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Agrivoltaics: The Environmental Impacts of Combining Food Crop Cultivation and Solar Energy Generation

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Abstract: The demand for food and renewable energy is increasing significantly, whereas the availability of land for agricultural use is declining. Agrivoltaic systems (AVS), which combine agricultural production with solar energy generation on the same area, are a promising opportunity with the potential to satisfy this demand while avoiding land-use conflicts. In the current study, a Consequential Life-Cycle Assessment (CLCA) was conducted to holistically assess the environmental consequences arising from a shift from single-use agriculture to AVS in Germany. The results of the study show that the environmental consequences of the installation of overhead AVS on agricultural land are positive and reduce the impacts in 15 of the 16 analysed impact categories especially for climate change, eutrophication and fossil resource use, as well as in the single score assessment, mainly due to the substitution of the marginal energy mix. It was demonstrated that, under certain conditions, AVS can contribute to the extension of renewable energy production resources without reducing food production resources. These include maintaining the agricultural yields underneath the photovoltaic (PV) modules, seeking synergies between solar energy generation and crop production and minimising the loss of good agricultural land.

Keywords: agrivoltaics; photovoltaics; CLCA; environmental impact; land-use change

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1. Introduction

Global energy consumption is forecasted to increase by nearly 50% between 2018 and 2050 based on a projection of the U.S. Energy Information Administration [1]. Currently, the global energy supply is still dominated by energy from fossil sources such as oil or coal. In the case of electricity, for example, only 26% globally originates from renewable sources such as solar or hydroenergy [2]. A large share of the future energy supply must be provided by using renewable energy sources in order to drastically reduce the greenhouse gas (GHG) emissions associated with the energy generation and achieve the Sustainable Development Goals (SDGs) [3]. In particular, the provision of solar photovoltaics (PV) electricity using large scale ground-mounted PV facilities can play a major role, as it is currently not only one of the cheapest options to produce renewable energy [4,5] but is also price-competitive in comparison to fossil energy sources [6]. However, the installation of large-scale ground-mounted PV systems, as well as other renewable energy types such as bioenergy, require land area. This puts additional pressure on land availability which is already constrained due to an increase in global food demand caused by a rise in world population and changing consumption patterns [7]. Tilman et al. (2011) predict that, as a result, the global crop demand will increase by up to 110% from 2005 to 2050 [8]. Furthermore, there is a strong increase in the biomass demand for bioenergy, biofuels, and biobased materials due to the ongoing development towards a bioeconomy [9]. However, an expansion of land used for energy provision and agriculture should be avoided, as land-use change is a major driver of anthropogenic GHG emissions [10] and can lead to loss in soil quality and biodiversity [11]. This means that land which is available at the moment has to be used much more efficiently and land-use conflicts between food production and energy generation should be avoided.

One solution which could help solve this problem are agrivoltaic systems (AVS), a concept which was first introduced by Goetzberger and Zastrow (1982) about 40 years ago [12]. AVSs combine agricultural production with solar energy generation on the same area and thus lead to an increase in land productivity [13]. In a broad definition, AVSs can be classified into open and closed systems [14]. While closed AVSs mainly represent PV greenhouses, open systems can be differentiated in overhead and interspace systems. In overhead AVS, PV modules are typically mounted on a 2 to 7 m high structure which enables the agricultural machinery to pass underneath [12,13,15,16]. Currently, there are several AVSs in operation worldwide, with a total installed capacity of more than 64 GW [17], and with various crops being cultivated underneath the PV modules, such as winter wheat, maize, clover grass or several cabbage varieties [15]. First results on overhead AVSs showed that the shading effect due to the installation of the PV panels can have a significant influence on the yield of the crops cultivated underneath [18]. The average yield of winter wheat, for example, was reduced by 8% [15]. In addition, there is less land available for farming compared to a conventional agricultural system, as around 2% of the area is needed to install the pillars of the mounting structure [19]. In arable farming applications with larger machinery employment, this area can increase to around 8%, as it is practically not possible to cultivate the strips of land between the pillars [20]. Therefore, the question arises of whether the installation of an AVS on agricultural land makes sense from an economic and environmental perspective. This would be the case if the benefits of the additional electricity production are greater than the negative impacts due to the production and installation of the mounting structure and the increase in cultivation area needed for the production of the displaced crops. A recent study demonstrated that, from an economic perspective, the costs of overhead AVSs mounted with tensile structures are comparable to those of roof- or ground-mounted PV systems [21]. The installation of an AVS offers, under the appropriate conditions, a chance to enhance the economic performance and leads to a significant increase in the farm income [22,23]. Agostini et al. (2021) showed that for tensile overhead systems, besides the economics, the environmental performance of AVSs is comparable to other PV systems [21]. In their study, though, they focused only on the output of electricity produced. They did not assess the effects which the installation of the PV modules has on the agricultural system underneath, for example, in the form of reduced yields or changed microclimate. However, for a holistic assessment of the environmental performance of an AVS, the potential interactions between the PV and the agricultural system have to be included, as Leon et al. (2018) emphasized [24]. They assessed the life-cycle CO_2 emissions of an AVS installed on a tomato greenhouse and showed that the global warming potential (GWP) is considerably lower compared to a separate production of tomatoes and electricity [24,25]. However, the GWP assesses only a single environmental impact and does not allow a comprehensive evaluation of the environmental performance of AVS. Therefore, in the present study, a Consequential Life-Cycle Assessment (CLCA) [26] is conducted applying a multiple-output functional unit to holistically assess the environmental consequences arising from a shift from single-use agriculture to overhead AVSs. Biodiversity effects that might occur when changing from single-use agriculture cultivation to AVSs are not considered in this study. A CLCA can be defined as a "system modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit" [27]. CLCA should be applied to assess the environmental consequences of decisions [26], such as in the current case, the decision to install an AVS.

2. Materials and Methods

2.1. Goal and Scope

The goal of the current study is to assess the environmental impacts and benefits arising from a change from 1 hectare (ha) single-use agriculture to an overhead AVS with a fixed mounting structure for an arable application in Germany. The study is based on data from an existing AVS which was developed in the APV RESOLA project [15,23]. The climatic conditions of the side are described in Weselek et al. (2021) [20]. The analysed agricultural system includes the organic cultivation of four crops: winter wheat, celery, potatoes and a grass–clover mixture, and thus encompasses major staple crops and vegetables as well as fodder crops. As a consequence of the installation of the AVS, there is a reduction in the crop yield due to the decrease in cultivation area mainly caused by the pillars of the mounting structure, as well as shading effects due to the PV modules which can affect the yield significantly depending on the crop type and the climatic conditions [15,19]. As the global production of wheat, potatoes and vegetables such as celery has been increasing over the last years according to the FAO statistics [28], it is likely that the replaced cultivation area of these products will be relocated somewhere else. The assessed agricultural production system is managed following the rules of organic farming which forbid the use of mineral nitrogen fertilizers. Hence, it requires the use of clover grass mixture in the crop rotation for the nitrogen supply. Therefore, it can be assumed that the replaced clover grass yield also has to be produced elsewhere and cannot be replaced by other fodder crops. Besides the changes in the crop yield, further environmental consequences of the installation of the PV facility are also assessed in the current study. The common functional unit (FU) of the two systems which are compared is thus the provision of a certain amount of food and fodder crops as well as the generation of electricity (Table 1). Crop yields are based on the average yield harvested in an agricultural system within an AVS field trial [20,29]. The electricity generated is based on the power generation of the AVS facility per year as measured in the context of the APV RESOLA project [23,30]. The agricultural production of the analysed four -year crop rotation as well as the electricity generation are calculated on a ha basis. Therefore, the yield of the four crops of the crop rotation is indicated in each case for 0.25 ha (Table 1).

Table 1. Functional unit (FM: fresh matter; DM: dry matter).

Reference Flow	Amount	Unit
Wheat grain	1.3	t DM yr^{-1}
Celery bulb	2.7	t FM yr^{-1}
Potato tuber	6.5	t FM yr^{-1}
Clover grass	1.6	t DM yr^{-1}
Electricity	713	MWh yr^{-1}

2.2. Methods

This study assessed the environmental performance of the AVS by conducting a CLCA following the structure of the ISO standards 14,040 and 14,044 [31,32], applying the 16 impact categories and assessment methods required by the Product Environmental Footprint (PEF) methodology of the European Commission [33]. The results are presented as a single score which can be derived through the aggregation of the results of all categories by the means of normalization and weighting [34]. In addition, there is a detailed presentation of the results of the most important impact categories defined as those impact categories contributing cumulatively at least 80% to the total score, starting from the most contributing impact categories to the less contributing ones. The three toxicity-related impact categories are excluded from the calculation of the single score as they are deemed not sufficiently robust [35]. In order to provide a holistic picture, they are still displayed in the result section.

The data used for modelling the foreground system such as the changes in crop yield, the electricity produced or the material needed for the mounting structure stem from an existing AVS which is installed on an organic managed farm near Lake Constance in the framework of the APV RESOLA project [15,20,23,29]. Additional technical details of the AVS system are described in Schindele et al. (2020) and Trommsdorff et al. (2021) [23,30]. Background data on emissions associated with the cultivation of the displaced crops or the production of the balance of system (BOS), which encompasses all components of the AVS and the mounting structure excluding the photovoltaic modules, are based on the ecoinvent database 3.8 using the consequential system model [36]. The environmental performance of the PV modules is estimated based on the Life-Cycle Inventory presented in Müller et al. (2021) [37]. Market datasets are used as these include average transport impacts [36]. The software openLCA 1.10.3 is used for modelling as well as for the impact calculation.

2.3. System Boundaries

In Figure 1, a schematic representation of the system under study is displayed. The main environmental consequences of the installation of an AVS are included in the present study. Therefore, the environmental impacts will be assessed of the production and installation of the AV facility on agricultural land. In addition, the changes in the output of the agricultural production system, due to variations in yield and area losses caused by the mounting structure, will be included through the substitution of the reduced productivity by marginal producers elsewhere in the world. In order to substitute these reductions in the output, 0.15 ha of additional agricultural land is needed to produce the same amount of crops as the reference system (see Figure 1). The electricity produced by the AVS will substitute the marginal electricity mix in Germany [38]. In accordance with other studies, the temporal boundaries of this study are based on an expected lifetime of the AVS of 25 years [21].

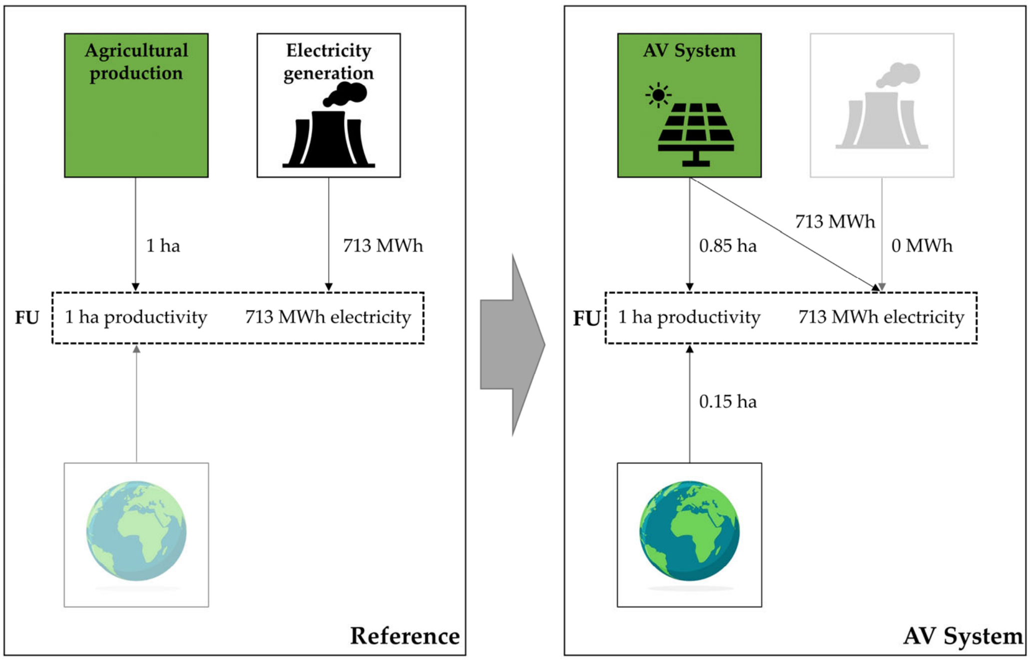

Figure 1. System boundaries for the AVS and the reference system which will be replaced.

Through the combination of energy generation and agricultural cultivation in the AVS, considerably less land is needed compared to the separate production of crops and energy [13,30]. Hence, it is hypothesised that more land becomes available due to decreasing electricity demand from external sources than additional land is needed to compensate for yield reductions in the AVS (Figure 1). The influence of the use of this land on the environmental consequences of the shift from single-use agriculture to an AVS is critically reflected on in the discussion section.

2.4. Life-Cycle Inventory

In Table 2, the yield of the four crops included in the crop rotation is displayed as a two-year average for the AVS, as well as the reference system (REF) based on Weselek et al. (2021a, b) [20,29]. As described above, the yields are significantly lower in the AVS (Table 2). This is mainly due to shading effects and area losses of 8.3% caused by the mounting structure. The yield difference caused by the change from the single-use reference system to the AVS must be substituted in case of the AVS by crop production elsewhere.

Table 2. Crop yields in the AVS and the reference system per ha.

Crop Yield	REF	AVS	Unit
Wheat grain	5.2	4.3	t DM ha^{-1} yr^{-1}
Celeriac bulb	10.8	9.4	t DM ha^{-1} yr^{-1}
Clover grass	6.6	5.6	t DM ha^{-1} yr^{-1}
Potato tuber	25.9	22.5	t DM ha^{-1} yr^{-1}

The marginal datasets which will be used to model the displaced crops in the AVS are based on the ecoinvent database, applying the consequential system model [36]. In the current study, the following datasets are used: "market for wheat grain, organic, global (GLO)", "market for celery, GLO", "market for ryegrass-red & Egyptian clover-mixture silage, GLO" and "market for potato, organic, GLO".

In Table 3, the materials needed for the mounting structure as well as the PV modules are summarized. The input data stem from the APV RESOLA project [15,23]. In addition, the ecoinvent datasets are stated which are used to model the environmental impacts of the components of the PV system (Table 3). Ecoinvent datasets are used for all components except for the PV modules. The environmental performance of the PV modules is estimated based on the Life-Cycle Inventory presented in Müller et al. (2021) [37], as it is the most up-to-date data available for bifacial modules as used in the APV RESOLA project. The electrical yield of the AVS is 713.4 MWh ha^{-1} yr^{-1} based on Trommsdorff et al. (2021) [30].

Table 3. Inventory of the components and materials used in the AVS.

Components	Unit	Amount	Material	Dataset Used
Pillar total	kg ha^{-1}	37,714	Steel	Market for reinforcing steel, GLO
Framework long total	kg ha^{-1}	36,809	Steel	Market for reinforcing steel, GLO
Table total	kg ha^{-1}	70,677	Steel	Market for reinforcing steel, GLO
PV-Module	m^2 ha^{-1}	3500	PV panel	Müller et al. (2021)
Inverter	kg ha^{-1}	797	Steel, copper, plastic	Market for inverter, 2.5kW, GLO
Control Unit	kg ha^{-1}	14	Steel, copper, plastic	Market for electronics, for control units
Wiring	kg ha^{-1}	846	Copper, plastic	Market for cable, unspecified, GLO

In Table 4, the marginal electricity mix in Germany is displayed. These are the fossil energy sources which are most likely to be substituted through an increase in solar energy, according to the German Federal Environmental Agency [38].

Table 4. Marginal German electricity mix [38].

Fossil Fuel	Marginal German Electricity Mix in %	Ecoinvent Dataset Used
Nuclear energy	0.5	Electricity production, nuclear, pressure water reactor, DE
Brown coal	17.5	Electricity production, lignite, DE
Hard coal	49.4	Electricity production, hard coal, DE
Gas	32.6	Electricity production, natural gas, combined cycle power plant, DE

3. Results

In the following, the results are shown for the consequences which arise from the change of 1 ha single-use agriculture to an AVS in Germany. The dimensionless single score results are presented in Figure 2, divided into benefits and impacts. The category benefit summarizes the negative environmental impact avoided through the substitution of the marginal German electricity mix by renewable energy provided by the AVS (Table 4). The category impact includes the production of the PV modules and the BOS as well as the substitution of the reduced agricultural productivity by marginal producers elsewhere in the world. In both categories, impact and benefits, the results are shown for all impact categories which have a share of more than 2%. The five categories which contribute less than 2% are summarized as rest (i.e., eutrophication, marine and terrestrial; ionising radiation; land use; ozone depletion).

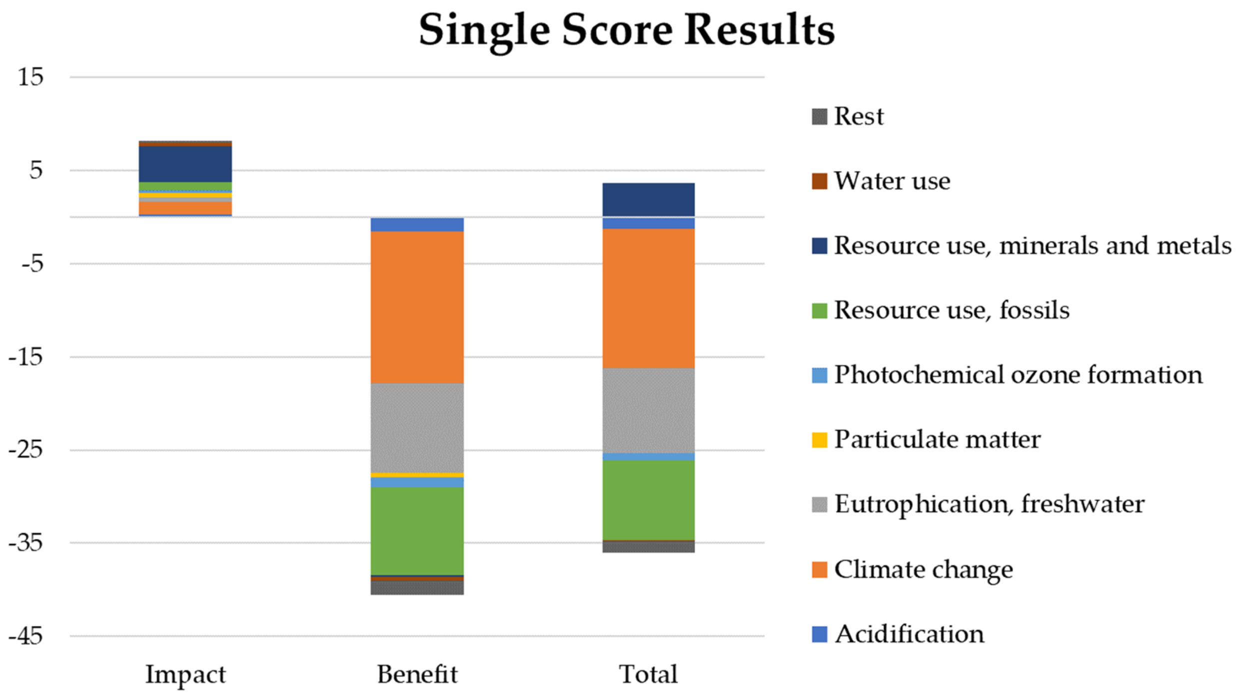

Figure 2. Environmental impact of the change of 1 ha single-use agriculture to an AVS in Germany presented as single score results per year.

The results clearly demonstrate that the change of 1 ha single-use agriculture to an AVS in Germany leads overall to considerable environmental benefits, especially in the categories of climate change, freshwater eutrophication, and fossil resource use. Only in the impact category resource use, minerals and metals, the change leads to a negative impact on the environment. In Table 5, the absolute and percentage contributions of the individual impact categories to the single score results are shown.

Table 5. Single score results of the change of 1 ha single-use agriculture to an AVS in Germany per year (n.a.: not applicable).

Impact Category	Absolute Values		In percent	
	Impact	Benefit	Impact	Benefit
Acidification	0.26	1.51	3.1%	3.7%
Climate change	1.43	16.34	17.4%	40.2%
Ecotoxicity, freshwater	0.86	3.01	n.a.	n.a.
Eutrophication, freshwater	0.47	9.60	5.7%	23.7%
Eutrophication, marine	0.10	0.59	1.2%	1.5%
Eutrophication, terrestrial	0.13	0.67	1.6%	1.6%
Human toxicity, cancer	0.17	0.10	n.a.	n.a.
Human toxicity, non-cancer	0.15	0.34	n.a.	n.a.
Ionising radiation	0.02	0.28	0.3%	0.7%
Land use	0.02	0.03	0.2%	0.1%
Ozone depletion	0.01	0.03	0.1%	0.1%
Particulate matter	0.46	0.50	5.6%	1.2%
Photochemical ozone formation	0.28	0.99	3.3%	2.5%
Resource use, fossils	0.86	9.49	10.4%	23.4%
Resource use, minerals, and metals	3.87	0.18	47.0%	0.4%
Water use	0.34	0.38	4.1%	0.9%
Total	9.42	44.04	100%	100%

Furthermore, there is a detailed presentation of the results of the most important impact categories defined as those impact categories contributing cumulatively at least with 80% to the total score. For the category impact, these are "resource use, minerals, and metals", "climate change" as well as "resource use, fossils"; for the category benefit, "climate change", "eutrophication, freshwater" as well as "resource use, fossils". The category impact thereby consists of the agricultural system (AS), which summarizes the substitution of the reduced agricultural productivity by marginal producers elsewhere in the world, and the BOS. The PV modules (PV) are displayed separately.

In Figure 3, the environmental consequences of the change of 1 ha single-use agriculture to an AVS are presented for the impact category climate change in t carbon dioxide equivalents (CO_2-eq.) based on 100-year Global Warming Potential values. The electricity generated by the AVS leads through the substitution of the marginal German electricity mix to a considerable reduction in the CO_2 emissions, especially through the substitution of electricity based on hard coal and lignite. The emissions of the AVS are mainly driven by the production of the PV modules and the BOS. In total, the change of 1 ha single-use agriculture to an AVS in Germany leads to a reduction in the impact category climate change of 572.94 t CO_2-eq.

The environmental consequences of the change of 1 ha single-use agriculture to an AVS in Germany for the impact category freshwater eutrophication are presented in Figure 4 in kg P equivalents. In total, the installation of the AVS leads to a reduction in freshwater eutrophication of 524.22 kg P eq. per ha. This reduction is mainly driven by the substitution of electricity based on hard coal and lignite by renewable energy produced by the AVS. The influence of the environmental impacts associated with the production of the AVS on the results are negligible for this impact category.

In Figure 5, the environmental consequences of the change of 1 hectare single-use agriculture to an AVS are presented for resource use, fossils in GJ. The electricity generated by the AVS causes the substitution of the marginal German electricity mix and leads thereby to a considerable reduction in fossil resource use, especially through the substitution of electricity based on hard coal, gas and lignite. In total, the change from single-use agriculture to an AVS in Germany leads per ha to a reduction in the impact category resource use, fossils of 6745 GJ.

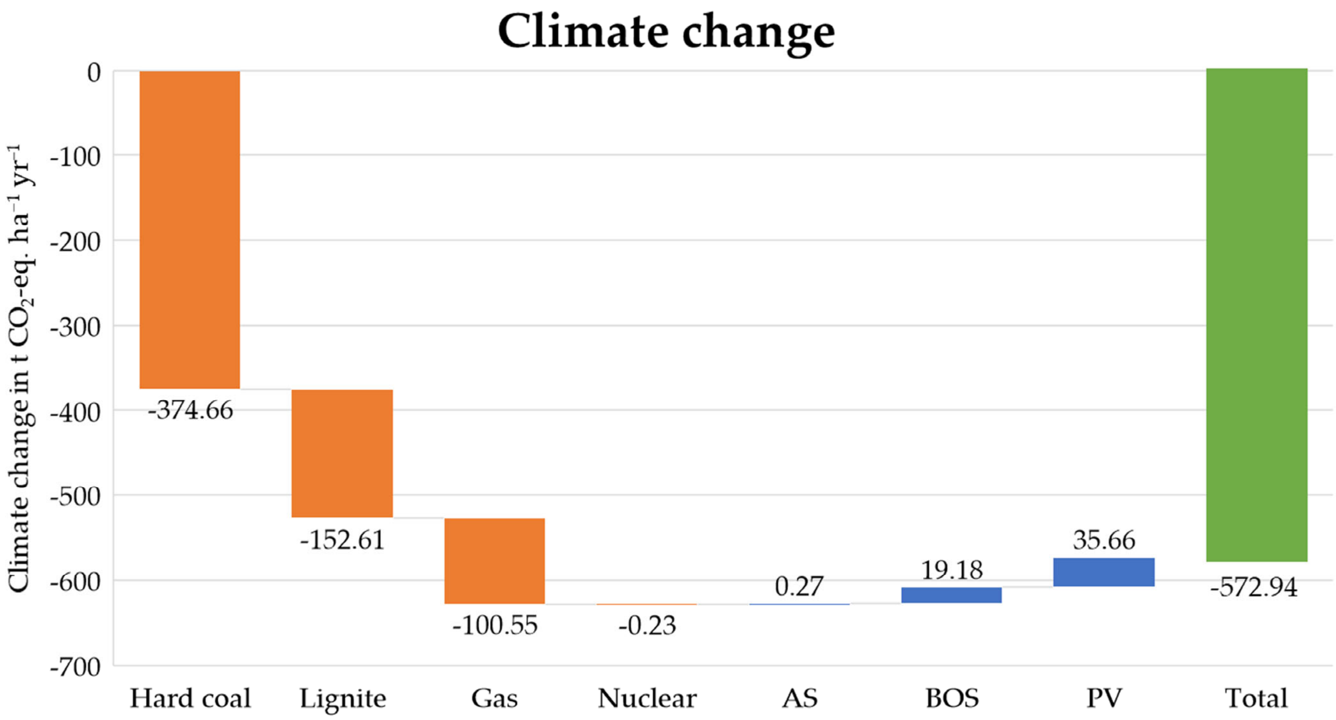

Figure 3. Environmental impact of the change of 1 ha single-use agriculture to an overhead AVS in Germany in the category climate change per year (AS: agricultural system, BOS: balance of system, PV: PV modules).

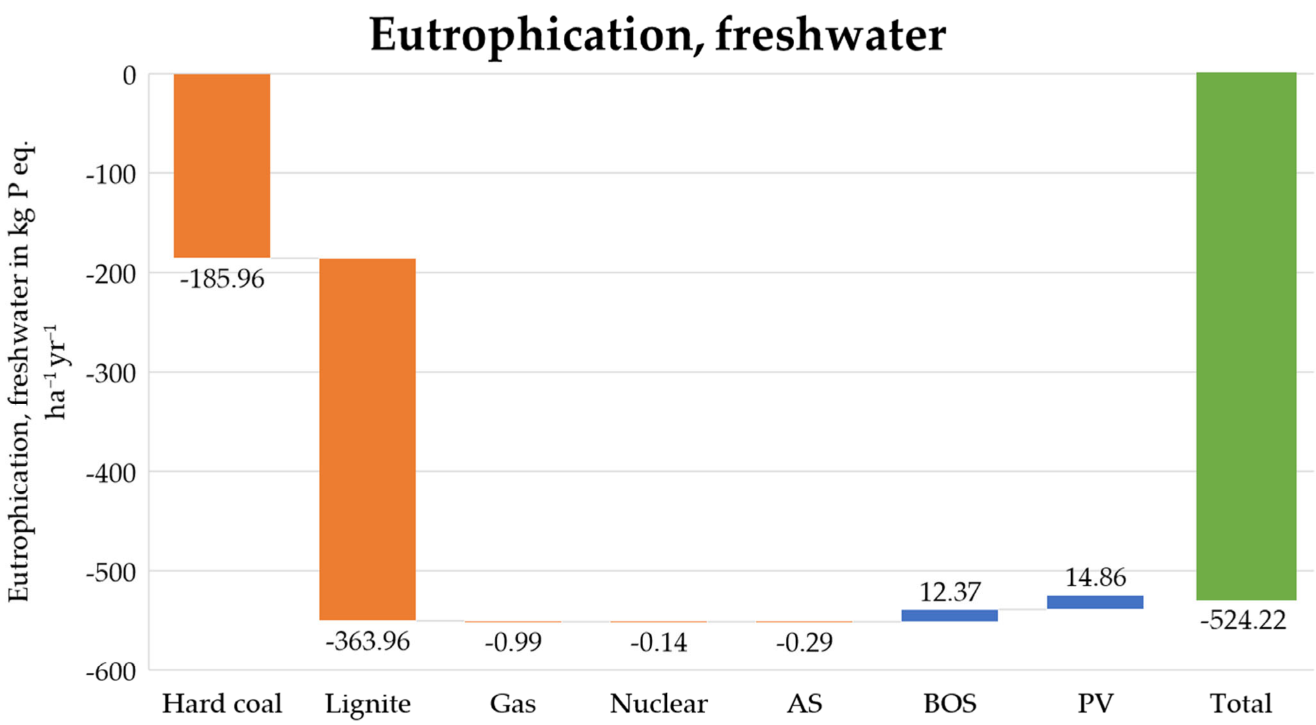

Figure 4. Environmental impact of the change of 1 ha single-use agriculture to an overhead AVS in Germany in the category eutrophication, freshwater per year (AS: agricultural system, BOS: balance of system, PV: PV modules).

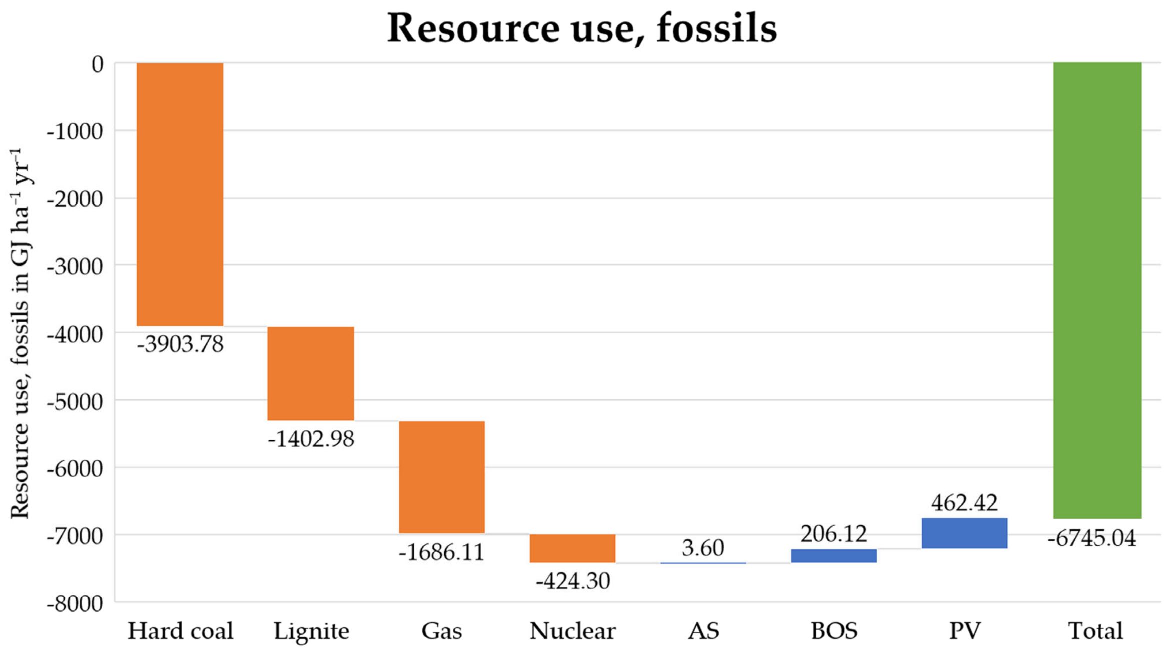

Figure 5. Environmental impact of the change of 1 ha single-use agriculture to an overhead AVS in Germany in the category resource use, fossils per year (AS: agricultural system, BOS: balance of system, PV: PV modules).

Resource use, minerals and metals is the only impact category analysed in the current study where the change from single-use agriculture to an AVS leads to a net negative impact (Figure 6). This is mainly caused by the resources needed to produce the PV modules as well as the balance of system, including the mounting structure, the inverter, and the control unit, as well as the wiring. In total, the change of 1 ha single-use agriculture to an AVS in Germany causes an increase in the impact category resource use, minerals and metals of 3.118 kg Sb equivalents.

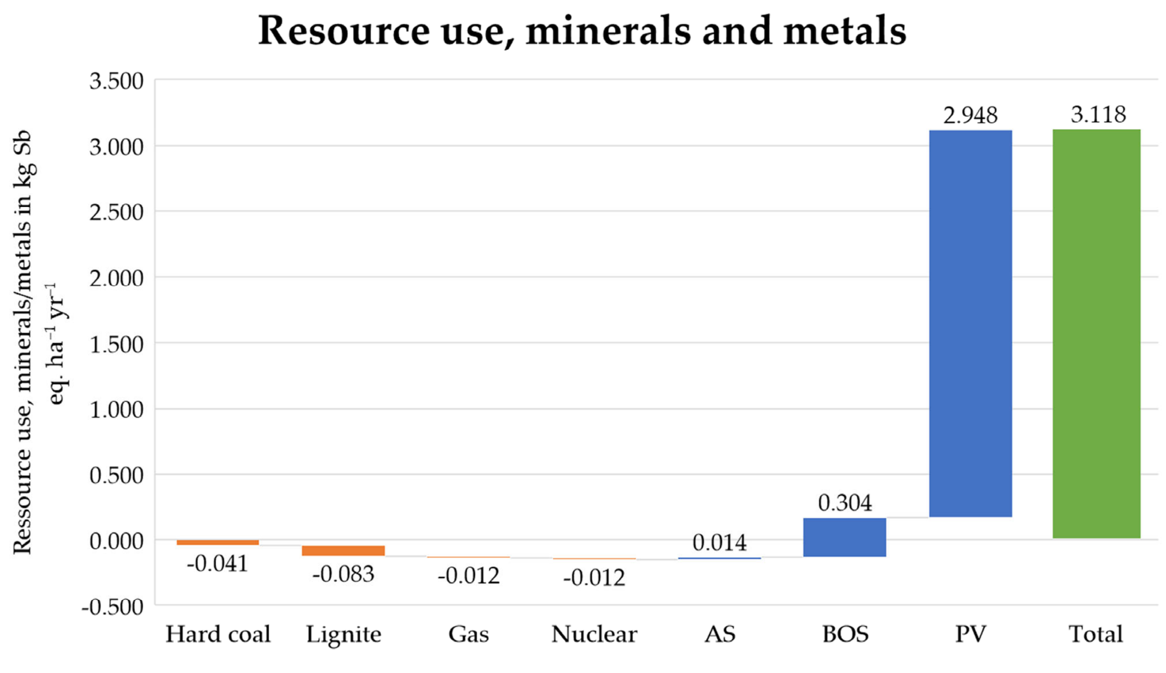

Figure 6. Environmental impact of the change of 1 ha single-use agriculture to an overhead AVS in Germany in the category resource use, minerals and metals per year (AS: agricultural system, BOS: balance of system, PV: PV modules).

4. Discussion

The current study assessed the environmental impact of the change of 1 ha single-use agriculture to an overhead AVS in Germany. The results of the study show the positive impact on the environment occurring as a consequence of this change. In the following, these results will be reviewed with respect to the main contributors. Furthermore, they will be compared to other studies which assessed the environmental performance of different AVS. In addition, the robustness of the results will be critically discussed with regard to the input data used as well as the assumptions made.

4.1. Environmental Performance

The results of the current study clearly demonstrate the positive environmental impacts which arise as a consequence of the installation of an AVS on agricultural land. This land-use change leads to environmental benefits in 15 out of 16 impact categories assessed. Only in the impact category "resource use, minerals and metals", the production of the PV modules and the balance of system elements causes a net negative impact on the environment. In the other relevant impact categories, the substitution of the marginal electricity mix, and here especially the substitution of the electricity production based on hard coal and lignite, is the dominating influence on the results. The influence of the agricultural system on the results is negligible. This is due to the comparatively low negative impact of the PV modules on the yield of the crop rotation cultivated underneath [20,29]. Besides the specific impact categories, single score results were calculated, which can be derived through the aggregation of the results of all categories by the means of normalization and weighting. They clearly demonstrate that even under consideration of environmental trade-offs, the net environmental impact of the installation of an AVS on agricultural land in Germany is positive under the given conditions.

The main reason for the relatively low influence of the impact category "land use" on the final results is that the positive impacts through the dual use of the area are only insignificantly larger than the negative impacts caused by the additional land used for the substituted crops which have to be replaced elsewhere. The substitution of the marginal energy mix leads to a release of land which is no longer used for electricity production. Therefore, this could be used for other purposes such as agricultural production or allocated as ecological zones [39]. This could at least partially compensate for the additional cultivation area needed for the displaced crops and the land use caused by the production of the AVS (including BOS and PV modules), and therefore offer the possibility to extend renewable energy production without reducing food production resources. However, this strongly depends on the quality of the land released, for example, in regard to soil quality [40] or the time needed to recultivate the land which was formerly used for electricity production. In case the quality of the land is significantly lower, the yield of the crops would also be diminished, and more land would be needed to produce the crops which were displaced through the AVS. This could pose the risk of a net increase in land use and therefore lead to indirect land-use change. This risk could be amplified through such AVSs, which focus more on maximizing the renewable electricity generation, which is more profitable, than on the agricultural production, whereby the agricultural yield reduction per ha due to the installation of the AVS increases. Therefore, it is crucial to develop a definition of AVSs which clearly states to which extent the main agricultural crop production has to be maintained, for example, in regard to the yield level [23]. The German technical rule DIN SPEC 91,434 specifies for the first time requirements for primary agricultural use in AVS: For high elevated overhead AVS such as the APV RESOLA research facility, the loss of arable land should not exceed 10% and the yield of the crops on the total area of the AVS should be at least 66% of the reference yield [16]. In addition to these specifications, synergetic AVS should focus on crops which are expected to substantially benefit from the shading or sheltering effects in terms of increased yields, such as certain tree fruit, horticulture or berry crops [15]. Another possibility to reduce the risk of land-use conflicts is the exploitation of integrated PV potential for instance on rooftops, building-integrated, along highways or in anti-noise barriers at railways, and the installation of PV systems on other idle land, where currently no food or biomass crops are cultivated. However, in view of the strong increase in demand for renewable energies, this is not likely to be an either-or decision.

Several other studies assessed the environmental performance of different AVSs [21,24,41,42]. A direct comparison of the results is not possible due to differences in the goal and scope of the studies as well as in the selected methodological approach. The development of a common methodological framework could be an important step in increasing the comparability of the LCA studies on AVS. However, they also show, in line with the current study, that AVS lead to considerable reduction in the emission of GHGs and in the depletion of fossil fuels in comparison to electricity produced by fossil sources [21,41].

4.2. Critical Evaluation of the Data Used and Assumptions Made

The data used for the Life-Cycle Inventory has a considerable influence on the results of the LCA. The impact of the agricultural system strongly depends on the crops which are cultivated beneath the PV modules and how sensitive these crops are to shading. Depending on the shade tolerance of the different crops, the shade produced by the PV modules can have positive or negative effects on the crop yield [15,43]. However, this effect strongly depends on the climatic conditions in the respective year. Weselek et al. (2021) [20] showed that in the hot and dry summer of 2018, the shading of the PV modules had a positive effect on crop yields. For example, in the case of organically grown potato, harvestable yields increased by up to 11% compared to the unshaded reference area. That means that, with the ongoing increase in annual temperature through the climate change, it can be expected that the positive impact on the crop yield through the AVS will increase. This leads to less crops which need to be substituted elsewhere in the world and thus to an improved environmental performance of the AVS. By using the land twice, less land is needed in comparison to the separate production of agricultural crops and electricity generation [30]. That means that, as a consequence of the change of 1 ha single-use agriculture to an overhead AVS, land becomes available for other uses such as reforestation. In addition, the strips between the pillars of the mounting structure which are currently not cultivated could be used as biodiversity areas, for example, in the form of flower strips, further strengthening the environmental performance of the AVS [20]. However, it should be avoided that the introduction of flower strips supports the proliferation of problematic weeds [44].

Besides the agricultural production, the system under study and the datasets used in the assessment of the AVS also have a significant impact on the results. Agostini et al. (2021) [21] assessed the environmental performance of different AVSs and showed considerable differences depending on the type of mounting system used, as well as the sun tracking configurations. For example, when comparing the steel needed for the mounting structure per kilowatt-peak (kWp), it can be derived that the Italian cable-post design with one-axis tracked AVS described by Agostini et al. (2021) accounts for 156.6 kg kWp^{-1} for the mounting system. This is a -39% reduction compared to the first-generation design used in the APV RESOLA research facility with around 250 kg kWp^{-1}. In addition, limited data availability and outdated datasets for system components are a common issue in the LCA context, restraining validity of such sustainability studies [45]. Therefore, as long as no standardized datasets for AVS exist, primary data collection is essential.

In the current study, the substitution of the marginal German energy mix has the greatest influence on the results. According to the Fraunhofer Institute for Solar Energy Systems ISE, renewable sources provided 45.8% of the German electricity consumption in 2021 [46]. According to current discussions towards an amendment of the German Renewable Energy Sources Act, the share of renewable energy sources in the gross electricity consumption in Germany is planned to increase to at least 80% in the year 2030 and should reach 100% by 2035 [47]. As AVSs have an expected lifetime of 25 years [21], the marginal energy mix will change significantly in the coming years, and therefore also the environmental consequence of the change of single-use agriculture to an AVS. In this context, it is reasonable to assume that the share of fossil energy sources in the marginal electricity mix in Germany will reduce over time, and thus also the positive environmental consequences of AVS installation on agricultural land will be reduced. Agostini et al. (2021) [21] compared the environmental performance of an AVS with other PV systems and electricity generated by biogas plants. Their study showed that the environmental performance of electricity produced by AVS is similar to other PV systems and considerably better compared to the environmental performance of biogas plants. Only compared to electricity produced by wind energy was the environmental performance of the AVS worse [21]. These results demonstrate that, even when the marginal electricity mix is changing over time, the environmental consequence of the change of 1 ha single-use agriculture to an AVS can still be positive. However, with an expansion of intermittent electricity generation such as PV, also the demand for energy storage systems increases, which affects the environmental impact of the energy provision [48].

The time dependency Is not only crucial for the composition of the marginal energy mix but also for the expected lifetime of an AVS. In the current study, a lifetime of 25 years was assumed in accordance with Agostini et al. (2021) [21]. However, this has to be seen as a cautious assumption. The International Energy Agency (IEA) assumes a lifetime of 30 years for the PV modules and a lifetime for up to 60 years for the mounting structure [45]. That means that, in practice, the influence of the mounting structure on the environmental performance is considerably smaller, as it is possible to repower the mounting structure after 30 years with new PV modules.

In addition, when evaluating the results of this study, it must be considered that the study only assesses the resource use impacts as well as the impacts on ecosystems and human health. The consequences of the change of 1 ha single-use agriculture to an AVS in Germany on regulating, maintenance and cultural ecosystem services, such as biodiversity or soil quality, are currently not assessed within the scope of the LCA method, as van der Werf et al. (2020) [49] showed. Further assessments are necessary in order to holistically analyse the impact of AVS installation on agricultural land availability and the overall consequences for food production.

5. Conclusions

In summary, the results of the study show that the environmental consequences of the installation of an AVS on agricultural land are positive and reduce the impacts in 15 of the 16 analysed impact categories as well as in the single score assessment, mainly due to the substitution of the marginal energy mix. It was demonstrated that, under certain conditions, an AVS can contribute to the extension of renewable energy production without reducing food production resources. However, in order to achieve this, agricultural production and yields underneath the PV modules have to be maintained and the loss of good agricultural land has to be minimised. This can be done through the selection of shade-tolerant crops which benefit through the installation of the AVS or by adjusting the shading level of the AVS to the specific crops.

In addition, the mounting structure has to be further optimized, thereby not only leading to a decrease in the environmental impact but also in the loss of land. However, it must be emphasized that, in the process of optimizing the BOS as well as the PV modules, the focus has to be on the overall system and not purely on optimizing electricity production. Therefore, the legal framework and the financial support instruments for AVSs should include clear rules for maintaining agricultural yields and minimising the loss of good agricultural land.

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