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Agrivoltaics in Norway: Microclimate Modelling and Grass Yields from the Highest Latitude Agrivoltaics System

Marisa Di Sabatino[1], Richard J. Randle-Boggis[2], Ronald Reagon Ravi Kumar[3], Harry Malhi[1], Gabriele Lobaccaro[1], Helge Bonesmo[4], Ashok Sharma[5], Steve Völler[1], and Gaute Stokkan[2]

[1] NTNU, Norway

[2] SINTEF, Norway

[3] Yinson Renewables, Norway

[4] NIBIO, Trondheim, Norway

[5] Malaviya National Institute of Technology, India

*Correspondence: Marisa Di Sabatino, marisa.di.sabatino@ntnu.no

Abstract. Agrivoltaics, also known as solar sharing or agri-PV, represents a pioneering concept that seeks to optimise land use by combining agriculture with photovoltaics on the same land area. While research and development on this topic have increased significantly, few studies address the issue in the Continental Subarctic Climate zone. In this paper, we report on the modelling and installation of a 48 kWp agrivoltaic system at the Skjetlein High School in Trondheim (Norway, lat. 63.34), which is currently the highest latitude system in the World, and we present the initial results of the impacts of the system on Timothy grass biomass. This work takes the first steps towards realising agrivoltaic opportunities for a broad area of Norwegian agriculture.

Keywords: Agrivoltaics, Agri-PV, Land Use Sustainability, Nordic Conditions, Vertical Bifacial PV

1. Introduction

Photovoltaic (PV) systems installation is estimated to have grown between 350 and 400 GWp in 2023 [1]. To reach net zero global energy-related carbon dioxide emissions by 2050, it is estimated that electricity generation from renewable energy sources (RES) must in- crease 25% by 2030 [2], and it is predicted that PV installations will continue to grow expo- nentially, putting pressure on the surfaces and land availability for these installations. At the same time, growing populations requires more food production and thus farming capacity.

Agrivoltaic systems (AVS) combine agriculture - crops or livestock - below PV modules and/or in-between rows of PV modules. Ideally, AVS creates a symbiotic relationship with the landscape where both the solar panels and the crops benefit through synergistic interactions. For example, solar panels can protect crops from extreme weather events, such as hail, strong winds, heavy rains, high temperatures, and drought [3]. Besides heat protection, PV installations safeguard against extreme weather and damage from storms, while rainwater can be collected for irrigation [4]. Plants have also been shown to keep PV panels cooler, improving generation efficiency [5]. The global installed capacity of AVS has grown from 5 MW in 2012 to 14 GW in 2022 [6]. The AVS market value was estimated to be USD 3.17 billion in 2021 and is predicted to grow to around USD 8.9 billion by 2030, creating a strong case for the research and implementation of this topic [7].

Agrivoltaics have been proven across Europe, for example in France [8], Germany [9] and Italy [10], but research in Norway is still limited. Whether the yield and the crop nutrients obtained are within acceptable limits or not is still unanswered in most publications, and the potential for AVS in Norwegian conditions is yet to be fully explored and exploited.

Introducing AVS requires farmers to adopt new practices, adding investment costs and learn- ing curves. Despite potential reductions in crop harvests due to shading, the electricity gener- ated can offset these losses by providing additional income or savings on energy bills. More R&D and policy support is needed to advance this field given its recent emergence and multi- disciplinarity, and national policies and support from the governments for PV and AVS differ significantly worldwide. While several countries such as Germany, France, the US and Japan have provided a definition of AVS, Norway lacks such a definition.

The Norwegian government has set a target to increase PV electricity generation to 8 TWh/year by 2030 [11], representing more than an eight-fold increase from 2024. While rooftop solar requires no land use change and should be a focal point, achieving such a target will require utility-scale ground-mounted solar. Two-thirds of the country is forestland or mountains, and flat land around populated areas is typically farmland – which currently, by law, cannot be repurposed for non-agricultural uses. Consequently, solar developers are turning to forests or heathlands for PV development, with potentially harmful impacts to local ecosystems due to habitat loss and fragmentation. AVS could mitigate this land use change and loss of habitat by facilitating the co-use of farmland for agriculture and PV, yet currently, the impacts of the technology on agricultural outputs are unknown here.

In this paper, we report on the modelling and installation of a 48 kWp AVS at the Skjetlein High School in Trondheim (Norway, lat. 63.34) before we present the initial results of the impacts of the system on Timothy grass biomass. The backbone of national agriculture is grasslands and livestock, where grassland covers 70% of Norwegian agricultural land, and thus our study takes the first steps towards realising AVS opportunities for a broad area of Norwegian agri- culture.

2. Selected literature studies

A selection of relevant keywords such as “agrivoltaics,” “agri-PV,” and “solar farming” was used across a range of academic search engines, e.g., Google Scholar and Science Direct to identify literature for the review in the research field of AVS. We reviewed 110 literature articles and found 67 crops studied under AVS, primarily in temperate and/or dry regions [12, 13]. Most systems are south-facing fixed-tilt, monofacial systems, and half of the studies involved raised stilted systems compared to conventional ground-mounted systems. Tomatoes were the most studied crop, followed by lettuce. These studies informed our AVS design, while also highlighting the gaps in research relevant to agrivoltaics in Norway.

3. Methods

3.1 Study location - Skjetlein High school

The installation of the 48 kWP system (Fig. 1) was completed at Skjetlein High School in Trondheim in June 2023. It comprises half-cell vertical bifacial silicon PV panels distributed in four rows long 32 m spaced 12 m apart. The panels have an East-West orientation and are elevated above ground by approximately 0.5 m. The module size is 1134 mm x 1724 mm. Before the installation, 17 modules were tested by electroluminescence (EL) to check the quality of the PV system. EL testing is a non-destructive method that can detect various types of defects, such as cracks, breaks, hot spots, and shunts, which can affect the module's performance and efficiency [14]. The imaging system comprises a charge-coupled device camera and a high-power LED light source, and a power supply for the panels. The camera is used to capture the EL images of the PV panels, and the LED light source provides the excitation for the EL process. The power supply is used to apply the voltage to the PV panel [14].

Figure 1. *The 48 kWp AVS at Skjetlein High School.*

3.2 Microclimate modelling

The initial studies focused on optimising the size of the system (e.g., number of modules, height of the modules from the ground, distance between panel rows). Radiation maps, which are integral to estimating the light energy available to crops, are generated using a plugin called ClimateStudio simulation program in Rhino3D software. These maps visually depict the annual total solar radiation on a specific surface. The ClimateStudio simulation program uses EnergyPlus and Radiance-based ray tracing algorithms to estimate the total, direct, or indirect (i.e., reflected) solar irradiation on a selected surface over a year. This estimation considers the shadows cast by nearby objects. The geometry of system was drawn in the Rhino3D software [15]. Initially the studied configurations consisted of two rows (20 m long and 10 m distance) with different orientations: East/West, 10° azimuth, 20° azimuth and North/South. Wind speed distribution within the AVS, which plays an important role in crop growth limiting evapotranspiration, was modelled using ENVI-met [16].

For the soil and leaf temperatures we use ENVI-met, a microclimate simulation software that models the complex interactions between the built environment and the natural environment. The software is based on a 3D model that integrates various physical and biological processes, including radiation, heat transfer, airflow, and vegetation growth.

Grass biomass studies

Timothy (*Phleum pratense L.*) grass for fodder has been grown on the plot since 2022 and harvested twice each summer. In August 2023 grass cuttings from 0.25 m^2 were collected every metre along three transects spanning each of the three plots between the panels. In May 2024, samples were taken every two metres along four transects in the middle plot only, due to prior disturbance to the edge plots. In each case, the sampling procedure was repeated in a control plot five metres south of the system. Samples were weighed and dried at 60°C for 24 hours to determine the dry biomass. Any effects of the AVS treatment on the biomass were tested for using a linear mixed-effects model comprising the treatment as the fixed variable and the blocks, transects and sample point as the random variables.

4. Results and Discussion

4.1 Optimisation studies

None of the 17 panels tested by EL showed any sign of cracks or defects (examples in Fig. 2). Different configurations give different solar irradiation distributions between the PV panel's rows (Fig. 3). The North/South appears to give the most inhomogeneity while East/West gives a more homogenous solar distribution along the entire area covered by the vertical PV panels. The conclusion of these preliminary studies was to have four rows (32 m long and 12 m dis- tance) of vertical bifacial PV panel East/West oriented.

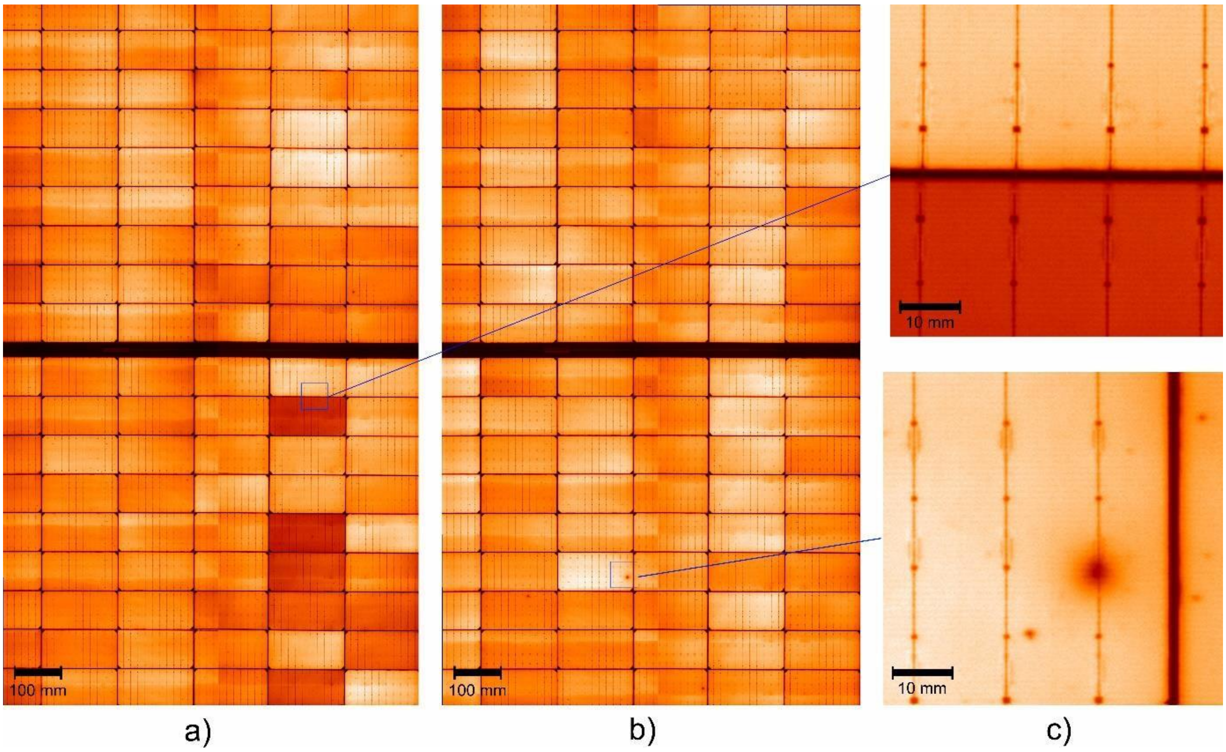


Figure 2. *Electroluminescence maps of two selected bifacial silicon PV modules (a) large in- tercell variations (b) homogeneous performance, c) magnified view, showing finger details and microscopic defects from production.*

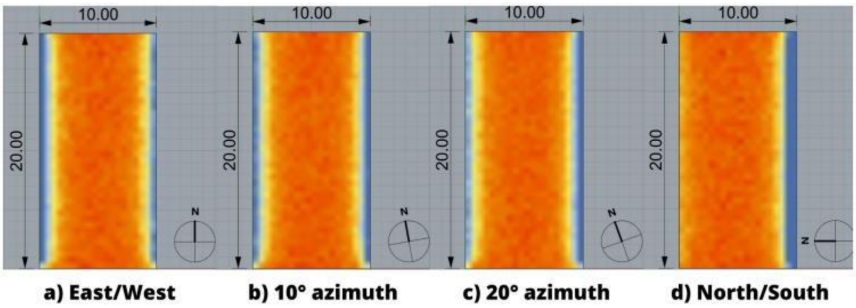
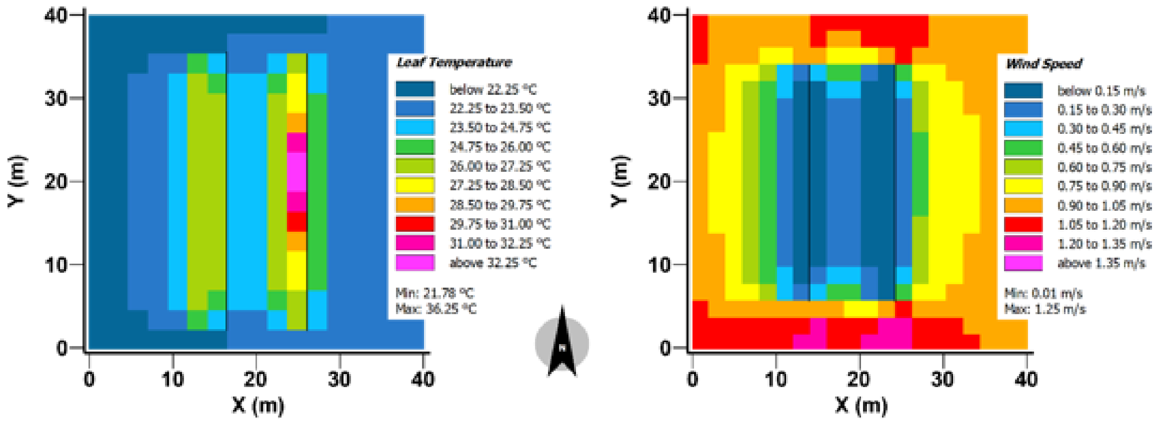


Figure 3. *Total solar irradiation between two rows of vertical bifacial AVS. Panels orientation is a) East/West, b) 10° azimuth, c) 20° azimuth, d) North/South. Panels are 1 m from the ground, Row Spacing = 10 m, Row length = 20 m. Blue: 600 Wh/m^2; Red: 1000 Wh/m^2.*

4.2 Microclimate simulation

Leaf temperature of the Timothy crop for the AVS scenario on June 21st at 11:00 by ENVI-met is higher closer to the panels (Fig. 4a). When comparing the data without AVS [16], the maxi- mum temperature for the leaves increases from 22.9 °C for the non-AVS scenario to 36.25 °C for the AVS scenario. A windspeed without AVS at 11:00 on June 21 was 0.92 - 0.95 m/s throughout the whole 40 m x 40 m area. The effect of the panels on the wind speed is clear, with significantly decreased speeds between the two rows of PV panels and a fairly symmet- rical distribution of wind speed (Fig. 4b). The PV panels act as a physical barrier that slows down the speed of the wind as it moves around the panels. This is akin to the windbreak affect that can be used in agricultural practices with the introduction of trees or shrubs and in turn modifies a nearby microclimate. Windbreaks are often used in agriculture to control erosion and improve plant survival in winter conditions [17]. Further, increased leaf temperature could improve plant growth. In this sense, the lower speed in between the rows of PV panels of the AVS can be a benefit.



(a) (b)

Figure 4*. (a) Leaf temperature and (b) Wind speed with AVS at Skjetlein High School for 11am on June 21st 2021.*

Soil temperature directly influences the availability of plant nutrients necessary for plant growth, and thus it becomes doubly relevant to measure [18]. There is a higher range in soil temperatures exhibited for the AVS scenario for the area between the PV panels when com- pared to that of the same area in the non-AVS scenario (Fig. 5). In fact, for the AVS scenario, both the minimum and maximum soil temperatures are located within the area between the two rows of PV panels. This highlights the spatial variation of the soil temperature, and the local effects caused by the PV panels of the AVS. Extracting the effect of the spatial variation of the soil temperature, this may result in non-uniform growth of the crop in between and around the PV panels.

As expected, the PV panels reduce the photosynthetic active radiation (PAR) available for the crops, which is likely to reduce plant growth, although increases in temperature could mitigate this. If the growth in general is water limited, due to windy conditions and soils with low water holding capacity, the PV panels can have a positive effect on the plant growth as evapotran- spiration is reduced. The achieved results from the simulations indicate that under Norwegian conditions, AVS can be beneficial for crop production in areas where the crop growth in general is water limited due to less drought resistant soil and windy and dry weather. However, these assumptions should be supported and confirmed by empirical field campaigns.

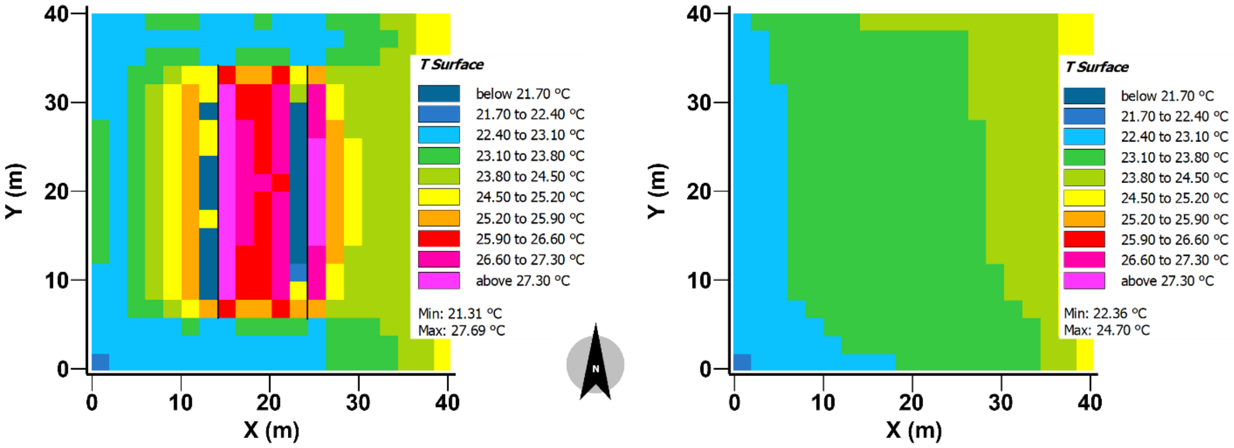


Figure 5. *Simulated soil temperatures at Skjetlein High School with AVS (left, rows of panels at x = 14 m and 24 m) versus soil temperatures without AVS (right) for 11:00 am on June 21st 2021.*

4.3 Grass biomass

The dry biomass of the grass was not significantly different between the agrivoltaics plot and the control plot in either of the growing seasons, and they were also comparable between the two growing seasons (Fig. 6). We also found no correlation between the biomass and the distance from the panels, further indicating a lack of significant influence of the PV panels on grass yields. These findings suggest that vertical bifacial PV agrivoltaics could be installed on grassland without negatively affecting agricultural outputs. They provide the first promising steps to understanding the opportunities for AVS to deliver low-carbon electricity and agricultural outputs concomitantly in Norway.

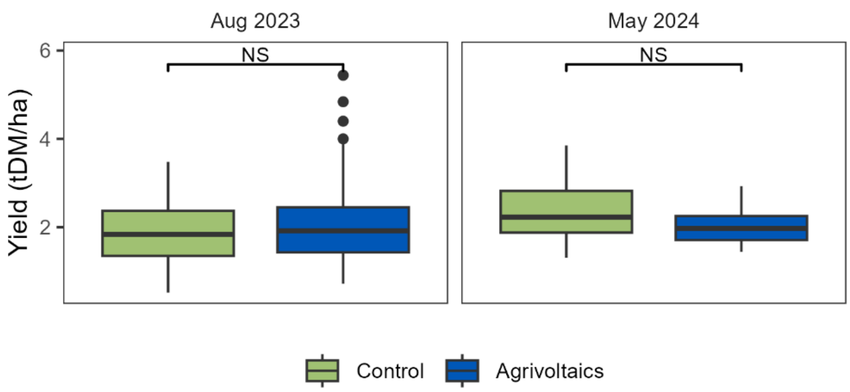


Figure 6. *The dry biomass yield of grass sampled between the plots in August 2023 (n = 54 per treatment) and May 2024 (n = 28 per treatment). Null hypotheses were tested using a linear mixed-effects model.*

5. Conclusions

The literature study indicates that most of the agrivoltaic studies are from northern hemisphere countries, and that research directly relevant to agrivoltaics in Norway is lacking. The reported research in AVS is focusing on matching the crop species with the PV system, electricity generation and structural design optimisation, and research in new technologies. Optimising PV systems that suit specific crops must be conducted for different locations with different environmental conditions, and design optimisation for particular group of crops relevant to each location, for example grasses and cereals in Norway, is necessary.

Simulations of solar irradiation aided to find optimal orientation of the PV system. Furthermore, simulations by ENVI-met show a significant spatial variation in microclimate between the PV panels. The preliminary results indicate that implementing vertical bifacial PV systems can have a positive effect on plant growth under windy and dry conditions. Thus, to fully demon- strate possible positive effects of AVS, further experimental research should be located in ar- eas where the crop growth in general is water limited due to less drought resistant soil and windy and dry weather.

The lack of significant effect on the solar panels on grass yields provides a promising first step towards understanding the potential for agrivoltaics in Norway, indicating land use compatibility between PV and agriculture. The results of this work can be used to compare with AVS at different latitudes, to show the benefits of an AVS also in artic climate regions.

Data availability statement

Data are available by request to the corresponding author.

Author contributions

MDS: conceptualisation, methodology, validation, writing-original draft, writing-review and editing, visualisation, supervision, project administration, funding acquisition, resources; RRB: conceptualisation, methodology, validation, writing-original draft, writing-review and editing, visualisation, data curation, formal analysis; RRRK: conceptualisation, methodology, validation, writing-original draft, writing-review and editing, visualisation, data curation, formal analysis; HM: conceptualisation, methodology, validation, writing-original draft, writing-review and editing, visualisation, data curation, formal analysis; GL: conceptualisation, methodology, validation, writing-original draft, writing-review and editing, visualisation, supervision, resources; HB: conceptualisation, methodology, validation, writing-original draft, writing-review and editing, visualisation, supervision, resources; AS: conceptualisation, methodology, validation, writing-original draft, writing-review and editing, visualisation, supervision; SV: conceptualisation, methodology, validation, writing-original draft, writing-review and editing, visualisation, supervision, project administration, funding acquisition, resources; GS: conceptualisation, methodology, validation, writing-original draft, writing-review and editing, visualisation, supervision, project administration, funding acquisition, resources.

Competing interests

The authors declare that they have no competing interests.

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