to abandon land cultivation below the AV system if contribution margins become negative.

In the following subsections, we first discuss possible and easily implementable modifications and then highlight the key limitations of the FEADPLUS framework.

4.1. Possible modifications of the framework

Modifications of the framework are necessary to account for settings in which the investor is external. The external investor would need to pay the landowner a land lease if the net absolute change in the agricultural contribution margin is negative and the landowner would consequently need to compensate the land-user, if both are not the same entity. In case the adoption of AV results in a net increase of the agricultural contribution margin (after the loss in land), farmers (or the landowner) would face a theoretical incentive to pay external investors for installing an AV system. Yet, at the same time external investors should also be competing for AV investments in farming systems where there are no trade-offs, or even synergies instead. At any rate, a change in the investor setting would require transfers between the different actors involved. These transfers can be included in the framework, but they would also be associated with transaction costs, which are unknown in their magnitude and moreover difficult to measure.

The adoption of dual land-use systems could imply changes in farmers' eligibility to receive payments from agricultural support policies, e.g., Europe's Common Agricultural Policy. Currently, at least in Germany, there is unclear legal practice whether farmers are still (partially) eligible for direct payments for those areas of agricultural land which are covered by an AV system (Fraunhofer ISE, 2020). The additional income from agricultural subsidies as well as the possible change in the eligibility to receive them could be incorporated into the framework as an additional term. With ongoing and future reforms of the Common Agricultural Policy to strengthen biodiversity conservation, scenarios are likely in which farmers are incentivized to bring back a certain share of their cultivated land under high-diversity landscape features. This may include "rotational or non-rotational fallow land" (European Commission, 2020, p. 8). The share of land which is lost for production due to the design of a dual land-use system (the second term of the profitability condition in eq. (10)) could (partially) count towards such requirements and thus reduce the loss in agricultural contribution margin. This could be incorporated into the framework in a straightforward manner, and is a particularly interesting aspect for those dual land-use systems in which a high share of land is lost for agricultural production, but which could alternatively provide habitat for a higher diversity of flora and fauna (Trommsdorff et al., 2021). Future research is, however, needed to thoroughly assess this potential.

The setup of FEADPLUS allows us to implement economies of scale in a straightforward manner. For the example of AV, we illustrated how the cost of upfront investment and annual maintenance can be expressed as functions of the capacity installed. Certain cost components such as the mounting structure, site preparation and installation, system design, grid connection and cost for permits and advisory services are expected to experience a decline in per unit cost with increasing installed capacity (Schindele et al., 2020). The same holds for annual maintenance costs such as surveillance and commercial management. Depending on the data availability, the per unit cost degression curves can be estimated using linear, logarithmic or other functional forms. Since the AV technology is still at the early stages of its development, it is likely that the relevance of farming system characteristics and agronomic effects will increase in future.

The framework can also be applied for AV designs, which do not result in an even shading of the system area, e.g., systems in which bifacial PV panels are vertically erected towards an East-West direction. In this case, the reduction in PAR is highest for crops growing directly next to the panel walls, while in the middle of the aisles shading would be the lowest. A straightforward solution could be to estimate yield losses in different zones of the AV system area where the degree of shading is rather homogenous. This could be used to calculate an area-weighted average of the yield loss. More sophisticated approaches may be necessary as the AV technology advances. For instance, setups may be developed in which the shading from the panels is dynamic (e.g., using either single- or double-axis tracking of PV modules). Such systems could be controlled to maximize either electricity production, crop production or the total economic return by minimizing the trade-offs between electricity and crop production. These approaches may also consider at which growth stage a crop is particularly susceptible to yield declines from shading and in which stage it may benefit from shading. Within this context, FEADPLUS could be coupled with dynamic crop growth models, which simulate yield changes due to different shading optimizations, accounting for higher water-use efficiency, lower heat stress and other favorable microclimatic conditions.

4.2. Limitations

FEADPLUS provides a straightforward profitability condition on an annual basis applicable to large datasets of farm-level data. This requires the use of various simplifying assumptions. For instance, it is assumed that farmers do not optimize their crop rotation. When analyzing the potential of dual land-use systems at the micro scale, accompanied with data availability on crop rotation constraints and site conditions, this assumption can be relaxed employing methods of mathematical programming. A further assumption is that future cash flows from both agricultural operations and the investment in the dual land-use system are static. This is a limitation when conducting uncertainty analysis, e.g., with regards to annual fluctuations in crop yields and solar radiation. Principally, the single-year form of FEADPLUS can incorporate stochastic components, yet they would always need to be interpreted as average changes over the whole simulated time horizon. When discounting future cash flows, results from investment analyses are quite sensitive towards adverse effects that occur during early years of the investment.

In theory, we can use the presented framework to calculate the farmers AV adoption potential with a high level of detail, if all parameters of the framework are well known. In practice, limitations in data availability could limit the confidence in results. For example, data on crop-specific allocation of input costs is usually not available. This could be especially relevant, when considering mixed systems combining cropping and livestock. Another limitation is that the FEADPLUS framework does not explicitly account for differences in farmers' preferences (e.g., risk aversion). Analyses on farmers' adoption attitudes towards new technologies, e.g., planting short-rotation coppices, found substantial differences in farmers' corresponding willingness to accept and risk premia and other adoption influencing factors (Gillich et al., 2019). Hence, while the framework defines an adoption threshold and identifies the main cost and benefit components, an additional component may need capture transaction and "psychological" costs.

Besides economic incentives and the institutional and legal settings, there are many further factors determining the adoption of new technologies, many of which are dependent on the adopting farmer, as for instance regards existing skills and knowledge or a motivation to protect the environment (Kuehne et al., 2017). In the case of AV, the acceptance and perceptions of local citizens and other farmers play an important role. So far, no research has been done on this topic besides from Ketzer et al. (2019), who describe an overall positive attitude of local citizens towards AV compared to ground-mounted PV at the location Heggelbach. However, competing land uses like tourism and recreation may restrict this acceptance and hinder the adoption of AV. Moreover, the environmental impacts of AV, e.g., on soil quality or biodiversity, are not fully assessed yet, which may also prevent farmers from adoption, even if current AV systems are designed in a way that allows a full removal of the AV construction with as little negative impact to the soil as possible, contrary to many ground-mounted PV systems. In contrast to ground-mounted PV systems, AV systems – like the one installed in Heggelbach, Southern Germany – do not require fencing, as both converters and PV modules are installed at elevated height, which reduces the risk of theft. Given that insurance companies waive the requirement of fences for AV systems, this may be another advantage over ground-mounted PV systems in terms of social acceptance and biodiversity. Neither local residents nor (most) wildlife[8] prefer fences in the open landscape for obvious reasons. AV may also offer an adaption to climate change as the profit from operating an AV system is likely to be negatively correlated with yield declines during drought years. Hence, an AV investment could be part of farmers' risk management strategies, particular in light of the current projections on climate change related weather extremes. In summary, many of the limitations discussed above could be addressed by future research, but this comes at the cost of increased complexity.

4.3. Concluding remarks

Agricultural land is a scarce factor: its availability is continuously decreasing and multiple land-use purposes fuel the competition. The demand for productive land is increasing with a growing population, while the projected shifts towards clean energy systems and a bio-based economy result in additional demand for land. At the same time, biodiversity conservation policies demand that land is set aside or managed specifically to enhance species richness. Dual land-use systems are one possible strategy to relieve the pressure on land and are thus becoming increasingly relevant. This study presented FEADPLUS, which is an analytical framework to estimate the economics and the adoption potential of dual land-use systems accounting for farming system-specific trade-offs and synergies. We demonstrated the functionality of FEADPLUS using the example of agrivoltaics, a dual land-use system, which is experiencing increasing attention given its potential to achieve a high level of land-use efficiency. Using FEADPLUS, it is possible to compare multiple designs of a dual land-use system, e.g., to find the most economically suitable AV design for a given farming system and location. FEADPLUS can be applied equally well to large-scale agricultural databases and to local high-resolution measurements or simulations of agrivoltaic systems. As the demand for studies on the potential of dual land-use systems, in particular AV, is likely to rise, FEADPLUS may serve as a simple analytical framework that can be adjusted to different contexts and technologies even with limited data availability. Since the framework captures the heterogeneity of farming systems, while still being easy to grasp and communicate, it is the authors' hope that it may serve future applications at the science-policy interface.

Declaration of Competing Interest

None.

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Appendix A. Intermediate steps of FEADPLUS: Crop specific contribution margins

The crop-specific contribution margin is first defined as

$$\widetilde{e}_i = (1-\beta)\left(u_i - \sum_{v=1}^{V} c_{i,v}\right) + \beta(1-\varepsilon)\left(u_i(1+\delta_i) - \sum_{v=1}^{V} c_{i,v}\left(1+\gamma_{i,v}\right)\right) \tag{A.1}$$

Which after factoring out and rearranging yields A.2:

$$\begin{aligned}
\widetilde{e}_i &= \left(u_i - \sum_{v=1}^{V} c_{i,v}\right) - \beta\left(u_i - \sum_{v=1}^{V} c_{i,v}\right) + \beta\left(u_i + u_i\delta_i - \sum_{v=1}^{V} c_{i,v} - \sum_{v=1}^{V} c_{i,v}\gamma_{i,v}\right) - \beta\varepsilon\left(u_i + u_i\delta_i - \sum_{v=1}^{V} c_{i,v} - \sum_{v=1}^{V} c_{i,v}\gamma_{i,v}\right) \\
\Leftrightarrow \widetilde{e}_i &= \left(u_i - \sum_{v=1}^{V} c_{i,v}\right) - \beta\left(u_i - \sum_{v=1}^{V} c_{i,v}\right) + \beta\left(u_i - \sum_{v=1}^{V} c_{i,v}\right) + \beta\left(u_i\delta_i - \sum_{v=1}^{V} c_{i,v}\gamma_{i,v}\right) - \beta\varepsilon\left(u_i - \sum_{v=1}^{V} c_{i,v}\right) - \beta\varepsilon\left(u_i\delta_i - \sum_{v=1}^{V} c_{i,v}\gamma_{i,v}\right) \\
\Leftrightarrow \widetilde{e}_i &= \left(u_i - \sum_{v=1}^{V} c_{i,v}\right) + \beta(1-\varepsilon)\left(u_i\delta_i - \sum_{v=1}^{V} c_{i,v}\gamma_{i,v}\right) - \beta\varepsilon\left(u_i - \sum_{v=1}^{V} c_{i,v}\right)
\end{aligned} \tag{A.2}$$

[8] For some species like ground-breeding birds fenced areas may offer better protection from predators.

As $e_i = u_i - \sum_{v=1}^{V} c_{i,v}$ the first and parts of the third term of the right-hand side can be substituted to obtain as shown in eq. (5) in the main text:

$$\widetilde{e}_i = \mathrm{e}_i + \beta(1-\varepsilon)\left(u_i\delta_i - \sum_{v=1}^{V} c_{i,v}\gamma_{i,v}\right) - \beta\varepsilon\ \mathrm{e}_i \tag{A.3}$$

which could be further simplified as shown below:

$$\widetilde{e}_i = \beta(1-\varepsilon)\left(u_i\delta_i - \sum_{v=1}^{V} c_{i,v}\gamma_{i,v}\right) + (1-\beta\varepsilon)\mathrm{e}_i \tag{A.4}$$

Appendix B. Levelized Cost of Energy formula for an AV system

The equation for the levelized cost of electricity for an AV system, $LCOE_{AV}$:

$$LCOE_{AV} = \frac{PVAF\ \left(-\beta(1-\varepsilon)\sum_{i=1}^{I}\left(U_i\delta_i - \sum_{v=1}^{V} C_{i,v}\gamma_{i,v}\right) + \beta\varepsilon E_{Base}^{Agri} + cap_{AV}\ M\right) + cap_{AV}\ INV}{PVAF\ \ cap_{AV}\ \ H\ \ ae}$$

Note: The present value annuity factor (PVAF) is the inverse of the capital recovery factor, CRF.

Appendix C. Calculation of annual full-load hours

The annual full-load hours, H, are expressed in kWh kWp^{-1} yr^{-1} and computed for a location l and a setup s as follows:

$$H_{l,s} = AR_{l,s}\ MPR_{l,s}\ bf_s\ ce_s\ ca_s\ \eta_s \tag{C.1}$$

Our location, l, is the district Esslingen (NUTS-3 region "DE113"). Our setup, s, follows the AV design of the research plant in Heggelbach as described in Schindele et al. (2020), where crystalline silicon PV modules (SolarWorld bifacial PV modules with 270 Wp peak capacity per module or 0.161 kWp m^{-2} under Standard Test Conditions) are installed at an angle of 20° and an azimuth of 52.2°. The annual incoming solar radiation in kWh m^{-2} yr^{-1}, AR, and the module performance ratio, MPR, were extracted from the EU's PVGIS online platform (https://ec.europa.eu/jrc/en/pvgis; Huld et al., 2012; Huld and Amillo, 2015; Šúri et al., 2005). This resulted in an $AR = 1248$ and an $MPR = 0.92$. The bi-facial factor, bf_s, is needed to account for the higher energy yielding bi-facial solar modules of our setup and equals 1.06 following Schindele et al. (2020). The converter efficiency, ce_s, in our setup is 98.6%, based on the Huawei SUN2000–36 KTL converter factsheet. The PV capacity per area in m^2 kWp^{-1}, ca_s, equals 6.2 and the PV module efficiency, η_s, is 16.1%. Multiplication of $\eta_s$with ca_syields 1, but both are nevertheless required to get the physical dimensions in eq. C.1 right $\left(AR_{l,s}\ \ ca_s = kWh/_{m^2yr}\ m^2/_{kWp} = \frac{kWh}{kWp\ yr}\right)$. Please note that all remaining parameters mentioned in eq. (1) are dimensionless. Using the data above, we arrive at 1202 full-load hours.

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