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Förord

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Innehållsförteckning

Sammanfattning

Solceller i Sverige har främst setts som en energieffektiviseringsåtgärd för att minska mängden köpt el för byggnader, både bostäder och kommersiella. Först nyligen har solcellssystem i bruksskala börjat öka sin andel på solcellsmarknaden för att stödja de nationella energi- och utsläppsmålen. På grund av stordriftsekonomins fördelar representerar markmonterade solcellsanläggningar den bästa lösningen för att producera el till lägsta initiala investeringskostnader. Detta relativt nya marknadssegment för solel, med storskaliga markmonterade solcellsparker på jordbruksmark har ställts inför flera utmaningar med tillståndsprocessen. Jordbruksmark som är lämplig för odling är av "nationell betydelse" enligt svenska Miljöbalken. Odlingsvärd jordbruksmark får varaktigt exploateras för andra ändamål endast om det behövs för att tillgodose väsentliga samhällsintressen och det inte finns någon annan möjlig mark att använda inom det aktuella området.

Traditionellt har markmonterade solcellsparker ökat konkurrensen om markresurser för livsmedelsproduktion och väckt kritik i den så kallade "mat-mot-elproduktion"-debatten, dvs om marken ska användas för elproduktion eller livsmedelsproduktion. Agrivoltaiska (APV) solcellssystem representerar en

intelligent lösning för att undvika konkurrensen om markanvändning genom att kombinera odling och elproduktion på samma markområde.

Huvudmålet med detta projekt var att studera hur APV-system presterar ur ett energi-, jordbruks- och ekonomiskt perspektiv jämfört med konventionella markbaserade solcellssystem och vanlig jordbruksproduktion. Projektet syftade till att belysa fördelar och nackdelar med APV-system på nordliga breddgrader med ett energi-mat-vatten-perspektiv. Syftet var att etablera en APV-testplats, det första APV-systemet i Sverige, övervaka dess prestanda både ur energi- och jordbrukssynpunkt och utveckla nya teknoekonomiska modeller. I synnerhet användes data från APV-testplatsen, Kärrbo Prästgård, Västerås, för att bättre förstå hur APV-system på nordliga breddgrader påverkar: 1) effektiviteten hos solcellsmoduler; 2) grödans produktivitet och 3) den ekonomiska avkastningen för markbaserade solcellsanläggningar.

Det första agrivoltaiska systemet i Sverige har byggts på en permanent vall och forskningsverksamhet har genomförts på vallgrödan under 2021 och 2022. Liksom i tidigare forskningsstudier i andra länder, definierade vi tre delfält på försöksplatsen: 1) ett delfält med enbart odling av vallgrödan (referensområdet), 2) ett delfält med ett konventionellt markbaserat 11,8 kW_p solcellssystem med två rader av solcellsmoduler med 30 graders lutning och 3) det sista delfältet med ett 22,8 kW_p APV-system med tre rader av vertikalt monterade solcellsmoduler, med odling av vallgrödan mellan de tre raderna av solcellsmoduler. Denna fältuppsättning möjliggjorde jämförelser mellan praxis (jordbruk och elproduktion) och teknik (markmonterade solcellssystem kontra APV-system).

Den beräknade specifika elproduktionen under ett typiskt meteorologiskt år för det agrivoltaiska systemet och det konventionella solcellssystemet var 1067 kWh/kW_p/år respektive 1116 kWh/kW_p/år. Ändå tenderar det agrivoltaiska systemet att ha högre verkningsgrad än de konventionella solcellssystemen på grund av solinstrålningsmönstren på solcellsytorna och vindkylning av modulerna.

Projektets huvudresultat, när det gäller skuggeffekter på skördens storlek, visade att det agrivoltaiska systemet inte förändrade vallgräsets produktivitet under 2021–2022. Det fanns ingen statistisk säkerställd skillnad mellan skördeutbytet av proverna som tagits i det agrivoltaiska systemet och referensområdet. Trots detta minskar skördeutbytet per hektar med ca 10 %, när det är 10 meter mellan raderna av solcellsmodulerna i APV-systemet, på grund av den yta under solcellsmodulerna som inte kan skördas maskinellt.

Mätningarna som utfördes vid testanläggningen gjorde det möjligt för oss att validera den sen tidigare utvecklade modellen för elproduktion och effekterna av skuggning på grödan mellan solcellspanelerna. Att ha en modell för att bedöma skörden i agrivoltaiska system är av yttersta vikt för att i förväg kunna bedöma APV-systemets effekter på livsmedelsproduktionen, vilket är ett av de viktigaste målen i regelverk för agrivoltaiska system över hela världen.

Ur ett strikt ekonomiskt perspektiv kan agrivoltaiska system inte konkurrera med konventionella markmonterade system på grund av högre produktionskostnader per kWh el, vilket huvudsakligen beror på lägre elproduktion per hektar, på grund av färre solcellsmoduler per hektar och högre investeringskostnader per hektar. Ändå kan agrivoltaiska system utgöra lösningen för att övervinna de legala hinder som förbjuder eller hindrar användningen av jordbruksmark för elproduktion med solceller.

Summary

Photovoltaic (PV) systems in Sweden have primarily been seen as an energy efficiency measure to reduce the amount of purchased electricity for buildings, both residential and commercial. Only recently utility-scale solar systems have begun to increase their share of the solar market to support national energy and emissions targets. Due to the economies of scale, conventional ground-mounted PV (CGMPV) installations represent the best solution for producing electricity at the lowest specific initial investment costs. This relatively new solar market segment, with large-scale ground-mounted solar farms on agricultural land, has faced several challenges with the permitting process. Agricultural land that is suitable for cultivation is of "national importance" according to the Swedish Environmental Code. Cultivable agricultural land may be exploited for other purposes on a permanent basis only if it is necessary to satisfy essential societal interests and there is no other possible land to use within the area in question.

Traditionally, ground-mounted solar farms have increased competition for land resources for food production and drawn criticism in the so-called "food-versus-fuel (electricity)" debate over whether agricultural land should be used for electricity generation or food production. Agrivoltaic (APV) systems represent an intelligent solution to avoid land use competition by combining arable farming and electricity production on the same agricultural land.

The main objective of this project was to study how APV systems perform from an energy, agricultural and economic perspective compared to CGMPV systems and agriculture production. The project aimed to highlight advantages and disadvantages of APV systems at northern latitudes with an energy-food-water perspective. The aim was pursued by establishing an APV test site, the first APV system in Sweden, monitoring its performance both from an energy and agricultural point of view, and developing new techno-economic models. Data from the APV test site were used to better understand how APV systems at northern latitudes affect: 1) the efficiency of the solar modules; 2) crop productivity, and 3) the financial return for ground-based solar PV systems.

The first agrivoltaic system in Sweden has been built on a permanent ley grass field, at Kärrbo Prästgård, Västerås, and research activities have been carried out on the ley grass during 2021 and 2022. As in previous research studies in other countries, we defined three sub-fields: 1) a sub-field is covered only by the ley grass (reference area), 2) a sub-field is a CGMPV system 11.8 kW_p solar PV system with two rows of solar modules with a 30° tilt and 3) the last subfield is a

22.8 kW_p APV system with three rows of vertically mounted solar modules, with ley grass between the modules. This field set-up allowed for comparisons between practices (agriculture and electricity generation) and technologies (CGMPV systems versus APV systems).

The calculated specific electricity production during a typical meteorological year for the APV system and the CGMPV system was 1,067 kWh/kW_p/year and 1,116 kWh/kW_p/year, respectively. Nevertheless, the APV system tends to have higher efficiency than the CGMPV systems due to the solar irradiation patterns on the solar cell surfaces and wind cooling of the PV modules.

The main results of the project in terms of shadow effects on the ley grass showed that the APV system did not significantly affect the productivity of the forage grass in 2021-2022. There was no statistically significant difference between the yield of the samples taken in the APV system and the reference area. Even so, the yield per hectare is reduced by approximatively 10%, when the distance between the vertically mounted solar modules is 10 meters, due to the area under the solar modules that cannot be mechanically harvested.

The measurements performed at the test site allowed us to validate the earlier developed model for both electricity production and the effects of shading on crop production. Having a model to assess crop yields under APV systems is of utmost importance to be able to pre-assess the system's effects on food production, which is one of the main goals of APV system regulations worldwide.

From an economic perspective, APV systems cannot compete with CGMPV systems due to lower electricity production per hectare, lower density of the solar modules per hectare, and higher investment costs per hectare. Nevertheless, APV systems can be the solution to overcome the legal obstacles that prohibit or hinder the use of agricultural land for electricity generation with PV systems.

Inledning/Bakgrund

Sweden has set highly ambitious renewable electricity and electrification targets, aiming at 100% renewable electricity production by 2040 and zero net emissions by 2045 (Statens Offentliga Utredningar, 2017). In 2022, the total electricity supply was 172 TWh, of which 29% was from nuclear power plants, 40% from hydropower, 19% from wind power, 9% from combined heat and power, and 1.14% (2 TWh) from solar power (Swedish Energy Agency, 2023a).

Photovoltaic (PV) systems in Sweden have been mainly seen as a way to reduce the need to buy electricity for buildings, both residential and commercial. Only recently, utility-scale PV systems have increased their share in the PV market to support national energy and emission targets. The national targets can be achieved with large-scale rooftop PV, and CGMPV farms. Due to the economy of scale, the latter represents the best solution to produce electricity at the lowest specific initial investment costs (Lindahl et al., 2022). As can be seen from Figure 1, in 2020, the utility-scale CGMPV systems represented a relatively new market segment, with a share of about 7% of the total PV market (Lindahl et al., 2022).

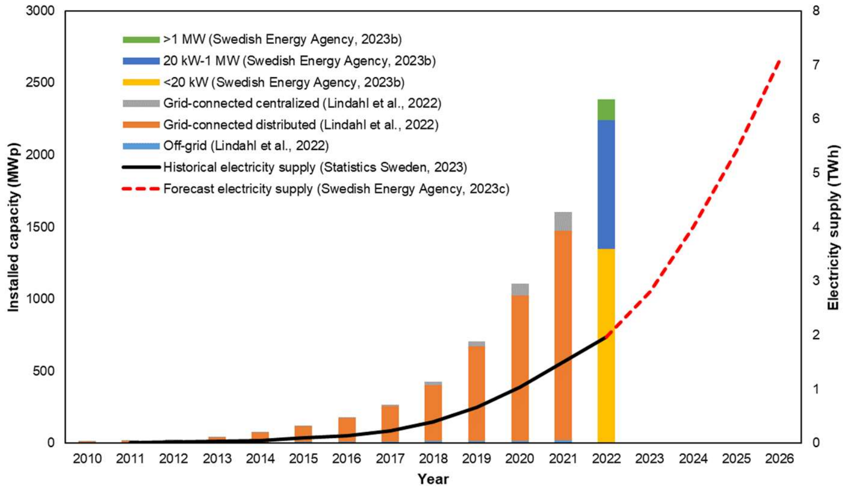

Figure 1: Installed PV system capacity by category for the period 2010-2022 (Lindahl et al., 2022; Swedish Energy Agency, 2023b) and historical and forecasted electricity supply from the PV systems (Statistics Sweden, 2023; Swedish Energy Agency, 2023c).

The share in 2021 increased from 7% to more than 8%. In 2022, the total PV installed capacity increased by about 800 MW_p, reaching 2.38 GW_p (Swedish Energy Agency, 2023b). According to Lindahl et al. (2022), the interest in the ground-mounted market segment has significantly increased and CGMPV parks are expected to increase in number and capacity. At the same time, the Swedish Energy Agency forecasts that the electricity supply from PV systems will increase from 2 TWh in 2022 to 7 TWh in 2026 (Swedish Energy Agency, 2023c).

Despite being a new market segment and despite the land availability in Sweden, the rapid interest in utility-scale CGMPV systems have encountered resistance from the County Administrative Boards, the institutional entities realising the permits, due to the competition between food production and energy conversion. According to Swedish law, agricultural land that is suitable for cultivation is of “national importance”, and it cannot be exploited for other purposes unless it is to satisfy a significant national interest and there is no other possible land to use (Chapter 3, Section 4) (The Swedish Government, 2000). Applying the above-mentioned specific Swedish law has produced some challenges to the CGMPV systems sector.

Traditionally, CGMPV farms have increased the competition for land resources for food production (Nonhebel, 2005; Dinesh and Pearce, 2016; Brunet et al., 2020); nevertheless, in recent years, researchers and companies mainly from France, Germany, Japan, Italy, and the USA have investigated agrivoltaic (APV) systems that are the combination of arable farming and electricity production (PV farms) on the same agricultural land.

An APV system is, according to the French law definition, a "*PV system located in the same area as the agricultural production, and it impacts the agricultural* *production by providing, without any intermediary, specific services, without inducing any significant degradation of the agricultural production, both qualitatively and quantitatively, or any farm income loss*" (Chatzipanagi et al., 2023; Légisfrance, 2023). The specific services are climate change adaptation (e.g., dealing with higher temperatures and lower precipitation rates), hazard protection (e.g., hailing protection), animal or human welfare (e.g., providing better working conditions for agricultural workers), and specific agronomic services (e.g., lower temperature or water stress).

Compared to a CGMPV system, an APV system uses innovative technologies, system configurations, and system operation that optimise combined land use for agricultural purposes while producing electricity from PV systems leveraging the synergies between PV systems and agriculture production. APV systems can be classified according to the system (e.g., open or closed), supporting structure (e.g., vertically mounted, overhead, stilt mounted), the tilt of the modules (e.g., fixed, one-axis tracking, two-axis tracking), and agricultural activities (e.g., grazing, arable farming, horticulture (Gorjian et al., 2022). A broad classification is provided in Figure 2, while a classification based on structure is provided in Figure 3.

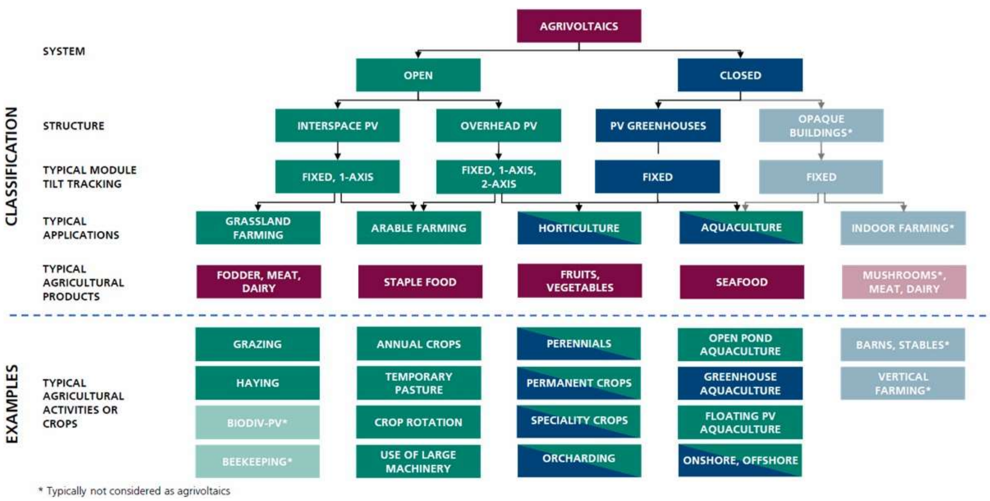

Figure 2: Broad classification of APV systems (Gorjian et al., 2022).

The APV concept was first introduced in the 1980s by Goetzberger and Zastrow (1982), while the first APV system in the world was installed by Akira Nagashima in Japan in 2004 (Nagashima, 2015). One of the first APV experiments was conducted in France in 2013 by Marrou et al. (2013), who successfully produced electricity and vegetables.

Figure 3: APV system classification based on structure (a) overhead structure with fixed PV modules; b) stilt-mounted structure with two axis-tracking system; c) single axis tracking structure; and d) vertically mounted structure).

A previous work conducted by the French research group proved through modelling that the combination of PV modules and agriculture could lead to an increased land equivalent ratio (LER) of 60-70% (Dupraz et al., 2011). The *LER* is defined as follows (Dupraz, 2011; Amaducci et al., 2018; Campana et al., 2021):

$$LER = \frac{Y_{c,APV}\chi}{Y_{c,rer}} + \frac{E_{APV}}{E_{CGMPV}}, \qquad (1)$$

where, $Y_{c,APV}$ is the crop yield in the APV configuration (t/ha), χ is a reduction factor that considers the land close to the mounting structure that cannot be used for agriculture, $Y_{c,r}$ is the crop yield in the reference area (t/ha), E_{APV} is the energy conversion of the APV system (kWh/m^2/year), E_{CGMPV} is the energy conversion of the CGMPV system (kWh/m^2/year). The LER is a typical key performance indicator for intercropping systems or agroforestry projects. APV systems having LER value greater than 1 show that the combined productivity of the APV system (i.e., PV electricity plus agriculture) is more than the separate production of crops and electricity, whereas LER values lower than 1 indicates that the productivity of APV system is less than the separate production of crops and electricity (Willockx, 2020).

More recently, Dinesh and Pearce (2016) have shown that agrivoltaic systems can increase the generated economic value of farms by 30% as compared to common agricultural practices in the USA. In 2018, the Fraunhofer Institute for Solar Energy Systems (2018) obtained a LER of about 180% compared to the reference case of only crop or electricity production in the experiment in Heggelbach, Germany. Amaducci et al. (2018) have demonstrated that agrivoltaic systems with an optimal density of PV modules can also increase crop yields since they can keep a higher soil moisture level in northern Italy. The work carried out by Amaducci et al. (2018) is considered a milestone for the technology since it indicated that APV systems can support crop yield, clean electricity production and water saving, playing thus a vital role in the energy-food-water nexus, and improving crop resilience to climate change or weather induced phenomena like droughts. Barron-Gafford et al. (2019) published their work on the energy-water-food nexus of APV systems in Nature Sustainability. Their results showed that combining PV systems with arable farm activities could reduce plant drought stress and higher food yield, as in Amaducci et al. (2018). Nevertheless, for the first time, through a fully monitored experiment, the authors showed that agrivoltaic systems can reduce PV panels' heat stress leading to lower solar cell temperature and thereby higher energy conversion efficiencies were achieved: 3% increase in electricity production during the growing months of May-July, with an overall 1% increase in electricity production annually. The experiments were carried out in Tucson, Arizona, USA under an overhead APV system.

By adopting a holistic approach, those advantages are crosscutting among three different macro-areas: energy, food, and water.

From the energy perspective, the combination of PV and agriculture crop production might allow higher solar energy conversion efficiencies because the microclimate produced by the crops can lead to lower solar cell operating temperatures (Barron-Gafford et al., 2019). Moreover, the configuration of the PV modules' supporting structure and the higher elevation of the PV modules compared to CGMPV systems lead to higher convectional cooling (i.e., higher windspeed or airflow) and, thus, again, lower solar cell operating temperatures (Johansson et al., 2022). Combining crops and bifacial PV modules can increase the specific electricity production per m^2 PV module when the crops are specifically selected to increase albedo during the crop growing season since the enhanced reflected irradiance increases PV production from both the front and rear sides of the PV modules (Potenza, 2023).

From the crop production and water consumption perspective, the presence of PV modules and the shading produced by the PV modules can reduce water and temperature stresses by altering the energy balance at the crop level (Amaducci et al., 2018). This advantage can increase crop production even under shading conditions (Laub et al., 2021). The PV modules and the supporting structure can beneficially alter the crop's wind speed distribution, avoiding soil erosion and evapotranspiration. APV systems with overhead structures can also protect crops from extreme weather events and, at the same time, provide an opportunity for water harvesting (Al Mamun et al., 2022).

Potential disadvantages of agrivoltaic systems include uneven precipitation distribution that can lead to increased runoff, erosion, and soil compaction (Elamri et al., 2018). The PV modules supporting structures reduce the practical usable cultivated area. Trommsdorff et al. (2021) reported an 8.3% loss of the total cultivated area for an overhead agrivoltaic system. Campana et al. (2021) reported a land loss of 0.5 m left and right of the supporting structure axis for vertically mounted agrivoltaic systems, which corresponds to a 10% loss of productive land in vertically mounted agrivoltaic system, with a 10 m row distance between the PV modules. This land loss translates to a potentially reduced yield per hectare and income from crop production for the farmers. The reduced and heterogenous cumulative solar irradiation at the crop level can negatively affect the crop yield. Other disadvantages include potential damage of agricultural machinery to the PV modules and PV modules supporting structure. This risk could be minimized by using the Global Positioning System (GPS) to steer or guide tractors and agricultural implements in a safe way between the PV modules.

From an economic perspective, the combination of power and crop production can increase the economic benefits of the combined system (i.e., PV plus crop production) compared to only crop production. Moreover, by combining farm activities, such as irrigation of crops, drying or refrigeration of harvested crops, and PV production, the self-consumption rate of power is higher since a lot of agricultural activities are concentrated during those months with higher solar irradiation and thus higher PV production. Higher self-consumption rates can lead to several benefits for the electric grid by avoiding congestion and thus increasing revenues due to the mismatch between selling and buying electricity.

Some critical aspects of the current food, agriculture, and energy situation in Sweden are provided in Figure 4.

Currently, according to the Federation of Swedish Farmers (Lantbrukarnas riksförbund, 2018), the country's food self-sufficiency is about 50%, with significant differences between food products (Figure 4a). Food self-sufficiency was about 80% during the 1970s, and it has been significantly decreased because of several factors, including dietary changes as well as reduction of internal production because of reduced agricultural land area and number of farms (Swedish Board of Agriculture, 2023a; Food and Agriculture Organization [FAO], 2023) (Figure 4b). The agricultural land area in Sweden has been drastically decreased from about 4.2 Mha in 1961 to 3 Mha in 2019 while the number of farms has passed from a total of about 232 thousand in 1961 down to about 72 thousand, with several differences among farms sizes. According to the electricity transmission system operator in Sweden, Svenska Kraftnät (2022), the forecasted electricity consumption in 2050 can be 30% to 110% higher as compared to the electricity consumption in 2020 depending on different electrification scenarios (Figure 4c).

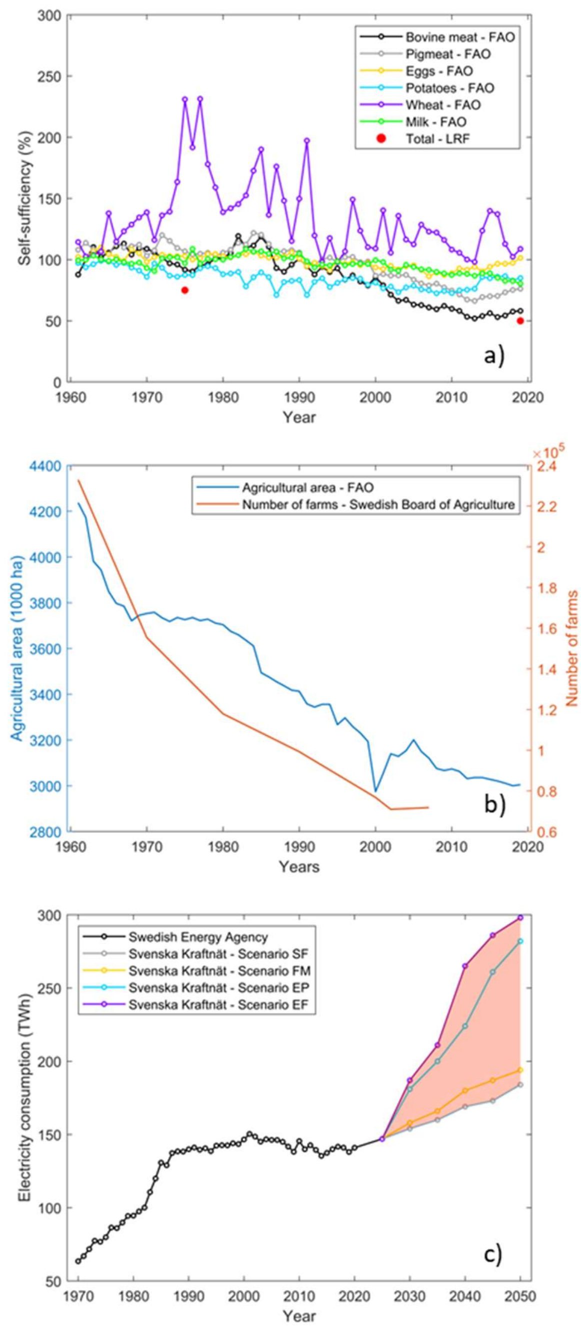

Figure 4: Food self-sufficiency (a), agricultural area and number of farms trend from 1960 until 2020 (b), and historical and forecasted electricity consumption in Sweden (c) (Campana et al., 2023).

In the Swedish context, APV systems can represent an intelligent solution to preserve food production while simultaneously allowing the attainment of the country's renewable electrification and emission targets.

The main goal of this project was to study how APV systems perform from an energy, agricultural, and economic perspective as compared to CGMPV systems and agriculture. The project aimed to shed lights on the advantages and disadvantages of APV systems at northern latitudes with an energy-food-water perspective. The aim was pursued by setting up an APV test site, the first APV system in Sweden, monitoring its performances both from an energy and agricultural point of view and developing new techno-economic models. In particular, the data from the APV test site were used to understand better how APV systems at northern latitudes affect: 1) the efficiency of PV modules, 2) crop productivity, and 3) the economic return of ground-mounted PV farms.

Specific objectives of this project were:

1. Set up an APV research test site;
2. Further develop the energy-food-water nexus model OptiCE, developed by Campana et al. (2018), for the management of drought in Sweden in collaboration with SMHI and NASA to simulate and optimize APV systems. The newly developed model will be called hereafter Agri-OptiCE;
3. Validate the Agri-OptiCE model with data from the research test site;
4. Develop an economic model for supporting the APV system market;
5. Scale-up of the Agri-OptiCE model to assess the potentials of APV systems on a larger scale.

Genomförande

The project was carried out as a collaboration between MDU (project leader), Kärrbo Prästgård AB, Solkompaniet Konsult Sverige AB, and SLU. People active in the project and their role were as follows:

MDU: Associate Professor Pietro Elia Campana, project leader and expert in PV and APV systems, and water-food-energy nexus; PhD Bengt Stridh, expert in PV and APV systems; PhD student Sebastian Zainali, his PhD studies focus on simulation and optimization of APV systems; PhD student Silvia Ma Lu, her PhD studies focus on solar radiation assessment in APV systems.

Kärrbo Prästgård AB: Ulf Andersson, owner of Kärrbo Prästgård AB and farmer.

Solkompaniet Konsult Sverige AB: Maja Wennerberg Fåhraeus, project manager and expert in PV system installations, Mikaela Liss, expert in PV systems installations, Christer Ljungbert Oxelius, CEO. From the beginning of 2023, Josefin Nordström, and Pontus Bergdahl were the project main responsible at Solkompaniet Sverige AB.

SLU: Senior lecturer Torsten Hörndahl, expert in agricultural management and technology; Senior lecturer Sven-Erik Svensson, expert in agricultural management and technology.

This project was composed by 5 work packages (WPs), which corresponded to the main project's specific objectives.

WP1 - Installation of the APV research test site

It focused on the installation of the APV field test site at Kärrbo Prästgård AB. The installation of the agrivoltaic system was performed by Solkompaniet Konsult Sverige AB. As in Barron-Gafford et al. (2019), we defined three sub-fields: one sub-field is only covered by crops (i.e., reference ley grass area), one sub-field is a CGMPV system, and the last sub-field is an APV system with ley grass between the PV modules. This field set-up was to allow comparisons between practices (i.e., agriculture crop production and electricity production) and technologies (i.e., CGMPV systems versus APV systems). The installation comprised a monitoring system for the measurements of PV power production, solar radiation, ambient temperature, ambient temperature underneath the PV modules, and soil moisture. The experience in agricultural practices from Kärrbo Prästgård AB was utilized for managing the ley grass on the site. Executors in this WP were: Solkompaniet Konsult Sverige AB, Kärrbo Prästgård AB, MDU, and SLU.

WP2 – Integrated water-food-energy nexus model development for APV systems

It focused on the development of an energy-food-water nexus model to understand the relationship between solar radiation, PV modules densities, electricity production, shadings, crop yields, and water savings. The model was developed to perform hourly and sub-hourly simulations and optimization. A starting point for the model development is the OptiCE optimization model developed by the project leader (Campana et al., 2018) and the work carried out by one of the scientific collaborators (Zhang et al., 2018). A thermal model of the photovoltaic system was also developed to study the effects of crop microclimate on the back-surface of the PV modules starting from the work performed by Mittag et al. (2019). Main executors: MDU, and scientific collaborators.

WP3 – Integrated model validation

We used the data collected in the field test to validate the model developed in WP2. To show the robustness of the model, we tried to reach other researchers in the same focused area if they could share data by aiming to joint research studies. Main executor: MDU, SLU, Kärrbo Prästgård AB, Solkompaniet Konsult Sverige AB, and scientific collaborators.

WP4 – Key performance indicators and profitability of APV systems

This WP focused on mapping different key performance indicators (KPIs) of APV systems especially with consideration to the economic viability of the project. KPIs included energy conversion efficiency, land use efficiency, water savings, revenues of the projects, lifecycle cost analysis, and profitability of the project.

New KPIs were investigated by considering the combination of effects due to PV production and crop production, and water savings. Based on the real economic input gathered from the industrial partners we developed the economic basis for a profitability model for APV systems in Sweden. Main executor: MDU, SLU, Solkompaniet Konsult Sverige AB, and Kärrbo Prästgård AB.

WP5 – Integrated model scale up and preliminary policy guidelines

Based on the results achieved during the field tests and the model validation in WP3, we extended the model developed in WP2 on a larger scale to study the impact of APV systems on the PV and agricultural sector. At this stage, we used a geographic information system (GIS) approach, like the work conducted by the project leader in Campana et al. (2018), to identify potential areas and assess potential benefits (i.e., increased electricity production, crop yield, and water savings) over all country. We studied the effects of agrivoltaic systems during extreme events like the drought in 2018. Using some selected KPIs identified under WP4, we will produce spatial maps of the KPIs. Guidelines for the implementation of the technology were produced in this WP. Main executor: MDU and scientific collaborators.

TIME PLAN

The project started in September 2020 and lasted until April 2023. The installation of the field test started at the beginning of 2021 to have it operational by the start of the growing season 2021 (WP1). WP2 and WP4 started from the beginning of the project and lasted almost until the end of the project and were finalized with the model validation using the measurement data from the field test (WP3). WP4 started from January 2021 until the end of the project. WP5 started at the end of 2021 until the end of the project.

Resultat

The results of this research project are organized per WP.

WP1 Agrivoltaic system test site in Kärrbo Prästgård

The siting for the agrivoltaic system experimental facility has been performed in the early 2021 by analysing differences in crop yield and chemical composition of the soil for a selected field within a farm located nearby Västerås, Sweden: Kärrbo Prästgård (59.5544N, 16.7534E). The aim of the siting was to find a plot in a field at Kärrbo Prästgård with an even vegetation. This task has been performed by using CropSAT (2023), a tool described in Söderström et al (2017). The crop variation within fields is visualized by using satellite images, processed to produce a vegetation index.

The research facility takes inspiration from the experimental set-up presented in Barron-Gafford et al. (2019). It is composed by an APV system and a CGMPV system to perform comparison between PV systems configurations, and a reference area to analyse the differences in crop production between open field conditions and under the shadings conditions produced by the APV system. The

APV system is designed with vertically mounted bifacial modules in a north-south direction, with a row distance of 10 meters to facilitate the ley grass crop harvest, as depicted in Figure 5. The APV system capacity is 22.8 kW_p. The PV system is composed of 60 bifacial PV modules arranged in three rows of 18 m length and a row distance of 10 meters. A reference CGMPV system is 11.8 kW_p. It is composed of 32 bifacial PV modules arranged in two rows of 8.5 m length with a tilt of 30°. A summary of the characteristic parameters of the APV and reference CGMPV system is provided in Table 1.

At the end of 2022, the experimental facility was monitored with more than 20 sensors for both weather, microclimate, power, and agricultural parameters. A schematic diagram of the monitoring system is presented in Figure 6.

Figure 5: Ley grass harvest in the APV system in 2021.

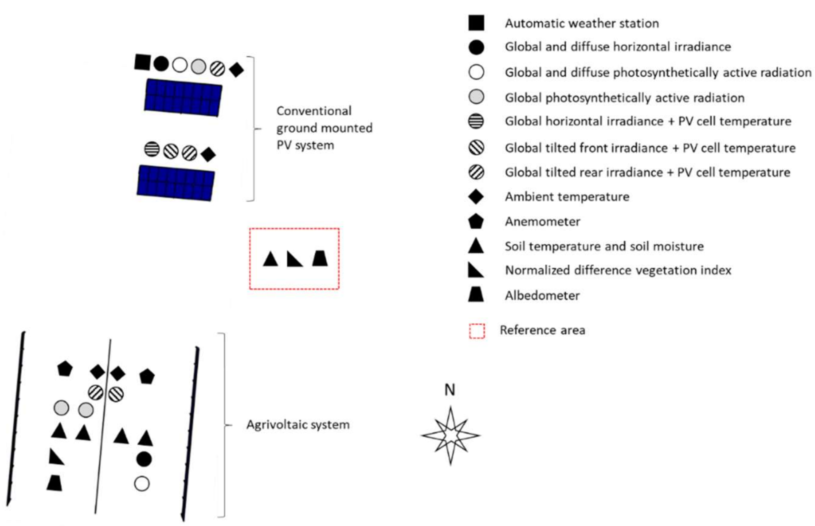

Figure 6: Schematic diagram of the experimental facility and sensors integrated at the end of 2022 (Campana et al., 2023).

Energimyndigheten

Table 1: Summary of the characteristic parameters of the APV and reference CGMPV systems (Campana et al., 2023).

	APV	**Reference CGMPV**
Azimuth (°)	-84	187
Tilt (°)	90	30
Power (kW_p)	22.8	11.8
Number of strings	2	2
Row-to-row distance	10	9.1
	PV modules	
Manufacturer	Jolywood	Longi
Model	JW-D72N-380	LR4-60HBD-370 M
Type	Bifacial, mono	Bifacial, mono
P_{mp} (W_p)	380	370
I_{mp} (A)	9.44	10.79
V_{mp} (V)	40.2	34.3
I_{sc} (A)	9.93	11.50
V_{oc} (V)	49.5	40.9
Length (m)	1.974	1.755
Width (m)	0.992	1.038
Module efficiency (%)	19.4	20.3
Front side efficiency (%)	19.4	-
Back side efficiency (%)	16.5	-
Temperature coefficient of max power (%/°C)	-0.38	-0.35
	Inverter	
Manufacturer	SunGrow	SunGrow
Model	SG20RT	SG15KTL-M
AC Power (kW)	20	15
Max efficiency (%)	98.4	98.6
Euro efficiency (%)	97.4	98.3
MPP inputs	2	2

The agrivoltaic experimental facility is built on a field that has been in grass production for many years before the project started. Hereafter, we will refer to the crop as “ley grass”. To study the influence of shading from the PV modules, hand harvest of the ley grass, both for the APV system and CGMPV system, in 2021, were performed in thirty squares (each 0.25 m^2) and distributed in six groups (A-E, R) of five plots, as shown in Figure 7. In 2022, fifty squares (each 0.25 m^2) were distributed in six groups of five plots, as shown in Figure 8 Thirty squares had the same position as in 2021. The other twenty squares were distributed in four groups of five plots to study more in-depth the plots in the same position as A, B, C and R. Thus, in 2022, there were four groups with ten plots (A, B, C and R) and two groups with five plots (D and E). The reference area for monitoring the differences in crop yield in the agrivoltaic system and the CGMPV system is located on the east side of the installation and in front of the CGMPV system. To study the effects of shadings produced by the PV systems on the crop, we have performed soil moisture measurements both at the APV system as well as in the reference area. Moreover, as performed by other researchers in the APV field, we have conducted measurements of the leaf area index (LAI) since it is one of the main morphological traits that tends to adapt in shading conditions.

More information concerning the experiments can be found in Campana et al. (2023).

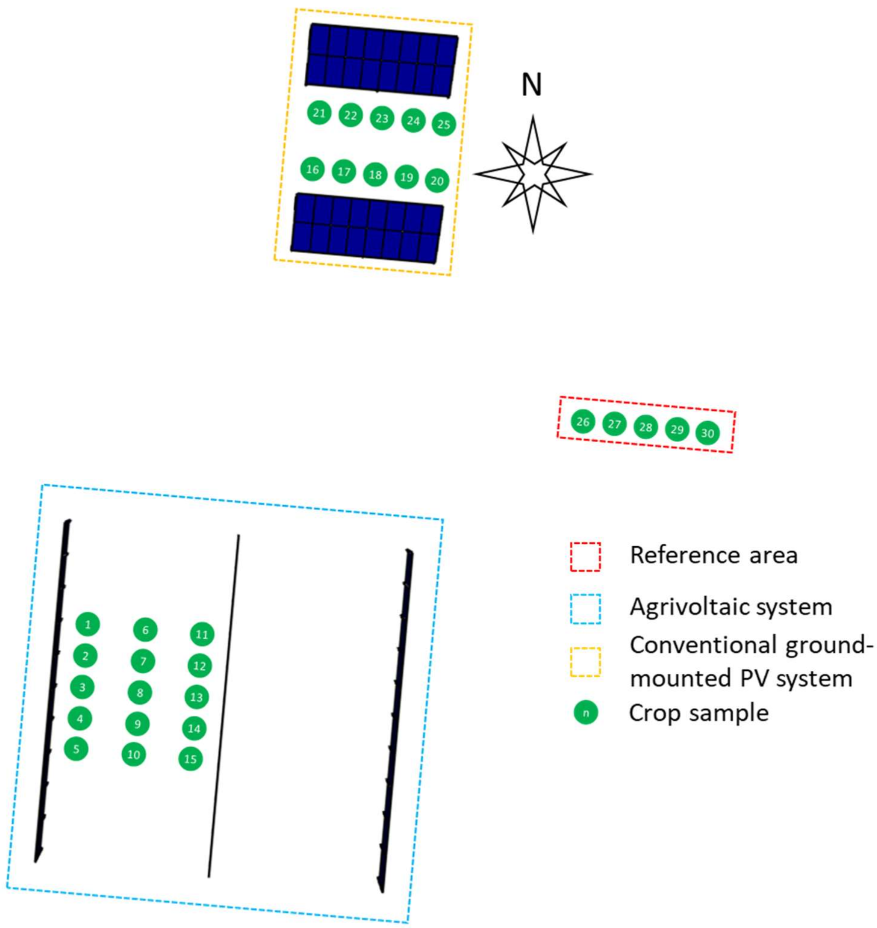

Figure 7: Crop yield experiment layout in 2021. “Group A” corresponds to samples 1-5, “Group B” corresponds to samples 6-10, “Group C” corresponds to samples 11-15, “Group D” corresponds to samples 31-35, “Group E” corresponds to samples 36-40, and “Group R” corresponds to samples 41-45 (Campana et al., 2023).

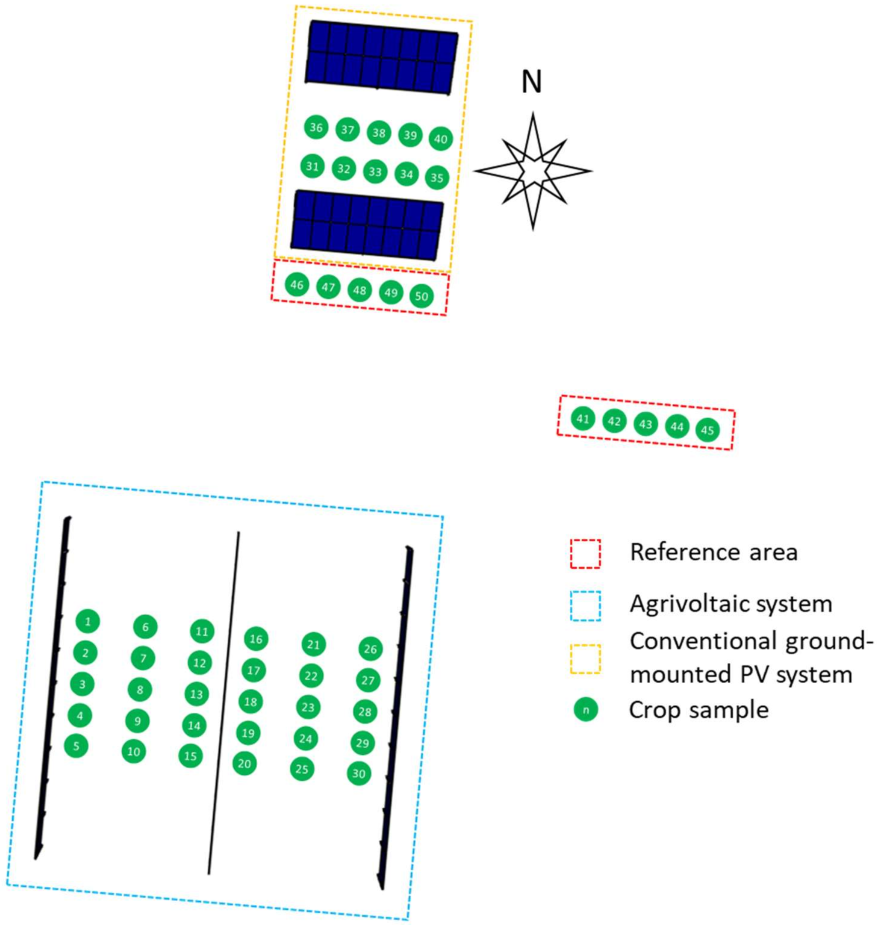

Figure 8: Crop yield experiment layout in 2022. “Group A” corresponds to samples 1-5 and 16-20, “Group B” corresponds to samples 6-10 and 21-25, “Group C” corresponds to samples 11-15 and 26-30, “Group D” corresponds to samples 31-35, “Group E” corresponds to samples 36-40, and “Group R” corresponds to samples 41-50 (Campana et al., 2023).

WP2 Integrated model development

During the project we have developed an integrated model to simulate and optimize APV systems, the model was based upon the open-source package OptiCE (Campana et al., 2017; OptiCE, 2023). Integrated APV tools typically combine algorithms for PV system electricity production, microclimate produced by the shadings, and crop growth. The integrated modelling platform developed in this project for both PV electricity production and crop yield response to environmental conditions is directly based upon a mathematical model for PV water pumping systems for irrigation (Campana et al., 2015). The model has at its core the shading model that calculates both shadings on the ground as well as on the PV modules. The shadings on the ground are used as a starting point to calculate the amount of total photosynthetically active radiation (PAR) and diffuse PAR reaching the crop. The computation of shading is also a starting point for calculating other microclimatic variables, such as ground temperature, and evapotranspiration, and soil moisture distribution, to cite some. A conceptual diagram of the integrated model is presented in Figure 9. The model calculates PV production, starting from climatological data and applying algorithms concerning solar position, solar decomposition and transposition, and solar shading. The PV production sub-model was based on the model presented in Campana et al. (2020), while in Campana et al. (2021) we have upgraded the model for simulating bifacial PV modules. The crop yield is calculated by feeding the crop yield model with the effective PAR and other key climatological and agricultural parameters. The crop model developed in this study is based on the modelling framework presented in Campana et al. (2018; 2022) and in Zhang et al. (2018). The crop model refers to the Environmental Policy Integrated Climate (EPIC) model developed by Williams et al. (1989).

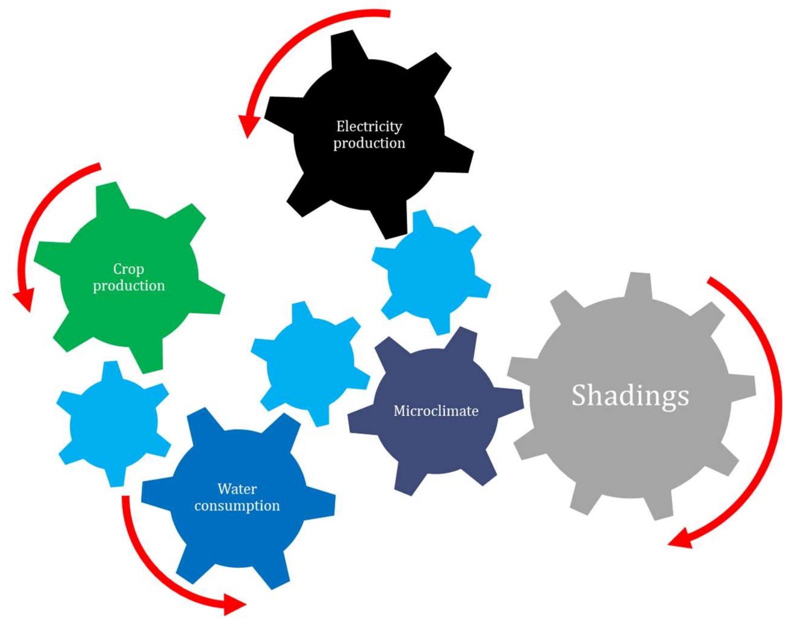

Figure 9: Concept of the integrated model for APV simulations.

The potential crop yield reduction under APV system is typically considered as a crucial key performance indicator for meeting policy requirements applied in different countries. Indeed, the development of the APV technology has led to a development of policies to promote and support the APV market providing first clear definitions on what an APV system is as compared to CGMPV systems. Moreover, countries where APV systems have been implemented since several years or at least research activities have been active since long time, have provided their definitions of APV systems and have identified clear targets on what the maximum crop yield reduction under APV system or the maximum area coverage from PV modules should be to be classified as APV systems. To cite some, in Germany the law set the maximum crop yield reduction under APV system is 34% (European Standards, 2023). In Italy, an APV system is marked out by a PV module area coverage lower than 40% while the continuity of the agricultural activities is guaranteed (Italian Ministry of the Environment and Energy Security, 2023). Thus, to meet policy targets, it is fundamental to have integrated tools that estimate the crop yield under APV systems before installations. Currently, despite there is a vibrant debate concerning the use of agricultural land for PV systems installation, in Sweden, there is no definition of APV systems and accordingly there is no policy targets or regulatory framework on the APV performances.

A flowchart illustrating the integrated model, AgriOptiCE, is presented in Figure 10. The orange boxes represent the framework's component focused on modelling the electricity production of bifacial PV systems. This modelling is implemented using Matlab® and incorporates specific modules from the open-source library pvlib (Holmgren et al., 2018). It enables the simulation of PV system performance at any given time resolution based on input data. The integrated model is continuously under development and factors such as spectral mismatch, soiling, snow losses are to be included in future versions of the platform. Additionally, the current model assumes the use of opaque silicon modules for PV technology. However, semi-transparent PV technologies are gaining popularity due to their ability to transmit higher levels of sunlight to the crops. Consequently, future versions of the integrated model will accommodate these semi-transparent PV technologies. For more detailed information on the current modelling of bifacial PV systems, refer to Ma Lu et al. (2023).

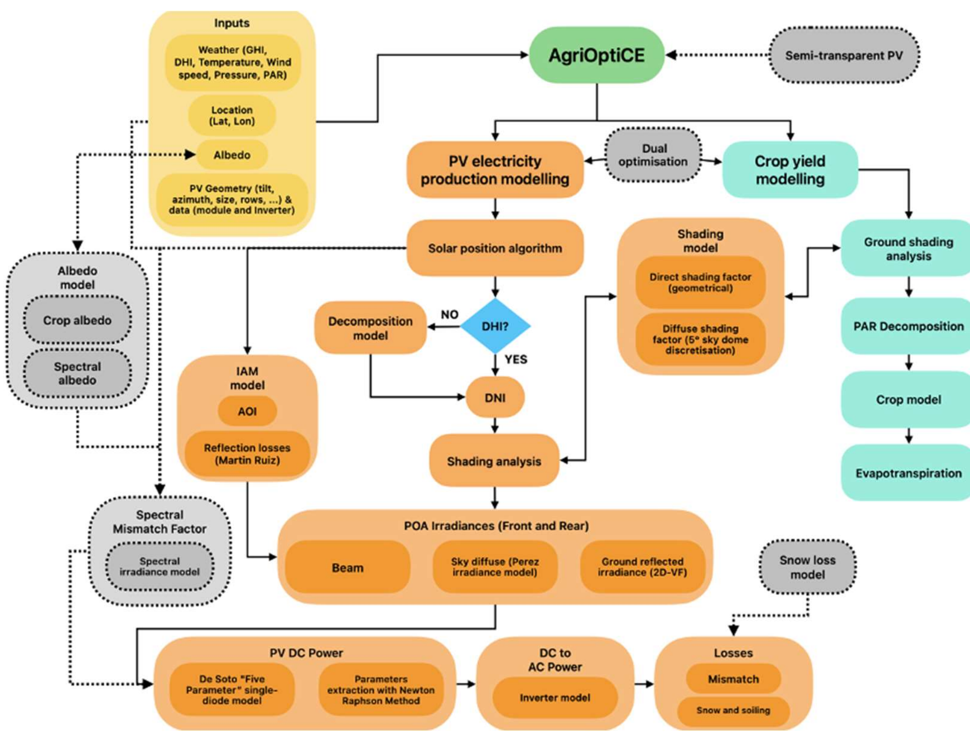

Figure 10: Flowchart of the modelling framework. The grey boxes and dashed lines indicate modules under development (Ma Lu et al., 2023).

To gain a deeper understanding of the microclimate within APV systems, computational fluid dynamics (CFD) simulations were conducted to study the effects of microclimate on a single module, as it can be seen in Figure 11 (Johansson, et al., 2022), as well as on the entire APV system, as it can be seen in Figure 12 (Zainali et al., 2023a). The model was created using Solidworks® computer-aided design software. The PV modules in the model consisted of two glass layers, two EVA plastic layers, and one cell layer, accurately representing the bifacial PV modules employed at Kärrbo Prästgård. To achieve a faithful replication of the vertical APV system, the PV modules were integrated with the ground and mounting structure, as illustrated in Figure 11.

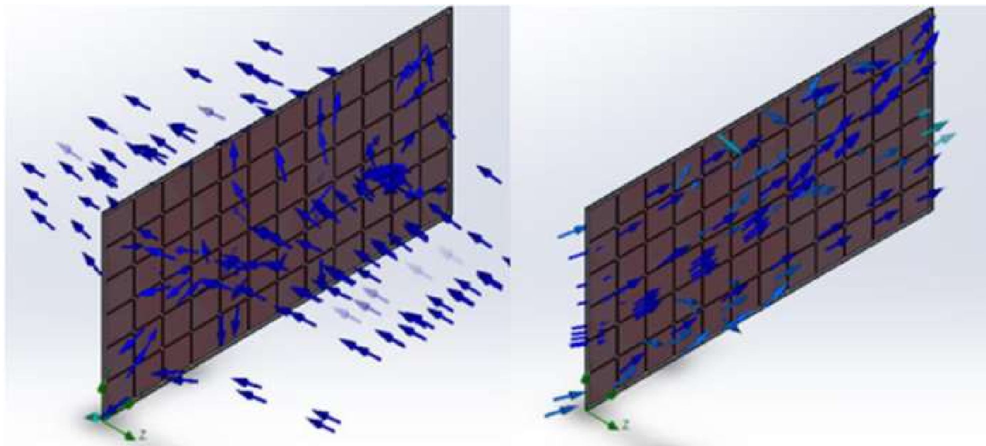

Figure 11: Wind directions on vertically installed PV module (Johansson, et al., 2022).

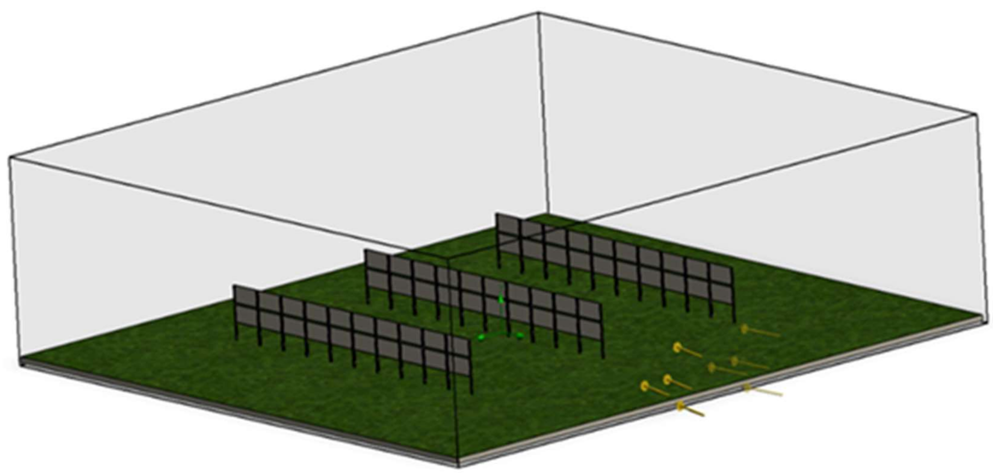

Figure 12: Vertical APV system in Solidworks® (Zainali et al., 2023a).

Solidworks Flow Simulation® was employed to generate a global mesh covering the entire computational domain. The domain encompassed the soil, reaching a depth of 0.3 meters. The soil properties were set to represent bare soil. The total height of the mounting structure was 2.8 meters, but the computational domain was extended to 7.5 meters to account for temperature, humidity, and velocity changes above the APV system. The adaptive meshing feature was utilized, defining approximately one million cells for the simulation. The transient model configuration allowed for analysing specific time steps individually. More information regarding dimensions, thermal properties, the materials used in the study, along with their specific heat capacity, density, and thermal conductivity can be found in Johansson et al. (2022) and in Zainali et al. (2023a).

WP3 Integrated model validation

This section provides a summary of the integrated model validation, both PV and crop model. While providing the validation of the crop model, it also presents some of the key results of the crop experiments carried out in 2021 and 2022. This section also presents the CFD models validation.

Bifacial PV model validation

The validation of the bifacial PV system model was conducted for both configurations: the vertical bifacial APV system and the reference ground-mounted fixed tilt 30° bifacial PV system at Kärrbo Prästgård. For simplicity, the mounting structure was excluded from the PV system geometry. Details regarding the system characteristics and dimensions can be found in the "WP1" section and Table 1.

On-site weather parameters were collected using specific instruments. The Lufft WS600-UMB Smart Weather Sensor was used to measure ambient temperature and wind speed. The Delta-T SPN1 Sunshine Pyranometer was utilized to measure global and diffuse horizontal irradiances. For plane-of-array (POA) irradiances, the Solar-Log Sensor Box Professional Plus was placed in the middle row, 4th pole from the northernmost position, and at mid-height. Albedo data was collected using the Apogee SP-710-SS Albedometer. All data was logged at one-minute intervals and underwent thorough quality checks to remove any outliers or missing values. Additionally, power inverter data (AC) for both the vertical bifacial system and the ground mounted system was logged every 5 minutes.

The validation process consisted of two parts. In the first part, the east and west plane-of-array (POA) irradiances of the vertical APV system were verified. This verification was done by comparing the modelled irradiances using Agri-OptiCE with the measured irradiances. The validation period spanned from July to August 2022 and from February to March 2023, with data collected at 5-minute intervals. The comparison results showed a high level of accuracy. For the east side irradiances, the R^2 value was 0.93, the Root Mean Squared Error (RMSE) was 50.32 W/m^2 and the Mean Absolute Error (MAE) was 16.81 W/m^2. For the west side irradiances, the R^2 value was 0.95, the RMSE was 39.20 W/m^2 and the MAE was 12.74 W/m^2.

The second part of the validation focused on verifying the power output (AC) of both the vertical APV system and the reference CGMPV system. The validation period spanned from June 2022 to March 2023, with some gaps due to limited data availability. The simulated power output closely matched the real power inverter data, indicating high accuracy. The R^2 values were above 0.9 and the RMSE values below 1.5 kW for both systems (Figure 13). Figure 14 provides a closer comparison of the simulated and measured power for specific days, demonstrating the accuracy of the integrated model under clear sky and cloudy conditions. For further information on the validation of the bifacial PV model, including an additional validation of a one-axis tracking system, see the study by Ma Lu et al. (2023).

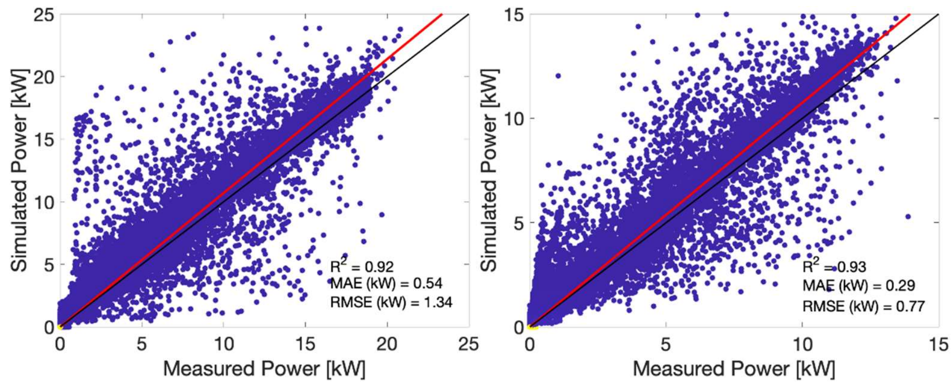

Figure 13: Simulated AC power using Agri-OptiCE compared to the measured AC power for the vertical APV system (left) and reference CGMPV system (right). Data points are represented by the dots. Red line indicates the fitting line for the data points and black line is the 1:1 line (Ma Lu et al., 2023).

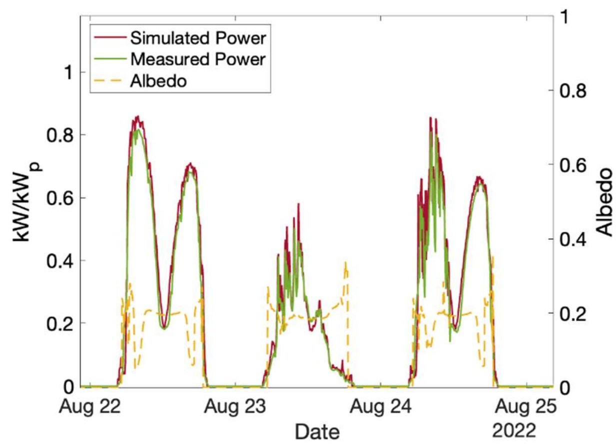

Figure 14: Comparison between the simulated and real measured from the inverter AC power for three specific days using 5-min data for the vertical APV system. Measured albedo is depicted in dashed line (Ma Lu et al., 2023).

After validating the bifacial PV system model, a yearly simulation was conducted for both systems to compare their annual performances using typical meteorological year (TMY) data obtained from PVGIS-ERA5. TMY data showed a yearly global horizontal irradiation for Kärrbo Prästgård of 928 kWh/m^2. The results, presented in Figure 15, show the average daily specific yield per month. The vertical APV system achieved an annual specific yield of 1,067 kWh/kW$_p$/year, while the reference CGMPV system yielded 1,116 kWh/kW$_p$/year. Although a more realistic comparison would have involved directly using inverter data, certain periods experienced inverter switch-offs and other issues, which could have led to misleads of the annual performance. Since the model has been validated with high accuracy, the simulated results can provide a reliable initial approximation of the performance of the studied systems. However, it is important to note that the current model does not account for snow losses. The reference CGMPV system would have been more affected by snow accumulation on the panels, leading to potential performance reductions. A parallel study is currently underway to determine the impact of snow losses, and preliminary results indicate higher snow losses for the CGMPV system particularly right after a snowfall. Despite this, the CGMPV system still achieves a higher overall seasonal performance.

More information can be found in Ma Lu et al. (2023) and in Zainali et al. (2023b).

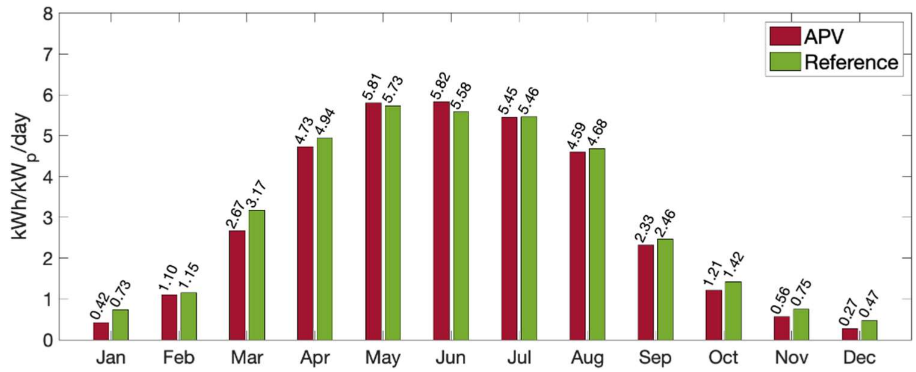

Figure 15: Simulated average daily specific yield per month for the vertical APV and reference ground-mounted fixed tilt 30° systems in Kärrbo Prästgård using TMY data.

Crop yield model validation

In the 2021 season, the harvesting dates were the 1st June 2021 (first cut), 20th July 2021 (second cut), and 17th September 2021 (third cut). In the 2022 season, the harvesting dates were 3rd June 2022 (first cut), 14th July 2022 (second cut), and 26th August 2022 (third cut). A summary of the precipitation during the seasons 2021 and 2021 as compared to the reference period 1990-2010 is provided in Table 2.

Table 2: Precipitation for the period May-August 2021 and 2022 compared to the reference period 1990-2010.

Month	2021	2022	Reference period 1990-2020
May	119	60	44
June	43	38	69
July	89	39	77
August	109	99	71

The total crop yield from 2021 and 2022 is presented in Table 3. The actual crop yield of the field in kg DM/ha should consider the losses due to the unused land. Those losses for the APV system are about 10%, as described by Campana et al.

(2021), if no specific agricultural management practices are applied (i.e., adopting special agricultural machineries to harvest the grass underneath of the PV modules supporting structure, or animal grazing). The losses due to unused land in the CGMPV system are about 35%.

Table 3: Total DM yield in 2021 and 2022 and statistical analyses for the crop yield using the Tukey Pairwise Comparisons (see Figures 7 and 8 for description of the position of the groups). The crop yield refers to the samples. The actual crop yield in kg DM/ha should be reduced by 10% for the APV and by 35% for the CGMPV system due to the non-harvestable area close to the PV modules supporting structures.

	2021			2022		
Area	Number of samples	Mean kg DM/ha	Grouping*	Number of samples	Mean kg DM/ha	Grouping*
Group A	5	6,348	ab	10	5,044	a
Group B	5	6,660	ab	10	5,454	a
Group C	5	6,265	ab	10	4,634	a
Group D	5	4,746	b	5	5,444	a
Group E	5	6,119	ab	5	5,668	a
Group R	5	7,894	a	10	5,326	a

*Grouping Information Using the Tukey Method and 95% Confidence. Means that do not share a letter are significantly different.

The total DM-yield shows a large variation in both 2021 and 2022. The crop yield in 2021 was higher but showed a wider variation between the groups. In 2022, the crop yield was lower, but the variation between groups was also lower. The statistical analyses show a significant difference in total crop yield between Group R and Group D in 2021 (see Figures 7 and 8 for description of the position of the groups). For 2022, there were no significant differences between the groups. The differences in botanical compositions among the groups, as depicted in Figure 16, make the analysis of the single effect of shading on crop production more challenging. Nevertheless, installing an APV system on an established ley grass field represents a likely actual situation in the APV sector in Sweden and, thus, a case worth investigating.

The metabolized energy content analyses, summarized in Table 4, show typical values for this kind of crop (Spörndly, 2003) and a small variation within the groups of about ±1-2%. A higher value indicates a crop with more carbohydrates produced in the photosynthesis. As in the study of total yield, Group R is used as reference for the content of energy. Few samples are significantly different using the Tukey post hoc method. Studying the six cuts, Groups A, C, and D are statistically different than Group R on one comparison and Group E is different than Group R in two comparisons. When just studying the values in Table 3, it is notable that 21 out of 30 samples´ mean values for Groups A-E show higher metabolized energy contents than Group R for the same cut each year. The analyses of the crude protein, summarized in Table 4, show in average typical values for this kind of crop (Spörndly, 2003), but there is a large variation between the plots, especially in the third cut. A high value is an indicator that plants have enough Nitrogen. As for energy, the influence of the PV modules is studied using group R as a reference.

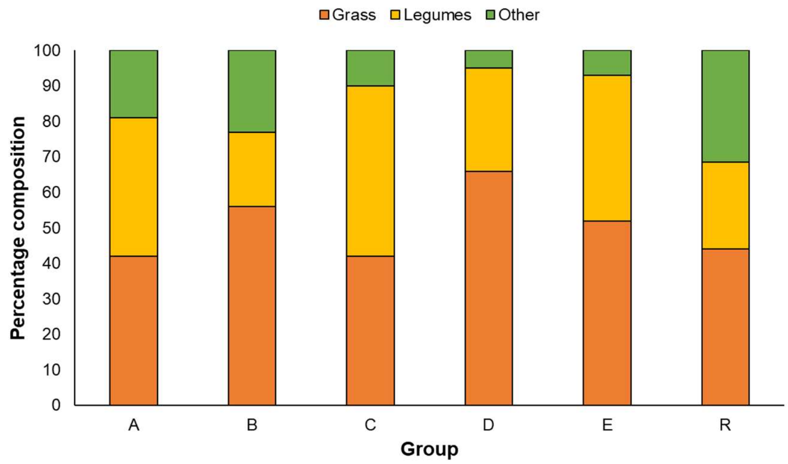

Figure 16: Results of the botanical analysis carried out the 14th of July 2022 (second cut).

Using the Tukey post hoc method more differences are found for crude protein. Studying the six cuts, Group A, C and D are different than Group R in four cuts and Group B is different than Group R in one cut. When just studying the values in Table 4 it is notable that 25 out of 30 samples show higher samples´ mean values for crude protein than Group R for the same cut each year. A significant factor for the high content of crude protein is the available Nitrogen. If there is high content of legumes, it also adds more protein to the plant. Another factor is the total yield, where a high yield can reduce protein content. Group E shows a lower content in most of the samples. Looking at the botanic composition in Figure 11, it is not evident that this can be the explanation. But since the crop was not divided into species, it is difficult to draw conclusions. Another explanation can be the available nutrients.

Table 3: Statistical analyses for the metabolized energy (MJ/kg DM) for first, second, and third cut in 2021 and 2022 including the statistical analyses for the crop yield using the Tukey Pairwise Comparisons (see Figures 7 and 8 for the position of the groups) (Campana et al., 2023).

Area	Number of samples	Metabolized energy 2021		Number of samples	Metabolized energy 2022	
		Mean MJ/kg DN	Grouping*		Mean MJ/kg DM	Grouping*
			First cut			
Group A	5	10.79	a	10	10.47	c
Group B	5	10.78	a	10	10.53	bc
Group C	5	10.69	ab	10	10.72	ab
Group D	5	10.52	ab	5	10.95	a
Group E	5	10.53	ab	5	10.62	bc
Group R	5	10.38	b	10	10.44	c
			Second cut			
Group A	5	8.97	bc	10	10.22	ab
Group B	5	9.73	a	10	10.58	a
Group C	5	9.24	abc	10	10.30	ab
Group D	5	9.00	bc	5	9.98	b
Group E	5	8.68	c	5	9.87	b
Group R	5	9.48	ab	10	10.17	b
			Third cut			
Group A	5	10.70	ab	10	10.25	ab
Group B	5	10.66	ab	10	10.15	b
Group C	5	10.79	a	10	10.42	ab
Group D	5	10.73	ab	5	10.68	a
Group E	5	10.38	b	5	10.16	ab
Group R	5	10.48	ab	10	10.22	ab

*Grouping Information Using the Tukey Method and 95% Confidence. Means that do not share a letter are significantly different.

Table 4: Statistical analyses for the crude protein (g/kg DM) for the first, second, and third cut in 2021 and 2022 including statistical analyses for the crop yield using the Tukey Pairwise Comparisons (see Figures 7 and 8 for the position of the groups) (Campana et al., 2023).

Area	Number of samples	Crude protein 2021		Number of samples	Crude protein 2022	
		Mean g/kg DM	Grouping		Mean g/kg DM	Grouping
			First cut			
Group A	5	129.1	ab	10	122.0	a
Group B	5	125.6	ab	10	101.5	b
Group C	5	142.8	a	10	124.9	a
Group D	5	131.6	ab	5	137.9	a
Group E	5	94.8	c	5	75.6	c
Group R	5	118.3	b	10	82.6	c
			Second cut			
Group A	5	107.0	bc	10	107.1	ab
Group B	5	115.5	abc	10	94.9	bc
Group C	5	118.6	ab	10	114.4	a
Group D	5	134.0	a	5	115.9	a
Group E	5	93.4	c	5	88.6	c
Group R	5	105.6	bc	10	94.4	bc
			Third cut			
Group A	5	178.1	a	/	130.1	a
Group B	5	150.2	bc	10	120.9	ab
Group C	5	167.7	ab	10	131.3	a
Group D	5	171.5	ab	5	135.4	a
Group E	5	132.0	c	5	110.0	b
Group R	5	139.4	c	10	109.7	b

*Grouping Information Using the Tukey Method and 95% Confidence. Means that do not share a letter are significantly different.

As typically performed in crop modelling, we have first calibrated the crop model in open field conditions, and afterwards we have tested the model accuracy in shading conditions produced by the PV modules of the APV system. The results of the crop model calibration and validation in open field conditions are presented in Figure 17. In particular, the crop yield at different cuts and the total crop yield are reported for the average crop yield measured in Group R in 2022, the crop yield simulated with literature values (i.e., non-calibrated), the crop yield after a simple calibration of the model (i.e., calibrated), and after a more advanced calibration (i.e., calibrated advanced) with the procedure described in Campana et al. (2023). From Figure 17 using literature data for the crop modelling leads to accurate seasonal crop yield assessment but the crop yield estimation across the different cuts shows significant differences with the actual measurements. The model calibration shows that on a seasonal basis there is a deviation of about 5%

from the actual measurements with the model tending to overestimate the seasonal crop yield. After model calibration, the modelling results show that the model can produce crop yield results that follows the actual trend of the measured crop yield across the three cuts. The most performing results are achieved by using two different biomass–energy ratios (i.e., calibrated advanced) as highlighted in Schils et al. (2013), with high accuracy both on a single cut as well as on the seasonal crop yield.

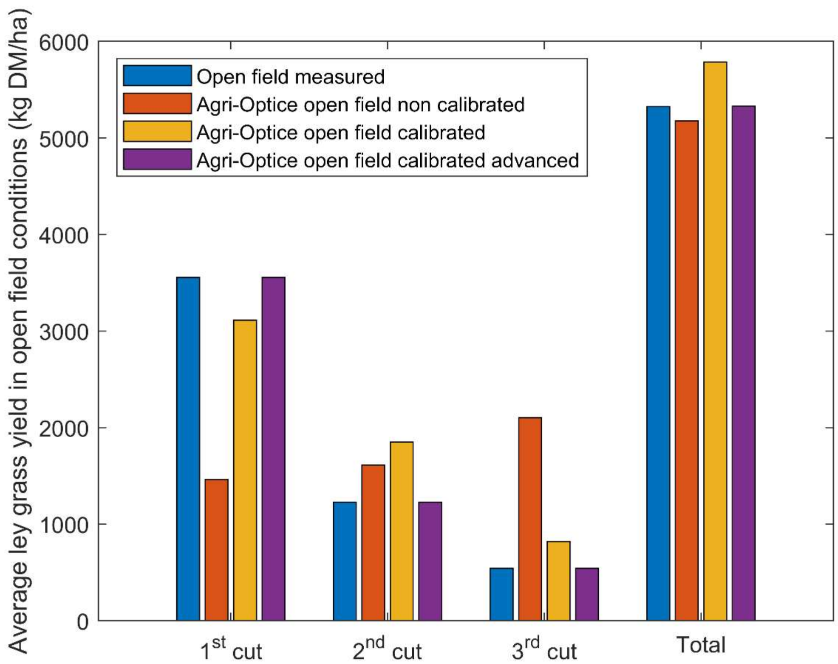

Figure 17: Average ley grass yield in 2022 in open-field conditions versus simulated yield using the integrated modelling platform Agri-OptiCE with literature data concerning crop parameters (i.e., Agri-OptiCE open field no calibrated), after calibration (i.e., Agri-OptiCE open field calibrated), and after an advanced calibration using two biomass–energy ratios for the first two and last cuts separately (i.e., Agri-OptiCE open field calibrated advanced) (Campana et al., 2023).

The validation of the crop model under shading conditions is provided in Figure 18. The results refer to the average yield under the APV system. The calibrated model in Figure 18 refers to the model calibrated with two biomass–energy ratios as performed in Figure 17, while Agri-OptiCE calibrated + adaptation refers to the model calibrated in Figure 11 with maximum LAI increase of 12% as derived from dedicated LAI measurement campaign in 2022. From figure 18, two main conclusions can be drawn. The first is that the calibrated model show a difference of 15% as compared to the actual measurements of the average crop yield under the APV system. Given the complexities of the modelling it can be still considered as a good result. As highlighted in Campana et al. (2021), the developed modelling platform can simulate the worst-case scenario for the impact of shadings on the crop yield if no crop adaption measures are measured or available. Such type of modelling and results can be of extreme importance while predicting the crop yield under the APV systems for assessing the performance of future installations, for instance at the design and permit stage. The second conclusion is that, as highlighted in Campana et al. (2021) supplying the model with adjust input parameters that can further depict the adaption measures of crops under shading conditions can enhance the model accuracy. As compared to the measured results, the model developed in this study underestimate the crop yield under shading conditions of about 5% as compared to the actual average measured values. This result shows how important is the availability of crop adaption measures for accurately estimating crop yield under shading conditions. As pointed out in the literature review, the crop yield under the agrivoltaic system and its percentage reduction as compared to open-field conditions is one of the most crucial key performance indicators for APV systems and it is used as target or design parameter in laws regulating APV systems. High accuracy in integrated APV platform can have significant impact on the APV system deign to meet policies and thus on the cost-benefit analysis of the system.

More information can be found in Campana et al. (2023).

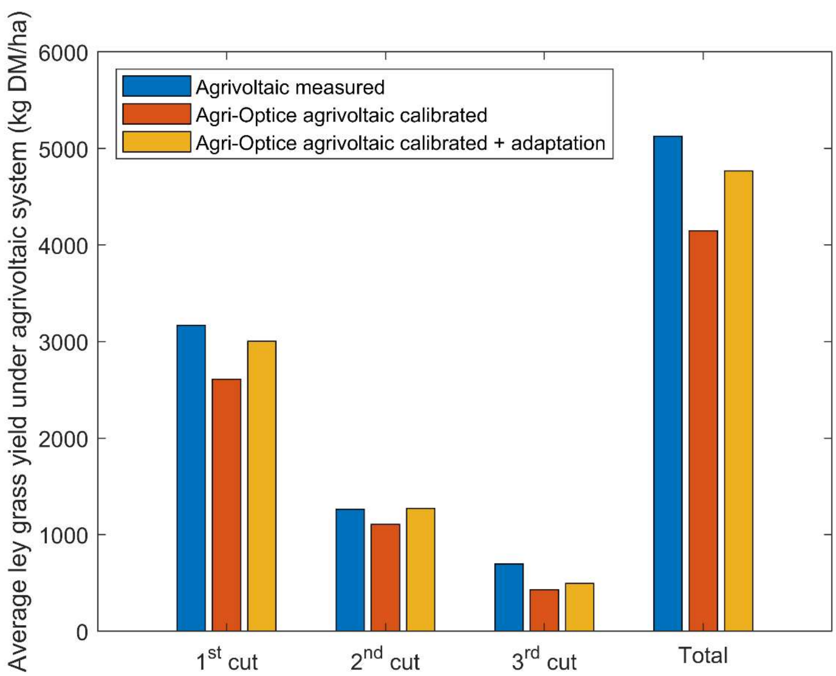

Figure 18: Average ley grass yield in 2022 in shaded conditions under the APV system versus simulated yield using the integrated modelling platform Agri-OptiCE. Agri-OptiCE calibrated refer to the model calibrated using two biomass–energy ratios as in Figure 11, while Agri-OptiCE calibrated + adaptation refers to the model calibrated in Figure 11 where the LAI curve input parameters are updated with the percentage increase as measured in the field) (Campana et al., 2023).

CFD model validation

The validation of the CFD model for the single bifacial PV module is presented in Figure 19. The weather data used for the model validation was gathered the 25th of September 2021. The model validation was performed by feeding the CFD model with weather data between 06:00 to 12:00 local Swedish time for the selected day with a 10-minute time step. The main motivation to perform the model validation within this period is because the solar cell temperature measurements are performed with the Solar-Log Sensor Box Professional Plus that is equipped with monofacial solar cells and thus do not consider the contribution from the rear radiation on the thermal balance of the solar cell.

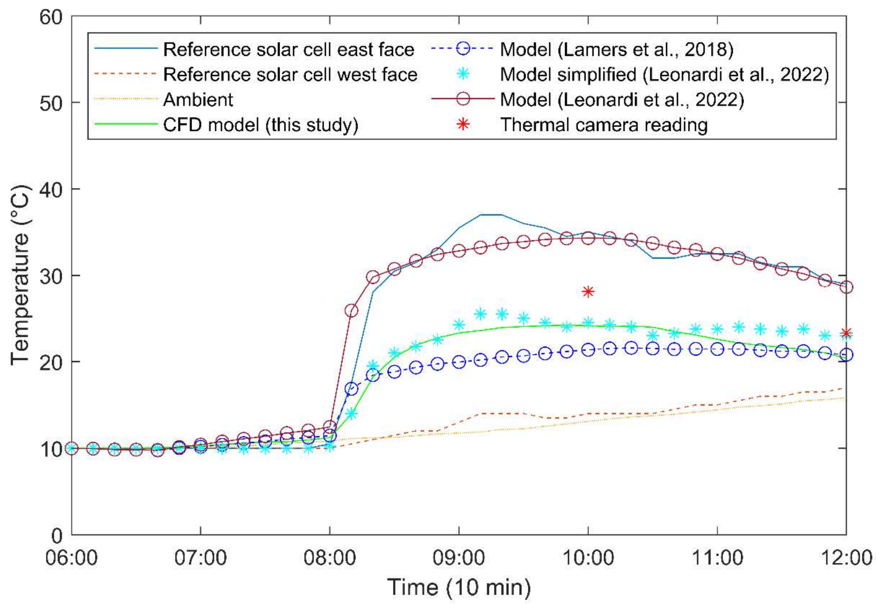

Figure 19: CFD simulated temperature against ambient temperature and measured temperatures with superimposed thermal camera temperatures. A further cross validation is performed by comparing the temperature calculated with the models presented in Lamers et al. (2018) and Leonardi et al. (2021) (Johansson et al., 2022).

The developed CFD model tends to underestimate the bifacial PV module temperature as compared to the thermal camera readings (red asterisks in Figure 19). The underestimation is in the order of 3-4 °C. The obtained results show a slightly better accuracy as compared to the results obtained in Riley et al. (2017), where a simple model to estimate the steady state PV module temperature was employed showing a root-mean-square error (RMSE) of about 3.4 °C for the bifacial PV module and with residuals varying between 10°C and -10°C. Similar deviation between CFD results and experimental results were reported in the work carried out by Naghavi et al. (2021). It must be pointed out that the model simulated in this study is placed in free space, thus it has heat losses in all directions. On the other hand, the bifacial PV module used for validation has modules in its proximity. Moreover, it must be mentioned that the measurements are carried out in the middle row of the vertically mounted APV system, where the effect of the edge rows might significantly decrease the heat losses due to wind. This represents one of the major limitations of this study, which focused on the detailed modelling of the single bifacial PV module. Future studies will focus on scaling up the current CFD model for system-level modelling. A model cross-validation has been carried out using the model presented in Lamers et al. (2018) and the simplified and more advanced models presented in Leonardi et al. (2021). The CDF model developed in this study showed good agreement with the model in Lamers et al. (2018) and with the simplified model presented in Leonardi et al. (2021). The validated model was then used to analyse the impact of the mounting structure (i.e., vertically mounted APV versus 30° tilted CGMPV PV system) on the temperature/efficiency of the solar cells and on the daily electricity production. The results are summarized in Figures 20 and 21. Figure 20 summarizes the average temperatures achieved in different simulated scenarios (S1: PV module mounted at 30° tilt, facing south, and wind applied south to north, or north to south; S2: PV module mounted at 30° tilt, facing south, and wind applied east to west; S3: Vertically mounted PV module, facing east-west, and wind applied south to north; S4: Vertically mounted PV module, facing east-west, and wind applied east to west).

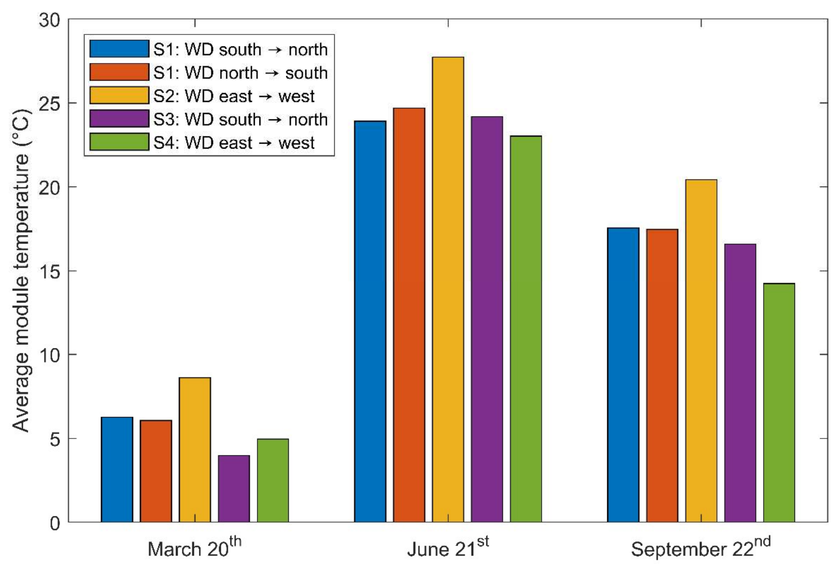

Figure 20: Average module temperature for each reference simulation day and simulated wind direction (WD). S1: PV module mounted at 30° tilt, facing south, and wind applied south to north, or north to south; S2: PV module mounted at 30° tilt, facing south, and wind applied east to west; S3: Vertically mounted PV module, facing east-west, and wind applied south to north; S4: Vertically mounted PV module, facing east-west, and wind applied east to west (Johansson et al., 2022).

The vertically mounted bifacial PV module have a lower average temperature during each investigated simulation day and wind direction. In scenarios S1 and

S2, the south 30° tilted PV module received higher solar radiation during the simulation days. It resulted in a higher average temperature in each scenario. On the other hand, scenarios S3 and S4 were marked out by lower direct solar radiation hitting the PV module at noon. This aspect, combined with the wind striking the module perpendicularly and accelerating the wind at the module edges, led to a better cooling for the vertical module and lower average operating temperature.

In Figure 21, we have compared the daily electricity production for the investigated reference days both for the vertically mounted and the 30° tilted bifacial PV module.

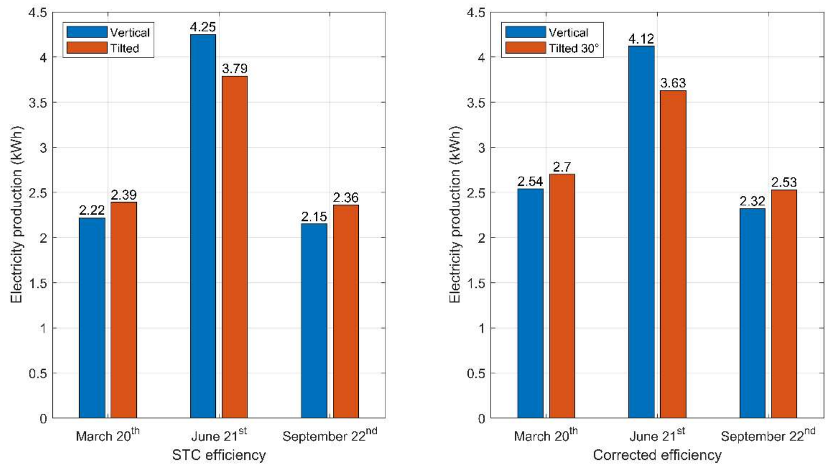

Figure 21: Daily production at standard test conditions (STC) efficiency (i.e., operating photovoltaic cell temperature fixed at 25°C) and at corrected efficiency (Johansson et al., 2022).

Figure 21 (left) shows the daily production for each simulation day assuming Standard Test Conditions (STC) temperature (i.e., the efficiency is calculated assuming that temperature of the PV cells is kept at 25 °C), while Figure 21 (right) shows the production during each simulation day with the corrected efficiency considering the temperature effects. In the real conditions, especially during summer, the operating temperature of the solar cells is most of the time significantly different from the STC temperature, nevertheless, this comparison was performed to analyses the effects of the different operating temperature cooling of the vertical and 30° tilted module. At STC, the daily production in March of the vertical module is 2.22 kWh, while for the 30° tilted module it is 2.39 kWh. However, as the ambient climate influences the modules, the corrected efficiency influences the production, resulting in the two modules producing 2.54 kWh and 2.7 kWh, respectively. The production increased by 14.6% compared to STC (i.e., the efficiency is calculated assuming that temperature of the PV cells is kept at 25 °C) for the vertical module, while the 30° tilted module's production increased by 12.9% compared to STC (i.e., the efficiency is calculated assuming that temperature of the PV cells is kept at 25 °C). Similar results were achieved for autumn (i.e., the 22nd of September) and were 7.63% and 7.22% for the vertical module and the 30° tilted module, respectively. As the temperature gets warmer in summer (i.e., the 21st of June), the vertical modules' efficiency is less influenced than for the tilted module. The difference in daily production considering STC efficiency and corrected efficiency for temperature is 3.0% decrease and 4.3% decrease for the vertical module and for the 30° tilted PV module, respectively.

More information can be found in Johansson et al. (2022).

The CFD model for the entire APV system was validated using data collected on June 23, 2022, with a temporal resolution of 5 minutes. The data was obtained from a weather station at the experimental APV plant in Kärrbo Prästgård. Five variables were measured and used as inputs for the CFD model: ambient temperature, global horizontal irradiance, diffuse horizontal irradiance, wind speed, and wind direction. The ambient temperature, wind speed, and wind direction were collected using the Lufft WS600-UMB smart weather sensor. Solar irradiance data was obtained from the Delta-T SPN1 sunshine pyranometer. The incident solar radiation on the modules was compared with vertical east and west-facing SolarLog sensor boxes, which measured both solar irradiance and panel temperature. The ground temperature was measured using a Solar Survey 200R temperature probe positioned in the middle of the row at a depth of 10 cm. The maximum ambient temperature recorded was around 26 °C at 15:00, while the minimum temperature of 13 °C occurred around 03:00. Some clouds were present in the morning between 06:00 and 09:00, affecting global and diffuse horizontal irradiance. The rest of the day had mostly clear skies, with a maximum global horizontal irradiance of approximately 900 Wm^{-2}. The wind rose showed predominant southwest winds throughout the day. To estimate the temperature of the bifacial PV modules, a simplified model by Leonardi et al. (2021) was cross-validated with the CFD model. The CFD model temperature ranged from 14 °C to 38 °C, while the SolarLog sensor boxes reached temperatures of about 40 °C. The thermal camera, positioned perpendicular to the PV module face, provided a temperature range of 12 °C to 37 °C, closely aligned with the CFD model results. Thermal camera pictures at different times of the day (11:00, 14:00, and 16:00) further validated the estimated PV module temperatures in the CFD model. The CFD model exhibited estimation errors of 0-2 °C compared to the thermal camera readings as seen in Figure 22. By conducting CFD simulations using this detailed model, a comprehensive understanding of the microclimate within the APV system at Kärrbo Prästgård was obtained.

More information can be found in Zainali et al. (2023a).

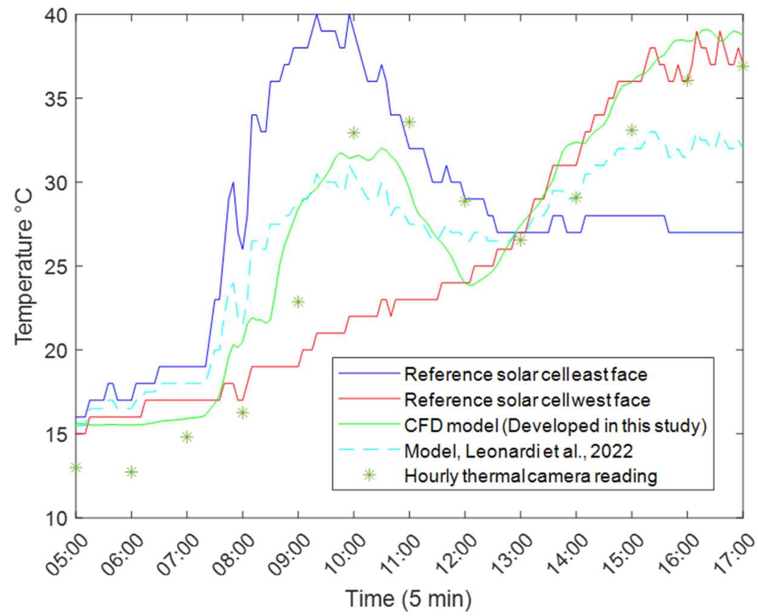

Figure 22: Comparison of PV module temperatures at Kärrbo Prästgård on June 23rd, 2022, using Leonardi's model, thermal camera measurements, and the CFD model developed in Zainali et al. (2023a).

WP4 Key performance indicators

Mapping of key performance indicators

Key performance indicators (KPIs) are the measurable values that can be used as an indicator to assess how effectively a particular target is being achieved. In APV systems, KPIs can refer to energy conversion, agricultural production, water use, land use, and economic performances. Since APV systems produces significant effects across the energy, food and water sectors, integrated water-food-energy nexus indicator can be deployed to characterize and compare APV systems. Various KPIs that can be used to describe and compare the performance of APV systems were mapped by Chaudhary (2021). Conventional KPIs for APV systems are provided below:

1) **Ground coverage ratio**
This KPI refers to the area covered by the PV modules and PV modules´ supporting structures. It is defined as the ratio of the PV modules area to the total area of the APV system as follows:

$$GCR = \frac{A_{PV}}{A_{ground}}, \quad (2)$$

where, A_{PV} is the PV modules area (m^2) and A_{ground} is the APV total area (m^2). High GCR value indicates high density of modules in the field (Willockx, 2020).

2) **Energy yield**

This KPI relates the total annual electricity production to the land area (Willockx, 2020). It is defined as the ratio of annual electricity production to the area of APV system. Energy yield of an APV system depends upon many factors like solar irradiance, temperature, efficiency of PV modules, cable losses, and APV system configuration, to cite some. The energy yield Y_{el} (kWh/m^2) can be calculated as follows:

$$Y_{el} = \frac{E_{av}}{A_{ground}}, \quad (3)$$

where, E_{av} is the annual electricity production (kWh).

3) **Agricultural yield**

The agricultural yield (Y_{ag}) relates the amount of agricultural produce to the land area (Willockx, 2020). It is the amount of fresh matter or dry matter of agricultural produce obtained per unit of land area. The agricultural yield is generally defined as follows:

$$Y_{ag} = \frac{AP_{AV}}{A_{ground}}, \quad (4)$$

where, AP_{AV} is the agricultural produce obtained from the APV system area (kg).

4) **Water Productivity**

The Water productivity (WP) relates the crop yield to the total water requirement for the crop, including rain and irrigation (Elamri, 2018). Crops having higher value of water productivity means that more agricultural produce can be obtained with less water input. It is generally expressed in kg/m^3 and it is given by the following equation:

$$WP = \frac{AP_{AV}}{TWU}, \quad (5)$$

Where, the total water utilization (TWU) can be taken as total water requirement of crop including both irrigation and rain or only irrigation.

5) **Water consumption**

This KPI shows the water consumption per specific area of the crop (El-Gafy, 2017). Water consumption WC can be calculated as follows:

$$WC = \frac{TWU}{A_{ground}}, \quad (6)$$

In APV systems, the water requirement of crops generally decreases as they require less water as compared to conventional agricultural practice due to shading of PV modules.

6) **Net present value**

The net present value (NPV) is an indicator to calculate the profitability of a project. NPV is calculated by taking the difference between the net present value of cash inflows and cash outflows. A positive NPV indicates that the project is financially feasible whereas a negative value indicates economic losses during the lifetime of the project. The higher is the value of NPV the more profitable is the project. The NPV value of the system can be calculated as follows (Agostini et al., 2021):

$$NPV = -ICC + \sum_{t=1}^{n} \frac{(CF_{in,t} - CF_{out,t})}{(1+r)^t}, \quad (7)$$

where, ICC is the initial capital cost (SEK), $CF_{in,t}$ is the cash inflow at year t (SEK), $CF_{out,t}$ is the cash outflow at year t (SEK), r is the discount rate (%), and n is the life of the project.

7) **Levelized cost of electricity**
The levelized cost of electricity (LCOE) is an important indicator to compare the actual cost of producing electricity by an APV system with any other sources of renewable energy like wind energy, natural gas, reference CGMPV system. IT can also be used to compare different APV technologies in terms of cost of electricity. The LCOE is given by the following equation:

$$LCOE = \frac{ICC + \sum_{t=1}^{n} \frac{(CF_{out,t})}{(1+r)^t}}{\sum_{t=1}^{n} \frac{EI_1(1-sd)^t}{(1+r)^t}}, \quad (8)$$

where, El_1 is the electricity produced during the 1st year (kWh), and sd is the system degradation per year (%/year).

APV systems produce effects across the energy, water, and food sectors. Water-food-Energy nexus (WEFN) KPIs are indicators that can be used to evaluate or assess the performance of APV systems based on the integration of KPI's related to water, food, and energy sectors. Indicators used in WFEN have different dimensions and to compare the data of each indicator normalization is required. For instance, El-Gafy (2017) used the minimum-maximum normalization technique. WFEN indicators (WFENIs) are listed below:

1) **WFENI1**
Feng et al. (2020) used an indicator consisting in the combination of a food index, water index, and energy index as provided in Equation 9:

$$WFENI1 = \sqrt[3]{W \times F \times E}, \quad (9)$$

where, W represents the water index, F represents the food index, and E is the energy index.

2) **WFENI2**
In the context of WFEN for biofuel production, Moioli et al. (2020) proposed a WFE nexus index combining water, food, and land indexes as shown in Equation 10:

$$WFENI2 = \mathrm{W} \times \mathrm{E} \times \mathrm{L}, \quad (10)$$

where, L represent the land index.

3) **WFENI3**
El-Gafy (2017) proposed a WFEN indicator based on the weighting of five indicators (i.e., the water consumption indicator, energy consumption

indicator, water mass productivity, energy mass productivity, and the economic water productivity of irrigation water) as follows:

$$WFENI3 = \sum_{i=1}^{n} w_i X_i \Big/ \sum_{i=1}^{n} w_i, \quad (11)$$

Where, w_i is the weight assigned to each indicator, n is the KPI number, and X_i is the normalized indicator.

Economic analysis

We have conducted an economic analysis using as KPI the NPV to compare the performance of APV systems, versus CGMPV systems, and versus sole agriculture (Campana et al., 2023). In the economic analysis, we have analysed a case where the landowner owns a commercial-scale APV system built on 0.2 ha. For the APV system, we have also analysed the case the landowner leases the land to a third-party company. We have assumed a permanent crop and a cropping system for the agricultural part of the APV system. In the first, the APV system is combined with permanent ley grass, while in the second, it is combined with a conventional crop rotation as follows: barley, ley grass, ley grass, winter rape seed, winter wheat, winter wheat (Tidåker et al., 2016).

The main input parameters of the economic analysis are provided in Table 5.

Some of the key results of the economic analysis are summarized in Figure 23 in terms of discounted cumulative cash flow for the reference CGMPV system, for the APV system on permanent ley grass and combined with a traditional crop rotation, and for the APV system owned and managed by a third-party company for which the land is leased by the farmer. The cumulative cash flows of the permanent ley grass and for the crop rotation are also provided.

The APV system shows a significant lower NPV (i.e., last value of the cumulative cash flow diagram) as compared to the reference CGMPV system. This is mainly due to the assumed lower electricity production and higher investment costs. Although crop rotation shows better profit than permanent grass, the effect on the cumulative cash flows and NPV of the APV system is minimal (it must be noted that the cumulative cash flows of the sole crop are multiplied by 10 to allow an easier comparison). From a farmer perspective, the area used for the installation of an APV system can lead to a 30-year profit of about 30 times (for crop rotation) to more than 600 times (for permanent grass) higher as compared to the agricultural production with EU farmer support, based on the input data in Table 5. Leasing the land leads to a NPV of 3.5 k€ that is about 40 times higher as compared to only permanent grass.

More information can be found in Campana et al. (2023)

Table 5: Summary of the technical and economic input data (Campana et al., 2023).

	Reference CGMPV	APV	Comment/Reference
Total ground area (m²)	2,000	2,000	Assumed.
PV system capacity (kW_p)	150	85	For the reference CGMPV system, we have assumed that 11.8 kW_p cover a net area of 8.6m*18.2m. For the APV system, we have assumed that 22.8 kW_p cover a net area of 30m*17.9m. Those geometries refer to the net area of the systems described in Table 1.
Area loss due to supporting structure (%)	35	10	For the reference CGMPV system, we have assumed that 11.8 kW_p cover a net area of 8.6m*18.2 m. The PV modules of one row covers an area of 8.6m*3.1m. An extra 1 m can be added as a clearance distance for agricultural machineries. For the APV system, a 10% loss due to the structure was assumed as in in Campana et al. (2021).
Electricity production ($kWh/kW_p/1^{st}$ year)	1,116	1,067	Based on simulations of the PV system with bifacial modules with OptiCE.
System degradation rate (%/year)	0.2	0.2	Lindahl et al. (2022)
PV system specific cost (€/kW_p)	880	940	For the reference CGMPV, 880 €/kW_p refers to 9,380 SEK/kW_p that was the average price for commercial projects in the order of 100-255 kW_p in Lindahl et al. (2022). For the APV system, 940 €/kW_p refer to 10,000 SEK/kW_p. Those values were used based on quotations for vertically mounted APV systems projects.
Operation and maintenance (% system cost/year)	1	1	Derived from Lindahl et al. (2022)
Invert replacement costs (€/kW_p)	55	55	55 €/kW_p refers to 582 SEK/kW_p occurring at the 17^{th} year as assumed in Lindahl et al. (2022).

Other replacement costs (€/kW$_p$)	0	0	This value can be changed depending on other planned equipment replacement.
Rent (€ha/year)	0	0	This value can be changed depending on the actor and business model adopted. For instance, a PV investor should consider land rental cost.
Other costs (€/kWh, or €/year, or €/ha/year)	0	0	This value can be changed depending on the actor and business model adopted. For instance, a PV investor should consider the crop management costs.
Decommissioning costs (% system cost)	0	0	Lindahl et al. (2021)
Electricity selling price (€/kWh)	0.07	0.07	0.07 €/kWh refers to 0.76 SEK/kWh that was the average electricity price during the period 2020-2022 in area SE3 (Nord Pool, 2023).
Electricity buying price (€/kWh)	0	0	We assumed 0% self-consumption while comparing the APV system with the CGMPV system. In Table 6 and section 3.5, we have investigated the effect of the self-consumption on the APV system built on 0.2 ha land.
Self-consumption (%/year)	0	0	This value can be changed depending on the actor and business model adopted, and simulations or measured data.
Other revenues (€/kWh, or €/year, or €/ha/year)	0	0	This value can be changed depending on the actor and business model adopted.
Salvage value (% system cost)	0	0	Lindahl et al. (2022)
Real discount rate (%)	1.4	1.4	Lindahl et al. (2022)
Annual profit ley grass (€/ha)	-	−151	−151 €/ha refers to −1,608 SEK/ha from Rosenqvist (2019). It refers to values classified as "Medium to high yield".
Annual profit barley (€/ha)	-	95	95 €/ha refers to 1,012 SEK/ha from Rosenqvist (2019). It refers to values classified as "Medium to high yield".

Annual profit winter rape seed (€/ha)	-	262	262 €/ha refers to 2,791 SEK/ha from Rosenqvist (2019). It refers to values classified as "Medium to high yield".
Annual profit winter wheat (€/ha)	-	371	371 €/ha refers to 3,948 SEK/ha from Rosenqvist (2019). It refers to values classified as "Medium to high yield".
EU direct support for farmers accounts for about (€/ha/year) Land lease (€/ha/year)	-	150 + 15.4	Swedish Board of Agriculture (2023b)

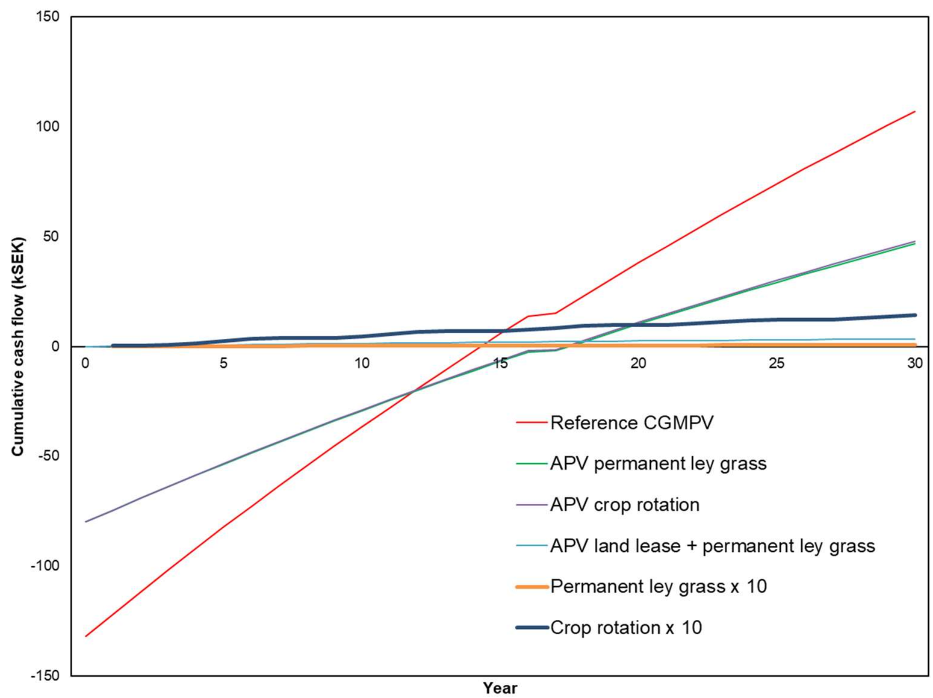

Figure 23: Cumulative cash flows for the reference CGMPV system, for the APV system with permanent ley grass and crop rotation, for the APV system owned and managed by a third-party company for which the land is leased by the farmer, and for the permanent ley grass and crop rotation (Campana et al., 2023). The cumulative cash flows of the permanent grass and crop rotation are multiplied by 10 for an easier visualization.

WP5 Scale up of the model and policy guidelines

Suitable areas for implementing APV systems in Sweden

In Elkadeem et al. (2023), a GIS approach has been developed to identify the suitable areas for implementing APV systems in Swedes. The GIS analysis was based upon the selection of different techno-agro-socio-economic criteria of

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interest such as annual global horizontal irradiation, seasonal precipitation and evapotranspiration, and land use, to cite some. The selection of the criteria and the definition of the restriction values were the basis for identifying the suitable areas for implementing APV systems in Sweden, as shown in Figure 24.

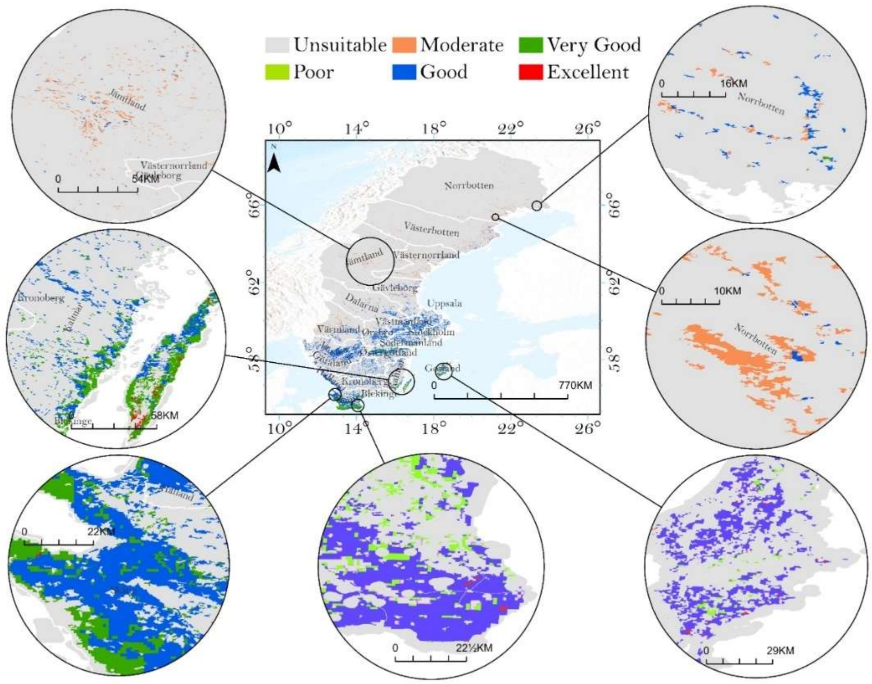

Figure 24: Final suitability map of APV projects over the Swedish territory (Elkadeem et al., 2023).

The feasible area for implementing APV system in Sweden was calculated as 38,485 km^2 out of a total 450,047 km^2. These feasible areas have the potential for installing about 1.5 TW_p APV systems for a total potential production of about 1.4 PWh.

More details concerning methodology and results can be found in the work by Elkadeem et al. (2023).

Policy guidelines

Recently, PV solar park developers in Sweden have claimed to have reached grid parity with the Nord Pool spot price, leading to a dramatic interest increase in solar parks, despite no subsidies being available for this market segment (Lindahl et al., 2022). Despite the relatively new utility-scale solar market segment, large-scale solar farms have faced several challenges with the authorisation and the environmental permission process to be built on agricultural land (Aspeteg and Bergek, 2020). Agricultural land is considered unsuitable for constructing utility-scale solar systems (Lindberg et al., 2021). According to Swedish law, agricultural land that is suitable for cultivation is of “national importance”, and it cannot be exploited for other purposes unless it is to satisfy a significant national interest, and there is no other possible land to use (Chapter 3, Section 4) (The Swedish Government, 2000).

APV systems have the potential to overcome this barrier, maintaining agriculture while producing green electricity from PV technology. In countries such as France, Germany, Italy, and Japan, where the APV technology is more established as compared to Sweden, the main issues around APV systems are not on using agricultural land but mainly on defining APV systems, maintaining and monitoring the agricultural production under the APV systems, and setting limit on the agricultural yield production under shading conditions as compared to open-field conditions.

For instance, the French law does not yet set any constraints on agricultural production below APV systems or concerning the maximum threshold for the coverage area of PV modules. However, it defines APV systems as systems where the colocation of agricultural activities and solar PV energy conversion is possible but agricultural production should be maintained and developed (Chatzipanagi et al., 2023; Légisfrance, 2023). Further, an APV system should provide at least one of the following services a) Improvement of the agronomic potential and impact, b) Adaptation to climate change, c) Protection against hazards, d) Improvement of animal welfare. In Germany, the Fraunhofer ISE, the University of Hohenheim, the German Institute for Standardization (DIN), and representatives from academia and industry have developed the standard DIN SPEC 91434 "Agri-photovoltaic systems — Requirements for primary agricultural use" (European Standards, 2023). The guidelines, among other specifications, set a threshold for the agricultural yield under APV systems to be at least 66% of the reference yield and categorise APV systems in different categories for which the land loss cannot be more than 10%, for category I, or 15% for category II. The guidelines for APV systems in Italy state that at least 70% of the agricultural areas should be kept for agricultural activities (Italian Ministry of the Environment and Energy Security, 2023). The ratio between the total surface area of the APV system and the total area occupied by the APV system should be lower than 40%. In Japan, the legislation allows the operation of APV farms only if the crop yield under an APV system is at least 80% compared to the yield before APV installation (US Department of Energy, 2022; Gonocruz et al., 2022).

It is worth mentioning that the most advanced policies on APV systems, for instance, in Japan, allow subsidies to be released for APV systems only if the crop reduction under the APV systems system is lower than 20% (Trommsdorff et al., 2021). The crop yield reduction can only be defined at the planning stage with a robust model that can accurately simulate the synergies between APV system design, PV module densities, shadings, and crop yield. This research project has filled this research and market gap.

As discussed in Elkadeem et al. (2023), as performed in other countries like France, Germany, Italy, and Japan, the Swedish Government should clearly define APV systems and categorise them based on performance (e.g., solar radiation reduction on the ground, land losses, and economy, to cite some) and applications (e.g., for grassland farming, or arable farming or horticulture, to cite some). This decision-making process should involve all the stakeholders affected by the installation and operation of APV systems, for instance, representatives of farmers, PV park developers, county administration, city planners, and water management agencies, to cite some. Second, as performed or being performed in other countries, guidelines should be developed to manage the integration of PV systems and agricultural activities, define standards, pose limits to the agricultural yield reduction under APV conditions, and identify the most suitable or optimal areas for implementing APV systems, to cite some.

This research project has shown that APV systems can increase land-use efficiency by at least 20% as compared to monoculture or sole PV farm (Campana, et al. 2021), and in the worst condition, the reduced crop yield is the same as the radiation reduction on the ground as compared to open-field conditions, plus a further 10% loss due to the unusable land for the supporting structure. The results of the first two-years experiments in Kärrbo have shown that no significant difference has been achieved between ley grass samples under the APV systems as compared to open-field conditions leading to a LER of 1.39 in 2022 (i.e., 39% higher land use efficiency as compared to sole ley grass and PV farm) (Campana et al., 2023). The unused land due to the supporting structures of the APV systems has the potential to boost pollinators, biodiversity, and thus crop productivity, as shown in previous research (Dainese et al., 2019; Kleijn et al., 2019).

From an economic perspective, the NPV of APV systems is significantly higher than sole agriculture, when compared to permanent grass and a conventional crop rotation. As shown in Figure 23, the economy of the APV system can be significantly higher than the sole agriculture, and farmers might be discouraged from conducting agricultural activities, leading to situations like CGMPV systems where land is used only for PV production. After defining what an APV system is, the Swedish legislator should also define how an APV system should be maintained with special consideration to farming.

In 2015–2021, the agricultural sector benefited from direct capital subsidy through the European Agricultural Fund for Agricultural Development for PV installation on agricultural buildings. The resulting cumulative installed PV capacity and subsidy were about 8.8 GW_p and 33.5 MSEK, respectively (Lindahl et al., 2022). The direct capital subsidy was in the order of 40% of the total investment cost. This type of subsidy was higher than residential and commercial PV systems since, due to tax regulations, the value of self-consumed electricity is lower for farmers than for residential and commercial PV applications. According to Lindahl et al. (2022), there are no plans to re-open this subsidy program, but farmers could receive capital subsidies for energy efficiency measures. In the context of APV systems, Campana et al. (2021) recommended that at the first stage, the Swedish Government could apply the same subsidy scheme for agricultural buildings to small-scale (i.e., lower than 50–100 kW_p) experimental APV systems to study more in-depth the impact that APV systems can have on the crop yield for different crops at different locations across the country. This first stage could allow for gaining more in-depth knowledge of the interrelationships between system configuration, electricity, and food production. Such an approach will benefit farmers' income and self-consumption due to the limited PV capacity of the APV systems and grid-related issues. It will also increase knowledge on APV systems, and support policy development. In Campana et al. (2021), we highlighted that fast-growing plantations for energy purposes have also received subsidies (Xu and Mola-Yudego, 2021) despite the energy yield per unit area of such plantations being considerably lower than that of APV systems. The electricity production per unit area of the APV system investigated by Campana et al. (2021) is about 30 kWh/m^2/year, while the average annual net energy yield for willow production at high nitrogen fertilisation is 175 GJ/ha/year (Nordborg et al., 2018), which is equivalent to about 4.86 kWh/m^2/year. In the second stage, after the impacts of different APV systems configurations are well known on different crops and at different geographical locations, the Government could start to support larger-scale APV systems through capital investment subsidies or through feed-in tariffs to stimulate the market and facilitate technology adoption.

It must be pointed out that since APV systems bridge agricultural, energy, and water sectors, thus, different ministries should be involved in deciding on subsidies and coordinating agricultural, energy, and water subsidies. In the second stage, the authorisation process for large-scale solar photovoltaic farms could be facilitated if those are configured as APV systems to minimise the impact on crop yields.

Dissemination

From a scientific perspective, this project has produced three conference abstracts, two book chapters, one book, three preprints, and eight scientific articles.

One special issue in the prestigious Elsevier journal Applied Energy is currently ongoing at the following link: https://journals.elsevier.com/applied-energy/forthcoming-special-issues/agrivoltaic-systems-for-avoiding-conflicts-between-the-sustainable-development-goals

A panel session with international experts in APV system was organized during the 2021 International Conference of Applied Energy.

From an educational perspective, we have educated 9 master students producing six master theses, as follows:

- Edvardsson, A., & Shafai, A. (2021). Agrophotovoltaic systems-A techno economic performance study: Technical and economical comparisons of APV systems in Sweden and abroad.
- Nygren, A., & Sundström, E. (2021). Modelling bifacial photovoltaic systems: Evaluating the albedo impact on bifacial PV systems based on case studies in Denver, USA and Västerås, Sweden.

- Johansson, F. (2021). 3D-Thermal Modelling of Bifacial PV-Modules.
- Chaudhary, M. (2021). Key performance indicators of agrivoltaic system: To evaluate the performance of agrivoltaic system technically, economically and in terms of water food energy nexus.
- Jakobsson, M. (2022). Solceller eller energiskog på jordbruksmark: En analys kring yteffektivitet på jordbruksmark.
- Qadir, O., & Cem Parlak, S. (2022). Thermal modelling of an agrivoltaic system: 3d performance analysis for bifacial PV-modules.

To disseminate the results of the project to a broader audience the following activities were undertaken:

- Organization of the workshop "Evaluation of the first agrivoltaic system in Sweden - Final workshop", 26th January 2023 with more than 230 participants across all the world. Available at: https://www.youtube.com/watch?v=_0bdzOIPTSU
- We have used Bengts nya villablogg to share the most important news and results of the project. Available at: https://bengtsvillablogg.info/
- We have created a LinkedIn page to continuously share the most important news and results of the project. Currently, the page has more than 1350 followers. Available at: https://www.linkedin.com/company/evaluation-of-the-first-agrivoltaic-system-in-sweden/
- The project has been presented in more than 50 events including articles in magazines, interventions in radios and tv programmes, blog, external presentations, webinars, MDU website, MDU project webpage, and YouTube. Some are as follows:
    - ATL, https://www.atl.nu/lantbruk/agrivoltaiska-solcellspaneler-pa-karrbo-prastgard/
    - Elbilen, https://elbilen.se/nyheter/solceller-pa-akermark-kan-ge-battre-skord/
    - Elektroniktidningen, https://etn.se/index.php/nyheter/68496-lat-solceller-ta-plats-pa-svensk-jordbruksmark.html
    - Energikontor Sydost, https://energikontorsydost.se/a/kan-man-ha-solceller-pa-samma-mark-som-man-odlar#
    - ETC, https://www.etc.se/miljo/solceller-pa-akern-ger-storre-skordar-och-mer-gron-el

- ETC, https://www.etcel.se/nyheter/prisat-solprojekt-ger-storre-skordar-och-mer-solel
- Forskning.se, https://www.forskning.se/2021/11/24/solceller-pa-akern-okar-skorden/#
- YouTube, https://www.youtube.com/watch?v=-3ooCJyvY_U
- Jordbruksaktuellt, https://www.ja.se/artikel/2228497/frst-i-sverige-med-nytt-solcellskoncept.html
- LAND, https://www.landlantbruk.se/debatt/solel-ger-tio-ganger-storre-skord-an-energiskog/
- LAND, https://www.landlantbruk.se/debatt/solcellspark-kan-samsas-med-vallodling/
- Landets fria, https://landetsfria.nu/2021/nummer-278/sa-kan-solceller-och-odling-dela-pa-marken/
- Ny Teknik, https://www.nyteknik.se/premium/kan-solcellsparker-ge-skjuts-at-odling-7012740 and https://www.nyteknik.se/premium/otydliga-resultat-fran-solceller-ihop-med-odling-7025352
- PV Magazine (reference PV systems magazine worlswide) https://www.pv-magazine.com/2021/04/30/optimization-algorithm-for-vertical-agrivoltaics/ and https://www.pv-magazine.com/press-releases/solar-energy-award-for-the-agrivoltaic-research-team-at-malardalen-university/
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jag-sager-aldrig-nej-till-nagot-som-kan-vara-bra-for-framtiden-och-miljon and https://www.svtplay.se/video/33831250/lokala-nyheter-vastmanland/svt-nyheter-vastmanland-11-jan-18-33-2?position=414&id=jLDrkkg

- TV4, https://www.tv4.se/artikel/1AGJ50DW3URmMS1yKtMnM2/unikt-svenskt-projekt-solpark-testas-pa-lantbruk
- Campana et al., “Earth Observations for the water-food-energy nexus: from hydropower to agrivoltaics”, presentation for the NASA Food Security Working Group Meeting, 22nd September 2022

In 2021, the project has been the Winner of the Solar Energy Prize in Sweden for the Achievement of the Year category, prize released by the Svensk Solenergi.

In 2021, the research project was included in the IVA's 100 List 2021.

Diskussion

From an energy perspective, vertically mounted APV systems east-west oriented show a substantially different hourly PV production profile than CGMPV systems, south-oriented at 30° tilt, as depicted in Figure 28. Although the model validated in this study showed that the specific production of the vertically mounted east-west oriented APV system is 1,067 kWh/kW$_p$/year versus 1,116 kWh/kW$_p$/year of the CGMPV, the revenue generated by a vertically mounted APV system at parity of installed peak power might be higher. The higher revenues at parity of installed power peak could be attained since the peak of power production from the APV systems occurs at hours of the day when the average electricity price is higher than hours close to noon when typically, the south-oriented CGMPV systems have the peak of power production (see Figure 29). Considering the strong interest in PV parks in Sweden, future installations conventionally oriented towards the south might lead to even lower electricity prices during noon due to the higher electricity supply in the grid. This cannibalization effect might lead to reconsidering the optimal orientation of PV parks and favour vertically mounted east-west oriented PV systems that can be easily configured as APV systems (Lindahl et al., 2023). The CFD model developed in this study also showed that from an efficiency point of view, vertically mounted PV systems have higher electricity conversion efficiencies than south-oriented 30° tilted PV systems (one of the research questions of the project was to show if APV systems are marked out by higher efficiencies).

From an agricultural perspective, the project's main result shows that establishing vertically mounted APV systems on permanent grass does not significantly affect productivity except for the land loss due to the PV modules supporting structures. The land loss due to the supporting structure is about 10% and 1 hectare of permanent grassland can host about 390 kW_p vertically mounted APV system (Elkadeem et al., 2023). Based on the approach and results in Elkadeem et al. (2023), on a country level vertically mounted APV systems on grassland have the potentials to supply about 84 TWh/year of electricity, that is about 60% of the total electricity consumption in 2020 while maintaining 90% of the national grass productivity.

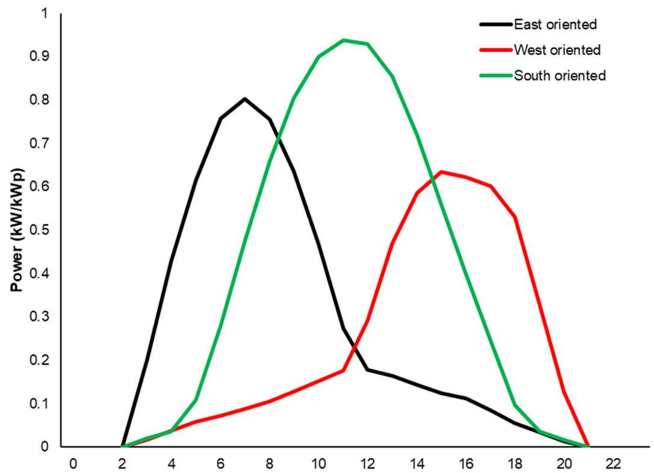

Figure 28: Specific power production profile for a clear-sky day for a bifacial PV system south-oriented versus an east-west oriented PV system. The difference in peak power production between the east- and west-oriented surface is given by the bifaciality factor and the direction of the PV module front side.

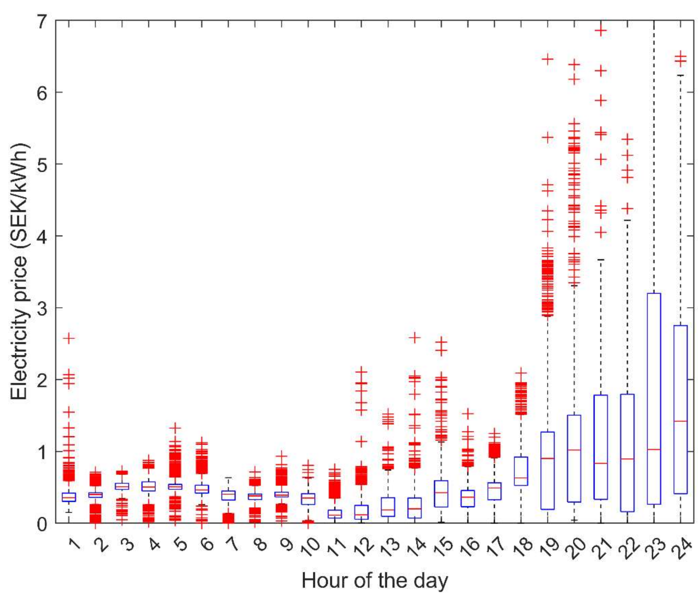

Figure 29: Box plot of the daily-hourly electricity profile for the period 2018–2022 in zone SE3.

An important aspect that the Swedish legislator should consider dealing with the support of the APV systems is that, although implementing APV systems might reduce crop production at high latitudes (Campana et al., 2021), implementing APV systems can significantly boost farmers' incomes, especially for smallholder farmers. As discussed in Elkadeem et al. (2023), increasing farmers' incomes is a pivotal concept that policymakers and stakeholders should further investigate since adopting APV systems can lead to a decreased farm-level crop production and area (i.e., in the order of 10% with vertically mounted APV systems on grasslands areas as measured in this project) but can simultaneously lead to a reverse trend of the regional and national agricultural area, number of farms, and thus domestic crop production. As shown in Figure 4b, the agricultural land area and the number of farms in Sweden have continuously decreased since the 1970s (FAO, 2023; Swedish Board of Agriculture, 2023a). Improving farmers' incomes can reverse this trend. Thus, adopting APV systems, as defined in this study, does not conflict with the Swedish Environmental Code since agriculture and electricity are national priorities. APV systems can increase food production on a regional or national scale while supporting clean energy conversion. One of the research questions of this project was if APV systems can increase crop productivity. In the first two years of the project, we found out that there was no statistical difference between seasonal ley grass productivity under the APV system as compared to the reference areas.

Nevertheless, two important aspects need to be considered. First, during the two-year project, we experienced no severe drought. Nevertheless, climate change scenarios foresee increasing temperatures and high uncertainties in precipitation patterns (SMHI, 2023). Higher temperatures can lead to high evapotranspiration rates and, thus, higher water consumption in the agricultural sector. Lower precipitation rates lead to more frequent dry periods with adverse effects on crop yield. At the same time, increased precipitation volumes but with higher intensity can also lead to lower soil moisture levels and thus increase crop water stresses and lead to yield reduction (Grusson et al., 2021). In this context, the APV system can play a key role as a climate adaptation technology. Second, we have only tested one crop in the first two years. In the coming years, we plan to test different crops with different water stress indexes and analyse how shading affects crop productivity. Since 2023, we have started investigating a typical Swedish crop rotation. Despite July 2023 has been a very wet month, with almost 143 mm of precipitation, much higher as compared to the reference period 1990-2010 (i.e., 77 mm), May and June have been extremely dry (i.e., 16.2 mm and 30.9 mm versus 44 mm and 69 mm for the reference period). The effects of this continued dry period can be easily seen on the barley density in Figure 30, showing the reference area (top) and under the APV system (down).

One of the hypotheses of this research project was that the APV system could increase the profitability of ground-based PV systems. The results of the project have shown that APV systems cannot compete with CGMPV systems in terms of profitability because of lower specific electricity production (e.g., the APV system and the CGMPV system's specific electricity production in Kärrbo Prästgård were 1,067 kWh/kW_p/year and 1,116 kWh/kW_p/year, respectively), lower density of

PV modules per area (i.e., lowers installed capacity per area), and higher specific installation costs. It must be pointed out that the lower specific electricity production might be counteracted by higher electricity prices in correspondence with the power production peaks. Concerning the installation costs of APV systems, these costs might decrease and reach the same levels as for CGMPV systems. Our cost assumptions were based on quotations for Sweden's first APV systems. On the other hand, APV system shows significantly higher profitability as compared to conventional crop rotations making them a solution for increasing farmers' incomes while maintaining crop production.

Figure 30: Preliminary status of the barley sown in Kärrbo Prästgård in 2023. Barley in the reference area (top), and barley under the agrivoltaic system (down). Photo taken 12th July 2023.

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Bilagor

Besides the administrative attachments, we also attach the following confidential files:

- Large-scale implementation of APV systems in Sweden KÄNSLIG INFORMATION
- A Gridded Simulation Model for Regional Assessment of Agrivoltaic Systems Towards the Implementation of a Decision Support System KÄNSLIG INFORMATION