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Environmental life cycle assessment of a stilted and vertical bifacial crop-based agrivoltaic multi land-use system and comparison with a mono land-use of agricultural land

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ABSTRACT

Agrivoltaic, the use of agricultural land for food/feed and electricity production via photovoltaic-modules, has been promoted as a possible solution to alleviate the land use conflict of arable land. This study aims to compare two agrivoltaic systems (stilted and vertical bifacial) from cradle-to-gate with the life cycle assessment method using a system expansion approach. Further, an unmodified agricultural production and total substitution of the latter by photovoltaic-modules (photovoltaic-scenario) are assessed. For an objective comparison the same outputs must be produced in every scenario. Hence, in the unmodified agricultural scenario an additional production chain for electricity (Austrian average or green electricity production) was added; while agricultural production was added in the photovoltaic-and stilted agrivoltaic scenario. Results show, that the photovoltaic system has higher (up to 99.32 %) environmental impacts than the agricultural system in all studied impact categories in all scenarios. Compared to the unmodified agricultural scenario with Austrian average electricity both agrivoltaic systems can reduce environmental impacts in 3 of 9 assessed impact categories, but in none compared to the unmodified agricultural scenario with green electricity. A hotspot in both agrivoltaic and photovoltaic-scenario is the photovoltaic-module production in China, due to the high demand and impact of electricity, in the stilted agrivoltaic scenario further the resource intensive steel mounting structure. Reduction potential of environmental impacts with a production in Europe is possible. Overall, it is demonstrated that agrivoltaic systems can reduce environmental impacts in some categories compared to the unmodified agricultural scenario with Austrian average electricity.

1. Introduction

Climate neutrality by 2050 is the main goal of the European Union's (EU) Green Deal besides the aim to support sustainable practices (e.g., circular economy, efficient use of resources) which is, among other things, regulated in the EU-taxonomy [1]. To become climate neutral requires a transition to clean energy production. An additional 48 GW of solar PV and 36 GW of wind electricity are required annually to have an approximately 70% share of renewable electricity in the EU by 2030 [2]. Both types of production reduce the emissions of greenhouse gases drastically, but especially large-scale photovoltaic plants require land area. The needed expansion of PV electricity, nevertheless is not practically feasible on roofs only, underlining the indispensability of ground mounted PV installations on other areas, such as landfills, parking spaces, but also agricultural areas.

The use of agricultural land for electricity production is a controversial topic, due to land use conflicts with food/feed/fibre and electricity production [3]. One solution to alleviate these competing interests is agri-photovoltaics/agrivoltaics (APV), which is the combined use of agricultural land for food/feed (primary use) and PV based electricity production (secondary use) [4]. The advantage of the combined utilisation can be shown with land equivalent ratios (LERs), which are indicators for the productivity of land units with more than one type

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Abbreviations

APV	Agri-Photovoltaic/Agrivoltaic
CC	Climate Change
CH4	Methane
CO2	Carbon Dioxide
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
Eq	Equivalent
EU	European Union
FE	Freshwater Eutrophication
FM	Fresh Matter
FPMF	Fine Particulate Matter Formation
FRS	Fossil Resource Scarcity
FU	Functional Unit
GHG	Greenhouse Gas
HCT	Human Carcinogenic Toxicity
HNCT	Human Non-Carcinogenic Toxicity
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
K2O	Potassium Oxide
LER	Land Equivalent Ratio
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
MRS	Mineral Resource Scarcity
MC	Monte Carlo
N2O	Dinitrogen Monoxide
P2O5	Phosphorus Pentoxide
PV	Photovoltaic
SALCA	Swiss Agricultural Life Cycle Assessment
SD	Standard Deviation
Si	Silicone
S-APV	Stilted APV
TAP	Terrestrial Acidification
TEP	Terrestrial Ecotoxicity
VB-APV	Vertical bifacial APV

of production [5]. A monoculture system (either solely agricultural or electricity production, respectively) has a LER of 1; while LERs higher than 1 were reported for APV systems (e.g., Refs. [5–8]). Simulations by Amaducci et al. [9] even found values up to 3.

In the DIN SPEC 91434 [4], which is an attempt of a uniform standardisation of APV systems, two different categories are reported: (1) Stilted APV systems (S-APV), which are installations with a clear height of at least 2.10 m, in which agricultural production is performed under the APV system; and (2) ground level installations (either PV-modules permanently installed on one or two stilts or adjustable or vertically mounted PV-modules on a stilt) with farming performed between the APV system rows. The vertically mounted system is often combined with bifacial PV-modules. The stilted system is the most widespread system [10], especially for research facilities.

In the last decade APV has been a popular topic of research due to its promising characteristics. So far, several studies provided information on impacts of crop production in different APV systems (e.g., Refs. [5,9,11]), microclimatic changes (e.g., Refs. [12–15]) or combined techno-economic or sole economic analysis (e.g., Refs. [16–18]). However, it was already pointed out that assessments of the environmental impacts of APV systems are required [9]. Still, the respective literature is limited so far. Agostini et al. [19] only assessed the PV system of two stilted APV-plants and compared it to conventional and renewable electricity production systems and found that their tensile overhead system is comparable with other PV systems in economic and ecological terms. The agricultural part was not assessed by Agostini et al. [19], so no holistic environmental assessment of APV was made. Leon and Ishihara [20,21] enhanced the life cycle assessment (LCA) methodology for application on APV systems by developing a solar allocation approach and further by proposing new functional units (FU) (a modified area-based and a monetary FU). Both novel approaches were only tested on greenhouses and no further APV systems, further only focusing on the climate change (CC) impact category, which is only one of many existing ones. Pascaris et al. [22] and Handler and Pearce [23] conducted an integrated assessment of PV electricity production and animal husbandry and further comparing it to conventional production systems (conventional animal husbandry with either solar PV or different grid electricity mixes) by using a system expansion approach. Both found a possible reduction for CC impacts in the integrated production, but only assessed one more possible environmental impact (cumulative energy demand and Ecotoxicity indicator). Another LCA was conducted by Choi et al. [24] who did a comparison of a hypothetical co-located land use for small-scale electricity and patchouli production with a hectare of solar PV at full and half density to assess trade-offs and synergies in terms of land use, energy and GHG emissions. Recently, Wagner et al. [25] assessed the shift from solely agricultural production to a stilted APV system with a consequential LCA and assumed that the electricity produced in the APV system substitutes fossil energy sources which are most likely to be substituted by renewables in Germany consisting mainly of hard coal (49%), gas (33%) and brown coal (18%). The LCA assessed for the first time holistically impacts of an APV system by including both electricity and the agricultural part and further including 16 environmental impact categories from the Product Environmental Footprint impact assessment method. Still, only one type of APV system was assessed.

To the knowledge of the authors, there are no studies comparing a vertical bifacial APV system to a stilted APV system and an in-depth overall comparison of both crop-based APV systems with mono-use scenarios. This comparison is crucial for understanding overall impacts of APV systems compared to status quo scenarios or alternative uses of agricultural areas in order to give policy makers a reason for decision if APV can support a decrease of environmental impacts compared to the status-quo electricity production mix by simultaneously being conform with EU-taxonomy requirements. Results will also help to design APV systems in a way to produce high output in a sustainable way by demonstrating efficient land management and technology choices.

Therefore, the novelty of this work is to fill the current knowledge gap in literature as a first step for the case study region of Austria by conducting a life cycle assessment of two crop-based APV systems (stilted and vertical bifacial) for typical Austrian production systems to assess overall environmental impacts of such systems. Another novelty is that these results are further compared to two mono-use scenarios of agricultural land: (1) unchanged agricultural production (Agri-scenario), and (2) total substitution of agricultural management with PV-modules (PV-scenario).

2. Material and methods

2.1. Agricultural background

Although the environmental life cycle assessment was carried out for the whole of Austria, there is a wide variety of agricultural practices, which cannot be all displayed in this work. Therefore, a few assumptions regarding the agricultural production needed to be made. For this study the focus is on arable land, permanent grasslands are not taken into account. However, even agricultural crop production in Austria is very diverse, with the majority being produced on arable land in the far east. Further, when assessing agricultural systems with a holistic approach it is necessary to include whole crop rotations, since crop-based (APV) systems need to perform not only for one season, but for praxis relevant time frames. This means to cover a crop rotation that can be repeated and is representative for an average Austrian production system.

Crop rotations are very diverse and depend on a number of factors, such as soil type and weather conditions, structural and economic factors [26] as well as machinery and labour endowment of the farmer [27]. Hence, for this study a crop rotation is covered that is defined for the specific location of Bruck an der Leitha in the east of Austria and reflecting a typical location with the main focus on crop production.

The crop rotation is based on data from the tool 'AMA Flächenauswertung' [28] to assess which crops are mainly produced in this area; further crops are selected that do not grow too high in order to avoid shading of PV-modules by crops. Based on this information the following crop rotation is used in this work: sugar beet – winter wheat – soybean – winter wheat. Green manure is assumed to be planted before sugar beet and soybean production, respectively, to protect the soil-borne nitrogen from leaching and make it useable for the following crop (defined as good agricultural practice).

So far, little practical knowledge is available about the effects on yields of different crops in APV systems, since no long-term experiments with relevant repetitions are published (see Ref. [29] for a short overview of yield reduction in APV systems). As long as these long-term data of yield changes under APV systems for Austria are not available, the 10-year average yield of 2011–2020 of Austrian production from Statistik Austria [30] of every crop is used, respectively, which is displayed in Table 1. The influence of a potential decrease in yields under APV systems on environmental impacts is examined in section 4.2.

Another assumption regarding the agricultural production is that the headland is not assumed to be part of the systems. This is the case because the arrangement and shape of the headland is very dependent on the actual conditions. Since only hypothetical systems are used in the study, it is neglected.

2.2. Comparability of scenario outputs

In this study four main scenarios are assessed, which are the multi-output APV systems (stilted (S-APV) and vertical bifacial (VB-APV)), and the mono-use of land for either agricultural production (Agri-scenario) or electricity production (PV-scenario). In every scenario a different amount of electricity and crops are generated, an overview is given in Table 1. Electricity production is based on simulations from Mikovits et al. [31], while the output of agricultural crops is based on the 10-year average yield of the years 2011–2020 of Austria [30] and the assumed available area for agricultural production. The outputs of electricity production and all crops refer to a cultivation period of 4 years, i.e., one single pass through the assumed crop rotation.

There are different ways described in the International Organization for Standardization (ISO) 14044 [32] how to deal with multi-output systems in LCA. In principle, allocation shall be avoided, by either dividing the affected processes in sub-systems or by expanding the product system to consider additional functions related to the co-products. In this study the second option was used, implying that, if needed to deliver the same system output, the studied systems were expanded, making the systems comparable without using allocation factors, which can lead to inconsistent results (see e.g., Krexner et al. [33]).

Table 1
Overview of outputs of all assessed scenarios over the timespan of 4 years which is representing one crop rotation. The crop rotation consists of sugar beet, winter wheat, soybean and again winter wheat. The yield of agricultural crops in the Agri-scenario is the 10-year average yield of the assessed crops, respectively, based on data from Statistik Austria [30] and is used for the yield calculation in the APV-scenarios based on how much land is available for agricultural production (see section 2.3.2.1). Due to the use of rounded values in the table, inaccuracies of ±1% may occur.

Scenario	Electricity [MWh $(4a)^{-1}$]	Crops [t fresh matter ha^{-1}]			
		Year 1 (Sugar beet)	Year 2 (Winter wheat)	Year 3 (Soybean)	Year 4 (Winter wheat)
S-APV	1629.00	69.35	5.41	2.65	5.41
VB-APV	1196.00	65.52	5.12	2.50	5.12
Agri		72.24	5.64	2.76	5.64
PV	3492.00				

2.3. Life cycle assessment

Life cycle assessment is used to estimate environmental impacts of a product or a service throughout its entire life span (e.g., production of raw materials, manufacturing, use, end-of life treatment, recycling and disposal of the product). The methodological framework is based on the ISO standard 14040 [34] and 14044 [32]. An LCA includes four phases: the goal and scope definition, the life cycle inventory (LCI) analysis, the life cycle impact assessment (LCIA) and finally the interpretation of the results [34]. The application of the LCA methodological framework on the before mentioned scenarios is explained divided in the four phases in the following sections.

2.3.1. Goal and scope definition

The goal and scope of this study is to compare the environmental impacts of the parallel production of electricity and crops on one plot (S- and VB-APV plants) with a mono-production; either sole agricultural or PV-electricity production (Agri- or PV-scenario).

Since the advantage of the APV concept is the parallel production of energy and crops on the same agricultural land, it was essential to consider both outputs in the definition of the functional unit, which is the reference to which all inputs and outputs are referring to [34]. For reasons of comparability this FU also has to be applied to the mono-production scenarios making system expansion necessary in order to produce the same benefit across all scenarios [35,36]. This means that in every scenario the FU consists of two parts: (i) the provision of energy in the form of electricity and (ii) the provision of crops in the form of agricultural output (sugar beet, winter wheat and soybean).

Having comparable electricity and food outputs via system expansion leads to systems that go beyond the consideration of solely the individual plot of arable land with the consequence of different sizes and quality of land being consumed, see Table 2. An assessment comparing just the system output of 1 ha of arable land is therefore not applicable if a holistic and fair comparison of the provision of outputs is the objective.

The basis for the first part of the FU is the electricity production of

Table 2
Agricultural land use for all assessed scenarios.

Scenario	Agricultural area used for			Additional area needed to fulfil functional unit	Total area
	APV-plant	solely agricultural production	solely PV-electricity production		
[ha]					
S-APV	2.32	/	/	0.42	2.74
VB-APV	2.92	/	/	/	2.92
Agri-AUT	/	2.65	/	/[a]	/[a]
Agri-green	/	2.65	/	/[a]	/[a]
PV	/	/	1	2.65	3.65

[a] The system was only expanded for agricultural land use due to a wide variation of numbers reported for land use of electricity production. Therefore, the additional area needed to fulfil the functional unit and the total area demand for Agri-AUT and Agri-green are not displayed.

the PV-scenario over four years on 1 ha (since the highest amount of electricity is produced in this scenario), which corresponds to 3492.50 MWh. For the second part of the FU the highest amount of crops produced in all assessed scenarios is set as basis. In the VB-APV plant the highest total area is required to produce the electricity output, which is around 3 ha. Therefore, the amount of food produced on 3 ha over the time-frame of four years (one full crop rotation, see section 2.1) is calculated and set as basis: 191.30 t fresh matter (FM) sugar beet, 7.30 t FM soybean and 29.90 t FM winter wheat (numbers rounded).

For simplicity and clarity, these numbers are scaled down to the production of 1 kWh of electricity, which sets the FU to 1 kWh_{el} combined with a basket of agricultural crops consisting of 54.76 g FM sugar beet, 8.55 g FM winter wheat and 2.09 g FM soybean. Using a mixed FU, based on a system expansion approach makes it necessary to expand the Agri-scenario to also produce electricity and to expand the PV-scenario to produce food and even the S-APV scenario (producing electricity and food) needs to be expanded by average Austrian food production to produce enough crops to fulfil the FU (see Figs. 4–6).

The Agri-scenario is expanded by using diverse electricity mixes to cover the additional production. The choice of an electricity mix is very important as the related environmental impacts differ greatly: for the consumption mix of Austria a CC impact of 220 g carbon dioxide (CO_2) equivalent (eq.) kWh^{-1} is reported, for the production mix 180 g CO_2 eq. kWh^{-1} and for a green electricity mix (Umweltzeichen “Grüner Strom") a CC impact of 10 g CO_2 eq. kWh^{-1} [37].

A cradle-to-farm gate approach is used, which means that in the end the crops are available at the farm gate, while the electricity is ready for use by consumers at a low voltage level, including 5.33% transformation losses from high to low voltage level [38].

2.3.2. Life cycle inventory

The database ecoinvent v3.8 cut-off [39] was used for background data and as a basis for processes that are adjusted to Austrian conditions based on primary and secondary data from literature. The software applied is openLCA v 1.10.3 [40].

2.3.2.1. Stilted and vertical bifacial APV-scenario. In the S-APV plant the PV-modules are stilted from ground on a steel structure including ground anchoring and agricultural production is performed underneath. The used S-APV plant (see Fig. 1) is based both on the APV system described by Amaducci et al. [9] and Agostini et al. [19], as well as on the Heggelbach APV research site in Germany [8,25]. PV-modules with mounting structure are arranged in rows 12 m apart. On one hectare 2048 mono-silicone (Si) PV-modules are installed, which adds up to approximately 430 kWp per hectare. As model PV-module, a mono-Si module with aluminium alloy, 210 Wp, 28 kg and an area of 1.62 m^2 per module is used. In the first year a degradation of 2.67% of the PV-module is assumed, in the remaining lifetime the annual rate is 0.64% [41]. To protect mounting posts, an intermediate strip of 0.5 m is assumed to be located directly under the modules, which is mowed once a year. Hence, in total, 96% of the stilted APV plant area can be used for agricultural production, while the rest is needed for the mounting structure as well as the intermediate strip. A North-South orientation (azimuth of 0°) and a zenith angle of 35° are assumed [31].

In the vertical bifacial APV (VB-APV) plant two PV-modules are mounted on top of each other on a mounting structure consisting of two posts with included ground anchoring, three crossbars and respectively three module holders per module, see Fig. 2.

The design of the system is based on own assumptions (e.g., interrow space) and personal communications with stakeholders (e.g., material consumption for mounting structure with anchoring) [Next2Sun GmbH, 2021 (personal communication)]. The distance from ground to the bottom edge of the lower installed module is 1 m. An interrow space of 10 m is assumed with an intermediate strip of 0.4 m on each side of a row, which is mowed once a year. In Fig. 3 the layout of the VB-APV plant is displayed.

A bifacial mono-Si PV-module without aluminium frame, 415 Wp, 21.50 kg, and an area of 2.07 m^2 per module is assumed. Degradation rates for glass-glass modules are slightly less than for the glass-foil PV-modules with 2.55% in the first year and 0.45% for the remaining life span [41]. On one hectare 840 modules can be installed, which sums up to 348.60 kWp ha^{-1}. A total of 90.69% of the area can be used for agricultural production, while the rest is needed for the mounting structure (1.55%) and as buffer zone (7.76%). As common for such a system an East-West orientation (azimuth of 90°) is assumed with a vertical installation of PV-modules (90° zenith angle) [31].

To provide the same outputs in every scenario an additional production of crops is needed in the S-APV scenario (see Fig. 4), which are provided by average Austrian production processes (same supply chains as in the Agri-scenario, see section 2.3.2.2), while the VB-APV scenario needs no system expansion, since both the outputs electricity and crops are provided in the right amount by the assessed APV-plant, see Fig. 4.

For both APV-scenarios the PV-module as well as the mounting structure lifetime is assumed to be 30 years, the one of the inverter is assumed to be 15 years [43]; therefore, the input of the latter are adjusted according to the needed lifetime to fulfil the FU. Both the production of the module as well as of the inverter is assumed to take place in China according to data from Masson and Kaizuka [44] and subsequently transported to Europe by ship over the distance of 19,994

Fig. 1. Example of a stilted APV-plant (Photo taken by Theresa Krexner, 2021).

Fig. 2. Example of a vertical bifacial APV-plant (Next2Sun Technology GmbH [42]).

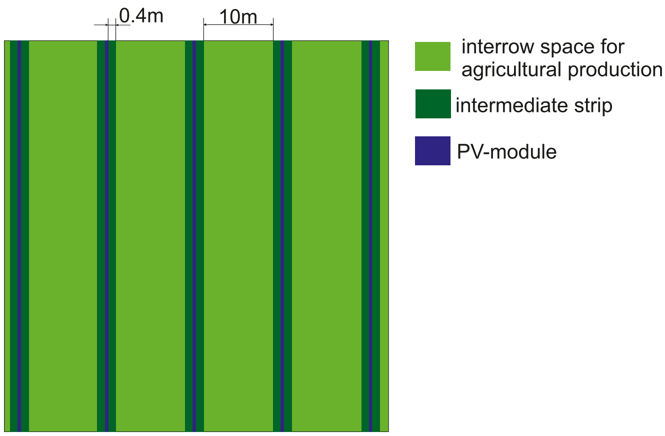

Fig. 3. Layout of the hypothetical VB-APV plant assessed in the study. The displayed scale is for illustration only and does not cover the whole plant area.

km [43].

PV-module production is based mainly on the LCI from Müller et al. [41] as the data is state-of-the-art of the industry. For the S-APV scenario the use of a glass-foil module is assumed, for VB-APV-scenario the glass-glass module. The LCIs for both module types also contain data from the ecoinvent database v3.8 [39]; transport distances for materials like chemicals is used from Frischknecht et al. [43]. For both APV-scenarios an additional PV-module demand of 3% is assumed due to needs for replacing damaged modules as well as losses during handling according to Frischknecht et al. [43] (see Table 3).

The mounting structure for S-APV is assumed to be mainly made of reinforcing steel (36.23 kg m^{-2} PV-module) and to a lesser extent of aluminum (1.76 kg m^{-2} PV-module); the demand is calculated based on data from Agostini et al. [19] and Wagner et al. [25]. In contrast, the mounting structure for VB-APV is assumed to be made solely of reinforcing steel (three crossbars, two posts and the associated anchoring have a demand of 60–90 kg of steel, in which around 40% are needed solely for the anchoring), while module holders consist of aluminium (two holder with 160 g and one holder with 200 g for one PV-module). Approximate material demands and not exact data, as they can differ significantly depending on the specific project, of both materials are provided by a renewable energy project developer company [Next2-SunGmbH, 2021 (personal communication)]. In both APV scenarios the additional process 'metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER' is included covering inputs for treatment of the steel [39].

The inverter production process 'inverter production, 500 kW | inverter, 500 kW | Cutoff, U - RER' is used as a basis dataset and adjusted to Chinese production conditions by using Chinese providers (e.g., for the electricity). Further, the needed demand is adjusted to 430.08 kWp ha^{-1} (S-APV) and 348.60 kWp ha^{-1} (VB-APV), respectively, by assuming that an inverter of 4–9 kg kW^{-1} [45] is needed.

Electrical installation including the fuse box, electric cables, and the electric meter are based on the ecoinvent process 'photovoltaics, electric installation for 570kWp module, open ground | photovoltaic plant, electric installation for 570kWp open ground module | Cutoff, U - GLO', adjusted to reflect in each case S- and VB-APV scenario assumptions; and further with more recent data from Frischknecht et al. [43].

The diesel demand for the construction of the VB-APV plant is calculated depending on the needed posts with diesel and energy data from Jungbluth et al. [45] and Mason et al. [46]. Due to the lack of data the same is assumed to be needed for the S-APV construction. For both APV-scenarios the electricity demand is upscaled from a 3 kWp PV-plant [39].

While in the S-APV scenario due to the stilted PV-modules no fence is needed, the assumption is made that a fence is built around the VB-APV site and is modelled based on material inputs concrete, wire drawing steel and zinc coat coils from ecoinvent [39] and adjusted to specific characteristics of the VB-APV plant.

The production of the agricultural crops sugar beet, winter wheat and soybean in both APV-scenarios are based on the following ecoinvent processes and adjusted to Austrian conditions, respectively.

- sugar beet production | sugar beet | Cutoff, U – CH

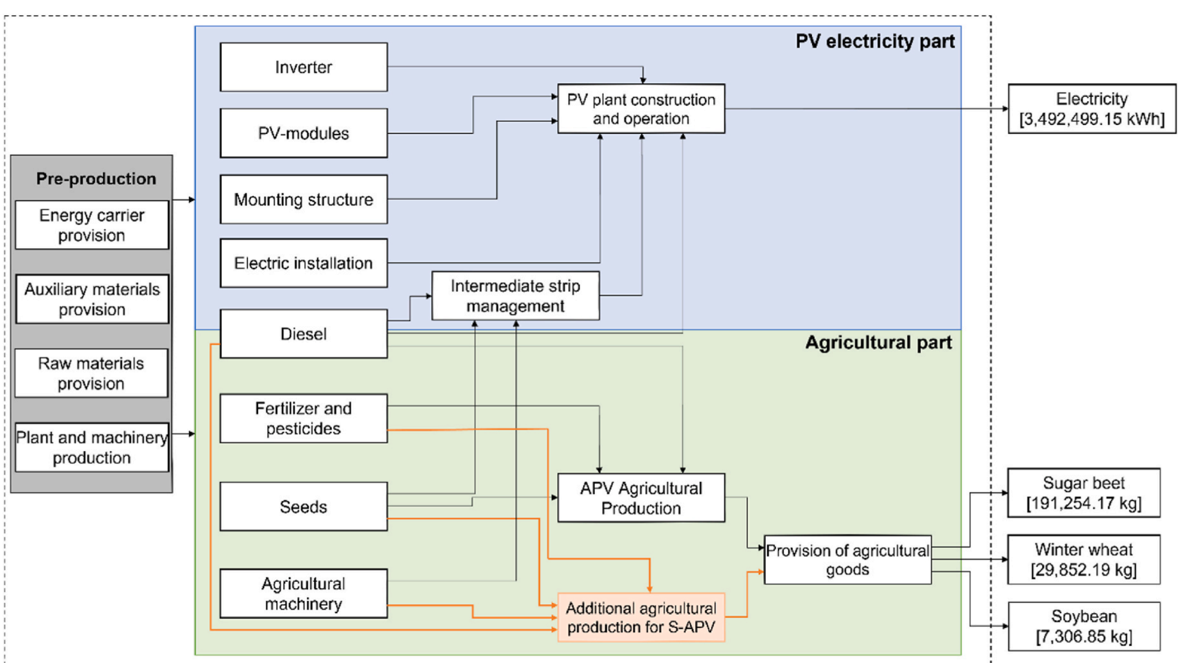

Fig. 4. System diagram of the S- and VB-APV scenario; the dashed line illustrates the system boundaries; the PV production part is highlighted with a blue background; the agricultural production part with a green one. The additional agricultural production (displayed in orange) is only needed in the S-APV scenario and refers to the supply chain of crops by average Austrian production processes that is included in the scenario due to the system expansion approach.

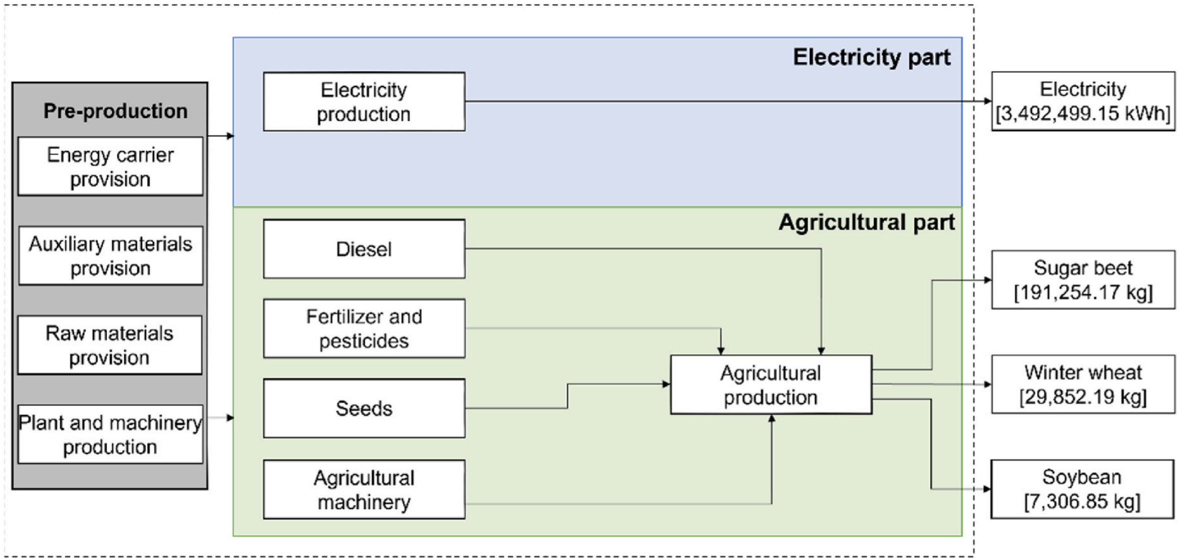

Fig. 5. System diagram of the Agri-scenario; the dashed line illustrates the system boundaries; the PV production part is highlighted with a blue background; the agricultural production part with a green one.

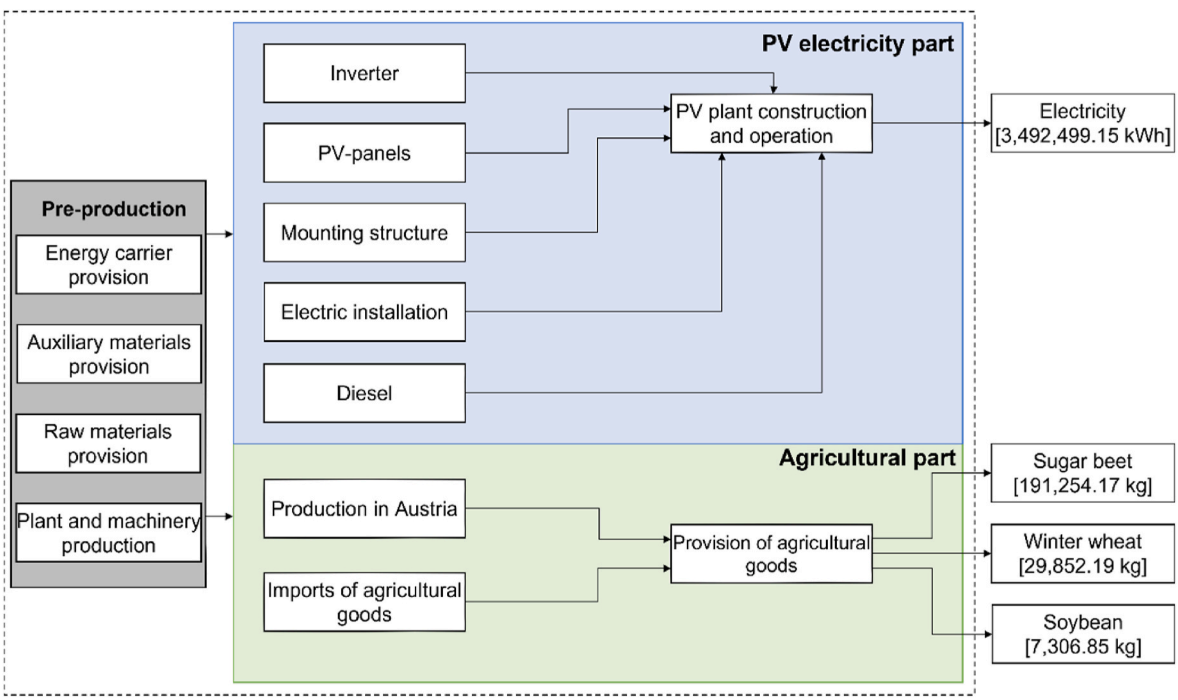

Fig. 6. System diagram of the PV-scenario; the dashed line illustrates the system boundaries; the PV production part is highlighted with a blue background; the agricultural production part with a green one.

- wheat production, Swiss integrated production, extensive – CH
- soybean production | soybean | Cutoff, U – CH

The average transport distance from field to farm is set to 3 km. The number and type of field operation steps (e.g., fertilizing, tillage, pesticide usage) for sugar beet and soybean production are adopted from ecoinvent; for winter wheat production only changes for fertilizing (adjusted to 4 cycles) and preparation of the soil (adjusted to one cycle) are assessed (see Ref. [29]). Used machinery is adopted from ecoinvent, but working widths are adjusted to the interrow space of 12 m for S-APV and 10 m for VB-APV. By using KTBL-Feldarbeitsrechner [47] (database including datasets of agricultural working procedures with working time requirement, the machine costs and the diesel requirements) appropriate machine working widths are considered. The working width with the least passing cycles for a row and the least fuel usage is applied. Hence, diesel demand and associated emissions are adjusted for every working step for the crop production, respectively. Emissions from diesel combustion are scaled linearly based on the altered consumed amount, except for CO_2 emissions, which are calculated according to the emission factor 3.12 kg CO_2 (kg fuel consumption)$^{-1}$ from Ref. [48]. Used machinery with associated working width and adjusted diesel consumption can be found in Ref. [29].

Pesticide use with associated inputs and outputs are adjusted to Austrian conditions and it was verified that the pesticides used in the

Table 3
Life Cycle Inventory of the stilted and vertical bifacial APV plant with an assumed life-span of 30 years in the S-APV scenario.

Flow		Amount		Unit	References
		S-APV	VB-APV		
Inputs	diesel[a]	3.42	3.42	GJ	[45,46]
	electricity, low voltage 230/400V	32.97	26.73	kWh	[39]
	inverter	1.87	1.52	Item (s)	[45]
	photovoltaic module	3449.00	1824.00	m^2	[39,41]
	mounting structure	1.00	1.00	Item (s)	S-APV [19,25]: VB-APV: [Next2SunGmbH, 2021 (personal communication)]
	electric installation	1.00	1.00	Item (s)	[43]
	fence -concrete	/	0.99	m^3	[39]
	fence - wire drawing steel	/	2007.00	kg	[39]
	fence - zinc coat, coils	/	201.00	m^2	[39]
Output	photovoltaic plant	1.00	1.00	Item (s)	

[a] Based on data from Mason et al. [46] for the diesel input a uniform distribution is assumed (min: 2.71; max: 4.13).

ecoinvent processes are also approved for use in Austria.

The amount of fertilizer applied is influenced by many factors, e.g., altering the amount of available N in soils [49]. To base this study on conservative assumptions, the highest recommended nutrient amount of N, phosphorus pentoxide (P_2O_5) and potassium oxide (K_2O), respectively is assumed for every crop, which was calculated with the programme LK-Düngerrechner [50], which is based on nutrient demand of crops and Austrian legal obligations. Sugar beet is assumed to be fertilized with 155 kg N, 85 kg P_2O_5 and 170 kg K_2O; winter wheat with 145 kg N, 55 kg P_2O_5 and 30 kg K_2O and soybean with 60 kg N, 65 kg P_2O_5 and 50 kg K_2O, respectively. It is assumed that solely mineral fertilizer (calcium ammonium nitrate, urea, potassium chloride and diammoniumphosphate) is used (for exact amounts of every fertilizer see Ref. [29]); further 20 kg N is supplied by green manure [48], which grows before sugar beet and soybean, respectively.

Direct and indirect field emissions (nitrous oxide, ammonia, nitrogen oxides, nitrate, phosphate and phosphorus, heavy metals, carbon dioxide and particulate matter) are calculated with a wide range of models which were found to best reflect or being adjustable to Austrian conditions: Intergovernmental Panel on Climate Change (IPCC) Tier 1 and 2 [51,52] with additional Austrian specific values from Refs. [53,54], European Monitoring and Evaluation Programme (EMEP)/European Environment Agency (EEA) [55,56], Swiss Agricultural Life Cycle Assessment (SALCA)-Nitrate [57], SALCA-Heavy Metals [58], SALCA-Phosphorus [59] with additional Austrian specific changes implemented for all SALCA models [60]. For further information which field emission is calculated with which model, see Ref. [29]. This approach is based on studies from Herzog et al. [61] and Quantis et al. [62]. For the LCI of the production of the three crops, see Ref. [29], in which only adjusted inputs or outputs can be found while the original dataset and unchanged values can be found in the respective ecoinvent datasets [39].

For the mowing of the intermediate strip once a year the ecoinvent process 'mowing, by motor mower | mowing, by motor mower | Cutoff, U – CH' is used and adjusted. For the S-APV scenario it is assumed that the mowing of the intermediate strip can be done in one crossover, despite the posts in the middle every 12 m, due to a swiveling mowing tool. In contrast, in the VB-APV scenario the intermediate strip on every side of a PV row needs to be mowed individually. For both APV-scenarios the ecoinvent process is adjusted as instead of the use of petrol diesel is used; the demand and associated emissions are calculated based on data from KTBL-Feldarbeitsrechner [47]. Due to the lack of data in KTBL-Feldarbeitsrechner, the proxy 'mowing of a meadow orchard' is used. For details see Ref. [29].

2.3.2.2. Agri-scenario. The Agri-scenario assumes sole agricultural production on agricultural land. This approach made it possible to use a typical crop rotation (see section 2.1) reflecting agricultural practice. To fulfill the FU in the Agri-scenario, it needs to be expanded to include an additional production chain for electricity provision, see Fig. 5.

The influence of the choice of electricity mix was already mentioned in section 2.3.1. Hence, two options are assessed: (1) Agri-AUT-scenario: Provision of electricity produced in Austria (production mix) based on data from BMK [63] and E-Control [64]; (2) Agri-green-scenario: production of a green electricity mix based on data from oekostrom GmbH [65], which is a producer and supplier of electricity from renewable energy sources and today the largest independent energy service provider in Austria.

The agricultural production part of the Agri-scenario is based on the following ecoinvent processes.

- sugar beet production | sugar beet | Cutoff, U – CH
- wheat production, Swiss integrated production, extensive – CH
- soybean production | soybean | Cutoff, U – CH

The number of field operations is adopted from the original processes, but machinery working widths are set to the largest working width available in KTBL-Feldarbeitsrechner [47]; the diesel demand is simulated and associated emissions are adjusted as in the S- and VB-APV scenarios, see Ref. [29] for working widths and diesel consumption.

2.3.2.3. PV-scenario. This scenario assumes a total substitution of agricultural production by PV-modules. A typical ground-mounted PV-plant is assumed with an installed capacity of 1 MWp ha-1. The used PV-plant is based on the 570 kWp ground-mounted PV-plant from the ecoinvent database [39]. A north-south orientation (azimuth of 0°) and a zenith angle of 35° is assumed, the same as for S-APV. Since in this scenario the same PV-module type (glass-foil) is used as in the S-APV, also the same degradation level is used (see section 2.3.2.1).

For a fair comparison and to provide the same outputs in every scenario, system expansion is applied via the inclusion of production chains for crops in the scenario, see Fig. 6.

In this scenario the agricultural production is completely substituted by a ground mounted PV-plant. As a basis the ecoinvent process 'photovoltaic plant construction, 570kWp, multi-Si, on open ground | photovoltaic plant, 570kWp, multi-Si, on open ground | Cutoff, U - GLO' is used. The process is adjusted to the use of mono-Si PV-modules, other inputs are adjusted to the 1 MWp ha^{-1} installed. The inverter and mounting structure lifetime, as well as the production and transport of modules and inverter is the same as for the S- and VB-APV scenario, the PV-module the same as in the S-APV scenario. Further, as for the VB-APV scenario a fence is assumed to be built around the production site.

Based on the self-sufficiency rate, which specifies to what extent a country depends on its own production, of the assessed crops, respectively, the provision is divided in the inland production and import from foreign countries. For the Austrian production, processes from the Agri-scenario are used (see section 2.3.2.2). For sugar beet the self-sufficiency rate is assumed to be 100% [66], hence no import is modelled. In 2020 the self-sufficiency rate of wheat was 87% [67], with imports coming mainly from Hungary (43.10% of imports), Czech Republic (31.70%), Slovakia (18%) and Germany (3.40%) [68]. The self-sufficiency of soybean was 92% in 2020 [69] with imports coming mainly from the US and South American countries (e.g., Brazil or Argentina). Average transport distances are assumed for each country; mode of transport is a lorry for the European countries importing wheat; for the countries providing soybean a transport by container ship and subsequent transport in a lorry is assumed.

2.3.3. Life cycle impact assessment

The impact assessment method ReCiPe 2016 Midpoint (H) [70] is used to calculate environmental impacts. The selection of impact categories must not only be consistent with the goal and scope of the LCA, it should also reflect possible environmental risks of the analysed product system [32]. Hence, the selection is both based on recommendations from the European Commission [71] for the PV production part and on Brentrup et al. [72] for the agricultural part. Consequently, in this work the following impact categories are assessed: CC, Human Carcinogenic Toxicity (HCT), Human Non-Carcinogenic Toxicity (HNCT), Terrestrial Ecotoxicity (TE), Freshwater Eutrophication (FE), Terrestrial Acidification (TA), Fine Particulate Matter Formation, (FPMF) Mineral Resource Scarcity (MRS) and Fossil Resource Scarcity (FRS). For the impact category CC, a time span of 100 years is chosen.

2.3.4. Statistical analysis

In this study Monte Carlo (MC) simulation is used to quantify the probability distribution of outputs. In this approach the impact analysis calculation is run for a predetermined number with random values within the probability distribution for each input. In this work 1,000 MC runs are conducted, since a higher number of simulations does not lead to more precise results [73]. MC-simulations are showing the median value with the 5% and 95% interpercentile range probability distribution function.

The statistical significance between the scenarios was tested with a Kruskal-Wallis test, followed by a pairwise Wilcoxon rank sum test. The Kruskal-Wallis test was used since it is a non-parametric test for more than two samples which are not normally distributed (this is tested by the Kolmogorov-Smirnov test first). The significance level used is 0.05.

3. Results

3.1. Relative environmental impacts

Relative environmental impacts of all the assessed scenarios and impact categories are shown in Fig. 7. The highest environmental impacts in each impact category are resulting either within the S-APV-scenario (six of nine assessed impact categories: HCT, HNCT, TE, TA, FPMF and MRS) or the Agri-AUT scenario (three of nine impact categories: CC, FE and FRS). The Agri-green scenario has in seven of nine assessed impact categories (CC, HCT, HNCT, FE, TA, FPMF and FRS) the least impact.

In the category CC the S- and VB-APV scenario have less impact (31.94% and 63.37% less impact, respectively) compared to the Agri-AUT-scenario. Further, also in the impact categories FE and FRS both S- and VB-APV-scenario have significant less environmental impacts compared to the Agri-AUT-scenario (36.41% and 70.39% less for FE and 49.64% and 74.50% less for FRS, respectively). In all assessed impact categories, the VB-APV scenario has less environmental impacts (between 3% in TE and 70% in HCT) than the S-APV one.

What can be clearly seen is that the electricity production (displayed in blue) is the main contributor in the majority of the assessed impact categories, while the agricultural production (displayed in orange) only contributes to a medium share to TA (between 16.34 and 42.38%) and FPMF to 8.41–23.76%.

The negative contribution in HNCT for both the APV-scenarios is due to the fact that the crops, especially sugar beet, take up heavy metals from the soil when using Austrian specific model inputs, which leads to a negative impact.

3.2. Contribution analysis

The contribution analysis for all scenarios is individually analysed for the most representative impact categories for APV systems which are CC, HCT, HNCT, FE, TA and MRS. The contribution analysis of TE, FPMF and FRS, as well as an overview of all results can be found in Ref. [29].

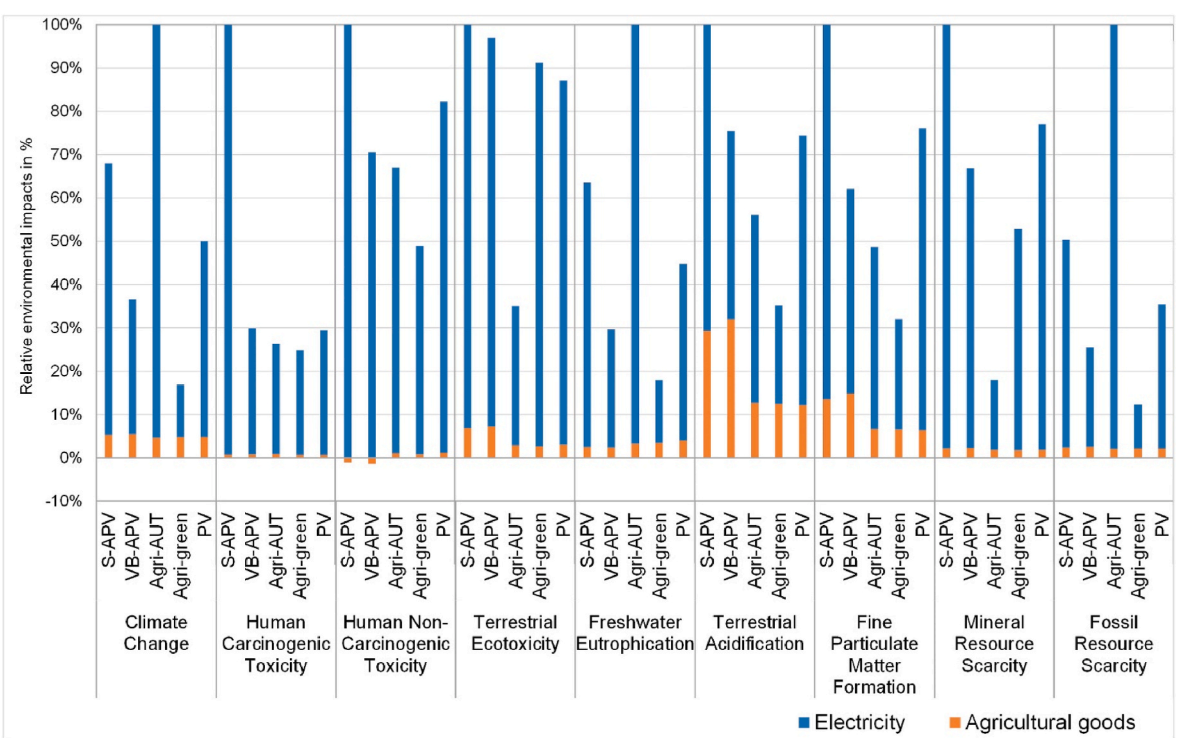

Fig. 7. Relative environmental impact for all scenarios and impact categories.

For the contribution analysis the PV electricity part includes the electrical installation, inverter, mounting structure, PV-panel and the PV-plant Miscellaneous (S-APV: PV-plant construction and mowing of intermediate strip; VB-APV: PV-plant construction, mowing of intermediate strip and fence and for the PV-scenario the PV-plant construction and the fence). The Agricultural part includes the production of winter wheat, sugar beet and soybean.

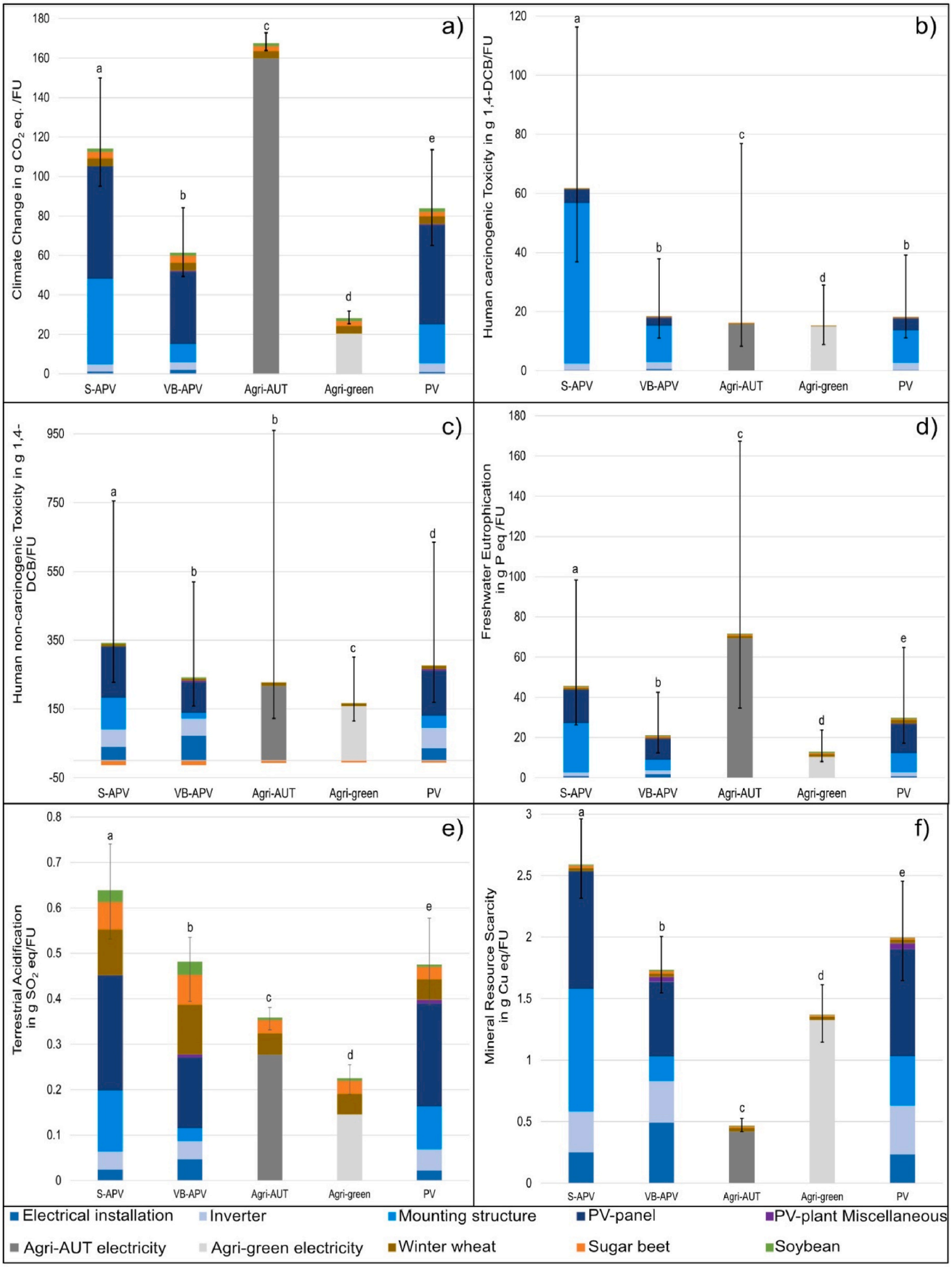

Fig. 8. Contribution analysis of the following impact categories (a) Climate Change, (b) Human carcinogenic Toxicity, (c) Human non-carcinogenic Toxicity, (d) Freshwater Eutrophication, (e) Terrestrial Acidification, (f) Mineral Resource Scarcity of all assessed scenarios; error bars show the 5% and 95% interpercentile range of indicator's probability distribution function, based on 1000 Monte Carlo runs; lower-case characters represent significant differences.

3.2.1. Climate change

The S-APV scenario has a CC impact of 114.09 g CO_2 eq./FU of which 92.24% are contributed by the PV-part. The largest contributor overall is the PV-module production with 49.96%, followed by the mounting structure with 38.07% and the inverter with 3.17%, see Fig. 8. The electrical installation, PV plant construction and the mowing of the intermediate strip are negligible due to a contribution below 1%. While the agricultural production in the S-APV system is of minor importance (7.76%), the additional production on other agricultural land is even negligible due to the system expansion approach.

The VB-APV scenario has a 46.18% lower CC impact (61.41 g CO_2 eq./FU) than the S-APV scenario; yet again the PV part is contributing the majority with the highest share from the PV-module with 59.85%. Further the mounting structure contributes only to 15.04% to the total CC impact. This is due to the lower steel and aluminium need in this scenario compared to S-APV. In this scenario the PV plant construction, the fence and the mowing of the intermediate strip are negligible. Agricultural production is resulting in a contribution of 14.95% to the total CC impact.

The PV-scenario has also a significant lower CC impact compared with the S-APV scenario with a reduction of 26.49%–83.87 g CO_2 eq./FU. As for both APV scenarios the PV-module production has the highest share with 60.25%, followed by the mounting structure with 23.63%. Further, the electrical installation, PV plant construction and the fence are negligible.

For both the APV scenarios as well as for the PV-scenario the most significant hotspot is the bifacial and glass-foil PV-module production in China, due to the high electricity demand for the cell production and all upstream processes. Further, the Chinese electricity mix has a high CC impact since it is mainly fossil-based, which leads to high CO_2 emissions when producing electricity and further high methane (CH_4) emissions during hard coal mine operation and hard coal preparation. Another hotspot is the mounting structure due to the high reinforcing steel demand in the S-APV scenario, in which especially the CO_2 emissions during pig iron production and CO_2 and CH_4 emission during iron sinter production contribute to CC. In the PV-scenario the high aluminium demand and the consequential high fossil-based electricity demand and aluminium production in general are main contributors.

The Agri-AUT-scenario has the highest CC impact of all the assessed scenarios with 167.63 g CO_2 eq./FU in which the electricity part has a share of 95.38% due to high emissions (especially CO_2, dinitrogen monoxide (N_2O) and CH_4) of fossil-based electricity production. In contrast, the Agri-green-scenario has the lowest CC impact with 28.32 g CO_2 eq./FU with 71.76% contribution of the electricity part. This is due to the extremely lower emissions of hydro and wind electricity production. Nevertheless, the highest share of the electricity part is the electricity produced by wind turbines >3 MW due to the high steel and concrete demand and the related high CO_2 emissions by producing pig iron and clinker.

3.2.2. Human toxicity

In all scenarios the PV or electricity part is the main contributor, see Fig. 8. The clear hotspot for the S- and VB-APV and the PV-scenario is the mounting structure with 87.96% (54.38 g 1,4-DCB), 66.78% (12.35 g 1,4-DCB) and 60.25% (10.96 g 1,4-DCB), respectively. The high share is especially due to high chromium VI emissions when treating slag and dust from steel production. Due to lower steel demand the mounting structure of the VB-APV scenario leads to significant reductions in HCT impact. In all three scenarios the winter wheat, sugar beet and soybean production are either negligible or of minor relevance. In the Agri-AUT-scenario the hydro electricity production has the main contribution (38.02% or 6.19 g 1,4-DCB) due to on the one hand high electricity demand for pumping water and the high steel demand for hydro power plant construction, which leads again to Chromium VI emissions. The Agri-green-scenario has slightly lower HCT than the latter scenario, also resulting from high steel demand for both wind turbine production as well as hydro power plant construction.

For S- and VB-APV and PV-scenario the PV-module production is a hotspot contributing 45.52% (149.65 g 1,4-DCB), 39.52% (89.99 g 1,4-DCB) and 48.59% (131.32.58 g 1,4-DCB), respectively, see Fig. 8. The inverter and electrical installation have also high contributions between 15.57-21.78% and 11.96–31.85%, respectively. The high contribution of the PV-module is due to the use of silver in the metallization paste in the cell production. Further, due to the copper used for the cathode in module production, for the electrical installation and for the inverter. The therefore occurring lead emissions from silver mine operation as well as arsenic and lead emissions when treating copper cake or sulfidic tailings that arise in silver and copper mine operations lead to high impacts.

In the Agri-AUT-scenario the hydro pumped storage plant due to the high fossil-based electricity needed for pumping, the electricity production from coal and wood chips are the main contributors to HNCT; for the latter two especially due to zinc, arsenic, mercury and cadmium emissions to ground water or soil. In the Agri-green-scenario 86.90% are contributions by wind turbines >3 MW due to the copper demand and the following treatment of copper cake and sulfidic tailings which lead to emissions of arsenic, lead and zinc.

3.2.3. Freshwater Eutrophication and Terrestrial Acidification

The hotspots for S-, VB-APV and PV-scenario is the PV-module production (32–50%) in both impact categories; in FE due to the high amount of coal-based electricity needed for the production, which consequently leads to phosphate emissions to water when treating spoil from mining, in TA due to SO_2 and NO_x emissions of the mainly coal-based electricity used in China, flat glass production and freight sea shipping. In FE the mounting structure is another hotspot in the three scenarios, but mainly in S-APV (53.91%, 16.70 mg P eq./FU).

In FE in the Agri-AUT-scenario hydro-electricity (57.32%, 41.07 mg P eq./FU) is the main contributor due to the high fossil-based electricity needed for pumping. In TA the high contribution of the electricity part is mainly due to emissions of natural-gas-, coal- and wood chips-based electricity, and due to the needed electricity for pumping in hydro plants, which is also to a certain extent fossil-based.

In both impact categories in the Agri-green scenario the main contributor is electricity produced by wind turbines >3 MW.

TA is the impact category in which the agricultural part contributes the most to total impacts; between 16.34% (PV-scenario) and 42.38% (VB-APV). In all scenarios the winter wheat production contributes at least 53% to the agricultural part. For the winter wheat and sugar beet production NH_3 field emissions are a hotspot in all scenarios with a share around 80% of the production of the respective agricultural good.

3.2.4. Mineral Resource Scarcity

For S-, VB-APV and PV-scenario the PV-module production (36.93%, 35.11% and 43.50%, respectively) is a hotspot due to the ore extraction of silver and also magnesium dependent on the ore composition, for S-APV and the PV-scenario further the mounting structure (38.53% and 20.27%, respectively) while for the VB-scenario further the electrical installation (28.45%, 0.49 g Cu eq./FU) and inverter (19.42%, 0.34 g Cu eq./FU) being also of importance due to copper demand. In the Agri-green-scenario (1.37 g Cu eq./FU) 85.05% of the impact is contributed by electricity production by wind turbines >3 MW, due to high copper and reinforcing steel demand and the resulting high resource demand. The Agri-AUT-scenario (0.47 g Cu eq./FU) has the lowest impacts in MRS with 81.99% less than the S-APV scenario. Hotspot in the latter is wind-, hydro- and PV-electricity due to mineral resource needs.

4. Sensitivity analysis

Sensitivity analyses are carried out in order to determine the influence of specific decisions and assumptions to the results and thus to the stability of these. In the following sections the conducted sensitivity analyses are explained in detail, results are shown and discussed.

4.1. Production in Europe

For all the scenarios the PV-module and the inverter production was assumed to be in China since the majority is produced there [43]. In this sensitivity analysis for both APV-scenarios the production is now assumed to be in Europe. Hence, the LCI is changed accordingly (e.g., electricity mix, heat production, transport distance and mode are changed to European processes).

A decrease of total CC impact of 17.60% is found for S-APV and 21.14% for VB-APV due to the lower impact of the European electricity mix. For both PV-modules the decrease of CC impact is around the same with ~35% reduction potential, while for the inverter the impact can be reduced by 19.70% for S-APV and 16.58% for VB-APV. The results of the PV-module production are in line with findings of Müller et al. [41], who found a 30% and 40% CC impact reduction when producing in Germany and Europe, respectively, and with findings of Leccisi et al. [74] who found a ~25% lower CC impact for European production, for both studies compared to Chinese production. Overall, it underlines the importance of the used electricity mix for high electricity demand processes.

Results of all impact categories and a detailed description can be found in Ref. [29].

4.2. Yield decrease

For the baseline scenarios no yield decrease was assumed, since no data for the used crop rotation is available. In this sensitivity analysis it is analysed how the CC impact of both APV scenarios would change if there is a yield decrease and hence, crops need to be imported from foreign countries. The import from foreign countries is the same as in the Agri-scenarios. Crop yields are simulated for the timespan from 1981 to 2020 to get a long time average by using the bio-physical process model EPIC that includes solar radiation losses due to shading from PV-modules for both APV-scenarios (for more information see Mikovits et al. [31]). Reductions of yields are different for both APV-scenarios due to their individual setup. Simulations show that for S-APV there is a yield decrease of 17.87% of sugar beet, 23.80% of soybean and 18.67% of winter wheat, while in VB-APV lower yield reductions of 10.86% for sugar beet, 15.57% for soybean and 10.94% for winter wheat are found.

Since the agricultural part only contributes to 7.76% and 14.95% to the S- and VB-APV scenario, a decrease in yield of every crop would result in an increase of the total CC impact of both scenarios to only 2.21% and 2.50%, respectively.

5. Discussion

In the following section, a comparison with other studies is made mainly based on hotspots and relative contributions due to different functional units, goal and scope definitions used in each study, and due to diverse modelling approaches; e.g., system expansion approach vs. allocation, evaluation of PV part only or no utilisation equality at all. While Agostini et al. [19] found similar CC, FE and TA results for the assessed PV system of two-stilted APV systems and roof or ground-mounted PV systems, in this study significant differences were found between the scenarios. The VB-APV scenario has lower, the S-APV scenario has higher impacts in all the assessed impact categories compared to the PV-scenario. Pascaris et al. [22] and Handler and Pearce [23], in their LCA with a system expansion approach, found a reduction of the CC impact for the integrated production, which is in line with the findings of this study, although they both assessed APV with animal husbandry and not, as would be more practical for the east of Austria, with crops being produced between/below panels. Also, Pascaris et al. [22] and Handler and Pearce [23] only assessed the two other impact categories cumulative energy demand and an ecotoxicity indicator, which is not representative of a holistic assessment on environmental impacts, especially for a rather new technology. Therefore, a total of nine impact categories were assessed in this study to avoid a shift in favour of one impact category but at the expense of another. Wagner et al. [25] also assessed a wide range of impact categories, but only assessed one specific APV system. Therefore, this study aims to fill this knowledge gap.

The hotspots identified by Agostini et al. [19], the PV-modules and the mounting structure in the CC impact category, are in line with the findings in this study, for the latter in line with findings for the S-APV scenario. The lower demand for steel in the VB-APV compared to the S-APV scenario and the lower aluminium demand compared to the PV-scenario led to significant lower overall environmental impacts. This underlines that stilted APV-scenarios have to focus on material efficiency in the mounting structure. It must be taken into account that the S-APV scenario is based, among other things, on a plant with first--generation design for which it has also already been communicated that significant material savings can be made [25]. Furthermore, the mounting structure of the PV-scenario in this study is not based on state-of-the-art data due to a lack of data, which could also lead to reductions. These data availability issues underline the need for more primary data collection in order to produce robust state-of-the-art results. These limitations of the study need to be kept in mind when discussing the results and also communicated transparently. For all mounting structures a life-span of 30 years is assumed, nevertheless in practice steel could have a higher life-span of up to 60 years or more. However, due to the rapid development of PV-modules in recent years and change in module size, it cannot be guaranteed that the mounting structure that is installed today will still be suitable for the modules in 30 years, also making the topic of repowering at least uncertain. This is in any case an important point to consider in the design of APV systems, as this would benefit a longer use of the mounting structure and result in a decrease of environmental impacts overall.

Although LCA studies of PV-modules and PV-systems in general have been a popular topic for several years, mono-Si PV-modules produced in China and mounted in Central Europe, which also use as FU 1 kWh electrical energy have only been assessed to a limited extent, which makes a direct comparison difficult. While Hou et al. [75] found a CC impact between 60.1 and 87.3 g CO_2 eq./kWh solely for the module production in China, in this study lower values were found with 55.22 g CO_2 eq./FU for the glass-foil and 36.76 g CO_2 eq./FU for the bifacial module. This is due to the use of state-of-the art inventory data from Müller et al. [41], who reported a CC impact of 29.9 and 23.2 g CO_2 eq./kWh for the production in China for a glass-foil and glass-glass module, respectively. The lower impact is most likely connected due to the different transport distances used, different efficiencies of PV-modules and different radiation data. Nevertheless, the lower CC impact of the bifacial glass-glass module is in line with the findings of Müller et al. [41]. For S-APV systems the use of bifacial PV-modules without aluminium frame should be assessed in the future, again emphasizing the need for more available primary data for APV systems. Another issue that needs to be addressed in the future, is the end-of-life treatment of PV-modules with recycling of valuable resources. Again, primary data is scarce for this aspect.

High variations of CC impacts of PV-systems are also already reported due to factors like assumed design parameters, different LCIs, module efficiency or manufacturing locations [41,76]. This underlines the need for transparent communication which data is used for LCI. Overall, findings that the module production, but especially the cell production with the beforehand ingot growth and wafer production and the consequently high energy demand for these steps are hotspots, is in line with literature (e.g., [41,74,75,77]). In the future, environmental impact assessments will be required that evaluate the entire life cycle of APV systems and focus on the recycling of the mounting structure and PV-modules to underline the advantage of a circular economy. For PV-module recycling it is essential that data are available for a process for widespread use, which is currently not the case.

Overall, this study shows that the PV electricity production is the main reason for environmental impacts in APV systems, while the agricultural part is of minor importance, which is in line with Wagner et al. [25] and in addition that APV systems compare favourably to the studied alternative options with a focus on sole electricity or agricultural production. This highlights the importance of using the system expansion approach, which is not used in most other studies, as it allows for a holistic assessment of environmental impacts of both the agricultural and the electricity production in an APV system and a fair comparison of such multi-output systems. Furthermore, the results show that the electricity production in both assessed APV plants can achieve compliance with the EU-taxonomy, which makes these two APV plants a possible solution to achieve climate targets, especially when compared to average grid mixes. Based on the results of this study, the VB-APV scenario is more sustainable from an environmental point of view.

If the issues raised in this discussion are focused on in further research APV plants, especially S-APV ones, can be even more efficient and useable for longer periods of time. In order to assess not only environmental impacts, but also social, techno-economic and landscape impacts a method suitable for assessing such broader impacts is needed, e.g., a multi-criteria analysis.

6. Conclusions

In this research environmental impacts of a stilted and a vertical bifacial APV-plant are assessed and further compared to the mono-use of land with either solely agricultural or electricity production via PV-modules. The VB-APV scenario shows lower environmental impacts compared to the S-APV scenario in all assessed impact categories due to the lower material (especially steel) demand for the mounting system and lower impacts of glass-glass module compared to glass-foil modules.

When comparing APV-scenarios with the mono-use of land for agricultural production, the origin of electricity for a fair comparison using system expansion is a key element. When comparing with Austrian produced electricity both APV-scenarios lead to a reduction of environmental impacts in three of nine assessed impact categories. If the comparison is made with a green electricity mix (mainly hydro and wind electricity) both APV-scenarios have higher impacts in all impact categories.

In both APV- as well as in the PV-scenario, the PV-module production is a hotspot in all impact categories, especially due to high electricity demand as well as the mounting structure for the S-APV and PV-scenario due to high steel demand. Both hotspots indicate further research areas in terms of increasing material and energy efficiency, as well as the importance of locations of production sites with the used electricity mixes. Additionally, it has to be taken into account that if assessing the whole life cycle and assuming recycling environmental impacts could possibly still be reduced, emphasizing the need for more research. Especially, the production of the PV-module with green electricity mixes only and higher material efficiency overall in the future should be assessed, as these are the main hotspots.

A uniform approach with a comparable FU for LCAs of APV plants should be developed in order to make a fair comparison in the future as this is still lacking and hence, direct comparisons with literature are not possible.

Overall, the study provides first results of how environmental impacts of APV-plants in Austria could look like. In addition, it is shown that with the expansion of VB-APV plants and the combined production of electricity and agricultural goods, in contrast to a mono-use of land environmental impacts can be reduced in some impact categories, emphasizing the need for more research and optimising APV-plants.

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CRediT authorship contribution statement

T. Krexner: Roles, Writing – original draft, Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization, Investigation. **A. Bauer:** Writing – review & editing, Supervision, Project administration. **A. Gronauer:** Supervision. **C. Mikovits:** Writing – review & editing. **J. Schmidt:** Writing – review & editing. **I. Kral:** Roles, Writing – original draft, Writing – review & editing, Supervision, Methodology, Conceptualization, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have shared the ZENODO DOI number to the additional data.

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