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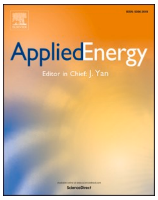

Performance evaluation of high latitude agrivoltaic systems with vertically mounted bifacial panels

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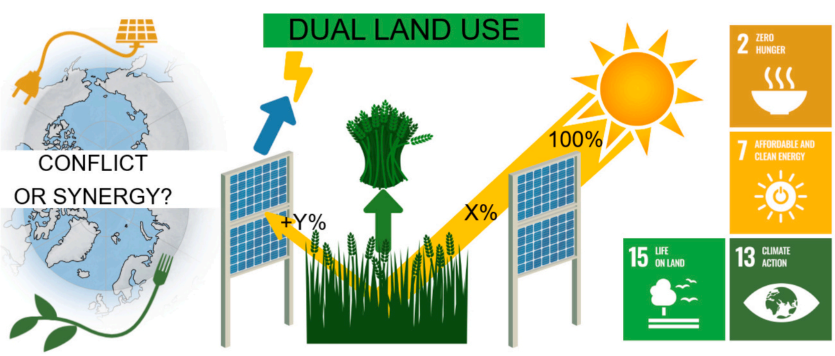
HIGHLIGHTS

- Vertical bifacial agrivoltaic systems can be feasible in high latitudes at row separation of above 8 m.
- Crop albedo has the potential to boost PV electricity production, though row spacing remains the main determining factor in system design.
- Revenue depends primarily on the spot price of electricity rather than exact row spacing.
- Vertical PV systems occupying merely 10 % of agricultural land produce over 1/3 energy output of a dedicated system.

GRAPHICAL ABSTRACT



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ABSTRACT

This work presents a comprehensive analysis on the impact of the environment on a large-scale east-west oriented vertical bifacial agrivoltaic installation in high latitude conditions. These vertical panels perform particularly well in high latitudes due to low sun elevation angles and long summer days. Along with atmospheric effects, these conditions necessitate different models to produce accurate PV system results, as low latitude results are not applicable. As solar photovoltaic (PV) power production continues to grow, effective dual use of land, such as integrating PV production to agricultural land (agrivoltaics), becomes attractive to increase energy independence and grid resilience. The specific novelties of this study are defining of the impact of (1) row spacing and on solar panel energy yield, revenue and row spacing on crop irradiation loss, and (2) an analysis of shading objects at high latitudes. The Yang2 decomposition model was used, alongside measured and satellite derived irradiance data for Finland at 60°N and verified with a measured power production (R^2 of 0.975). At row

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Abbreviations: APV, agrivoltaics; VBPV, vertically mounted bifacial photovoltaics; PV, photovoltaics; PAR, photosynthetically available radiation; LER, land equivalent ratio; TUAS, Turku University of Applied Sciences; BSRN, Baseline Surface Radiation Network; CAMS, Copernicus Atmosphere Monitoring Service; MPP, maximum power point; *GHI*, global horizontal irradiance [W/m^2]; *Z*, solar zenith angle [°]; G_{sc}, solar constant [W/m^2]; *DHI*, direct horizontal irradiance [W/m^2]; *DNI*, direct normal irradiance [W/m^2]; k_t, clearness index [no unit]; *AST*, apparent solar time [no unit]; k_{tc}, clearness index of clear-sky GHI [no unit]; $k_d^{(s)}$, satellite derived diffuse fraction [no unit]; k_{de}, part of diffuse fraction that is attributed to cloud enhancement [no unit]; R^2, coefficient of determination [no unit]; *MBE*, mean bias error [no unit]; *RMSE*, root mean square error [no unit].

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separation of 10 m equivalent to 10 % land coverage, crops received 79.9–82.5 % irradiance compared with an unshaded reference. Energy output was 276–280 kWh and revenues 13.04–13.25 EUR per panel (2019). The variation comes from different crops, winter barley cultivation resulted in the highest energy yield and revenue. These yields were achieved using only a fraction of the land leaving the rest for agriculture, highlighting the potential of vertical agrivoltaic installations in high latitude locations.

1. Introduction

As the world struggles with climate change and resource supply issues, the need for reliable, resilient, and green energy sources is rising [1,2]. Another concern is achieving higher energy independence to avoid importing energy, especially fossil fuels [3]. Renewable energy sources are regarded as part of a solution to both those problems. Currently, the leading renewable energy sources in Finland are hydro power and wind power, with the production of 15 TWh and 14 TWh respectively in 2023 [4,5]. The total amount of wind power in the energy mix is growing while hydro power remains at a comparable level. Solar power production is growing quickly and more than doubled between 2021 and 2022, but currently still accounts for less than 1 % of Finland's energy mix [6,7]. Large-scale solar energy installations currently planned in Finland amount to 23 GW [8,9]. As large-scale systems in Nordic conditions are still uncommon, research that focuses on them is needed to ensure effective use of land and resources. Due to wind being an intermittent phenomenon, and the need to decrease reliance on fossil fuels, diversification of energy sources is required [6,10]. Depending on location, wind and solar energy are weakly complimentary on long (more than 24 h) timescales [11], and our previous study shows that in Finland there is an inverse correlation (complementarity) between wind and solar production [12].

There are currently limited ways to produce PV power through dual use of land, and those that exist are used primarily in low-to-mid latitude locations. Because of lower sun elevation angles and high seasonal variability, high latitude system energy production distribution and total yield differ from that of lower latitudes. Additionally, due to high fraction of renewable energy in the Nordpool electricity market in northern Europe, the energy prices in that region create a unique combination of factors that create a need for focused studies. Agrivoltaics or agriphotovoltaics (APV) is a concept that combines solar panels with agricultural use of land which allows for more effective and sustainable land use [13–15]. Many types of installations have been considered and tested in latitudes below 60°N, including conventionally mounted panels suspended over the crops using tall constructions (overhead systems) [16–20] and vertical systems [21,22], which allow farming equipment to freely pass between the rows. Combining solar energy production with agriculture was shown to increase the efficiency of land use [19,23]. Partial shading from APV systems reduces evaporation which can increase crop yield depending on meteorological conditions [24–26]. Other potential benefits could be achieved through the increased green transition of the agricultural sector. Majority of energy use by agricultural vehicles and many processes happen during times of high solar energy production. Energy use through the year in agricultural sector matches solar power production more closely than it does for residential buildings, therefore utilizing APV electricity in agricultural processes could allow using the excess cheap energy produced during the peak and help with the decarbonization of the farming sector [27,28].

In addition to land utilization, there are research gaps pertaining to PV system designs suitable for high latitude locations. Extensive periods of low sun elevation angles and snow cover affect traditional south facing installations to a much larger degree than in low latitudes. Thus, high latitudes require solutions more resilient to those effects. One interesting design for high latitudes is using vertically (east–west) mounted bifacial photovoltaic (VBPV) panels [29–31], which have shown the potential to be uniquely suited to northern conditions. In high latitudes even the overall production of VBPV can surpass that of the conventional south facing PV [32] and the east-west orientation increases the temporal match between use of energy and its production (i.e. morning and evening peak instead of noon peak) [21,32–34]. Thus, VBPV panels alleviate price cannibalization [12,35]. The effects of soiling, including snow cover, are reduced for vertically mounted panels which decreases related performance losses and the need for cleaning [36–38]. Vertical panels are also less affected by heating. South facing panels heat up primarily at noon when irradiance is typically the highest, as VBPV produce energy primarily in the morning and afternoon the air temperature tends to be lower while the panel production is spread across more time, which reduces heating related performance losses [39].

One of key benefits of VBPV in agriculture is that it covers less land area than conventionally mounted PV which facilitates dual use of land [26]. A common challenge with VBPV installations in many cases is that the vertical installation necessitates larger gaps between rows of panels and from other structures. This requirement limits locations suitable for VBPV in urban settings, however agricultural land offers ample space suitable for this type of installation [40]. While in an overhead APV systems the crops and the PV panels compete for sunlight, in the case of vertical mounting this effect is reduced because self-shading of solar panel rows necessitates distances between those rows to ensure PV panel efficiency. At the same time, in the case of vertical panels, the crops can increase the albedo (the reflectivity of the surface) of the surroundings causing higher energy gains. As an additional potential benefit, the unused patch of land directly below and around the solar panels creates areas that can allow biotope connectivity and increased biodiversity in areas dominated by monoculture, thereby reclaiming some agricultural land for biodiversity [27,28,41,42]. One issue with APV is a current lack of clarity in legislation. For instance, EU financial support eligibility for farmers lacks clarity, but there are cases where direct payments were granted for APV locations [43]. For example, among countries that define the impact of PV installation on the crops through the yield reduction, France regulates the PV installation to result in at most 10 % and Japan at most 20 % crop yield loss compared with a reference field [44,45]. To conclude, APV is a particularly interesting use-case of VBPV since it allows efficient land use and reduces the mismatch between energy production and demand peaks, but clear legislation is needed for APV become attractive to farmers [27,28].

Research focusing on high-latitude APV systems, especially those concerning VBPV, is needed to fill the existing literature gap. APV using VBPV already exists and was the subject of study in many locations around the world (e.g. Italy, Germany, Japan), primarily at latitudes below 50°N [46–50]. Only one study analyses APV in Norway, and a study on viable APV locations in Sweden exists, however there still a limited amount of research on such systems in high latitudes [51,52]. It has been shown that crop albedo affects solar panel yield and that depending on the placement of the solar panels their effect on crops can be minimal [52,53]. A detailed model was previously developed for estimating a potato yield at a high latitude depending on available photosynthetically available radiation (PAR) [22]. However, because the installation analysed has only three rows and is relatively small, the results have limitations in accurately representing large-scale installations, especially when it comes to energy production [54,55]. Specifically, inaccuracies arise firstly from increased albedo affecting the first and last rows of a vertical installation disproportionately, and secondly because the shading of crops is more significant further away from the installation edges.

There are a number of differences between low-to-mid and high latitudes which create the need for research focused on those conditions, select differences are shown in Table 1. High latitude locations are characterized by low solar elevation angles, reduced irradiance compared with lower latitudes, long summer days and long periods of snow cover and different weather patterns compared to medium and low latitudes. Out of those conditions, the sun elevation angle and total irradiance have the most prominent effect on the PV systems. This affects both optimal system design and modelling of systems, especially VBPV. VBPV systems perform better than conventional systems at low solar elevation angles and benefit from the increased albedo snow cover provides, which results in VBPV being uniquely suited for northern countries [32,56]. However, this also means that the temporal distribution of solar irradiance and therefore energy production, both on short (24 h) and long (year) time scales, significantly differs from locations further south, rendering existing research from those areas inaccurate for Nordic conditions. Likewise, commonly used solar decomposition models are typically fitted based on data from latitudes below 60°N and low solar elevation angles cause uncertainties that are minor in low latitudes but need to be accounted for when analysing northern locations. Even quasi-universal models underperform in high latitude locations, necessitating targeted approach with models proven to be suitable to high-latitudes [57].

VBPV can alleviate temporal mismatch between production and demand typical in conventional systems; however, research on VBPV in high-latitude locations is limited. APV is an effective way to increase the proportion of VBPV, which is otherwise difficult to create large installations with, in the grid. Thus, APV installations are an attractive prospect for increasing the share of solar energy [35]. Currently, very few studies focused on high latitude APV systems exist. This necessitates more research before such dual systems can be widely adopted. As a relatively new concept in the Nordics, APV research is still in early stages and due to interconnected nature of the agricultural and PV systems as well as the unique conditions at above 60°N information is sparse. Overall, vertical APV systems show promise and some research showing the validity of APV systems at those latitudes already exists. However, studies featuring vertical APV systems in high latitude locations are scarce, and there is an urgent need for a more complete understanding of vertical APV systems due to active and rapid development of solar power in Nordic countries. A study in Canada focused on the irradiation reaching crops by analysing the crop irradiation reduction for different vertical PV row spacing [54]. However, the latitudes analysed in that study were significantly further South (42.98°N–51.04°N). A group in Sweden implemented a small high latitude agrivoltaic system at a comparable latitude and climate conditions to Southern Finland, the primary focus of studies conducted in that area was the effect vertical APV installation has on crops [58–61]. For example, Campana et al. performed an optimization for a small-scale system where rows were spaced 5–20 m apart [22]. In that study energy yield, as well as crop yield for oats and potatoes were analysed for the highest land equivalent ratio (LER). Ma Lu et al. compared the accuracy of simulations using different albedo sources using AgriOptiCE® model for Matlab® and demonstrated that measured albedo results in better accuracy than satellite albedo [53]. Small scale installations are more affected by edge effects such as uneven shading and irradiation of rows than large-scale systems [62,63]. Edge effects in VBPV systems are less pronounced than, for example, in overhead systems; nevertheless, they are present and depend on the number and length of rows. Currently no studies focusing on large-scale VBPV APV systems in high latitude locations exist.

Table 1
Typical differences between high latitude and mid-to-low latitude conditions relevant to APV systems.

Parameter	Mid-to-low latitude	High latitude	Effect type
Seasonal irradiance variability	Medium to low	High	Large differences in seasonal energy production
Temperature peaks	High	Medium	Temperature related losses and degradation
Humidity	Highly location dependent	Low to medium	Humidity related degradation
Midday sun elevation angle	Medium-to high	Low-to medium	Optimal angle, energy production time
Winter snow cover	Short or none	Long-term	Albedo, covering non-vertical panels
Optimal tilt angle for south oriented systems	Usually 20–30°	Above 30°	Optimal system design parameters

Experimental setups are lacking at this time, with only a few small-scale installations existing in high latitudes. This work is computational, with a focus on the energy production and factors affecting APV system, and is needed to motivate further experimental studies. The goal for the irradiance study for crops was to estimate how to avoid excessive shading of crops in an APV system. This study addresses the following gaps in literature regarding high latitude APV systems: evaluating a large-scale APV system using methods suitable for high latitude locations including system revenue based on NordPool spot price, verifying the effect of varied crop albedo on an APV system using VBPV, and a verification of the effects of shading on VBPV. To that end a solar decomposition model chain suitable for high latitudes is used to increase the accuracy of estimated energy yield. Weather and PV power production data from a site in Finland is used together with satellite data and crop albedo measured at a comparable latitude. Besides our scientific aims, an additional goal is to provide practical insight for society, both to farmers considering APV but also decision makers on the benefits of such novel systems.

The main research questions are:

1) How much shading do the solar panels cause to the crops and themselves?
2) How does the crop choice affect vertical agrivoltaic system energy gain through albedo change?
3) How do different surroundings affect shading in high latitude locations?

2. Methodology

Fig. 1 is a representation of the workflow used in this study. The measured, satellite-derived and literature data were collected and, in case of the measured data, processed using data quality filters described in further detail in section 2.2. To improve the accuracy in high latitude locations, the Yang2 irradiance decomposition model described in further detail in section 2.3 was used to create the input irradiation files for PVsyst, as recommended in the literature [57]. The agrivoltaic and validation systems reported here, described in further detail in section 2.4, were modelled with commercial software PVsyst version 8.0.

2.1. Data description

The measured PV system data and meteorological data used in the APV model and its validation comes from Turku University of Applied Sciences (TUAS), and the measurements were done in 2019 containing the PV system power, global horizontal irradiance (GHI), temperature and wind speed [64]. The measurement site is in Turku at 60.45°N, 22.30°E and the conditions — primarily GHI — should closely match surrounding areas in southern Finland, making it a good representation for systems located in that area. The measurement site is an urban location while the simulations assume an agricultural location. However, this test site is affected by shading only to a small degree because of its rooftop location, thus it should give results comparable to an open

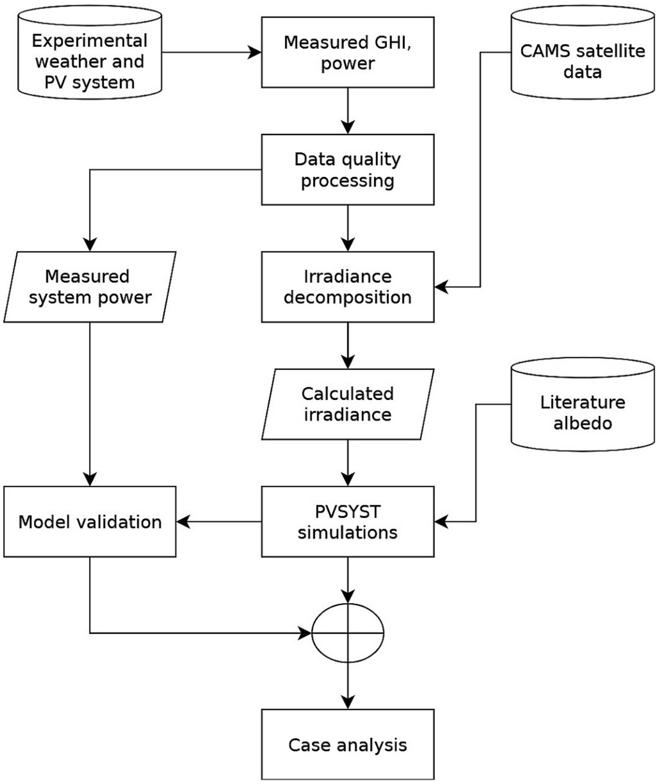

Fig. 1. The modelling framework followed in this study.

field. A detailed description of the PV panels and weather monitoring system setup was published recently as part of an analysis of performance loss rate of VBPV using the same data [65]. Satellite data for the same location was retrieved from Copernicus Atmosphere Monitoring Service (CAMS) database [66–70].

Monthly average albedo values were used as part of the system model to determine the albedo impact on PV energy production. This is necessary for bifacial panels, as even in case of a south facing panels the rear side benefits additionally from reflected irradiance, meaning that varied albedo of different crops and cultivation methods has a direct effect on the PV energy output. The effects of the changing albedo are especially prominent in VBPV systems which receive significant reflected irradiance on both sides and thus benefit from it through the whole day. While albedo changes depending on crop, temperature and precipitation as well as location-dependent ground cover, the largest variation occurs in the winter. Bare soil has very low albedo while snow cover can reach very high albedo values. Albedo values in December for example are very high which results in an increased PV output, as shown in Table 2. The overall effect of snow cover on the PV energy yield of VBPV is minor, and was thus omitted from this study. This is because during the time snow cover is likely to be present, significantly less irradiation reaches solar panels compared with the snowless period. This is especially true in locations such as Southern Finland where the snow cover rarely extends into high irradiance months, and the winter months are characterized by extremely short days.

Table 2
Average albedo (–) for each month for selected crops [71].

Month	Winter barley	Spring barley	Winter wheat	Spring wheat	Oats	Ley grass
January	0.18	0.11	0.08	0.09	0.09	0.22
February	0.25	0.12	0.12	0.07	0.07	0.24
March	0.22	0.15	0.14	0.12	0.12	0.20
April	0.23	0.17	0.17	0.14	0.14	0.21
May	0.22	0.15	0.18	0.14	0.13	0.23
June	0.22	0.20	0.21	0.22	0.22	0.21
July	0.23	0.20	0.20	0.21	0.22	0.20
August	0.25	0.21	0.20	0.20	0.19	0.21
September	0.12	0.18	0.26	0.16	0.09	0.21
October	0.11	0.08	0.06	0.05	0.05	0.22
November	0.16	0.08	0.08	0.06	0.06	0.22
December	0.87	0.74	0.84	0.84	0.84	0.78

Finland is a major barley exporter followed by oats and wheat; therefore, this study considers barley along with oats, wheat and ley grass. Monthly albedo of chosen crops is shown in Table 2. Estimated monthly albedo values were based on data from Sweden (59.82°N, 17.65°E) measured by Sieber et al. in 2019–2020 [71], closely matching the latitude of the south coast of Finland. The measured period contained a particularly low number of snow-covered days, affecting albedo in the winter. Crops have no direct impact on the PV installation around them other than through increased albedo. Ground albedo is affected by the choice of the crop, as well as harvest time. Albedo in turn has an effect on the energy yield gains of PV panels, especially pronounced for vertically mounted panels. The fraction of irradiation available to the crops was calculated as the difference between irradiation reaching crops and the total irradiation (GHI) during the growing season. The start and end of the growing season in the area around Turku, southern Finland is 27.04.2023–17.10.2023 [72].

2.2. Data quality control

To control the quality of data used in the calculations, a set of quality control filters was applied. The measured power used for the validation of simulated results was missing from the period between 29.05.2019–04.06.2019 and contained invalid non-zero values. Values below a threshold were filtered to ensure data quality. The threshold was established by locating the highest value in the missing data period (7.85×10^{-4} kW) and rounding up to the nearest decimal (8×10^{-4} kW). To account for expected low power values at nights, periods with more than 120 consecutive power values below the threshold limit were ignored (equivalent to 120 min). To account for the missing days, periods of more than 1440 consecutive power values below the threshold were removed. The total number of filtered values was 12,391.

The measured weather data was also filtered to ensure data quality by applying the following constraints:

1. For $Z > 85^\circ$ GHI was set to 0 to avoid $\cos(Z)$ uncertainty that causes inaccuracies at high solar zenith angles [73]
2. GHI < 0 was set to 0
3. GHI $< 1.5 \cdot G_{sc} \cdot \cos^{1.2} Z + 100$ Wm^{-2}, and GHI $< 1.2 \cdot G_{sc} \cdot \cos^{1.2} Z + 50$ Wm^{-2} was set to 0, based on BSRN (Baseline Surface Radiation Network) quality assessment and control algorithm [74].

Where Z is the solar zenith angle and G_{sc} is the solar constant.

Before the filters were applied, the initial number of data points was 525,961. The total number of values set to 0 or removed was 302,016, which corresponds to 57.4 % of used data – most of which was night and very low irradiance values.

2.3. Irradiance decomposition model

Measuring GHI is technologically much easier than measuring individual irradiance components, such as DHI and Direct Normal Irradiance (DNI). Because of this, in most cases decomposition models are used on the measured GHI. Recent studies found that Yang2-Hay1 model chain is currently the most accurate model chain in high latitude locations for east-west VBPV for west side [57]. Yang2 was applied to the measured GHI [75]. As PVsyst offers Hay1 as the default transposition model, the Yang2-Hay1 model chain was used. The Hay1 transposition model used in this study came from the PVsyst software [76]. Measured GHI data was processed using Yang2 solar decomposition model, given by the following Eq. [75]:

$$k_d^{Yang2} = C + \frac{1 - C_s}{1 + e^{\beta_0 + \beta_1 k_t + \beta_2 AST + \beta_3 Z + \beta_4 \Delta k_{tc} + \beta_6 k_d^{(s)}}} + \beta_5 k_{de}, \tag{1}$$

where C_S, $\beta_{0\text{–}6}$ are fitted coefficients, k_t is clearness index, AST is apparent solar time, Z is solar zenith angle, k_{tc} is clearness index of clear-sky GHI, $k_d^{(s)}$ is satellite derived diffuse fraction and k_{de} is part of diffuse fraction that is attributed to cloud enhancement [77]. Codes used to process and visualize data can be found at [78].

2.4. Simulations and APV model validation

The results were obtained by modelling all configurations in PVsyst [79], which is widely used both commercially and academically for PV simulations and has the capacity to calculate the shading factor [59,80–82]. Furthermore, one study found that PVsyst simulations are accurate for a similar system at a high latitude location [22]. The PV panel model uses full cell modules to match the weather and PV measurement system in Turku, Finland, which was used for verification of measured data from the same site (described in section 2.1). All further models for the same location were also done in PVsyst. Currently, half-cut cells are most common as they tolerate shading better resulting in lower losses. Using full cell panels as done here can result in an overestimation of shading losses on the system compared to most new installations. However, the overall relationship between the shading and the energy output should remain relevant. The 1-min data measured at the site was averaged into hourly values due to PVsyst requirements.

To simulate a bifacial panel in PVsyst and to ensure that the direct irradiance is correctly calculated for both sides, two faces were modelled separately and the total production of both panels was summed. PVsyst currently lacks the ability to model a single-row bifacial system, and the experimental setup used for verification consists of a single row. As the verification required simulations of a single bifacial panel row, two panel option was necessary. Additionally, this allowed access to separate data for each side, which cannot be done using bifacial models in PVsyst. The bifaciality factor of 0.9 was applied by modelling the front and the back panel separately, based on manufacturer information of front and back sides, shown in Table 3. East-facing side was modelled as the front, and west-facing side as the back. This approach was necessary, because PVsyst currently offers only limited simulation options for bifacial panels, the two-panels model was validated using experimental data which can be found in the supplementary material along with Fig. A.2 and Fig. A.3 depicting the R2 of measured (0.975) and satellite (0.904) data as well as a comparison of the measured and simulated power for select summer days.

Modelling the front and back sides separately can result in underestimation of the panel temperature, which can lead to an overestimation of energy production; however, it was found that models applicable to monofacial panels perform adequately for bifacial panels in lower output and temperature ranges, which is the case in VBPV systems due to their orientation [83]. The highest inaccuracies are characteristic of the noon irradiance peak causing particularly high temperatures, which is absent from a VBPV system [84]. As the production peak is split between two smaller peaks in the morning and evening rather than a single peak at noon, the monofacial temperature model should remain sufficient. A monofacial panel equivalent in rated power to the front face of the bifacial panels was chosen for a comparison system. Snow cover on solar panels (which has little effect on VBPV) was omitted, which can result in a small overestimation of the production of the south facing comparison. However, as winter PV production is generally low, particularly at high latitudes, this effect is limited.

Table 3
Parameters of bifacial solar panel Bi60-375BSTC and monofacial ZT-295S.

Parameter	Bi60-375BSTC front	Bi60-375BSTC back	ZT-295S monofacial
Rated Power (W)	295	266	295
Rated Voltage (V)	32.4	32.4	36.7
Rated Current (A)	9.10	8.19	8.06
Open Circuit Voltage (V)	40.2	40.2	45.93
Short Circuit Current (A)	9.64	8.67	8.63

Several scenarios were created to determine the impact of chosen variables, the different scenarios are described in Table 4.

In the agrivoltaic VBPV scenario an example field has been created. The goal of this system was to assess the effects of row-to-row separation and varied crop albedo. This example field had 15 rows of 66 × 2 east-west oriented vertical panels in a landscape configuration with 1 m ground clearance and rows of agricultural land between, leaving 0.5 m clearance on each side of the solar panels to account for areas inaccessible to farming equipment. Simulations were done for row spacing of 5–100 m. 100 m separation between panels serves as a “no shading” variant for the comparison of maximum calculated performance. A “generic 500 kWac” inverter was used for east and west side. In order to avoid design-specific results, the system power was measured as Array MPP (Maximum Power Point) energy after all array losses. System revenue was calculated for the VBPV system with 10 m row separation using spring barley albedo and 1 h spot price resolution, in years 2019–2023 using the following equation:

$$revenue = \sum\nolimits_{t=1}^{n} \left(p_{spot,t} \bullet E_{PV,t}\right), \tag{2}$$

where p_{spot} is the spot price E_{PV} panel output (kW) for the hour t. The revenue simulations were carried out using satellite meteorological data [85], as measured data was only available for parts of that period. Spot price data came from NordPool [86]. Additionally, a south facing monofacial system was created as a direct comparison. South facing monofacial panels were placed in a conventional system with 2 panels placed one above the other, in a horizontal orientation and 5 m separation between the rows. The inclination of 30° was chosen because it matches a typical south facing installation of this type which is chosen based on factors such as row spacing required to limit self-shading and wind load. It’s also close to an optimal inclination for this type of installation in the Nordic conditions [87]. The number of panels were matched to the VBPV system (1980).

The relationship between irradiance reaching crops and crop yield is complex and depends on many variables other than the total irradiance, such as precipitation, air temperature, soil type, fertilization and even the composition of the air [88,89]. Each grain has different optimal light requirements and varied ability to adjust to different shading conditions, and weather patterns can result in a loss or gain of yield compared with an unshaded reference. For example, barley, which is the grain grown the most by weight in Finland, is more shade-tolerant than wheat [90].

Table 4
Overview of PV systems used in simulations.

Parameter	Agrivoltaic VBPV*	South facing APV	South facing dedicated	Shading VBPV
Row separation (m)	5–100	27	5	–
Number of panels	1980	620	4640	12
Agricultural yield	yes	yes	no	–
Objectives / purpose	Effects of row distance and crop type on output power, revenue and crop irradiance	Land use comparison	Land use comparison	Effect of near forest shading on power

[*] Includes a south facing reference with the same number of panels equivalent to the front face of VBPV panel.

For the purpose of this study, only the irradiation reaching the crops was studied to determine a minimum row separation expected to result in minimal crop losses. A threshold of 25 % irradiation reduction was considered as a maximum cut-off value, as it was found that for shading of less than 25 % most crops were not significantly impacted by shading [24,91]. Some shading-sensitive crops such as maize are affected disproportionately by even minor shading; however, those crops are rarely grown in Finland and as such were omitted from this study [92].

A single average value for irradiance reaching the ground directly underneath the rows was simulated due to program limitations. In supplementary information, Fig. A.1 depicts one of the simulations of ground shading. Ground irradiance readings have been achieved by placing horizontal solar panel sheets at 0.05 m height between the rows leaving 0.5 m of empty space between the crop model and the VBPV. That allowed for the determination of the average shading value for the whole ground. Realistically shading varies with distance from the panels and affects ground unevenly, though this effect is less pronounced with increased separation between rows [50]. The shading data was then grouped by months to allow for an accessible comparison with crop sowing times.

To compare land use, a south facing APV and a dedicated south facing systems were made. The 10-m row separation VBPV scenario (10 % land covered by the PV installation) using spring barley was used as the VBPV comparison. The two south facing systems were created to closely match the total land area of the VBPV variant (15,844 m^2). The south facing conventionally mounted monofacial APV system was designed to cover 10 % of available land, the same as the VBPV system. The dedicated PV system was covering all available area. The south facing APV and dedicated system consisted of the same monofacial panel in a horizontal orientation at 30° inclination, and in case of the dedicated installation 5 m separation between the rows.

A shading VBPV scenario was developed with the goal of evaluating the impact of shading near forests and other obstacles. The shading obstacle was represented by a coniferous forest, as trees are typically the highest objects near agricultural land. A single-row system consisting of 6 × 2 panels and a “generic 3 kWac” inverter was used to estimate the worst-performing area of an installation. The primary tree species in Finland are the Norway spruce, Scots pine, and birch [93], and the maximum height of 90 % of Finnish forests is 23 m, based on data from Global Land Analysis and Discovery, which can be considered a typical worst-case scenario for shading [94]. The surrounding obstacle – forest has been modelled to reflect a situation in which the field is shaded from each side separately for forest heights of 7–23 m.

3. Results and discussion

The results section describes scenarios including an unshaded field with VBPV and conventionally mounted panels, and a single VBPV row being shaded from different directions by a tree line. Among the studied parameters, energy spot price was the most significant factor affecting the final revenue. VBPV is affected by shading differently than south-facing installations and is the most affected by obstacles directly to the east and west of the installation.

3.1. Row separation and crop albedo effect on energy production

VBPV are characterized by production profiles that better match typical energy demands than south facing installations [35]. The average energy production of a VBPV system with row spacings of 10 m, and a south-facing comparison through the year are presented in Fig. 2. Notably, in a south-facing system, the timing of energy production peaks around noon. In contrast, VBPV production has two peaks: one in the morning and one in the afternoon. Power production starts earlier and ends later in a VBPV system than that of a south facing system, and having two peaks ensures a more even temporal distribution of energy production. Decreasing separation between rows results in a decrease of energy production per panel, resulting mainly from decreased albedo and diffuse irradiance reaching VBPV, which is illustrated in Fig. A.4 which can be found in supplementary information. The morning and evening production is nearly unaffected by self-shading at the row separation of 10 m.

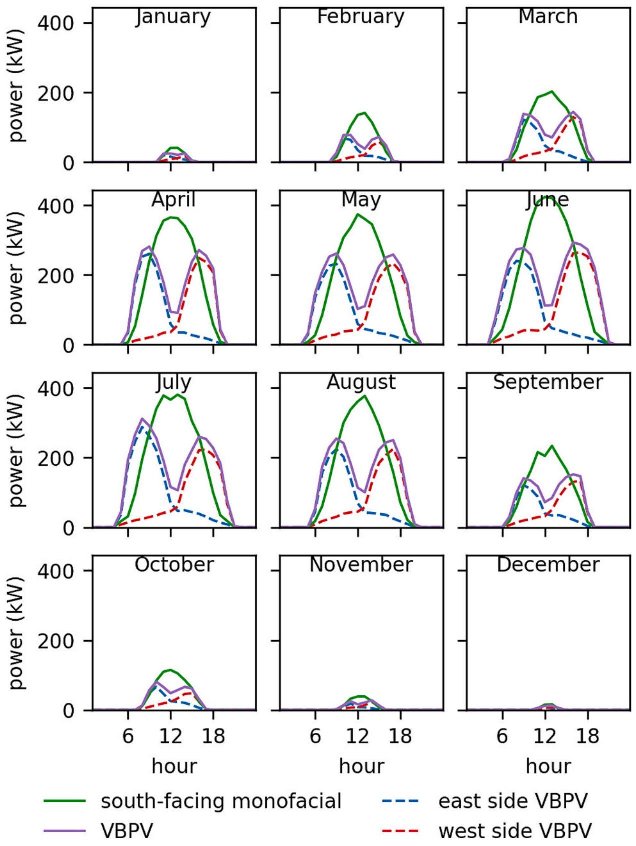

Fig. 2. Average hourly energy production profile for each month for 10 m separated VBPV (purple) and south-facing (green) installation with east (blue) and west (red) face of VBPV shown separately. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

When planning an APV installation, it would be important to consider how to effectively space that installation for farming equipment. For example, tractor mounted sprayers typically span up to 20 m which necessitates a wide row separation between solar panels. With 20 m separation, 93–95 % of reference production is reached, and crop irradiance loss is only 8–9 % (Fig. 3). More detailed comparison of conventional south-facing systems and VBPV for dual land use is discussed in section 3.3.

Fig. 3 shows the energy output per panel in systems with row separations up to 100 m in a field growing different crops, and in a dedicated PV comparison system. The difference between albedo of different crops can result in around 2 % difference in power output for short row separation, and 4 % for large row separation. While the impact of crop albedo can lead to a notable increase in energy production, the determining factor is still row spacing. The impact of row spacing is more pronounced for crops with higher albedo such as ley grass or winter barley, showing a positive effect from high-albedo crops on the solar energy production. High-albedo crops can positively affect the PV power yield, but overall the effect on the total yearly output is minor. Since the crop choice affects only the albedo irradiance, the direct and diffuse irradiance guarantees a sufficient energy yield even in case of low albedo crops. Oats are however a special case as they can grow much taller than most other crops, which could force taller PV constructions to avoid the panels being shaded by the crops. Out of the studied crops,

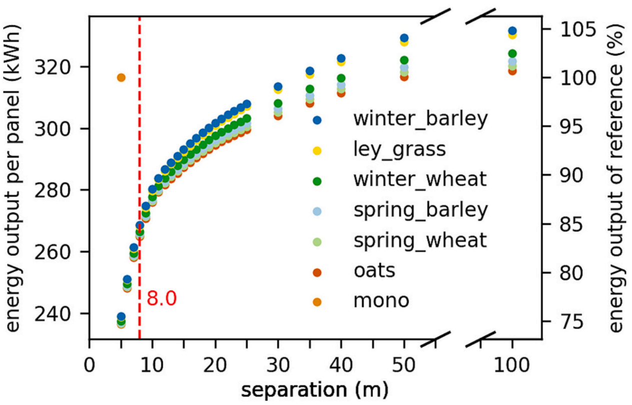

Fig. 3. Energy output per panel at nominal power of 375 (bifacial) / 295 (monofacial, same as front side of VBPV) W for different crops, depending on the solar panel row separation. Red line represents 25 % reduction in crop irradiation at ground level at 8 m row separation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

oats resulted in the lowest performance. However, even at the highest separation where albedo gains are the highest, the difference between oats and the second lowest crop (spring wheat) is less than 0.5 % of the total output. As a study in Northern Europe demonstrated that increased cropland albedo can have a reducing effect on climate change, this could offer a beneficial synergy to reduce the climate impact of agriculture [71]. However, winter crops have been losing popularity because of increased losses compared to spring sewn crops due to climate changes, which can affect the most effective crop choice [95,96]. Fig. 4 shows the energy produced per total area of land (including agriculturally productive land). The results are very closely distributed because the differences in energy production are minor compared to the increase of total area taken by the solar panels and agricultural land.

Panel self-shading effects decrease rapidly with increased row spacing. This effect is more pronounced for shorter row separations (up to about 15 m), after which the effect slowly diminishes. At analysed row separations, this is caused primarily by increased albedo and diffuse gains, direct shading has only minor effect. Increase of up to 16 kWh/m^2 was observed when the row separation was increased from 10 m to 20 m.

3.2. Row separation and spot price effect on revenue

The relationship between the power produced and revenue depends on evolving spot price electricity prices. Because spot prices are typically higher in the morning and afternoon, the power produced at those times tends to have a higher value than power produced at noon. In the summer months, daylight savings time causes a shift in demand times compared to the PV energy output, which is always dependent on solar time (Fig. A.5 in supplementary information). As the value of electricity produced at noon is expected to continue decreasing, the relationship between energy production and revenue for different systems will continue to change to the benefit of VBPV systems [12].

Even though factors such as system type, panel spacing or crop albedo impact the energy production, and therefore also revenue, the single most significant factor is the spot price of electricity. Fig. 5 presents a comparison of how row spacing and albedo affect the revenue of a system in 2019. In contrast, Fig. 6 depicts how the revenue of a single system with rows separated by 10 m and spring barley albedo changes between 2019 and 2023. Because of high energy prices in 2022, even at the lowest separation of 10 m revenue was roughly 3 times higher than of the next-best year. The increase in revenue with increasing row separation is present, though even that difference only becomes significant for the year 2022 when the energy crisis caused high spot prices. Fig. 7 shows revenue for years 2019–2023 using average spot price data for years 2019–2021 prior to the energy crisis. The revenue in this case closely follows the energy output.

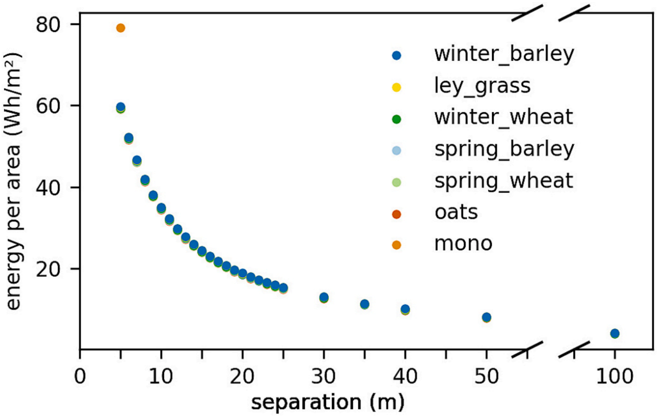

Fig. 4. Energy output per area of land (m^2) at nominal power of 375 (bifacial) / 295 (monofacial, same as front side of VBPV) W for different crops depending on the solar panel row separation and number of panels per area; the differences between studied crops are minimal.

3.3. South-facing reference system

Dedicated south facing systems are currently the default PV system design. This section discusses a reference system showcasing the differences between an APV systems using VBPV and conventionally mounted south facing panels.

As shown previously in Fig. 3, the energy produced by the panels reach approximately 90 % of the comparison at a separation of only 11–14 m between the rows. With 20 m separation required to accommodate large farming equipment, 93–95 % of reference production and only 8–9 % crop irradiance loss can be reached. It is difficult to increase the efficiency of the production significantly beyond that: to achieve the same energy output per panel as the reference, it would require increasing row separation to 33–50 m. APV systems have the highest performance at very large row separations that are sufficient to consider them free standing single row installations. Due to cable losses and land required, this high separation is impractical for multi row systems, but the benefits of large separation can also be utilized by single-row installations making them the most efficient choice in situations when only a small energy output is needed (e.g. self-consumption on site).

One way to demonstrate the advantage of VBPV in dual land use

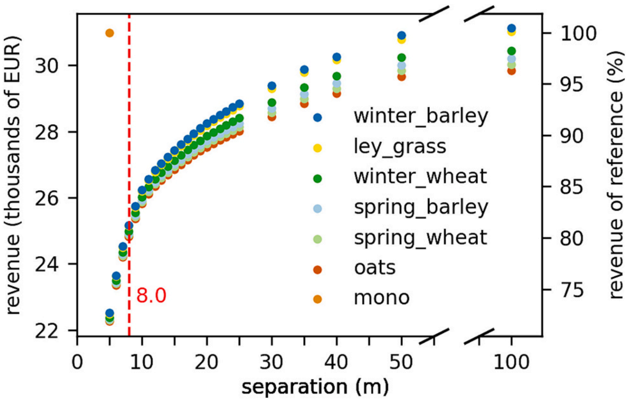

Fig. 5. Total system revenue for different crops depending on the solar panel row separation. Red line represents 25 % reduction in crop irradiation at ground level at 8 m row separation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

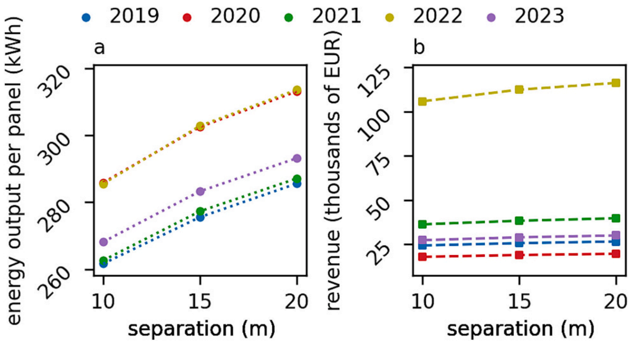

Fig. 6. Energy produced and system revenue for 10, 15 and 20 m row separation VBPV using spring barley albedo in Finland 2019–2023; revenue in 2022 is significantly higher than typical due to energy crisis. Simulations made using satellite data.

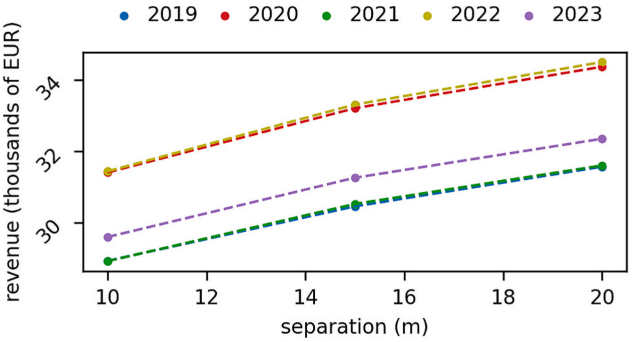

Fig. 7. System revenue for 10, 15 and 20 m row separation VBPV using spring barley albedo in Finland 2019–2023; revenue has been normalized using average spot-prices for years 2019–2021, before the energy crisis. Simulations made using satellite data.

scenarios, is to assume that a certain fraction of available land can be dedicated to the PV installation and compare different system types. To that end, a comparison was made where the APV systems both cover 10 % of the available land leaving 90 % available for crops. Fig. 8 depicts a representation of three systems in which the agrivoltaic installation, together with a necessary empty space buffer, takes 10 % of available land. In case of a VBPV system, 10 % land coverage is achieved at a 10 m separation, assuming that the row spacing is maximized to increase VBPV effectiveness. The conventional south facing installation would require row spacing of 27 m to achieve 10 % coverage, due to the width of the strip of land covered by the panels themselves, alternatively closer situated rows could be utilized on only a part of the available land. Here, it was assumed that in all systems the available area is covered evenly. Because VBPV take up very little space themselves, and only require a small buffer between them and productive land, the number of panels that can be fit in such a system covering only 10 % of available space, is higher. While the fraction of the land dedicated to a PV system is not the only factor affecting the choice of the system design, in situations when VBPV is a valid option, it can offer a significant advantage in the form of a minimal use of land.

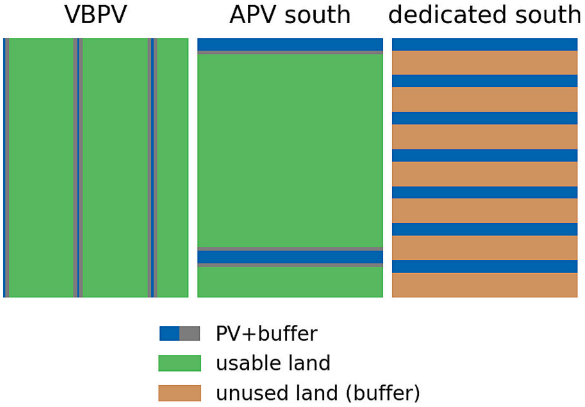

Fig. 8. Visual representation of distribution of land use in case of VBPV and south facing agrivoltaic for 10 % total land coverage with a dedicated south facing installation for comparison. VBPV occupies very little space, south-facing PV occupies more space because of their orientation, the dedicated system requires a larger patch of unused land between rows.

Table 5 shows a comparison of three PV systems with a total land area of 15,840–15,760 m^2. Two of those systems are APV cases; a VBPV and a south facing installation, and the third is a dedicated south facing system. At 10 % land reduction, assuming 0.5 m land around solar panels that must remain unutilized, the VBPV installation covers 1584 m^2 containing 1980 individual panels. For comparison, if south facing panels angled at 30° were to be placed as rows between agricultural land, it would allow for 620 individual panels. A dedicated installation covering the whole area contains 4640 panels. VBPV installation produced 37 % energy of the dedicated system while covering only 10 % of the total area, leaving 90 % of the area available for farming, while in case of a dedicated installation there is none. In the case of agriculturally active systems, the land between rows is not counted towards the total area occupied by the installation, as only a small additional strip of land around panels is lost. In a similar comparison, at row distance of 9 m at a lower latitude, Willockx et al. report a 40 % energy yield [47], while Campana et al. at a similar latitude report a yield of 44 % compared to the reference system [22].

The disparity between the number of panels is caused by agrivoltaic installations requiring less dedicated space between panels to prevent self-shading and allow access to the installation, as the land can serve other purposes. A dedicated PV system requires more unproductive spacing between rows, in an APV system this space is instead ensured through the use of productive land. In all cases longer rows result in a more efficient use of land, as each new row requires additional empty space. This affects conventionally mounted dedicated PV installations more than APV installations, as the land between rows is unused and thus the width of unused land is necessarily larger. VBPV benefit directly from increased albedo and diffuse irradiance as the row separation increases, but their direct land use is minimal.

3.4. Row separation effect on irradiation available to crops

The agricultural land in Finland and many other countries is being consolidated, with the number of farms decreasing but the total agricultural area remaining similar and the average size increasing, the average being 56 ha in 2024 [97]. As PV installations take up space and require a buffer from agricultural vehicles, the installation reduces the

Table 5
Parameters for 10 m separated VBPV, conventionally mounted panels between farmland and dedicated conventional PV at 30° inclination. Simulations made using measured 2019 weather data.

Parameter	VBPV agrivoltaic (spring barley)	South-facing agrivoltaic	Dedicated south facing
Area required total (m^2)	15,844	15,760	15,804
Area taken by PV + buffer (m^2)	68 + 1516	1061 + 515	5488 + 10,316
Area available (m^2)	14,256	14,184	0
Number of panels	1980	620	4640
System energy production (kWh)	548	201	1468
Revenue (EUR)	25,934	9935	72,616
Agricultural yield	yes	yes	no

total area available for farming. The agriculturally usable land area reduction decreases sharply with increased row separation, and while increased row separation reduces solar energy produced per unit of area, as shown in Fig. 9, the power per panel is increased.

The change of irradiation reaching crops at ground level (0.05 m) and directly below solar panels (1 m) during growing season is depicted in Fig. 9 a. Land reduction based on row separation is depicted in Fig. 9 b. While agrivoltaics allow for production of both crops and energy, potentially creating a supplementary source of income for farmers, the energy output per area used is significantly decreased compared to a dedicated system. This is because the number of panels in a given area is decreased to leave space for dual land use, which means that fewer or more sparsely placed solar panels have lessened effect on the farmland (Fig. 9 b and Fig. 9 c). At low row separation the number of panels per m^2 is high, however this results in higher shading of both the PV system and crops and leaves less land available to agriculture. Conversely, at higher row separation, the number of panels per m^2 is reduced, but this results in the land being nearly unaffected and higher PV panel performance. As shown in Table 5, the efficiency of land utilization is significantly increased in APV systems. Such dual use may be particularly effective if the location allows for an easy electricity connection or contains structures that can utilize the energy on the spot, such as greenhouses.

As crops grow, the shading effect from the solar panels decreases, which is more pronounced for smaller row separation. Here the minimal irradiation for crops at 0.05 m was considered as a reference and irradiation at a maximum level (in this case 1 m, assumed to be the lower edge of the solar panel) was also modelled. For the whole period, the loss compared with the reference (100 m separation, 1 m height) is 22.3–25.3 % for 8 m separation, 8.8–10.3 % for 18 m separation and 0.00–0.3 % for 100 m separation. Fig. 10. depicts daily photosynthetically active radiation (PAR) [98] reaching the crops during the growing season, although it is important to note that impact of shading on crops is more complex than a simple correlation with absolute irradiance values [92]. Fig. A.6 in supplementary information contains a detailed depiction of the daily irradiation reaching crops during growing season for row separations of 8, 18 and 100 m.

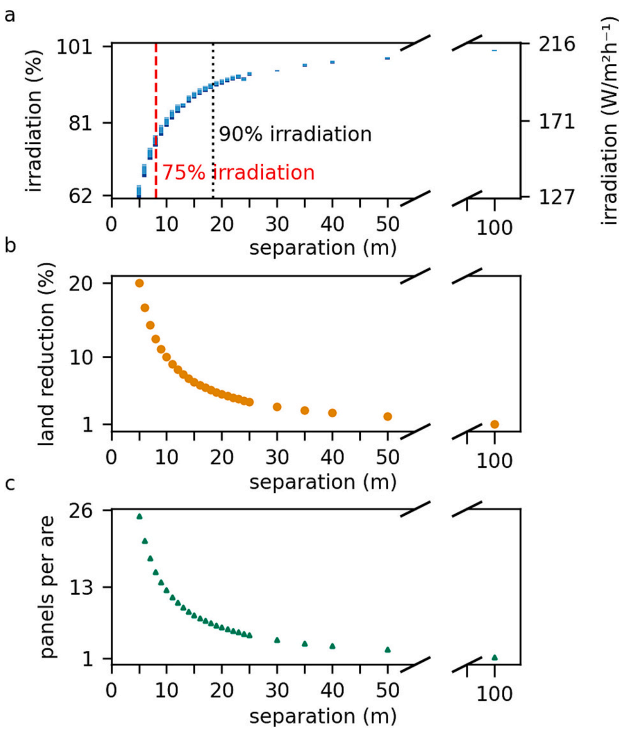

Fig. 9. Total irradiation range between 0.05 m height and 1 m height for 6–100 m separation (a), percent of arable land reduction for row separation of 6–100 m (b) and number of panels per m^2 (c).

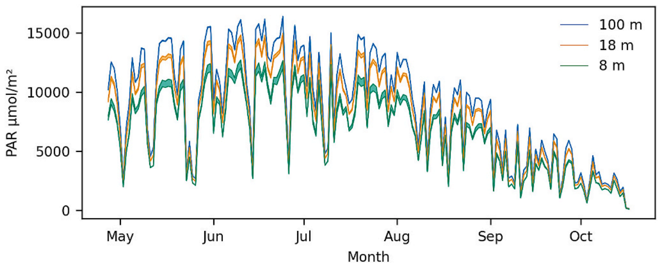

Fig. 10. PAR available between 1 m height and at ground level for 8, 18, 100 m row separation.

The effect VBPV installation has on crops grown around it depends on row spacing, as with increased row spacing more sunlight reaches the crops. At row separation distances above 8 m, crop irradiance loss was within the chosen threshold of 25 % irradiance reduction. Therefore, in high-latitude locations, VBPV with a row separation of at least 8 m should be feasible for dual land use applications. And indeed, a study focusing on optimization of a field in Sweden found that the system row distances of 8–10 m can result in LER above 1.2 [22].

3.5. *Shading direction effect on energy production*

The effect of shading on the panel's energy output depends heavily on its direction. That direction determines at what times of day or year a direct line of sight between the solar panels and the Sun allows for direct irradiance to reach PV panels, and affect the diffuse irradiance resulting from different albedo of crops and shading obstacles.

Example of the system with southern shading and a distance of 20 m between the trees and the panels can be found in the Fig. A.7 in supplementary information. The estimate shown in Fig. 11 shows expected energy output per panel based on the tallest obstacle in line of sight depending on direction. The height difference is the distance between the tallest shading point that is expected to continuously affect panels, and the lower edge of the solar panel. Distance from the obstacle is the horizontal distance between the solar panel and the shading object. Solar panels performed best, regardless of distance, when shading objects were directly on the northern side. A system shaded from north-east and north-west outperforms a system shaded from the south for short distances from the shading object. For example, for a tree line at 18 m height, the distance between the solar panels and the shading object below 13 m favors shading from north-east and north-west over shading from south.

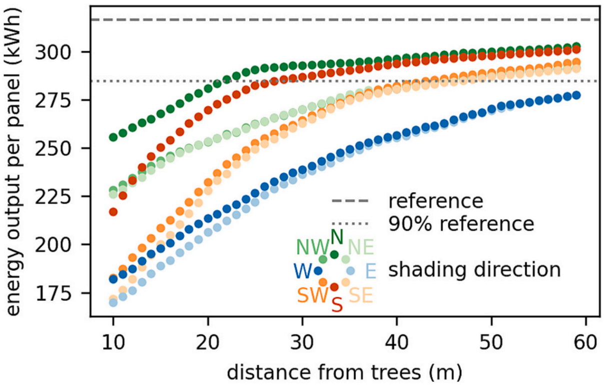

Fig. 11. Energy output per panel depending on distance from 18 m tall trees. Production increases with the distance from shading objects, southern shading has the most dramatic change due to typical solar elevation angles when the sun is in the south.

For longer distances, the effect of shading on the energy output decreases, and the output of the panels shaded from south are close to those shaded from the north. South-western and south-eastern shading has poor performance when the rows are closely situated but the performance increases significantly for very large distances between the shading object and solar panels. Direct eastern and western shading results in poor performance. As the panels face east and west, it severely limits light availability to one side, this can cut performance nearly in half depending on how close the shading object is. This effect can be lessened depending on the connection type and size of the installation, which was not a part of this study and thus was not compared.

One of the most common shading obstacles surrounding agricultural areas are trees. As trees mature, their height increases which affects solar panels mainly through direct shading and to a lesser degree through changing albedo of the surroundings. In case of VBPV, the effect is pronounced for obstacles located to the east and west of the panels. A detailed representation of the power production per panel depending on the shading object height ranging 6–23 m, direction and distance from the shading object ranging 10–40 m for cardinal directions has been shown in Fig. 12. Shading from north has nearly no effect on the PV energy output, and shading from the south affects it only when the panels are very close to the source of the shading as the sun in the south is typically high above the horizon causing very short shadows. In contrast, shading from east and west causes significant losses. This is especially pronounced for the VBPV panels as they produce energy when the sun is in the east and west, making them sensitive to obstacles much further away than obstacles to the south of the installation, which cast shadows when the sun elevation angle is typically high [99]. While the low sun elevation angle and the resulting shading affects all systems more compared to lower latitudes, south oriented panels are significantly less sensitive to shading from eastern and western directions primarily due to the power production times characteristic for south-facing installations. The intercardinal directions can be viewed in the supplementary information Fig. A.8.

An increase in distance allows more reflected and diffuse light to reach solar panels which increases PV power output and, in case of high-albedo surroundings, increases gains. Because of both the production profile having peaks in the morning and evening and surrounding albedo effects, VBPV are impacted primarily by obstacles to the east and west, while being less impacted by shading from the south than a conventional installation.

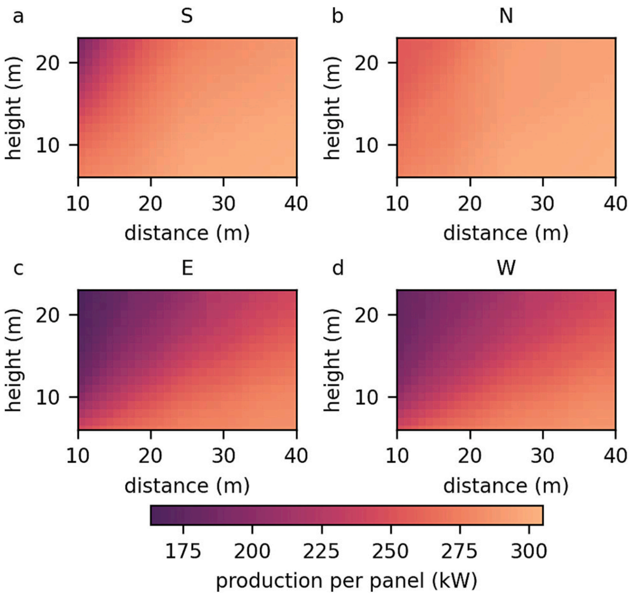

Fig. 12. Performance estimate for solar single row panels based on obstacle height and distance to panel, for shading from cardinal directions: south (a); north (b); east (c); west (d). For intercardinal directions see supplementary material.

4. Conclusions

This article showcases the benefits of a VBPV installation in a dual use of land system where electricity production and agricultural activity can be efficiently combined. The goal was to determine the impact of the surroundings typical for APV installations in Finland. The main conclusion is that APV is feasible in high latitude locations with row separation of as little as 8 m and can benefit from surrounding crops through increased albedo. When dedicating 10 % of available land to PV production using VBPV, the agricultural activity can freely continue on 90 % of the land. In case of a 1.6 ha field production of 548 kWh was achieved, resulting in nearly 26,000 EUR revenue from the PV system.

This study presents a novel insight on the impact of row spacing, shading and albedo on VBPV output in high latitude conditions, as well as the impact of electricity spot price on the revenue. To answer the research question of how much shading do the solar panels cause to the crops and themselves we determined performance thresholds. The separation between rows required to achieve 90 % of annual production of a reference system ranges from 11.3 to 13.7 m depending on the crop grown. Increasing row spacing has a significant impact on production, which increases quickly up to 10 m, though above 20 m the gains start to saturate. At a separation of 8 m, crops received a minimum of 75 % irradiation, which is expected to result in minimal impact on crops, compared with an unshaded scenario. The crop choice was found to positively effect VBPV system energy gain by creating an area of higher albedo. The agrivoltaic farm growing winter barley was characterized by the highest energy output, while the farm growing oats produced the lowest output. However, the maximum difference was only 4 % which indicates that even with low-albedo crops APV performance is minimally affected. In contrast, shading caused major differences: the largest losses occurred when obstacles were present in the directions the installation is facing, and for VBPV, this is typically east and west. This necessitates large distances from east and west side shading — even up to 50 m for tall trees. The impact of shading cast from the south is significantly reduced when the distance from the PV installation increases, making south shaded locations potentially viable for VBPV, provided some distance is maintained.

The revenue generated by a PV installation depends primarily on the spot price of electricity. PV power production in 2022 and 2020 was comparable, yet the revenue was roughly 5 times higher during the energy crisis in 2022 as compared to 2020 (the lowest revenue year). Thus, evaluating the profitability of an APV system requires evaluating of market trends and energy production times. The price of energy is affected by energy production time, determined by the panel orientation. In case of VBPV, it is expected that the value of produced electricity will remain higher than that of south-facing systems as the share of PV in the energy mix increases. This is because both energy prices and VBPV production have two peaks — in the morning and evening. Additionally, prioritizing self-consumption can be the most viable option as self-consumed energy has a higher value than energy sold to the grid, due to lack of additional costs. Critical aspects for farmers include how APV impacts subsidies, as currently clear regulations are lacking, and what is the impact on the system performance of designs necessitated by different farming practices (e.g. tractor mounted sprayers). This computational work gives ground for testing real implementations as part of future works which could allow for verification of LER though crop yield measurements. Future simulation work could focus on comparing different system design strategies such as MPPT optimization algorithms suitable for VBPV systems. The key message of this work is that combining VBPV with agriculture can increase local resilience through increasing electricity production, using only a fraction of farmland, for energy production. It is imperative that policies are updated to allow efficient utilization of available resources.

CRediT authorship contribution statement

Magda Szarek: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Sami Jouttijärvi:** Writing – review & editing, Supervision, Conceptualization. **Lauri Karttunen:** Writing – review & editing, Software. **Teemu Hynnä:** Writing – review & editing, Data curation. **Samuli Ranta:** Writing – review & editing, Resources. **Kati Miettunen:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2025.127022.

Data availability

The data is openly available through references included in text.

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