Publizierbarer Endbericht

Gilt für Studien aus der Programmlinie Forschung

A) Project data (Projektdaten)

Allgemeines zum Projekt	
Kurztitel:	PA³C³
Langtitel:	Potential analysis of AgroVoltaics in Austria in the context of climate change – with special respect to environmental, economic and social aspects
Zitiervorschlag:	PA³C³
Programm inkl. Jahr:	ACRP 12. Ausschreibung 2019
Dauer:	01.10.2020 bis 31.03.2023
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Schlagwörter:	Agrivoltaics, multi land-use, life cycle assessment, social acceptance
Projektgesamtkosten:	249.826,00€
Fördersumme:	249.826,00€
Klimafonds-Nr:	KR19AC0K17594
Erstellt am:	29.06.2023

B) Project overview (Projektübersicht)

1 Kurzfassung

Österreich hat das Ziel bis 2030 100 % des gesamten nationalen Stromverbrauchs (national bilanziell) durch erneuerbaren Strom zu decken, was einen durchschnittlichen zusätzlichen Ausbau erneuerbarer Energien um 27 TWh pro Jahr bedeutet. Mit 11 TWh pro Jahr soll der überwiegende Teil durch Photovoltaik (PV) erbracht werden (BGB, 2021), was einen entsprechenden Flächenbedarf und damit Nutzungskonkurrenzen mit sich bringt. Untersuchungen haben bereits gezeigt, dass ein Ausbau auf Agrarflächen zur Erreichung der 2030- und vor allem der 2040-Ziele der Klimaneutralität unbedingt erforderlich ist (Fechner, 2020; Mikovits et al., 2021). Die Verwendung landwirtschaftlicher Flächen ist jedoch kontrovers, vor allem wegen des Nutzungskonflikts zwischen Nahrungs-/Futtermittel und Energieerzeugung. Eine Lösung, um diese konkurrierenden Interessen abzumildern, ist die Agri-Photovoltaik (Agri-PV, APV), d.h. die kombinierte Nutzung landwirtschaftlicher Flächen für die Nahrungs- und Futtermittelproduktion (Primärnutzung) und die Stromerzeugung durch PV-Module (Sekundärnutzung). Da in Österreich bisher nur wenig Forschung zu APV betrieben wurde, ist es das Ziel des Projekts, die Potenziale und Chancen von APV in Österreich zu evaluieren, indem techno-ökonomische, ökologische und soziale Aspekte in einem integrierten Modellierungsrahmen berücksichtigt werden. Im Rahmen des Projekts werden hoch aufgeständerte APV-Systeme ohne Nachführung (S-APV), bodennahe Systeme mit Nachführung und vertikale bifaziale Systeme (VB-APV) bewertet.

Um abschätzen zu können, wie sich Erträge in der Landwirtschaft durch die Beschattung von PV-Anlagen ändern, wurden die landwirtschaftliche Erträge auf 1 km^2 Auflösung für ganz Österreich für landwirtschaftliche Flächen mit und ohne APV simuliert, wobei Sonneneinstrahlungsverluste aufgrund von Abschattungen durch PV-Anlagen berücksichtigt wurden. In Folge wurden die Verluste an Deckungsbeiträgen aufgrund der verringerten Pflanzenproduktivität mit den Einnahmen aus PV-Strom verglichen. Dieser Ansatz ermöglicht eine Einstufung der Flächen nach ihren landwirtschaftlichen und Stromerzeugungspotenzialen. Die Simulation der PV-Leistung basiert auf der zeitlichen Herunterskalierung von Sonneneinstrahlungswerte in den Zeiträumen 1981-2020 und 2031-2070 aus den CCCA ÖKS 15 Klimamodellen und der Bestimmung der Beschattung von PV-Modulen (und Kulturen) unter Verwendung einer 10m x 10m großen digitalen Höhenkarte. Die PV-Leistung wird mit pvlib (Holmgren et al., 2018) simuliert.

Die Ergebnisse zeigen, dass zum Erreichen des erneuerbaren Ausbauziels bis 2030 nur 2,5-3 % von insgesamt etwa 4.700 km² geeigneter Ackerfläche mit dem S-APV-Systemen und 4-5 % mit dem VB-APV-System benötigt würden. Die landwirtschaftlichen Produktionsverluste auf Grund von Flächenverlusten betragen bei S-APV 8 % und bei VB-APV 12 %. Beschattungsverluste sind für weitere 22-32 % (S-APV) und 14-18 % (VB-APV) an Produktionsrückgängen verantwortlich. Nahezu unabhängig von den Energie- oder Erntepreisen sind finanzielle Einbußen für die Landwirte nicht zu erwarten, da das Einkommen aus der Energieerzeugung das Zehnfache des Gewinns aus der landwirtschaftlichen Produktion beträgt. Insgesamt sprechen die Ergebnisse für die Installation von APV-Systemen auf weniger produktiven und rentablen landwirtschaftlichen Flächen.

Im Projekt wurden auch die Umweltauswirkungen von S- und VB-APV Systemen mit der Methode der Ökobilanz bewertet und mit einer einfachen Nutzung von

Agrarflächen verglichen: (i) nur landwirtschaftliche Produktion (Agri-only) und (ii) nur Stromproduktion mittels PV-Freiflächenanlage (PV-only). In der Bewertung der Szenarien wurden die Systemgrenzen so gesetzt, dass die Beschaffung der Rohstoffe, die Produktion bis inklusive der Nutzungsphase untersucht werden. Um einen objektiven Vergleich zu ermöglichen, müssen in jedem Szenario die gleichen Outputs erzeugt werden. Daher wird der methodische Ansatz der Systemerweiterung verwendet: Im Szenario Agri-only wird daher eine zusätzliche Produktionskette für Strom (entweder österreichischer Produktionsmix oder Ökostrommix) implementiert, während im Szenario PV-only eine Produktionskette für die landwirtschaftliche Güter erforderlich ist. Insgesamt werden 9 Wirkungskategorien (z.B. Treibhausgaspotenzial (THG)) bewertet.

Die Ergebnisse zeigen, dass das VB-APV-Szenario in allen bewerteten Wirkungskategorien geringere Umweltauswirkungen hat als das S-APV-Szenario. Ein Hotspot in beiden APV-Szenarien ist die PV-Modulproduktion in China, aufgrund des hohen Strombedarfs und der Auswirkungen für die Herstellung von Silizium, im S-APV-Szenario weiters die Aufständerung aufgrund des hohen Stahlbedarfs. Beim Vergleich des Agri-only-Szenarios mit österreichisch produziertem Strom mit beiden APV-Systemen ist eine Reduktion der Umweltauswirkungen in drei Wirkungskategorien möglich.

Die Ergebnisse der Potenzialberechnungen wurden mit Hilfe eines räumlichen Planspiels (Serious-Game-Ansatz) zum APV-Ausbau in zwei ausgewählten Fallstudiengemeinden verwendet, um die Auswirkungen potenzieller Ertragsverluste, Einkommen aus der Energieerzeugung und Auswirkungen auf die Landschaft im Hinblick auf die soziale Akzeptanz zu bewerten. Vertreten waren dabei lokale Interessenvertreter aus Landwirtschaft, Verwaltung und Planung, die in einem ersten Schritt potenzielle Gebiete für einen APV-Ausbau auf Gemeindeebene identifizierten und in einem konkreteren Planungsschritt die visuellen Auswirkungen verschiedener APV-Systeme mithilfe von interaktiven 3D-Visualisierungen und VR-Brillen bewerteten.

Hinsichtlich der sozialen Akzeptanz und der Auswirkungen auf die Landschaft gab es zwar große Zustimmung für APV, vor allem im Hinblick auf ihre mögliche Doppelnutzung, die Auswirkungen auf das Landschaftsbild sowie der Erholungsfunktion wurden aber besonders bei den hoch aufgeständerten APV-Anlagen oder großflächigen Installationen in Siedlungsnähe kritisch betrachtet. Besonders wichtig im Planspiel war daher eine entsprechende Distanz zum Siedlungsraum sowie die Nutzung von Flächen entlang bestehender Infrastruktur (z.B. Straßen, Stromleitungen, Windräder) sowie die vorrangige Nutzung von geringwertigen Ackerflächen. In beiden Fallstudiengemeinden wurden die auf kommunaler Ebene berechneten Ziele für 2030 erreicht.

Grundsätzlich zeigen die Ergebnisse, dass für die Erreichung der 2030 Klimaziele je nach System rund 20.000 Hektar nötig sind. Zudem sichert das zweite Einkommen aus der Stromproduktion in APV-Systemen das Überleben der Landwirt*innen ab. Aus Sicht der Nachhaltigkeitsbewertung wird eine Reduktion von Umweltwirkungen gegenüber einer einfachen Landnutzung ermöglicht. Weiters erhält APV tendenziell Zustimmung aufgrund der Doppelnutzung, die genauen Standorte und der Einfluss der APV-Anlagen auf das Landschaftsbild haben jedoch großen Einfluss.

2 Executive Summary

Austria has the target to cover 100% of the total national electricity consumption (in the national balance) by renewable electricity by 2030, which means an additional expansion of renewables by 27 TWh per year. At 11 TWh per year, the majority is to be provided by photovoltaics (PV) (BGB, 2021), which entails a corresponding land demand. Studies have already shown that expansion on agricultural land is necessary to achieve the 2030 and especially the 2040 climate neutrality targets (Fechner, 2020; Mikovits et al., 2021). However, the use of agricultural land is controversial, mainly because of the land use conflict between food/feed and energy production. One solution to mitigate these competing interests is agri-photovoltaics (agrivoltaics, APV), i.e., the combined use of agricultural land for food and feed production (primary use) and electricity generation by PV-modules (secondary use).

Since little research on APV has been done in Austria so far, the aim of the PA³C³ project is to evaluate the potentials and opportunities of APV systems in Austria in an interdisciplinary approach by considering techno-economic, environmental and social aspects in an integrated modeling framework. The project will evaluate stilted APV systems without tracking (S-APV), ground-mounted systems with tracking, and vertical bifacial systems (VB-APV).

To estimate how agricultural yields change due to shading from PV systems, agricultural yields were simulated at 1 km2 resolution for all of Austria for agricultural land with and without APV, considering solar radiation losses due to shading from PV systems. Subsequently, the losses in contribution margins due to reduced crop productivity were compared with the revenues from PV electricity. This approach allows land to be ranked according to its agricultural and electricity generation potential. The simulation of PV output is based on temporal downscaling of solar irradiance values in the 1981-2020 and 2031-2070 time periods from the CCCA ÖKS 15 climate models and determination of shading of PV panels (and crops) using a 10m x 10m digital elevation map. PV power is simulated using pvlib (Holmgren et al., 2018).

The results show that to achieve the 2030 target, only 2.5-3% of a total of about 4,700 km² of suitable arable land would be needed with S-APV and 4-5% with VB-APV. Agricultural production losses due to land loss are 8% with S-APV and 12% with VB-APV. Shading losses account for another 22-32% (S-APV) and 14-18% (VB-APV) of production losses. Almost regardless of energy or crop prices, financial losses for farmers are not expected, as the income from energy production can be expected to be tenfold the profit from agricultural production. Overall, the results favor the installation of APV systems on less productive and profitable agricultural land.

In the project, the environmental impacts of S- and VB-APV systems were also assessed using the life cycle assessment method and compared with a simple use of agricultural land: (i) sole agricultural production (Agri-only) and (ii) sole electricity production by a ground-mounted PV system (PV-only). In the evaluation

of the scenarios, the system boundaries were set to examine the acquisition of raw materials, production and the use phase. To enable an objective comparison, the same outputs must be produced in each scenario. Therefore, the methodological approach of system expansion is used: In the Agri-only scenario, an additional production chain for electricity (either Austrian production mix or green electricity mix) is therefore implemented, while in the PV-only scenario a production chain for agricultural goods is required. In total, 9 impact categories (e.g., global warming potential) are assessed.

The results show that the VB-APV scenario has lower environmental impacts than the S-APV scenario in all assessed impact categories. A hotspot in both APV scenarios is the PV module production in China, due to the high electricity demand and the impacts to produce silicon, in the S-APV scenario furthermore the mounting structure, especially due to the high steel demand and the related environmental impacts. When comparing the Agri-only scenario with Austrian-produced electricity with both APV systems, a reduction of environmental impacts is possible in three impact categories.

The results of the potential calculations were used with the help of a spatial planning game (serious game approach) on APV expansion in two selected case study communities to assess the impacts of potential yield losses, income from energy production and impacts on the landscape in terms of social acceptance. Represented were local stakeholders from agriculture, government, and planning who, in a first step, identified potential areas for APV expansion at the community level and, in a more concrete planning step, assessed the visual impacts of different APV systems using interactive 3D visualizations and VR glasses.

In terms of social acceptance and impact on the landscape, there was strong support for APV, especially regarding their potential dual use, but the impact on the landscape as well as the recreational function was viewed critically, especially for the S-APV systems or large-scale installations near settlements. Therefore, it was particularly important in the simulation to maintain an appropriate distance from the settlement area and to use areas along existing infrastructure (e.g., roads, power lines, wind turbines), as well as to give priority to low-value farmland. In both case study communities, the 2030 targets calculated at the municipal level were achieved.

In principle, the results of the project show that APV can be used to reduce land-use competition on agricultural land. Depending on the system, around 20,000 hectares are needed to achieve the 2030 climate targets. In addition, the second income from electricity production in APV systems ensures the livelihood of farmers. From the point of view of the sustainability assessment, a reduction of environmental impacts compared to simple land use is possible. Furthermore, APV tends to be socially accepted due to the dual use of land, however, the exact locations and the influence of the APV systems on the landscape have a great impact.

3 Background and objectives (Hintergrund und Zielsetzung)

In the coming years, it will be globally necessary to increase the production of agricultural goods (FAO, 2018; Tilman et al., 2011) as well as the production of renewable energies (Rogelj et al., 2018). The latter is also reflected in the European Green Deal which aims to achieve climate neutrality by 2050 (European Commission, 2019). Austria has even more ambitious targets, aiming to cover 100% of total national electricity consumption (in national balance terms) by renewable electricity by 2030 and to be climate neutral as early as 2040. In order to achieve the former, electricity generation from renewable sources must be expanded by 27 TWh, with most of this to be covered by photovoltaics (PV) (+11 TWh) and wind power (+10 TWh) (BGB, 2021). Fechner (2020) assessed the area potential of a PV expansion in Austria and concluded that meeting the 2030 target with rooftop PV is theoretically possible, but only if 80-90% of the technical potential of buildings is used. However, due to the short time frame, this is not practically feasible. This is consistent with the findings of Mikovits et al. (2021), who also found that even higher expansion targets for PV are needed to achieve full decarbonization. Both studies emphasize the need of PV systems on other land, such as landfills, parking lots, but also agricultural land (Fechner, 2020; Mikovits et al., 2021). However, the use of agricultural land for electricity generation is a controversial issue, especially due to the land use conflict of food/feed and electricity generation (Capellán-Pérez et al., 2017). Especially as climate change is already having a negative impact on agricultural production, with serious consequences for global food security, particularly for important crops such as wheat, corn and rice. The main climatic factors that are having a negative impact are increases in extreme temperatures, drought stress, and extreme precipitation events. Individual years are already highlighting the challenges for Austrian agriculture. For example, the federal government's "Grüner Bericht" for 2018 (BMNT, 2018) shows income losses of around 10% for Austrian farmers due to high temperatures and droughts. One solution to mitigate these competing interests could be agrivoltaics (agri-photovoltaics, APV), i.e., the combined use of agricultural land for food and feed production (primary use) and electricity generation by PV-modules (secondary use) (DIN, 2021). This combination is expected to increase the overall production of an agricultural area and additionally contribute to the adaptation of agriculture to climate change, as PV-modules can provide shade to crops or potentially protect them in general from extreme weather conditions (e.g., hail). So far, there is little research on APV in Austria, therefore the aim of the PA^3C^3 project is to evaluate the potentials and opportunities for APV systems in Austria in an interdisciplinary way by including techno-economic, environmental and social aspects. Potential locations in Austria will be localized, the techno-economic potential will be evaluated and future developments with regard to climate change will be considered by means of the ÖKS15 scenarios. In addition, data on agricultural opportunity costs and a combined assessment of mitigation and adaptation potentials in high resolution for the national scale are added. Since there has been little research regarding the environmental impacts of APV systems, the project will conduct a life cycle assessment (LCA) of two different APV systems and further compare them with a simple land use (either unchanged agricultural production or only production of electricity by means of an open-space PV system). Since APV systems will change the landscape and thus have an impact on landscape-related activities, the social acceptance of this new technology will be evaluated using a "serious game" approach. Participants in two case study workshops in representative regions can thereby play along a predefined set of rules in order to achieve certain goals without any "real world" consequences (Gugerell and Zuidema, 2017). In the project, the consequences of the game are visualized using 3D environments, which allows different points of view to be reflected in a participatory approach.

The goal of the PA³C³ project is to provide a database of agricultural yields for a variety of common crops and grasslands in Austria at 500 m resolution. This database will be complemented by estimating the impact of APV systems on different yields. It will be beneficial to government actors and agricultural stakeholders by providing a basis for structural planning and future land management adaptation. In addition, the project team will provide information regarding annual, seasonal, and hourly PV generation, with the addition of levelized cost of electricity and system value. This is an extremely useful database for stakeholders to understand the impact of different system configurations on potential PV generation. The environmental impacts of the entire scenarios, as well as the assessments of the selected APV systems, are published and serve as a source of advice and knowledge for government and stakeholders. Knowing where the environmental impacts come from means that the most efficient production chains can be implemented to support sustainable food and energy production. The social acceptance of APV in Austria will be determined, furthermore which APV system is preferred, and which areas can be considered as potential sites from a social acceptance point of view.

4 Project content and results (Projektinhalt und Ergebnis(se))

The description of the detailed content of the project and its results is based on the individual work packages (WP). For each of the different work packages, the objectives, the activities carried out and the results are described in this chapter.

Project objectives

WP1 "Project Management and Dissemination" covered all project management activities and coordinated the project team. Furthermore, WP1 ensured that project objectives were achieved, regular meetings and thus an intensive exchange of the whole project team took place and was responsible for the coordination of the project workshops (kick-off, stakeholder and final workshop).

In WP2 "AgroVoltaic based development of adapted mechanization possibilities", the state of knowledge in the field of agrivoltaics was determined by means of intensive literature research. Thereby, the mostly used APV systems at the beginning of the project, as well as their management and the associated limitations due to the technical setups were researched. The three most promising APV systems were identified and served as the basis for work packages 3, 4 and 5. Another focus of the project was the possible influences of PV-modules on selected environmental indicators (microclimate/yield, changes/water, and balance/erosion) and their effects on the productivity of selected crops.

WP3 „Analysis of potential areas for AgroVoltaics in Austrian agriculture" analysed the bio-physical crop yield effects, i.e., shadow effects from PV-modules, and the opportunity costs of APV systems resulting from yield effects and loss of land. Therefore, we applied the bio-physical process model EPIC on all Austrian cropland at 1 km² resolution and gross margin calculations. We considered a reference scenario without APV installations and two types of APV installations. Each of the three scenarios was coupled with a reference and one future climate scenario for the year 2050. The gross margins were calculated by using publicly available data from the IDB database (idb.agrarforschung.at) to assess realistic values for economic losses due to the APV installations. It allows to rank locations according to their APV provision costs which can contribute to find optimal locations for APV on Austrian cropland.

In WP4 „Analysis of electricity generation potential of AgroVoltaic systems in Austria and its impacts on the power system", we explored the PV potential and eligible areas from the energy perspective. We assessed areas, based on the agricultural areas from WP3, by suitability criteria found in literature and applied them within an automated GIS analysis for all agricultural areas in Austria, also considering technical restrictions. The energy output from the different APV systems was furthermore simulated on an hourly basis, considering shading from the surrounding area. Additionally, we provided input data for WP3 to account for the shading of the APV system on the agricultural area. Cost estimations are based on historical price data for Austria and were adjusted for the workshops to match the situation on the municipality level.

WP5 "Environmental impact assessment of selected utilization concepts using a comprehensive LCA method" aimed to perform a holistic life cycle assessment (LCA) to evaluate for the first time the environmental impacts of crop-based agrivoltaic systems in Austria. The APV scenarios were not only compared with each other, but also with two simple utilization scenarios; the unchanged agricultural production and the complete substitution by PV-modules (common ground-mounted PV facility). Furthermore, sensitivity analyses were performed, and uncertainties were integrated. Another focus of the LCA was the identification of hotspots, i.e., processes that have a large share in the environmental impact.

The aim of WP6 „Case study based determination of social acceptance and visual impacts of agrivoltaics using interactive 3D models and gaming approaches" was to identify and discuss aspects of social acceptance with regard to APV. For this purpose, workshops were held in two case study communities. The case study communities were selected to cover as many regions as possible and Wolkersdorf im Weinviertel (Lower Austria) and St. Stefan ob Leoben (Styria) were chosen. Wolkersdorf is characterized by very intensive agriculture but also has many vineyards. Due to its proximity to Vienna, it is a growing community and has been implementing wind energy projects for many years. In contrast, St. Stefan has agrarian predominantly grassland use and large forest shares.

The main objective of the project was to answer the following research questions with the help of the individual work packages:

- What are expected climate change impacts from the most recent climate scenarios (ÖKS15) in Austria?
- What is the techno-economic potential of agrivoltaics in Austria and where are potential areas located?
- What are the opportunity costs of agrivoltaic systems? Are there co-benefits of photovoltaics and agricultural production in particular under scenarios of climate change and on which areas are they the strongest?
- What are environmental impacts of agrivoltaics systems compared to separated production?
- How do citizens perceive agrivoltaics and which acceptance issues for large-scale expansion of agrivoltaics have to be expected?

Framework of the project

The PA^3C^3 project is divided into six work packages which were processed within the framework of integrated modeling, as shown in Figure 1.

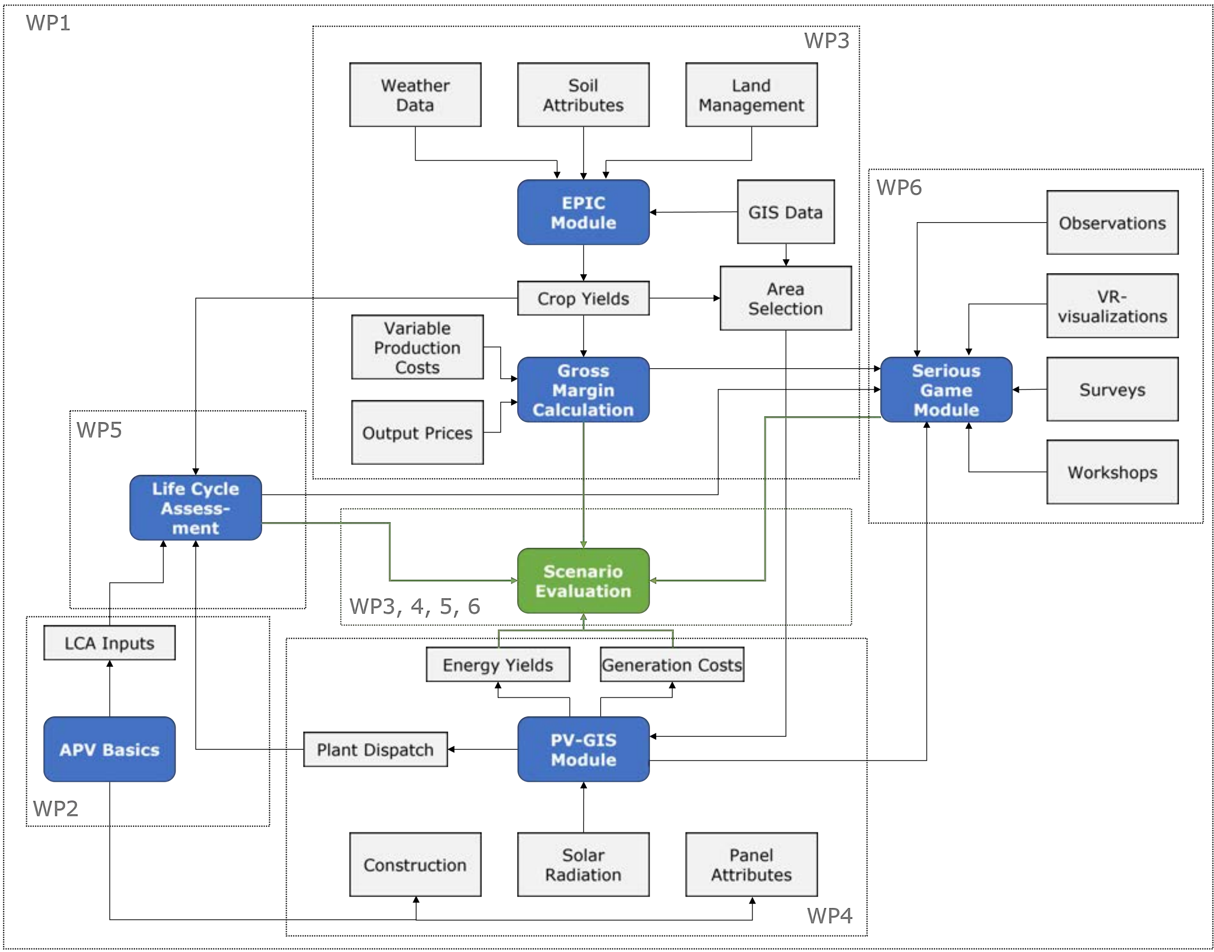

Figure 1. Framework of the project in which the blue colored boxes indicate the main methods of the individual work packages.

Activities and results (by work packages)

WP1. Project Management and Dissemination

Internal meetings on a regular basis were seen as an important element in achieving efficient communication within the project. Therefore, in addition to the kick-off meeting (**M1.1**) a total of thirteen project meetings with the whole project team were held over the whole project time. For each meeting, detailed meeting protocols made it possible to track and adhere to the respective agreements. In addition, several bilateral meetings were held in the different institutes to ensure work package progress.

WP1 included the management of the first interim report (**D1.1**), which was submitted in November 2021.

Another task in WP1 was to plan the virtual stakeholder workshop (midterm workshop, **M1.2**) on March 18th 2022, which not only included the presentation of the project, a talk of Max Trommsdorff from Fraunhofer ISE, but also a discussion of the stakeholders in a world café format. To find the most suitable format for such an online workshop and to ensure a smooth event, several meetings in advance to the workshop were held.

Another major event that required a lot of planning was the final evening event (wrap-up workshop, **M1.3**) on March 21st 2023 which was attended by around 115 people in person and streamed online by a large number of people. The planning included several meetings to prepare for the event, including organizing the project presentations, selecting suitable panelists for the panel discussion and writing invitations and project presentations as an online document for download. Press releases were written after the event.

Work package 1 further ensured that the most important project results were not only disseminated to the agricultural and scientific community in the form of publications and conference papers/talks, but also to the interested public by means of a factsheet (**M1.4**). Further, a joint publication of the whole project team is currently planned. The writing of the final report was also coordinated in WP1 (**D1.2**). A full list of all publications can be found in chaper 8 Publications and dissemination activities (Publikationen und Disseminierungsaktivitäten) (**D1.3**).

WP2. AgroVoltaic based development of adapted mechanization possibilities

In WP2, a comprehensive literature search on the topic of agrivoltaics was conducted. For this purpose, different search engines (the internal Boku literature search, Scopus, and GoogleScholar) were used. The results were processed and made available to all project members and served as a basis for WP3, WP4 and WP5.

The following literature overview is based on the interim activity report of the project (as this work package was already finalized then).

A first attempt of a uniform standardization of APV is the German DIN SPEC 91434 (DIN, 2021), which identifies two different APV categories:

(1) Category I: Systems with a clear height (at least 2.10 m), where agriculture is performed under the agrivoltaic system. In the following, this system is called a stilted APV facility (S-APV).

(2) Category II: Ground level systems with cultivation in between the PV-rows. In this category, there are two possible solutions: installation of PV-modules on one or two stilts and systems, where the modules are mounted vertically (often in combination with bifacial PV-modules) or adjustable on a stilt.

The stilted system was the most widespread system (Sekiyama and Nagashima, 2019) in the beginning of the project, especially for research facilities, while Category II APV systems were primarily used as business model of private businesses (e.g., Next2Sun GmbH, EWS Sonnenfeld).

APV systems can be further classified based on agricultural use, e.g., permanent grassland, arable farming (both classified as open APV facilities) and PV greenhouses with possible horticultural (also possible as open APV system) or aquacultural use as closed APV systems (Fraunhofer ISE, 2022) **(T2.1)**.

The suitability of plants for use in APV facilities is mostly determined by their shade tolerance, that is defined by the light saturation point. In general, very little is known about the impact of APV systems on crop production (Weselek et al., 2019), as there are no long-term research studies available yet. Overall, very shade-tolerant crops such as leafy vegetables, field forage (grass-clover mixture), various kinds of pome and stone fruits, berries, soft fruits, and other specialty crops (e.g., wild garlic, asparagus, hops) seem suitable for APV (Fraunhofer ISE, 2020).

The German definition of APV specifies that agricultural production is seen as the primary use while electricity generation via PV-modules is the secondary use (DIN, 2021). This is emphasized by the adaptation of the elevation of APV systems to the respective agricultural use. For instance, the clear height of the stilted system is chosen to allow conventional agricultural machinery to drive underneath (see, e.g., (Amaducci et al., 2018; Dupraz et al., 2011; Trommsdorff et al., 2021)), while in the vertical bifacial system, the row spacing (up to 20 m) is chosen to ensure that cultivation is also made possible with the use of conventional machinery. Inevitably, in APV-facilities with permanent grassland or arable farming there is some loss of production area of about 2% between the stilts, which is difficult to achieve with agricultural machinery (Weselek et al., 2019) **(T2.2+T2.3), (M2.1)**.

Agricultural production below or beside PV-modules is mainly affected by the reduction of solar radiation, which depends primarily on seasonal solar elevation, technical implementations such as orientation, tilt angle, and panel density (Beck et al., 2012; Dupraz et al., 2011). The shading in agrivoltaic systems is typically not uniform and moves throughout the day. According to the characteristics of the plants, the crop yield may decrease for shade-intolerant plants and remain the same or even increase for shade-tolerant plants. Marrou et al. (2013c) found that with 73% of incident solar radiation compared to a full-sun control, different lettuce varieties can still yield between 81-99%, with two varieties able to exceed the yields of the full-sun control. Furthermore, Barron-Gafford et al. (2019) found three- and two-fold greater production of fruit for chiltepin peppers and cherry tomatoes, respectively, and nearly equal production of jalapenos in a stilted agricultural photovoltaic system with a clear height of 3.3 m. Trommsdorff et al. (2021) observed that in 2017, a year with average weather data, yields of clover, celeriac, potatoes, and winter wheat were reduced in a German APV facility. In the dry and hot year of 2018, however, yields increased, except for clover grass. A recent meta-analysis from Laub et al. (2022) who assessed yield responses at varying levels of shade of various crops suggest that maize and grain legumes show a high vulnerability to shade, starting already at a minimum of reduced solar radiation. Also, the yields of C3 cereals seem to decline under shade, but at least less than proportional to the reduction of solar radiation until a 15% reduction of it, while the yield reduction of forages, leafy vegetables and tubers/root crops is declining less than proportional until a 20% reduction of solar radiation. They further state that it is important to determine the optimal shading level for maximum yield or where the yield loss is at least less than proportional to the reduction of solar radiation (Laub et al., 2022) **(T2.3)**.

While the reduction of solar radiation usable for crop production is the most apparent microclimatic factor in agrivoltaic systems, many other factors can be influenced, such as air and soil temperature, evapotranspiration, water availability, and relative humidity. Contrasting results are given for the influence of air and soil temperature in agrivoltaic systems and generally under shaded conditions. While Marrou et al. (2013c) found no significant changes, Marrou et al. (2013b) reported a tendency for higher air and lower soil temperatures under PV-modules. Other studies report a decrease in maximum air temperature (Pang et al., 2019) or soil temperature (Ehret et al., 2015) under shaded conditions, while Cho et al. (2020) found higher soil temperatures in spring and winter under PV panels. The contrasting results are most likely due to different locations and system designs; hence further research is needed, especially under Austrian conditions.

Agrivoltaic systems further have an impact on water distribution, e.g., during heavy rainfall runoff can lead to soil erosion. For mobile modules a time-variable tilt angle depending on wind direction could be a solution (Elamri et al., 2018b), while for fixed modules small modifications like rain gutters or distributors can be added (Trommsdorff et al., 2021). In addition, changes in water balancing leading to a reduced evapotranspiration was found by Marrou et al. (2013b), Hassanpour Adeh et al. (2018) and Elamri et al. (2018a). These observations lead to the conclusion that water use efficiency can be improved in agrivoltaic systems and help to prevent water losses in dry climates (Marrou et al., 2013a). Another influence of crop production in agrivoltaic systems is the delay in development of crops grown in agrivoltaic systems (Cho et al., 2020; Elamri et al., 2018a; Marrou et al., 2013b) **(T2.4)**.

In general, it can be said that agrivoltaic systems do have an impact on agricultural management. On the one hand, on the plants that can be grown (e.g., due to shade tolerance), but also on microclimatic effects. Nevertheless, the aim of APV is to adapt the APV system as closely as possible to the local agricultural conditions, and not the other way around to ensure that agricultural production is the main focus (**M2.2; D2.1**).

In principle, all types of PV solar modules can be used in APV systems, but the most commonly used ones are standard crystalline silicon ones and bifacial PV-modules in APV-facilities with permanent grassland or arable farming. Thin film or specialized modules (e.g., semi-transparent modules) were not widely used at the project beginning in permanent grassland or arable farming APV but are playing nowadays an increasingly important role for specialty crops (e.g., berries, apples). PV-modules can either be tilted at a fixed angle (stationary PV) or they can be tracked with 1- or 2-axis tracking (1D or 2D tracking); either tracking the sun or controlled tracking (aiming to minimize shaded area in the morning and late afternoon while maximizing shading at midday). Single-axis tracking follows the elevation angle or azimuth of the sun, while dual-axis tracking does both (Fraunhofer ISE, 2020; Valle et al., 2017).

The legal situation in Austria regarding APV systems has been changed with the Renewable Energy Expansion Act (Erneuerbaren Ausbau Gesetz - EAG). In the course of the new law, a new support system for PV systems and electricity storage was adopted. A market premium can be claimed for electricity fed into the grid to compensate for production costs in comparison to the fluctuating market price. The second option is the investment subsidy, which is paid out as a one-time grant during the new construction or expansion of PV systems. For ground-mounted systems, there is a deduction for both subsidy options. This is expected to be 25% if the area was previously used for agriculture or was a grassland area. What is new, however, is that there is no deduction for agrivoltaic systems in the case of both the market premium and the investment subsidy. However, this is only permissible if the dual use does not or only slightly affect the main agricultural use and if at least 75% of the area are used for the agricultural production (Bundesverband Photovoltaic Austria, 2021). Furthermore, under certain conditions, APV can also count as an innovative PV system, which would allow a 30% premium on the investment subsidy rates (OeMAG Abwicklungsstelle für Ökostrom AG, 2023).

Based on the thorough literature review the three most promising systems at the project beginning (2020) have been identified which will be further investigated in WP3, 4, 5 and 6 **(M2.2)**:

- Stilted system without tracking (S-APV)
- Vertical bifacial system (VB-APV)
- Ground-mounted systems with tracking

WP3. Analysis of potential areas for AgroVoltaics in Austrian agriculture

In WP3 we decided not only to simulate crop yields under climate change projections, but additionally focused on how the shading from the APV system affects yields. These shading effects have previously only been addressed in studies on single crops, single locations and with short term measurements. In the project, we assessed the yield effects of the reduction in radiation on a multitude of crops, for the whole country with high resolution, and under the influence of climate change in 2050 by simulating 40 years of the present (1981-2020) and 40 years of future climate (2031-2070) **(T3.1, T3.2)**. For that purpose, we applied the bio-physical process model EPIC to estimate crop yield effects at 1km² and daily resolution with the variables global radiation, minimum and maximum temperatures, humidity, wind speed and precipitation from an enriched and error corrected version of the ÖKS15 climate change scenario ICHEC RCP4.5 (CCCA Data Centre, 2016). Shadings implied by APV systems are assessed by comparing runs with and without reduced global radiation values. We present the method to quantify reduced global radiation in WP4. In EPIC, we considered crop rotations for a more realistic representation of real-world farming systems. Those crop rotations were modelled with CropRota (Schönhart et al., 2011) based on observed crop shares at municipality level. Hence, crop rotations are location specific and these regional differences were also considered when calculating the gross margins **(T3.3)**. Gross margins are the result of revenues from product sales minus variable production costs (e.g., for seed, fertilizer and mechanization). We do not consider subsidies assuming that they are not affected by APV systems. In this study, changes in gross margins result from changing crop yields and losses of land needed for the mounting structure of APV systems. Data for estimating gross margins were the modelled crop yields from EPIC and the crop prices and variable crop production costs published by the Federal Institute of Agricultural Economics, Rural and Mountain Research (2022).

Table 1 shows the 23 crops simulated in EPIC. Modelling represents 36,498 1km² grid cells for Austria, each with a typical crop rotation.

Table 1. Overview of the simulated crops

Nomenclatura	English	German	Shortname
Medicago sativa	Alfalfa	Luzerne	ALFA
Hordeum vulgare	Winter barley	Wintergerste	BARL
Trifolium	Clover grass	Kleegras	CLVA
Trifolium pratense	Red clover	Rotklee	CLVR
Zea mays	Maize	Körnermais	CORN
-	Vegetables	Gemüse	CRRT
Zea mays (sil)	Maize (silage)	Silomais	CSIL
Durum	Durum	Hartweizen	DWHT
Vicia faba	Faba bean	Ackerbohne	FABN
Novale	Fallow	Grünbrache	FALW
Pisum sativum	Pea	Erbse	FPEA
Sorghum bicolor	Sorghum	Hirse	CRSG
Avena sativa	Oats	Hafer	OATS
Solanum tuberosum	Potatoes	Kartoffel	POTA
Hordeum vulgare	Summer barley	Sommergerste	SBAR
Beta vulgaris	Sugar beet	Zuckerrübe	SGBT
Glycine max	Soybean	Sojabohne	SOYB
Partum	Fieldmeadow	Ackerwiese	SPAS
Helianthus annuus	Sunflower	Sonnenblume	SUNF
Tritico secale	Triticale	Triticale	TRIT
Brassica napus	Winter rape seed	Winterraps	WRAP
Secale cereale	Winter rye	Winterroggen	WRYE
Triticum aestivum	Winter wheat	Winterweizen	WWHT

Figure 2 shows the relative yields for the 5 major crops in each of the 8 main Austrian production regions (Landwirtschaftliche Hauptproduktionsgebiete). It compares APV systems and climate change impacts with the reference situation. In general, all simulated crops show reduced yields due to loss of area and reduced radiation. For the calculations a 12% reduction of area for the bifacial system (0.6m on each side of the modules with a distance of 10m) and 8% reduction for the overhead system were assumed (Fraunhofer ISE, 2022). Given these values the combined reduction of crop yields from loss of land and reduced radiation show drops by a maximum of around 30% (see also Figure 2). Red clover, temporary grassland, but also winter barley, winter wheat, oats and triticale seem to suffer less from a reduction of radiation. On the other hand, maize, soybean, sugar beet and winter rape seed seem to be less shade tolerant according to the model. The expected counter-effect of APV due to changing climate in the future can be seen in the simulation results. Shading from APV in the future scenario shows less yield losses for almost all simulated crops and regions and for both simulated APV systems compared to losses occurring under past climate, indicating substantial adaptation potentials of APV in the model. One may expect an even stronger effect for the future, since we modelled with the moderate RCP 4.5 scenario up to 2050, where greenhouse-gas emissions peak in 2040. For later periods in the century under higher emission scenarios, the adaptation effect of APV may therefore be even larger.

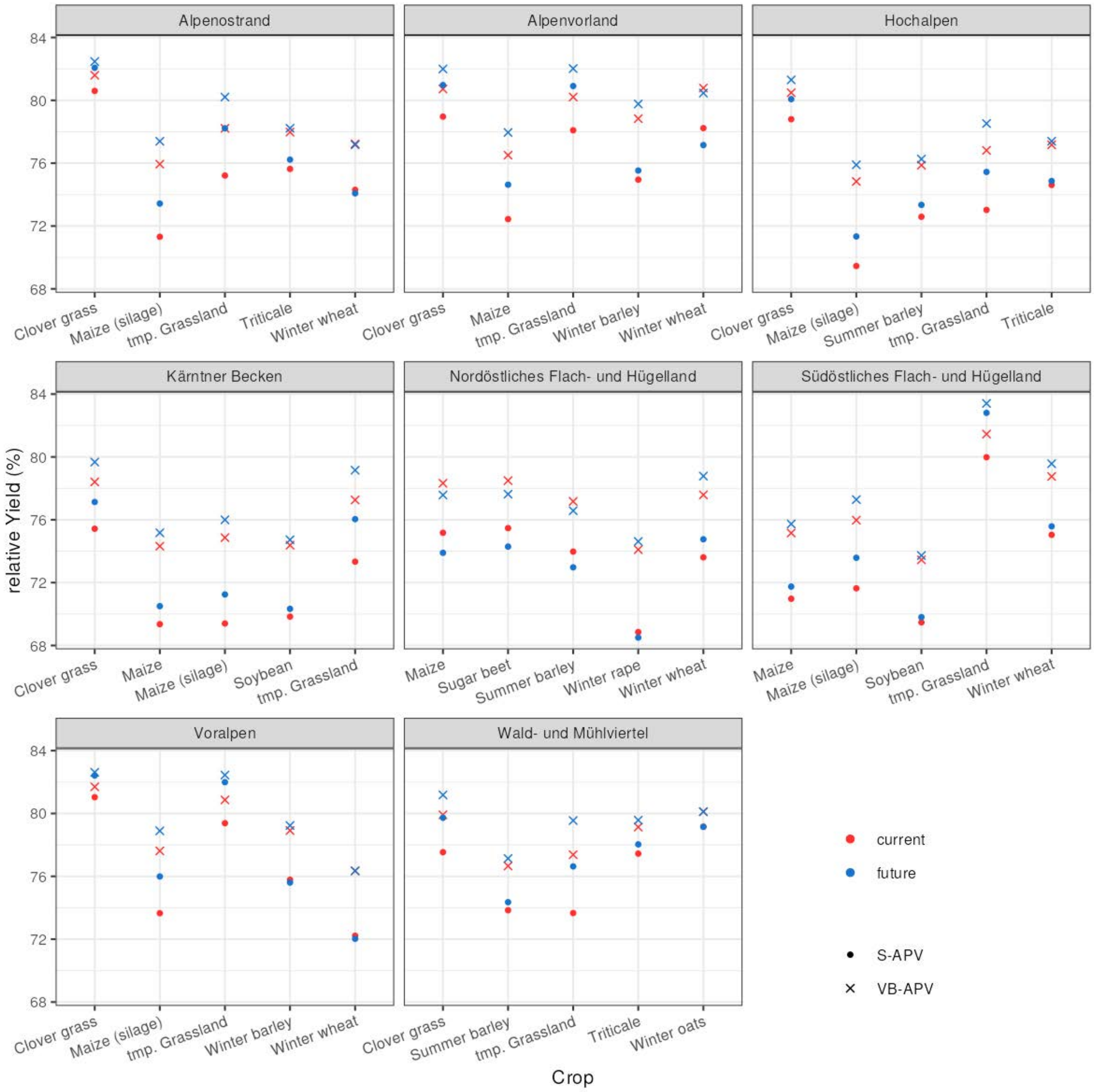

Figure 2. Relative crop yield in percent for each main production region in Austria, for the two analysed APV systems and for the current and the future period, reference (100) is the current period and without APV system.

The resulting gross margins per crop were calculated and aggregated again by main production regions, weighted by acreage and eventually ranked according to the least gross margin loss. The gross margin calculations were verified with the IDB database. We estimate gross margin losses of 34.2%-49.1% for the S-APV system and 27.1%-36.3% for the VB-APV system depending on the region and period; relative margin losses on a hectare basis can be seen in Table 2 **(M3.1)**.

Table 2. Relative margin losses for each main production region, period and APV system

Region	Period	margin loss	
		VB-APV	**S-APV**
Voralpen	current	31.3	41.3
Voralpen	future	28.6	37.0

Hochalpen	current	32.0	41.8
Hochalpen	future	27.1	34.2
Kärntner Becken	current	32.7	43.3
Kärntner Becken	future	33.0	43.6
Südöstliches Flach- und Hügelland	current	27.2	37.4
Südöstliches Flach- und Hügelland	future	30.8	42.2
Alpenostrand	current	31.5	41.0
Alpenostrand	future	28.4	36.2
Alpenvorland	current	27.9	38.5
Alpenvorland	future	30.4	31.3
Wald- und Mühlviertel	current	30.2	39.3
Wald- und Mühlviertel	future	36.3	49.1
Nordöstliches Flach- und Hügelland	current	31.8	44.2
Nordöstliches Flach- und Hügelland	future	35.3	48.4

In general, the losses in the main production areas *Alpenvorland*, *Südöstliches Flach- und Hügelland* and *Wald- und Mühlviertel* are the lowest, with margin losses from 27.2%-39,2% for VB-APV and 37.4%-39.3% for S-APV for the current period. For the future period we can expect a shift of regions with lowest losses towards alpine areas: *Voralpen* and *Hochalpen* instead *Alpenostrand* and *Südöstliches Flach- und Hügelland* (**M3.2**).

Gross margin losses were also calculated for a complete crop rotation, which makes results interpretation more realistic since it balances gains and losses of single crops that are part of crop rotations in the real world **(T3.4)**. Figure 3 shows the relative margins by APV system, period and main production region for the top 5 crop rotations, sorted by the margin of the reference system (no APV) and weighted by acreage of the crop rotation. In the header with the name of the production region, the percentage of the area of the respective region is shown. Throughout simulations we see higher gross margins in the future compared to the current period (past), independent of the APV system. Some crop rotations seem to be relatively robust with margin losses less than 20% for VB-APV, and less than 40% for S-APV. In contrast, crop rotations containing maize (CORN, CSIL) or soybean show both upward (future with CC effects) and downward fluctuations (APV systems) **(D3.1).** Further results on the agricultural production and suitability for agrivoltaic installations are currently under review in "Applied Energy" (http://dx.doi.org/10.2139/ssrn.4743081).

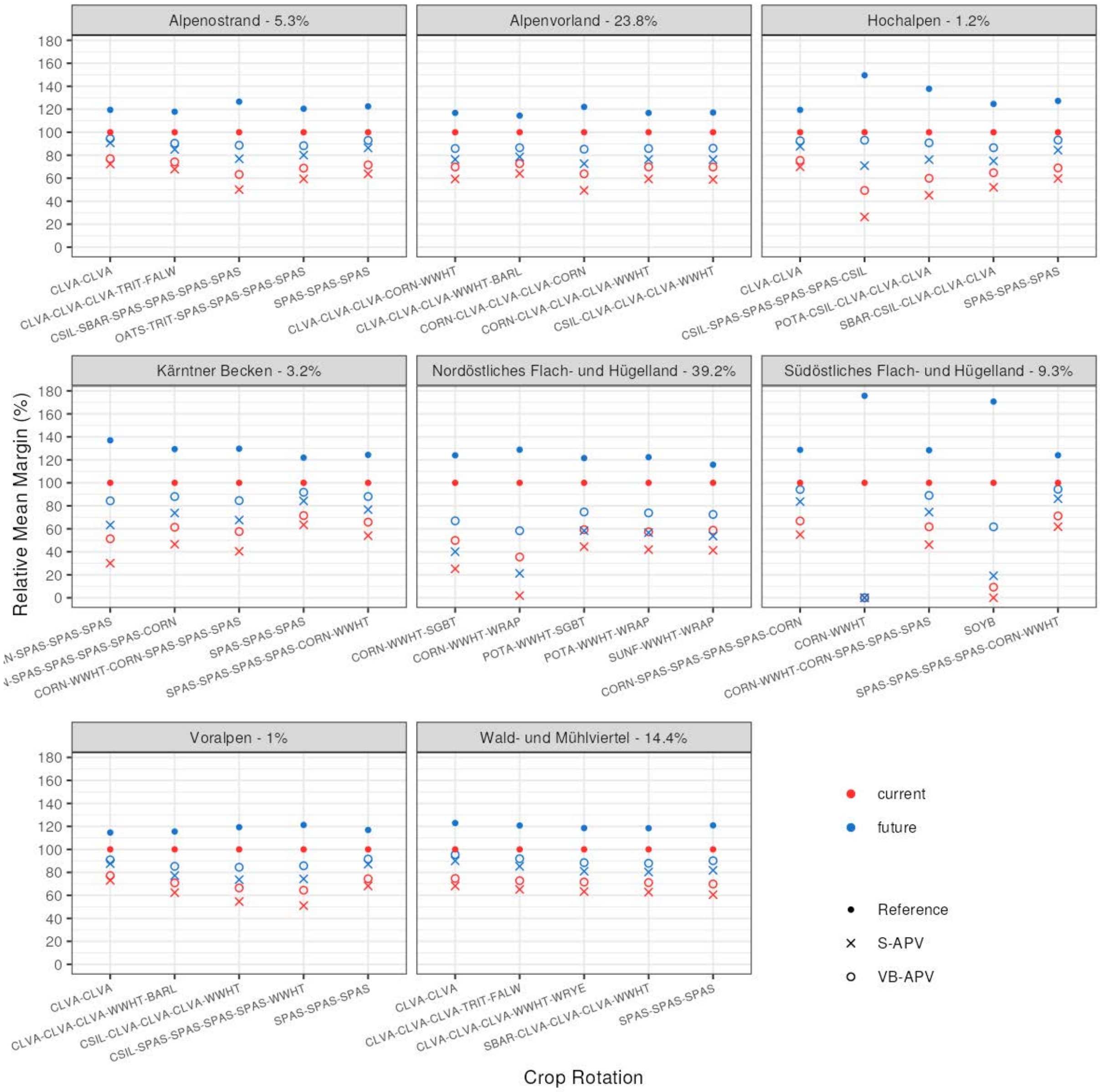

Figure 3. Relative gross margins by crop rotation, main production region in Austria, the top 5 crop rotations, by gross margin, for reach region are displayed, for the two analysed APV systems and for the current and the future period, reference (100) is the current period and without APV system.

Figure 4 shows the top 9 crop rotations and relative margins for all of Austria, where A shows the top crop rotations sorted by gross margins per hectare and B sorted by margin and additionally weighted by acreage. As before we can see higher gross margins for each of the displayed crop rotations for the future period and the reference simulation without losses from APV installation on top. High gross margins are estimated for crop rotations with fodder crops. These crops are traded on markets to a lower degree in Austria today. However, the price assumptions consider the value added from on-farm livestock production that depends on fodder crops. From a sustainability or food security point of view, one may argue that the loss of fodder crops (e.g., silage maize) from arable land is less of a societal problem than losses of grains or vegetables that can be immediately consumed by humans. The results shown here give an indication of where to find possibly suitable areas for APV systems on a large scale. Our simulations provide data and results on a high spatial resolution, e.g., on a cadastral municipality level and have already been applied during the two case study workshops in WP6.

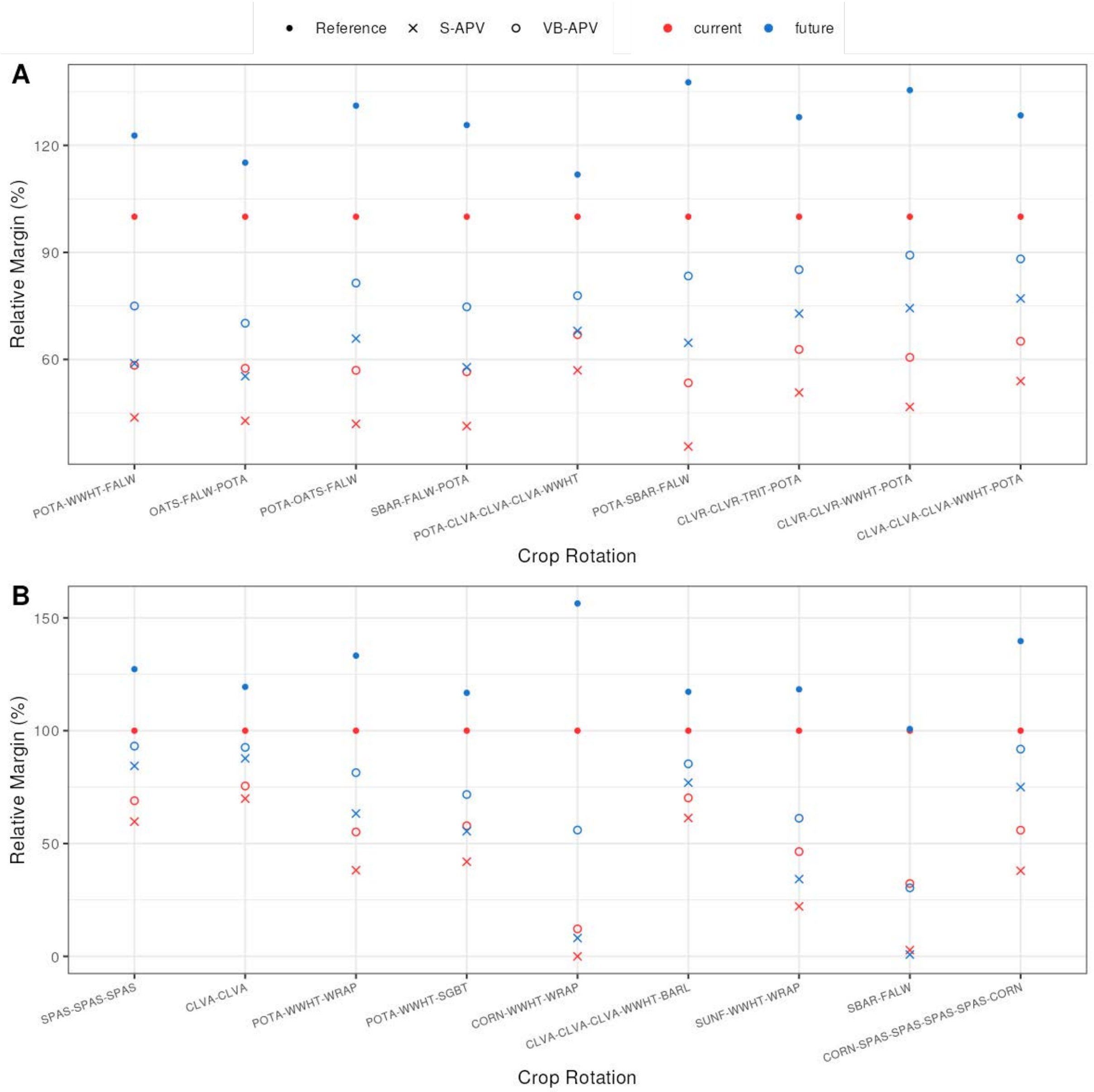

Figure 4. Relative gross margins by crop rotation for whole Austria; A: top 9 crop rotations by margin per hectare, B: top 9 crop rotations by margin and weighted by area, for the two analysed APV systems and for the current and the future period, reference (100) is the current period and without APV system.

WP4. Analysis of electricity generation potential of AgroVoltaic systems in Austria and its impacts on the power system

Within this work package we conducted a literature review assessing existing literature on APV systems, studies of the impact of shading on crop yields and assessments of existing installations in Europe and Worldwide **(T4.1)**. To date only a few studies with crop measurements have been conducted under experimental prototypes of agrivoltaic systems and small variation of plants, e.g., wheat, potato or clover. To our knowledge no long-term simulations with a multitude of crops and whole crop rotations have been conducted to date and simulations are mainly used for electrical yield predictions only or APV system optimization (e.g., Marrou et al. (2013b), Müller et al. (2016), Amaducci et al. (2018), Wagner et al. (2023)) **(M4.1)**.

In accordance with WP2, WP3 and WP5 two of the three APV systems were selected for a detailed analysis and for simulation of output for use in the WP6 interactive workshops: the stilted system (S-APV) and the vertical bifacial system (VB-APV), the two systems which in current practice and in literature are heavily discussed. During the project a newly developed framework was created to simulate PV output, where we decided to not support the ground-mounted APV system with tracking and invest more time in the calculation of shadow casting from the PV systems onto the crops. The simulation framework is based on software developed during the ACRP project *ReTour* and was extended and refined during the project. The layout of the framework is shown in Figure 5. It is openly available at https://github.com/inwe-boku/PA3C3.

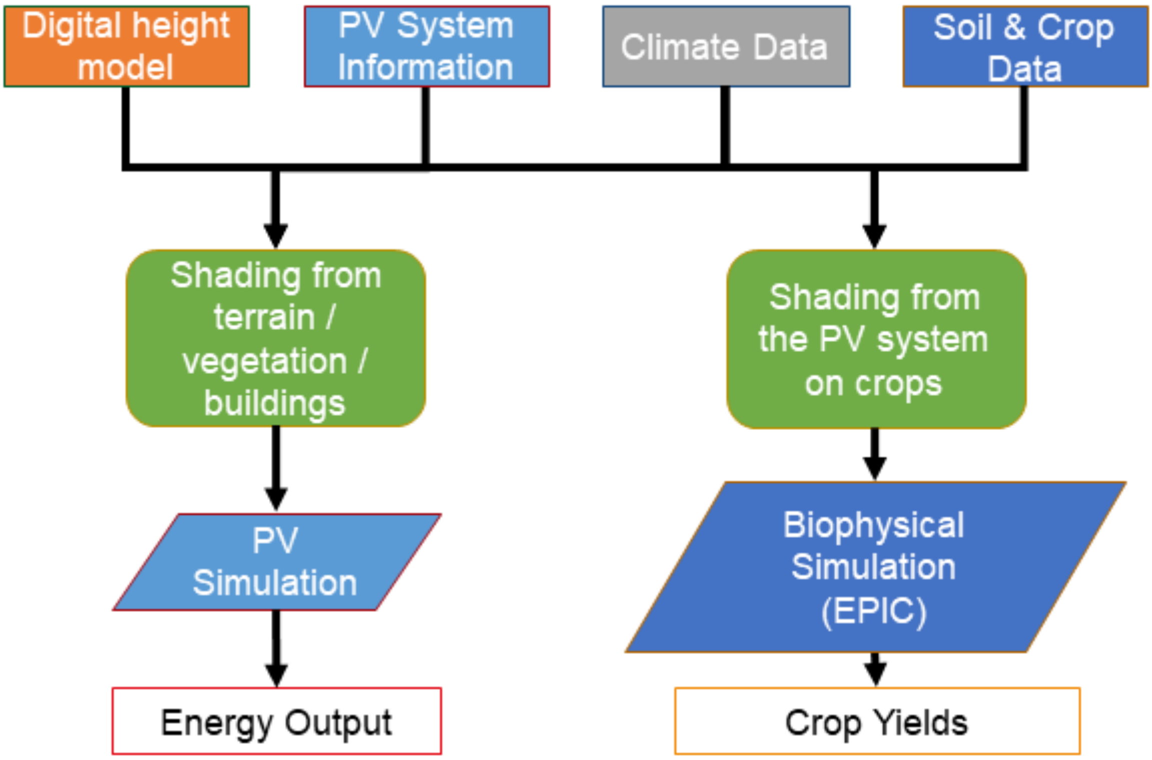

Figure 5. PV Simulation Framework, including the link to the biophysical simulation in WP3.

PV and APV system information can be defined easily via a human readable configuration file. The first step within the simulation framework is the analysis of potential agricultural areas suitable for the installation of APV systems, where the user defines allowed landcover types (e.g., wheat), minimum area, compactness, slope and altitude. Data from the Federal Ministry of Finance (2022) and INVEKOS (Integriertes Verwaltung- und Kontrollsystem) data (Agrarmarkt Austria, 2021) were used to automatically classify the areas as suitable for APV **(T4.2)**. The areas selected as suitable are used as input data of the energy module for PV energy output calculations. For each of these fields one or more, configuration dependent, PV simulations are conducted. For these simulations daily, or hourly, radiation data (rsds, surface downwelling shortwave radiation) is used, the temporal resolution of the analysis can be freely defined, usually hourly or half hourly, as well as the algorithm used to downscale the daily data to hourly or sub hourly data for the calculations (CCCA Data Centre, 2016). Shading from the surroundings (mountains, hills, forests, buildings) are considered by reducing the direct normal irradiation reaching solar panels accordingly. Finally, the output is stored as a geodatabase on a per field and on an hourly basis. Figure 6 shows the whole schematic calculation cycle, from the selection of hectare-based areas to radiation calculations **(T4.3)**.

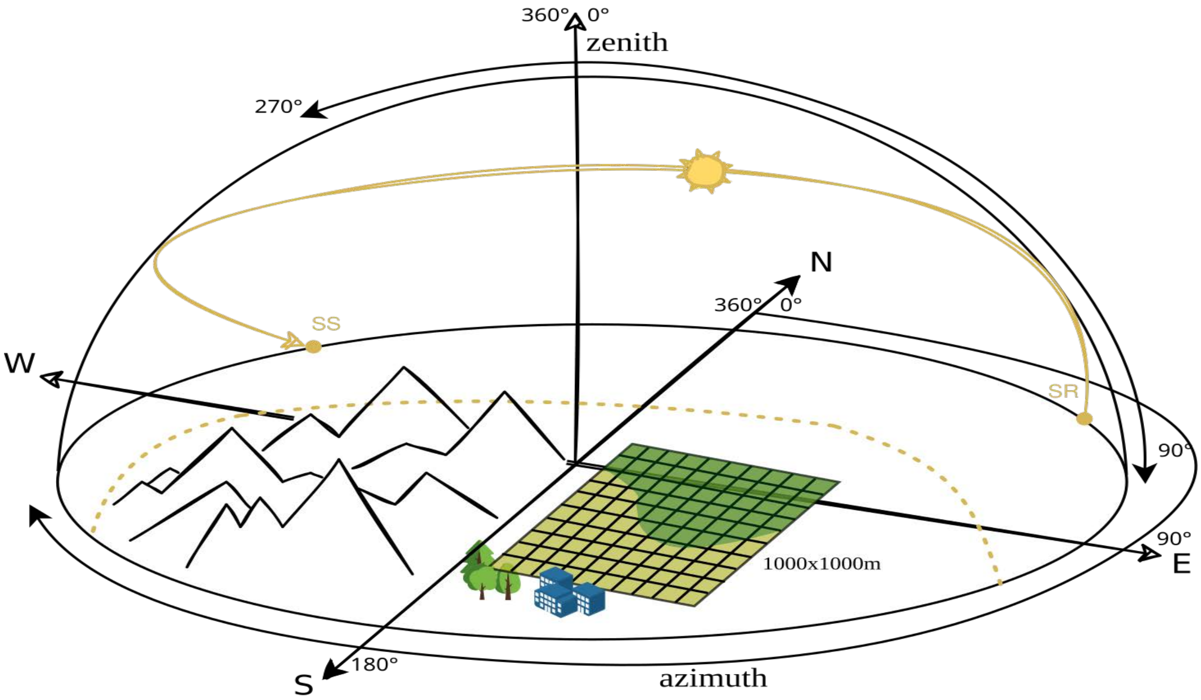

Figure 6. Schematic diagram of the land use, radiation and energy calculations.

Within this work the daily global radiation data from the ÖKS15 scenario 4.5 (CCCA Data Centre, 2016) was downscaled to hourly data using the algorithm introduced by Liu et.al. (1960). The PV electricity output is simulated utilizing the python library pvlib (Holmgren et al., 2018) which produces hourly timeseries per field and hectare, which were then further aggregated and stored as monthly and yearly averages. Table 3 presents the configuration of the different simulated PV systems, including the PV energy output on a yearly basis as an average for Austria.

Table 3. Definition of the APV systems for the simulations and a standard ground mounted system

	Ground mounted PV facility	S-APV	VB-APV
No. of modules	2500	2048	840
W_{peak} per module	400	280	415
kW_p / ha	1000	573	349

Azimuth	0	0	[90,-90]
Zenith	35	35	90
Yearly production (MWh/ha)	1173	684	373

Figure 7 shows the results produced by the framework exemplary for one municipality in Austria **(M4.2).** It shows in general a high potential for almost all fields calculated, except one small cluster of fields in the north of the municipality which are situated behind a small hill blocking some direct radiation from the sun. The tool can be flexibly used on a worldwide basis to simulate other APV systems, and other types of allowed landcover types, depending on the geodata available.

In addition to the tasks in the proposal we decided to include the calculation of the reduction of the solar radiation on the crops within this work package. On a hectare basis the shadow cast on the crops is calculated, leading to a reduction of direct normal irradiation (DNI). Further the reduction of the diffuse horizontal radiation (DHI) is estimated and both values are combined to global horizontal radiation (GHI). These values are used as input in the EPIC model in WP3.

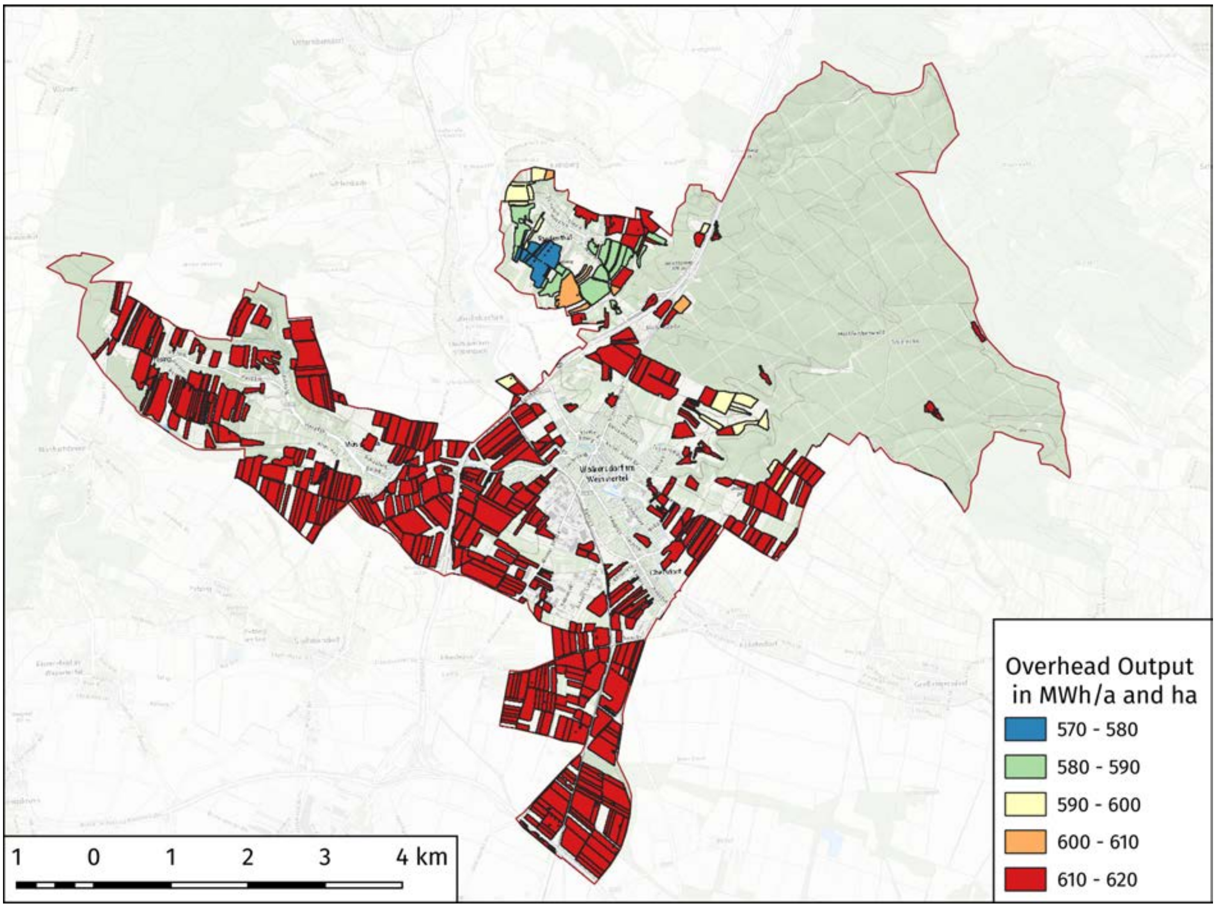

Figure 7. Exemplary high spatial resolution output for one municipality for the S-APV system.

The assessment of the levelized cost of electricity (LCOE) on the spatial aggregation level of main production areas shows only slight differences due to spatial averaging of differences in orography as shown in Table 4, where of course the siting within each region plays a significant role, especially in mountainous areas **(M4.3)**.

Table 4. Annual electrical energy production per region and APV system in MWh/ha

Region	S-APV	VB-APV
Hochalpen	712.3	388.4
Voralpen	690.5	376.6
Alpenostrand	747.3	407.5
Wald- und Mühlviertel	689.6	376.0
Kärntner Becken	777.2	423.8
Alpenvorland	692.7	377.8
Südöstliches Flach- und Hügelland	772.0	421.0
Nordöstliches Flach- und Hügelland	734.6	400.6

Based on PV electricity generation, we assessed the revenue and investment costs for the APV systems and compared them with the results of the agricultural simulations of WP3. According to Scharf et.al. (2021) investment costs for the S-APV and the VB-APV system can be expected to be 1234€ / kW_p and 688€ / kW_p without subsidies respectively, which translates to 0.85Mio € per hectare for the S-APV system and 0.26Mio € per hectare for the VB System. With an investment period of 25 years and an interest rate of 5% yearly costs amount to 60.000€ per hectare (S-APV) and 18.000€ per hectare (VB-APV). Revenues from solar PV can be highly variable in a dynamic market setting as in the past years when electricity prices varied between 0.05€/kWh to 0.5€/kWh (E-Control, s.a.) **(T4.4)**.

Estimates of electricity prices of about 0.1€ per kWh show revenues of 68,000€ and 37,000€ respectively. These prices can be expected to be effective at least for some years ahead, due to high CO_2-prices. Annual margins from the APV systems can range from even negative values up to 75,000€/ha (S-APV), given electricity prices of 0.15€ per kWh. In Figure 8 we show 2 investment scenarios and 2 electricity price scenarios. The plot shows the cumulative sum of energy production, sorted from high to low margin municipalities. Investment costs of the S-APV system assumed to be 1,111€ per kW_p and 1,234€ per kW_p, while the VB-APV system was calculated with 619€ per kW_p and 688€ per kW_p respectively (Scharf et.al., 2021). 25 years of term of investment with an interest rate of 5% were defined. We see that the S-APV system might not be profitable due to the high investment costs with low electricity prices, while the VB-APV system shows positive margins for all scenarios. This compares to a reduction in gross margins of agricultural production in the range of 27.2%-49.1%, depending on crop rotation and region – and are a magnitude smaller than profits from electricity generation **(M4.4)**. A compilation of all results (GIS data, energy production and LCOe) in combination with results from WP3 are currently submitted to "Applied Energy" and under review (http://dx.doi.org/10.2139/ssrn.4743081) (D4.1).

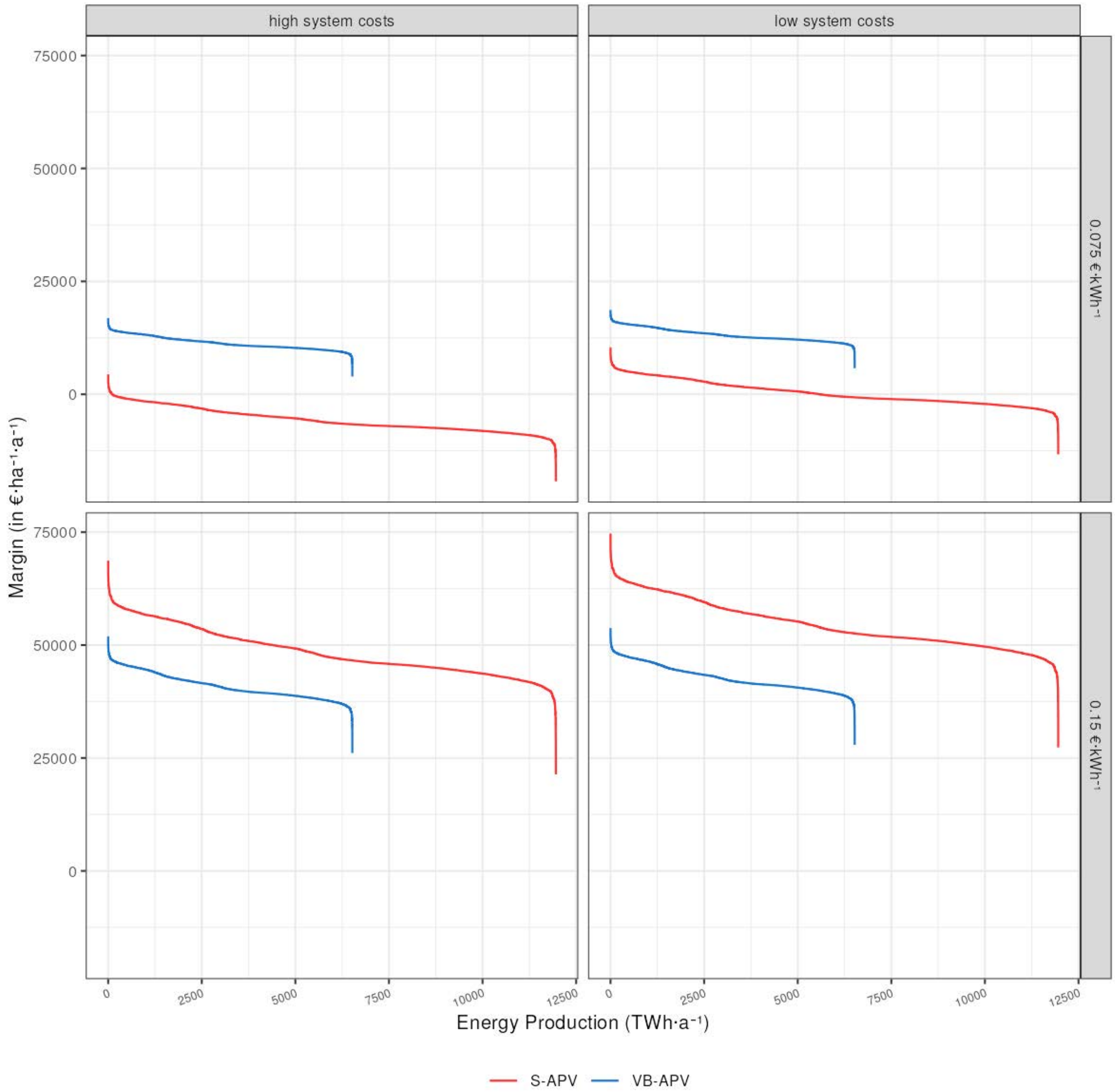

Figure 8. Cumulative energy production by highest to lowest margin for 4 scenarios: high and low system costs, and lower and higher electricity prices.

WP5. Environmental impact assessment of selected utilization concepts using a comprehensive LCA method

The description of WP5 is mainly based on the publication "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" (Krexner et al., 2024). Nevertheless, in this report the LCA is conducted for the Eastern-Austrian case study region Bruck a. d. Leitha, while the paper aims for a general Austrian assessment. The highlights of the methodological approach are explained, for further details see the publication.

The method used, Life Cycle Assessment (LCA), is a long-established method for estimating the environmental impact of a product or service over its entire life cycle and is based on ISO standards 14040 (ISO, 2006a) and 14044 (ISO, 2006b).

The four steps of a life cycle assessment are explained based on the project input below.

Step 1: Goal and scope definition (T5.1, M5.1 and M5.2)

The overall goal of the LCA is to compare the environmental impacts of producing electricity and agricultural crops simultaneously on one single plot (S- and VB-APV) with a mono-production, either sole agricultural or PV-electricity production (Agri- or PV-scenario). The system boundaries are set cradle-to-gate; hence, in the end the agricultural crops are available at the farm gate and the electricity is available to the consumer (transformation losses are included).

The scope of the LCA in this project is limited to arable land. Most crop production takes places in the far east of Austria, therefore, Bruck a. d. Leitha is chosen as case study region. Since only hypothetical APV facilities are assessed, the headland is neglected. The crop rotation employed is as follows: winter wheat, sugar beet, winter wheat and soybean with green manure before sugar beet and soybean, respectively. The 10-year average hectare yield from 2011 to 2020 (Statistik Austria, 2021a), is used for each crop. For the hectare yield calculation for both APV-systems only the usable area for agricultural production is considered (see Table 5 and Step 2: Life Cycle Inventory for more information about the usable agricultural area). In a sensitivity analysis the effect of a potential decrease in yields (simulated in WP3) under APV systems on environmental impacts will be examined. Electricity production is provided by WP4. In all the assessed scenarios (S-APV, VB-APV, Agri and PV), different quantities of electricity and crops are produced (see Table 5).

Table 5. Overview of the production of electricity (simulated in WP4) and agricultural crops (10-year average yield including land loss due to APV system in S- and VB-APV scenarios) in all assessed scenarios over the timespan of 4 years (one crop rotation). In the table, rounded values are used, hence, inaccuracies of ±1% may occur.

		Agricultural crops [t ha^{-1} fresh matter]			
Scenario	**Electricity [MWh (4a)$^{-1}$]**	**Year 1 (Sugar beet)**	**Year 2 (Winter wheat)**	**Year 3 Soybean**	**Year 4 (Winter wheat)**
S-APV	1,810	69.35*	5.41*	2.65*	5.41*
VB-APV	1,441	65.52*	5.11**	2.50**	5.11**
Agri	/	72.24	5.64	2.76	5.64
PV	3,974	/	/	/	/

* Yield is calculated based on the assumptions of an area loss of 4% in S-APV

** Yield is calculated based on the assumptions of an area loss of 9.31% in VB-APV

ISO 14044 (ISO, 2006b) provides a framework of how to deal with multi-outputs in LCA. It states that allocation should be avoided where possible. In this study, the system expansion approach was therefore employed, which involves expanding the studied scenarios, as needed, to deliver the same outputs over the timespan of four years (one crop rotation) in all assessed scenarios: 3,974,200kWh, 190,904kg sugar beets, 7,293kg soybean and 29,798kg winter wheat. To produce these amounts, different areas are needed (see Table 6). By means of this approach it is possible to achieve a fair and well-founded comparison of the different land use forms.

Table 6. Demand of agricultural land for all assessed scenarios

Scenario	Agricultural area used for			Additional area needed to fulfil same output in every scenario	Total area
	APV facility	solely agricultural production	solely PV-electricity production		
			[ha]		
S-APV	2.32	/	/	0.42	2.74
VB-APV	2.91	/	/	/*	2.91
Agri	/	2.64	/	/**	/**
PV	/	/	1	2.64	3.64

* Since both the electricity and agricultural output can be produced on the VB-APV area, there is no need for system expansion in this scenario

** Due to a wide variation of numbers reported for land use of electricity production, the additional area needed to fulfil the functional unit and the total area demand are not displayed.

The functional unit (FU), which is the quantitative reference to which all inputs and outputs are referring to (ISO, 2006a), is set in a way to consider both outputs, the electricity and the agricultural crops. It is set as 1 kWh_{el} and a basket of agricultural crops consisting of 44.11 grams of sugar beet, 7.50 grams of winter wheat, and 1.84 grams of soybeans (calculated down from the total output of all scenarios over 4 years).

Step 2: Life Cycle Inventory (T5.2)

As background data the ecoinvent v3.8 cut-off (Wernet et al., 2021) database was used and adjusted to the case study region of Bruck a. d. Leitha. As software openLCA v1.10.3 (Green Delta GmbH, 2020) was used.

- Stilted and vertical bifacial APV-scenario

The S-APV scenario is a combination of the APV facility described by Amaducci et al. (2018) and Agostini et al. (2021) and the Heggelbach research site (Trommsdorff et al., 2021; Wagner et al., 2023). A clear height of 4.8 meters and a 12-meter distance between stilts is assumed with the use of 280 Wp mono-silicon PV-modules with aluminium alloy. The degradation of the PV-module is included in the model based on Müller et al. (2021). A flower strip, which is mowed once a year, of 0.5m is assumed to be present between the stilts, which means that 96% of the area can be used for agricultural production.

The VB-APV scenario is mainly based on personal communication with stakeholders [Next2Sun GmbH, 2021 (personal communication)] and project based assumptions. While assuming an interrow space of 10 meters, the distance between the ground and the lower edge of the installed modules is one meter. The use of 415 Wp bifacial mono-Si PV-modules is assumed. Degradation of PV-modules is included based on data from Müller et al. (2021). Additionally, an intermediate strip of 0.4 meters on each side of a row is assumed, which is mowed once a year. In this system 90.69% of area can be used for agricultural practice.

To achieve the same outputs in all assessed scenario, additional crop production is required in the S-APV scenario, which is supplied by an average Austrian production process (same supply chains as in the Agri scenario). There is no need for system expansion in the VB-APV scenario, as both the electricity and crop outputs are produced in the required amounts (Figure 9).

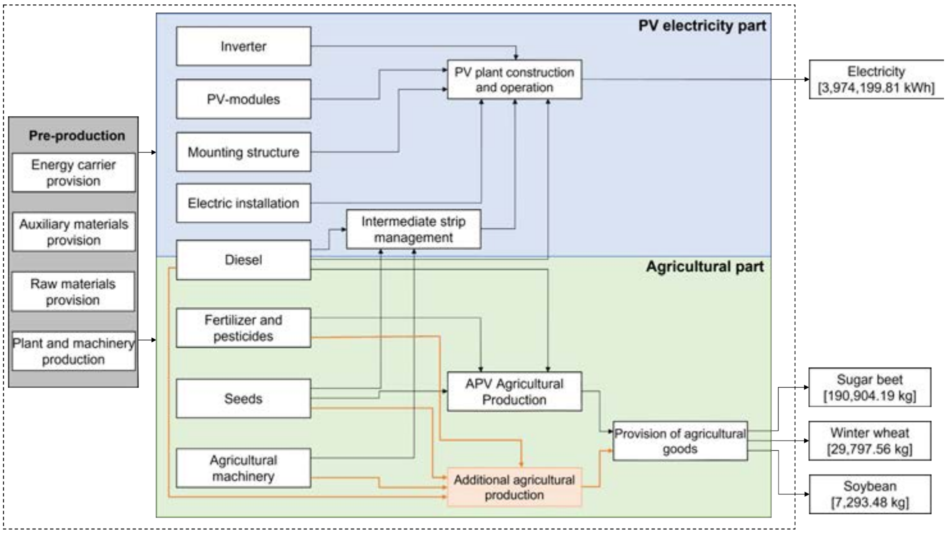

Figure 9. System diagram of the S- and VB-APV scenario; the dashed line illustrates the system boundaries. The orange-colored additional agricultural production is only necessary in the S-APV scenario and is included in the scenario as part of the system expansion approach.

The inputs and associated sources for the PV electricity part for both APV-scenarios can be found in Table 7.

Table 7. Overview of inputs and sources of the PV electricity part for both S- and VB-APV

APV facility part	Scenario	Life-time [a]	LCI main source(s)	Adjusted with/to	Additional information
PV-Module	S-APV	30	Müller et al., 2021	Chinese production conditions	Glass-foil module (S-APV), Glass-glass module (VB-APV)
Mounting structure	S-APV	30	Agostini et al., 2021 & Wagner et al., 2023	Additional process to cover the steel treatment	Steel: 36.23 kg m^{-2} PV-module; aluminum: 1.76 kg m^{-2} PV-module
Mounting structure	VB-APV	30	Next2SunGmbH, 2021 (personal communication)	Additional process to cover the steel treatment	Steel: 60-90kg for two modules; aluminium: 520g per module
Inverter	S-, VB-APV	15	Wernet et al., 2021	Chinese production conditions	Inverter of 4-9 kg kW^{-1}

Electrical Installation	S-, VB-APV	30	Wernet et al., 2021, Frischknecht et al., 2020	Adjusted to $kWp*ha^{-1}$	including the fuse box, electric cables, and the electric meter
APV facility construction	S-, VB-APV	/	Jungbluth et al., 2012; Mason et al., 2006; Wernet et al., 2021	Adjusted to needed mounting posts	
Fence	VB-APV	30	Wernet et al., 2021	Adjusted to $kWp*ha^{-1}$	

Agricultural production is modeled based on the ecoinvent database (Wernet et al., 2021) and adjusted to Austrian conditions. Machinery working widths are adjusted to fit the interrow space of the APV facilities. The appropriate machine working widths and diesel demand were selected using the KTBL-Feldarbeitsrechner (Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V., 2017). Emissions resulting from diesel combustion are adjusted in a linear fashion according to the changes, except for CO_2, where the emission factor of 3.12 kg CO_2 (kg fuel consumption)$^{-1}$ from ecoinvent (Wernet et al., 2021) was used.

Pesticide use was adjusted to Austrian conditions including verification that pesticides are approved for usage in Austria. The highest recommended nutrient amount of N, P2O5, and K2O, respectively, was assumed for every crop as conservative assumption, calculated using the LK-Düngerrechner program. The use of mineral fertilizer is assumed. Direct and indirect field emissions were calculated using a range of models that best reflect Austrian conditions (e.g., IPCC, EMEP/EEA and SALCA-models).

- Agri scenario

In the Agri scenario sole agricultural production is performed on the agricultural land. Hence, to fulfill the FU, the scenario needs to be expanded with an additional production chain of electricity, see Figure 10. If system expansion is done with an additional production chain of electricity, the used electricity mix has a big influence on results, as electricity mixes are very diverse. Hence, two options are assessed: (1) Agri-AUT: Austrian production mix (BMK, 2021; E-Control, 2021). (2) Agri-green: green electricity mix based on data from oekostrom GmbH (2020).

Agricultural production, diesel demand and associated emissions are adjusted in the same way as for both APV-scenarios. Machinery widths are adjusted to the local conditions of Bruck a. d. Leitha.

- PV scenario

In the PV scenario the agricultural land is used for sole electricity production by a common ground-mounted PV facility. As basis the ecoinvent database is used and adjusted to 1 MWp ha-1 and electricity output provided by WP4. Further, the use of mono-Si PV-modules with aluminium frame is assumed (same as in S-APV). The lifespan of both the inverter and mounting structure, as well as the production and transportation of the modules and inverter, is equivalent to both APV scenarios. Additionally, a fence is assumed. To fulfill the FU, an additional production chain of agricultural goods is needed, see Figure 10.

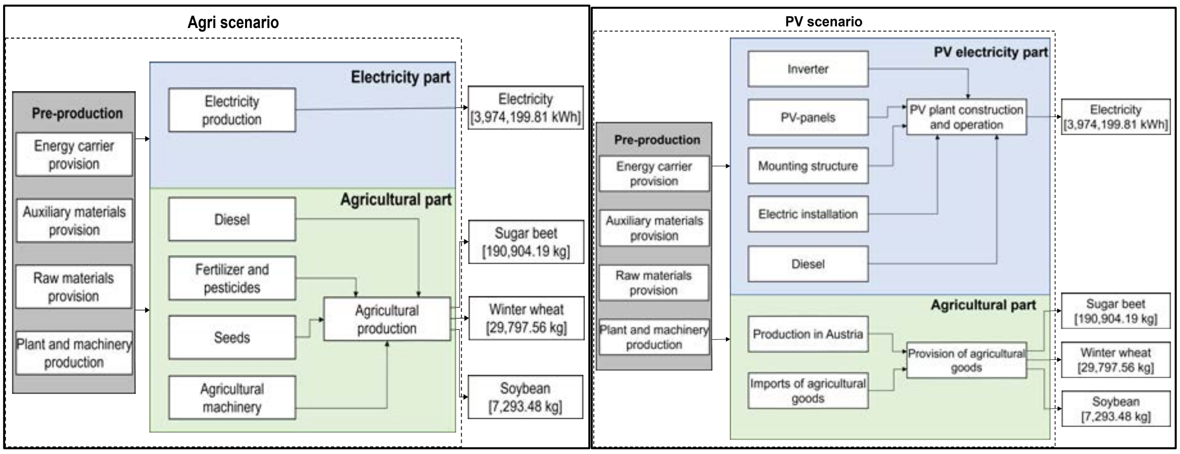

Figure 10. System diagram of the Agri and PV scenario; the dashed line illustrates the system boundaries.

The provision of agricultural goods in the PV scenario is based on the self-sufficiency rate, which indicates the degree of a country's reliance on its domestic production. The provision of each crop is divided into inland production (Agri scenario processes are used) and imports from foreign countries. The self-sufficiency rates used are 100% for sugar beet (Leeb, 2019), 87% for winter wheat (Statistik Austria, 2021b) and 92% for soybean (Statistik Austria, 2021c).

Step 3: Life Cycle Impact Assessment (T5.2)

The environmental impact assessment method ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2016) is used. The impact categories assessed are: Global Warming Potential (GWP) over 100 years, Human Carcinogenic Toxicity Potential (HCT), Human Non-Carcinogenic Toxicity Potential (HNCT), Terrestrial Ecotoxicity Potential (TEP), Freshwater Eutrophication Potential (FEP), Terrestrial Acidification Potential (TAP), Fine Particulate Matter Formation (FPMF), Mineral Resource Scarcity (MRS), and Fossil Resource Scarcity (FRS).

Step 4: Results

- Relative environmental impacts

In Figure 11 relative environmental impacts (absolute highest value is set to 100%) of all assessed impact categories are displayed. The S-APV scenario has the highest impact in 5 of 9 assessed categories (HCT, HNCT, TAP, FPMF and MRS), Agri-AUT only in 3. Agri-green has the lowest impact in 7 of 9 impact categories. The VB-APV scenario has lower impacts than S-APV throughout the whole assessment, compared to Agri-AUT in 4 categories. It is evident that (PV) electricity production (shown in blue) is the primary contributor in all the evaluated impact categories, whereas agricultural production (in orange) only has a moderate contribution to a few categories.

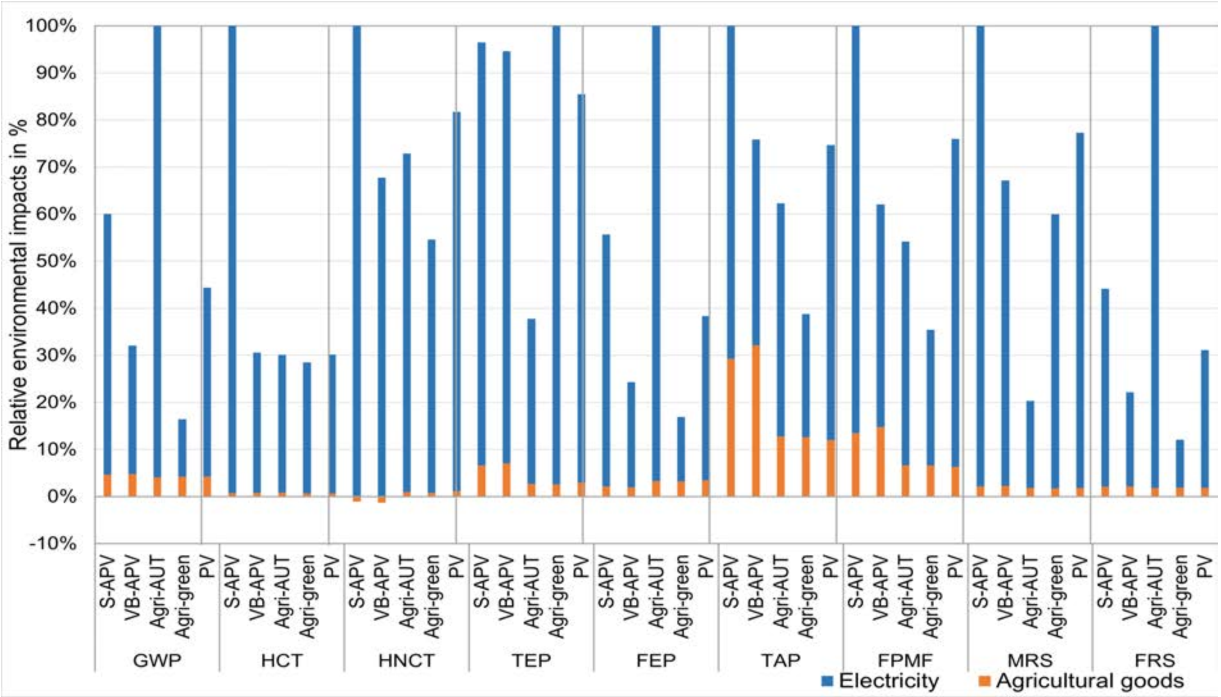

Figure 11. Relative environmental impact for all scenarios and impact categories.

- Contribution analysis **(T5.3, T5.4, M5.3, M5.4)**

While the PV electricity part includes the electrical installation, inverter, mounting structure, PV-panel and the PV plant Miscellaneous (PV facility construction, mowing of intermediate strip and fence; the latter two are not included in all scenarios), the agricultural part includes the winter wheat, sugar beet and soybean production. In the final report only results of exemplary impact categories are shown in Figure 12. For more information see the publication from Krexner et al. (2024).

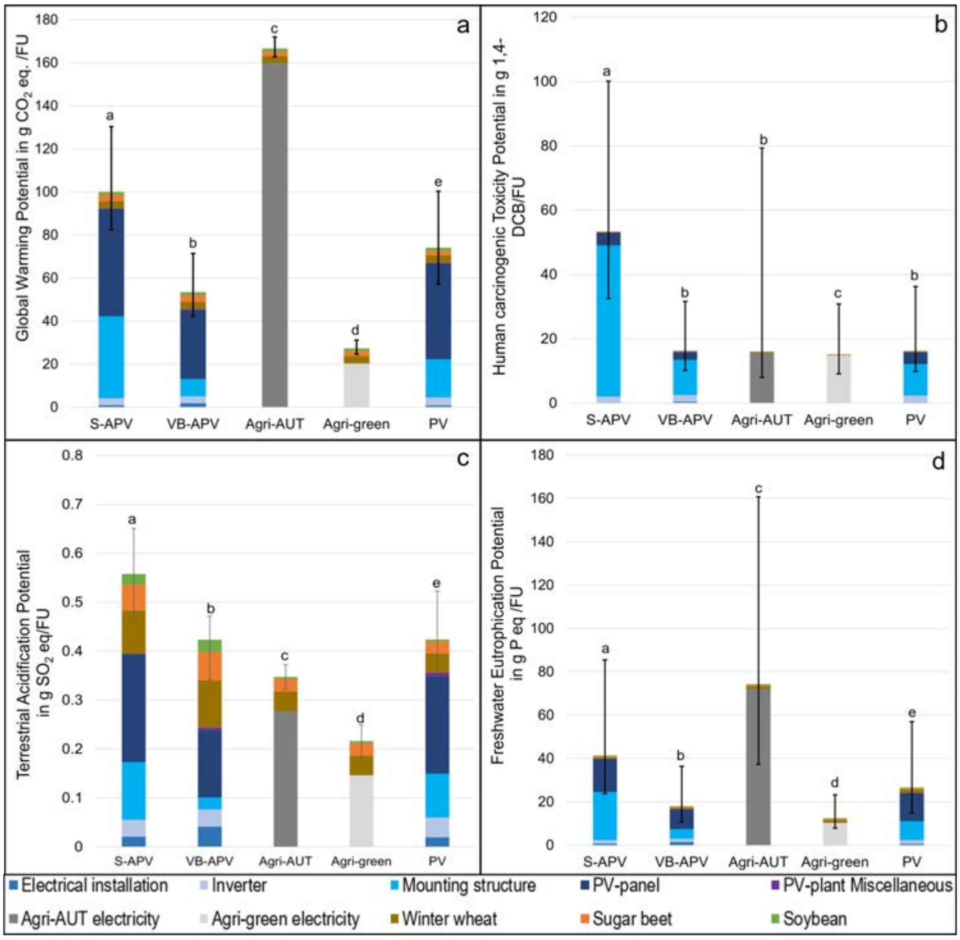

Figure 12. Contribution analysis of (a) Global Warming Potential, (b) Human carcinogenic Toxicity Potential, (c) Terrestrial Acidification Potential, (d) Freshwater Eutrophication Potential; error bars show the 5% and 95% interpercentile range of indicator's probability distribution function, based on 1,000 Monte Carlo runs; lower-case characters represent significant differences.

Agri-AUT scenario has the highest GWP (166.67g CO_2eq./FU); reductions of 40% and 68% are possible with S-APV and VB-APV, respectively. The PV-module production is the primary contributor in both APV- and PV-scenario, accounting for 50-60% of the total impact. This is due to the high electricity demand for cell production and preceding processes, as well as the Chinese electricity mix, which is mainly coal-based. Another hotspot is the mounting structure, particularly in the S-APV scenario, where high demand for reinforcing steel contributes to GWP through CO_2 emissions during pig iron production and CO_2 and CH_4 emissions during iron sinter production.

S-APV has the highest HCT (53.43g 1,4-DCB/FU); a reduction of 70% is possible with VB-APV, due to the lower steel demand for the mounting structure. Nevertheless, the mounting structure is the hotspot in both APV- as well as in the PV-scenario with contributions between 60-88%, due to the high emissions of chromium VI during the treatment of slag and dust from steel production.

The agricultural part has the most significant contribution to total impacts in TAP, ranging from 16.05% in the PV-scenario to 42.38% in the VB-APV scenario, mainly due to ammonia field emissions.

In FEP Agri-AUT has again the highest impacts; reductions of 44% and 76% are possible with S- and VB-APV, respectively. In FEP and TAP the PV module production in S-, VB-APV and PV scenarios is a hotspot, further again the mounting structure, especially in S-APV **(T5.5, M5.5).**

- Sensitivity analysis with yield decrease

In this sensitivity analysis the change in GWP for a yield decrease in S-APV of 17.87% for sugar beet, 23.80% for soybean and 18.67% for winter wheat and for VB-APV of 10.86% for sugar beet, 15.57% for soybean and 10.94% for winter wheat is assessed (yield decrease provided by WP 3). To compensate for the yield loss, an import of goods from foreign countries is needed. This would lead to a GWP increase of 2.52% in S-APV and 2.86% in VB-APV.

- 2050 Scenario

In the 2050 scenario it is assessed how the GWP of both APV-scenarios would change with a 2050 electricity mix (decarbonized) and sustainable produced steel. The used electricity mix is based on a 2040 scenario of Oesterreichsenergie (2022) with the assumption that the relative shares of electricity production types are not changed until 2050.

Results show that a reduction of 58% and 52% for S- and VB-APV scenarios are possible, respectively. This underlines the importance of a decarbonized electricity mix.

WP6. Case study based determination of social acceptance and visual impacts of agrivoltaics using interactive 3D models and gaming approaches

WP 6 started with literature research on existing APV systems and their suitability for Austrian agricultural areas (**M6.1**). This was done in coordination with WP 3, 4 and 5. The research also included a survey of the dimensions and the construction for the creation of the 3D models.

The selection of the case study municipalities (**M6.2**) was important because on the one hand an appropriate APV potential had to be available (WP3 and 4) and on the other hand the municipalities should be representative for other regions in Austria. We therefore selected a municipality in the agriculturally intensive eastern part of Austria as well as a municipality with pre-alpine characteristics and predominant grassland and forest use. A basic requirement was also the willingness of the municipalities to participate in this process which is why the municipalities of Wolkersdorf im Weinviertel and St. Stefan ob Leoben were selected after contacting municipal representatives (**M6.2**).

For both municipalities, a GIS data collection was conducted and the data relevant for the development of the 3D models (elevation and surface model, land use data, buildings and infrastructure, etc.) were collected and processed (see Appendix). The data were also used to determine contribution margins (WP 3 and WP 4) and energy yields for individual sites. In parallel, based on the progress in WP5, the 3D models for possible APV system were developed (stilted (S-APV) system and vertical bifacial (VB-APV) system) (**M6.3**).

The game logic (**M6.4**) was discussed and developed based on a proposal in an interdisciplinary discourse with the project team. We defined three game stages:

1. Pre-game: introduction of the participants, explanation of the game objective and gameplay.
2. Moderated game: Two rounds were used to develop scenarios for APV expansion in the community. In the first round of the game, basic Go/and NoGo areas for expansion were identified, which were then filled with concrete APV installations in the second round of the game. The game step (energy target 2030 and 2040/50) and possible impacts on energy production, contribution margins and food production were indicated. The players had to document their planning steps. The respective scenarios could also be viewed and discussed in 3D models as well as in VR glasses.
3. Debriefing: the results of the game were summarized and discussed in terms of game objectives and impacts.

The case study workshops were conducted on two consecutive days on 8.9.2022 (St. Stefan ob Leoben) and 9.9.2022 (Wolkersdorf im Weinviertel) each on site (**M6.5**). The premises were provided by the municipalities and visited in advance. The invitation and registration for the workshop was also handled by the municipalities. Due to the Corona pandemic, it was unclear for a long time whether and in what form the workshops could take place at all, and they were therefore scheduled for the end of the project. Retrospectively, it can be said that this decision was a good one due to the pandemic development and that the workshops could take place as planned in the application. The workshops were recorded, and a participant observation took place. The results of the game were saved as geodata.

The evaluation (**M6.6**) was carried out by a qualitative text evaluation of the workshop protocols interconnected with the participant observation and the analysis of the spatial game results. Basically, both communities showed a great openness towards APV. The synergetic dual use was seen as a great advantage, although the dimension of the installations (especially the S-APV system) was perceived as problematic when looking at the visualizations. In St. Stefan, especially in the peripheral regions, there were concerns about the impact on the landscape, but also about the possible grid connection. APV spots close to the edge of the village were also viewed rather critically. However, this suggests that pushing renewable energy infrastructure away into the landscape could affect natural areas even more. In Wolkersdorf, a very structured and goal-oriented (towards the 2040/50 targets) approach could be observed. It was quickly clear which regions would be suitable due to the existing local knowledge. There was generally less fear of contact with the technology, presumably because this municipality has long been active in the field of renewable energy (wind energy) and there are also large plants on the municipal territory. Here, there was a clear desire to concentrate the turbines and establish them on poor soils and away from municipal territory as well as along the highway on the one hand. The 40ha area necessary for the 2040/50 targets could be realized well there, but the large-scale application showed also here that the vertical dimension of the S-APV system should not be underestimated in terms of landscape impact.

5 Conclusions and recommendations (Schlussfolgerungen und Empfehlungen)

WP1:

Regular internal meetings with detailed protocols were recognized as a crucial component in facilitating effective communication within the project. Especially, since over the majority of the project time only virtual meetings were possible due to Corona.

The outcomes of the project have been presented not only to the scientific community as journal papers or at conferences but also to agricultural stakeholders and with the general public. During these latter project dissemination actions one of the most important aspects was to present the overall project approach and the results in a popular scientific way in order to reach all relevant stakeholders from the non-scientific area.

WP2:

A comprehensive literature review was conducted in this work package. According to the literature, APV systems can be divided into two categories, systems with a clear height and ground-level systems. In general, the APV definition clarifies that agriculture should be the primary focus, therefore the APV system should be adapted to the given conditions on site (e.g., to the existing machinery or already established crop rotations). Due to the mounting structure of the APV system, there is definitely a loss of agricultural area (up to 15%, depending on the system). Nevertheless, the most obvious difference in APV systems is that there is a reduction of solar radiation available for the plants. Depending on the type of plant, there may be an increase or decrease in yield. According to the current state of knowledge, the yield of C3 cereals or forages, leafy vegetables and tubers/root crops decreases, but not proportionally to the reduction of solar radiation (up to 15 or 20% reduction of solar radiation). Crops such as maize show a high shade intolerance even with only a slight reduction of solar radiation. This underlines that when building an APV system, the exact site conditions and all agricultural parameters must be taken into account in order to design APV systems in such a way that a maximum yield or at least no proportional yield loss occurs with the reduction of solar radiation. Hence, further research, especially in Austria is needed to gain insights in yield responses due to shading in APV facilities.

WP3:

We modelled yield losses and expected gross margin losses for single crops and crop rotations at high spatial resolution for two APV systems (S-APV and VB-APV) in two different periods. Although the estimated area loss is higher in the VB-APV scenario, it shows lower yield losses compared to the S-APV system due to lower shading impacts. According to the model results, the impact of radiation on crops is about twice as high for the S-APV system, with higher losses for specific crops like maize, rape or soybean and generally lower losses for hay crops (e.g., clover). Relative gross margin losses are expected to be higher than relative physical yield losses as gross margins per hectare account for variable production costs, which are assumed to be equal to management without APV. Furthermore, some crops show low gross margins even without APV installed. Subsidies have not been included in our gross margin calculations, though.

With regard to the effects of climate change, we see in the project model an overall yield improvement from APV in Austria, i.e., losses from APV installation are smaller under future climate change compared to the reference period with past climate. In our simulations we only consider the reduction in solar radiation and do not include other effects such as possible changes in wind speed and direction or the influence of precipitation blockage and run-off from APV systems. Similarly, the temperature effects below and between the APV systems have not been modelled and modified, as literature (e.g., Hassanpour Adeh et al. (2018)) shows that mean daily air temperatures are similar under direct sunlight and under the shade of PV panels. However, there may be effects on soil temperature and moisture. Therefore, while simulating radiation reduction only shows reduced yields for APV systems, further research is necessary to extend the model to also account for additional microclimatic effects such as altered humidity or soil moisture.

Results differ between regions and between regionally typical crops and crop rotations. Maize, rape seed and soybean appear to be particularly sensitive to radiation losses. It is recommended that APV systems are not installed on areas where these crops are part of the crop rotation. The installation of an APV system on fields areas where crops with high gross margin are grown, in particular potatoes, can lead to substantial losses in gross margins, therefore making these areas less suitable for APV installations. While we identify optimal areas for APV systems in terms of minimizing agricultural output losses and maximizing electricity yield, we did not account for distance to the power grid, which is a main determinant for making solar PV installations viable. We recommend further research into this direction. Although our results give a general overview on crops and areas and APV impacts on yield, subsequent research should focus on a broader understanding of production costs including impacts on labour productivity and variable production costs.

WP4:

In this work package, a tool has been developed which can be used for the identification of the best areas from an energy point of view at high spatial resolution, and it also allows easy configuration of different PV systems for comparison.

Potential aggregated electricity generation values are higher in Carinthia and South-East and North-East Austria, mostly because of orography and higher irradiation values. Nevertheless, the amount of electricity generated by the APV system is highly dependent on the specific area and orientation of the system. The amount of agricultural areas is significantly higher outside the alpine production areas, mainly concentrating in the North-East and the pre-alpine area north of the alps (Alpenvorland), making the North-East an important area for the development of APV systems, also as electricity demand is concentrated there.

The economic valuation depends mainly on the development of electricity prices and investment costs, and to a much lower extent on losses of agricultural production due to the installation of the system. In general, the VB-APV system with significantly lower investment costs reacts less sensitively to changes in the electricity prices and is profitable even with low electricity prices, while the S-APV system might not be profitable in case of a low-price regime. However, with higher electricity prices, S-APV systems become more competitive per unit of area due to their higher hectare yields. A major limitation of our analysis is that we assumed average electricity prices, which are currently sufficiently high to allow for profitable investments into APV systems. However, solar PV generation is temporally highly concentrated and prices in those hours may deteriorate rapidly, as long as temporal arbitrage opportunities are low. Investing into APV and solar PV in general on a gigawatt scale in Austria will have to take into account the economics of electricity markets therefore.

We show that there are areas and municipalities with particularly high profitability for APV systems, with the most profitable ones situated in Carinthia with more than 90% representation in the top 100 cadastral municipalities. These should be considered for development with a higher priority, and specific areas of course cross checked with beneficial crop rotations. However, most areas in Austria prove suitable and profitable for the installation of VB-APV systems under current market conditions, as regional differences in productivity are limited due to a rather uniform availability of solar radiation.

In conclusion, although APV systems have higher investment costs than ground-mounted systems, a quick return on investment is possible under current market conditions, with the benefit of maintaining agricultural production. However, ground-mounted system without integrating agricultural production will be most profitable on a per unit area, as monetary losses from agricultural production are more than compensated by potential income from electricity generation. If domestic agricultural production to maintain security of supply is highly valued by policy makers, this warrants policy interventions to make APV systems viable, e.g., by adjusting state subsidies depending on the installed system. Overall, the results support the installation of APV systems on less productive and profitable farmland since we assume that particularly productive and therefore valuable agricultural areas do not want to accept a loss of area and radiation reduction.

WP5:

In the project the environmental impacts of a stilted and a vertical bifacial APV-plant were evaluated and compared to the mono-use of land for either solely agricultural or electricity production using PV-modules. The VB-APV scenario demonstrates lower environmental impacts than the S-APV scenario in all assessed impact categories. This is because the VB-APV scenario requires less material, particularly steel, for the mounting structure and the glass-glass module has lower impacts compared to the glass-foil modules used in S-APV.

Comparing APV-scenarios to mono-use of land for agricultural production, it is essential to consider the source of electricity to ensure a fair comparison. When compared with electricity produced in Austria, both APV-scenarios result in lower environmental impacts in at least three assessed categories. However, if compared to a green electricity mix, which primarily relies on hydro and wind sources, both APV-scenarios have higher impacts in most categories.

The production of PV-modules is a hotspot in all impact categories for both APV and PV-scenarios. Another hotspot is the mounting structure in S-APV and PV scenario. This is mainly due to high electricity demand and steel usage. These hotspots highlight the importance of further research in increasing material and energy efficiency, as well as the significance of production site locations with the used electricity mixes. Additionally, considering the entire life cycle and assuming recycling, environmental impacts could potentially be further reduced, emphasizing the need for more research. In particular, assessing the production of PV-modules with green electricity mixes and increasing overall material efficiency in the future should be a priority since these are the primary hotspots. The 2050 scenario already provides insight in how environmental impacts could look like when using a decarbonized electricity mix.

Initial findings on the environmental impacts of APV-plants in Austria were found. It also demonstrates that expanding APV plants and producing both electricity and agricultural goods can reduce environmental impacts in some categories, as opposed to mono-use of land. These results highlight the importance of further research and optimization of APV-plants.

WP6:

The workshops had shown that there is a very high awareness of the need for energy transition at the local level. APV as a variant was not entirely new, but largely unknown in terms of its possibilities, system variants and dimensions. With our approach we were able to bundle very well local knowledge regarding landscape impact, soil qualities, use conflicts as well as grid infrastructure and implement it in a collaborative simulation game to identify and discuss questions regarding the social acceptance of APV with a qualitative approach. The direct feedback of APV installations on food production, energy production, and economic impacts in the game led to a very animated discourse on the potentials of this technology and resulted in the possibility of dual use in particular being highly valued. The targets broken down to the local level (2030 as well as 2040/50) could be achieved in both regions. From a technological point of view, we were able to show that geodata in combination with game engines have a very high potential to enable joint planning and discussion for the expansion of renewable energy. The high quality of the visualization as well as the VR technology allows a realistic evaluation of different scenarios, the interaction through free choice of location as well as adjustment of weather conditions and time of day gives a very comprehensive picture of the visual impact of large scale APV installations.

From this, a clear recommendation can be derived to use these new possibilities of participation especially in the site planning of renewable energy on a broad level, in order to create awareness on the one hand, to integrate local knowledge and to create a common and equitable planning base.

C) Project details (Projektdetails)

6 Methods (Methodik)

Methodology details are provided in section "4. Projektinhalt und Ergebnis(se)" in sub-section "Activities and results (by work packages)".

7 Work plan and schedule (Arbeits- und Zeitplan)

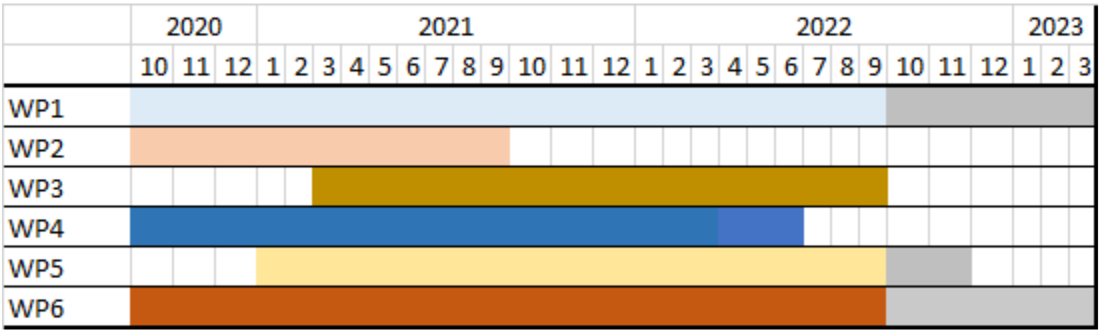

Figure 11. Revised schedule of the project, grey colour indicates which work packages were extended.

For the most part, the work packages were completed according to the set schedule. However, due to the Corona-related constraints, the case study workshops of WP6 could not be held on time. This required an extension of the project (see gray bars in Figure 10). WP1 was also extended to ensure coordination of the project team and to prepare for the final workshop in March 2023 after completion of all work packages. WP2 was carried out on time and was already completed at the time of the interim report in September 2021.

Work on WP3 started delayed for a better coordination with WP2 and 4, specifically to have a specific set of APV systems for analysis and the input data from WP4 for a detailed shading analysis of these systems.

WP4 was conducted on time and towards the end shared efforts with WP3 to perfect the assessment of shade effects were set.

In WP5, the research effort, especially for the 2050 scenario, was higher than expected and therefore was slightly delayed. Therefore, the work package was extended for two months.

WP6 had to be extended in order to hold the case study workshops (M6.5) in person and to be able to evaluate the results of these. The reason was the COVID19 pandemic and the uncertainties and legal regulations and responsibilities in case of possible infection with the virus.

8 Publications and dissemination activities (Publikationen und Disseminierungsaktivitäten)

- Publications
    - Mikovits, C., Schauppenlehner, T., Scherhaufer, P., Schmidt, J., Schmalz, L., Dworzak, V., Hampl, N., and Sposato, R.G., 2021. A Spatially Highly Resolved Ground Mounted and Rooftop Potential Analysis for Photovoltaics in Austria, ISPRS Int. J. Geo-Inf. https://doi.org/10.3390/ijgi10060418.
    - Schauppenlehner, T., Bittner, K., Baumgartinger-Seiringer, M., 2024. Large-Scale Agrivoltaics Visualisations for Assessing Landscape Impacts and Social Acceptance. AgriVoltaics Conference Proceedings, 1. https://doi.org/10.52825/agripv.v1i.596
    - Mikovits, C., Krexner, T., Kral, I., Bauer, A., Schauppenlehner, T., Schönhart, M., Schmid, E., and Schmidt, J., 2022. Energy production simulation of Agrivolatic Systems, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-9953, https://doi.org/10.5194/egusphere-egu22-9953, 2022.
    - Krexner, T., Bauer, A., Gronauer, A., Mikovits, C., Schmidt, J., & Kral, I., 2024. 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. Renewable and Sustainable Energy Reviews, 196, 114321. https://doi.org/10.1016/j.rser.2024.114321
    - Schauppenlehner, T., Baumgartinger-Seiringer, M., Bittner, K., 2024. Where should we place it? The potential of a serious planning game approach for participatory planning processes in the context of renewable energy development. Journal of Digital Landscape Architecture, 9-2024 (in press)
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    - Mikovits, C., Krexner, T., Kral, I., Bauer, A., Schauppenlehner, T., Schönhart, M., Schmid, E., Schmidt, J., Submitted. The Contribution of Agricoltaics to Reaching Climate Neutrality in Austria: Combined simulation of electricity and crop outputs of AgriVoltaic Systems.Krexner, T., Kral, I., Mikovits, c., Schmidt, J., Schmid, E., Ressar, K., Schauppenlehner, T., Bauer, A., 2022. Agri-Phovoltaik – Doppelnutzung agrarischer Flächen. BOKU-Energiecluster Factsheet Nr. 2/2022. ISSN 2791-4143 (Online). https://boku.ac.at/fileadmin/data/themen/BOKU_Energiecluster/Energiecluster/02-02_EC-FS_AGRI-PVneu.pdf.
- Talks and poster presentations
    - Poster presentation at the Klimatag 2021 (26.03.2021)

- Poster presentation at the AgriVoltaics2021 conference (14.-16.06.2021)
- Poster presentation at the BOKU Energiecluster (19.10.2021)
- Talk at the BOKU Energiecluster (19.10.2021)
- Poster presentation at the BOKU DocDay Conference 2021 (04.-5.11.2021)
- Talk at the EGU General Assembly 2022 (23.-27.05.2022)
- Talk at the AgriVoltaics2022 Konferenz (15.-17.06.2022)
- Talk at the CASEE 2022 Konferenz (22.-24.06.2022)
- Talk at the Austrian Energy Agency (28.06.2022)
- Talk at the SETAC Europe 25th LCA Symposium: (12-14.10.2022)
- Talk at the event 'Digitale Technologien in der Landwirtschaft – 3 Jahre DiLaAg' (11.11.2022)
- Three Talks at the Fraunhofer ISE Agrivoltaics Lecture Series (02.03 + 09.03 +16.03.2023)
- Poster presentation at the 23. Österreichischer Klimatag (11-13.04.2023)
- Talk at the AgriVoltaics2023 Conference (12.-14.04.2023)
- Talk at the SETAC Europe 33rd Annual Meeting (30.04-04.05.2023)
- Talk at the Expert*innen Tagung: Bodenschutz bei Photovoltaik Freiflächenanlagen (20.-21.06.2023)
- Two talks at SDEWES (24-29.09.2023)

* Workshops/Meetings
  - Project start with kick-off meeting
  - Stakeholder workshop (18.03.2022)
  - Serious game workshop in St. Stefan ob Leoben (08.09.2022)
  - Serious game workshop in Wolkersdorf (09.09.2022)
  - Closing Meeting (21.03.2023)
* Miscellaneous
  - Article in the municipal newspaper St. Stefan ob Leoben
  - Wissenschaftspfad BOKU poster "Mehrfachnutzung agrarischer Flächen: Agri-Photovoltaik"
  - CAS Newsletter 9/2021 short description of the project
  - Bauer, A., Krexner, T.; 2023. Agri-Photovoltaik - Strom vom Acker und Feld. Bio Austria Fachzeitschrift für Landwirtschaft und Ökologie, 1/2023, 38-39; ISSN 1027-0213.

- Krexner, T., Bauer, A., 2023. Photovoltaik auf dem Acker: Bauer sucht PV. BOKU-Das Magazin der Universität des Lebens, 28-29; ISSN 2224-7416.
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