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Mika Suontlahti

Agrivoltaic Applications

– Research Review and Implementation Into Nordic Environment

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Agrivoltaic Applications

- Research Review and Implementation Into Nordic Environment

Agrivoltaics, the combined use of land for agriculture and solar energy production, has become a viable solution in producing renewable energy while protecting crops from increasing extreme weather events in Central and Southern Europe. Energiequelle Oy commissioned this bachelor's thesis in order to develop the subject further and research it's feasibility and functionality in the Nordics.

The goal of this thesis was to research the state-of-the-art of agrivoltaics and to review earlier done research in order to plan a research project site for the Nordic climate of Finland. Also, the goal was to simulate the research system using industry standard PV simulation software for a preliminary feasibility analysis focusing on the perspective of electricity production. Two research sites with different research objects and designs were planned and simulated.

Feasibility results reveal that different implementations of agrivoltaic systems have different benefits and advantages over the others. To add, when properly implemented, agrivoltaic systems increase the efficiency of arable land and the feasibility of agricultural practices. Agrivoltaics is a broad topic and further research on its effects on crops have to be conducted in order to draw conclusions on its functionality and feasibility in the Nordics.

Keywords:

Photovoltaics, agriculture, agrivoltaics, research design

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Maatalousaurinkosähkö Menetelmät

- Tutkimus Katsaus ja Toteutus Pohjoismaiseen Ympäristöön

Maatalousaurinkosähkö, millä tarkoitetaan yhdistettyä maankäyttöä maatalouden ja aurinkoenergian tuotantoon, on osoittautunut käyttökelpoiseksi ratkaisuksi Keski- ja Etelä-Euroopassa uusiutuvan energian tuottamiseen samalla kun se suojelee viljelykasveja lisääntyviltä äärisääilmiöiltä. Toimeksiantaja Energiequelle Oy tilasi tämän opinnäytetyön kehittääkseen aihetta ja tutkiakseen sen kannattavuutta ja toimivuutta Pohjoismaissa.

Tämän opinnäytetyön tavoitteena oli tutkia maatalousaurinkosähkön teknologian tasoa ja tarkastella aikaisempia tutkimuksia, Suomeen toteutettavissa olevaa tutkimushankkeen suunnittelua varten. Lisäksi, mallintaa tutkimusjärjestelmä käyttäen alalla yleisesti käytössä olevaa simulointi ohjelmaa ja simuloinnin tulosten perusteella arvioida alustavaa kannattavuutta sähköntuotannon kannalta. Työssä suunnitellaan ja simuloidaan kaksi erilaista maatalous-aurinkosähkö tutkimusjärjestelmää, joilla on erilaiset painopisteet tutkimukselle.

Työn tulokset osoittavat, että maatalousaurinkosähköjärjestelmien eri toteutuksissa on erilaisia etuja toisiinsa verrattuna. Oikein toteutettuina järjestelmät kasvattavat peltoalueen tehokkuutta ja samalla maatalouden kannattavuutta. Maatalousaurinkosähköjärjestelmät ovat laaja aihe, joiden vaikutuksista viljelykasveihin täytyy tehdä jatko tutkimuksia, jotta voidaan tehdä johtopäätöksiä toimivuudesta ja toteutettavuudesta pohjoismaissa.

Asiasanat:

Aurinkovoima, maatalous, maatalousaurinkosähkö, tutkimuksen suunnittelu

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List of abbreviations or symbols

APV	Agriphotovoltaics, agrivoltaics
CAPEX	Capital expenditures
kWp	Kilowatt peak
LCOE	Levelized Cost Of Electricity
LER	Land Equivalent Ratio
NPV	Net Present Value
MWp	Megawatt peak
OPEX	Operational expenditures
PAR	Photosynthetically Active Radiation
PPA	Power Purchase Agreement
PV module	Photovoltaic module
ROI	Return of Investment

1 Introduction

As the world transitions away from fossil fuels and towards renewable green energy sources it calls for new innovations in technology. Photovoltaics (PV) has shown to be one of the major technologies of the future energy production. Utility scale PV plants are frequent headlines in media alongside increasingly more common sight of PV modules on the rooftops of commercial and private owned buildings. This correlates to the installation pace of photovoltaic plants in the EU which has been increasing by a large margin for the past few years. In 2022 the capacity of new PV modules connected to electricity grids was 41.4 GW, this was a 47% increase compared to 2021 (SolarPower Europe n.d). Unfortunately, this rate of installation still is not enough for collective climate goals of becoming carbon neutral by the year 2050 (European Commission 2023).

There are many challenges when trying to acquire land solely for the sake of installing more PV panels. That is why we mostly see them on top of rooftops since it allows for more efficient use of space by sharing the purpose, for example office space and energy production. This is the advantage PV has when compared to other means of producing clean renewable energy. One of the relatively recently researched technologies is agriphotovoltaics (APV), which is the shared use of land for agriculture and solar energy production. APV systems have been in rapid development for the past ten years with various research and commercial projects already implemented in central and southern Europe and in other parts of the world. Developing this method further makes land acquisition easier for companies contructing PV projects and secures agricultural farms harvest and income by diversifying and helps them adapt to extreme weather events, which are becoming more common due to climate change.

The rapid development of APV technology can be seen in the installed capacity, which has increased from an estimated 5 MWp in 2012 to over 14 GWp in 2021 (Trommsdorff et al. 2022). The increase in APV total capacity installed around the world shows that these kinds of systems have commercial feasibility. In the EU research and commercial projects are mostly realized in Central or Southern

Europe but not in the Nordic countries which shows a need for research projects in the Nordic climates to accelerate APV production in northern latitudes.

This bachelor's thesis was commissioned by Energiequelle Oy to find solutions to increase the efficiency of PV plants by combining the land used for solar energy production specifically with agriculture. Also, to increase consistency of quality and security of agricultural yield from extreme weather events. This thesis acts as a preliminary study by collecting relevant information on agrivoltaic research projects across Europe and considers how to apply them in the northern climate of Finland. Energiequelle Oy is a renewable energy project developer and operational manager acting in Finland. It is part of a larger German organization Energiequelle GmbH. Energiequelle Oy has developed multiple wind farms in Finland and utility scale solar farms are a new area of focus among other innovative renewable energy solutions. For now, there is a clear lack of research into APV systems in Finland, which makes it difficult to estimate the feasibility of such projects, both from a farmers and PV project developers perspective. This thesis will provide a first step into finding relevant information on the subject and how they apply to northern latitudes in order to act as a guide when considering implementing agrivoltaics in real cases.

The subject of the thesis is narrowed down to reviewing and presenting the results of earlier conducted research projects and then consider what has been learned from them. Also, utilizing earlier research as a basis designs a research project that is viable to implement in Finland with proper research goals in mind and simulates said research project using industry standard software to evaluate their economic feasibility. The goals of this thesis are to offer a collection of different research and insight into their results, consider how they apply to northern climates and bring out the major challenges of implementing these projects in Finland and possible ways to overcome them. Furthermore offer preliminary propositions on how a research project studying APV should be conducted in Finland.

2 Agrivoltaic projects

Agrivoltaics combines solar energy production with agriculture by creating a shared space for solar energy production, crop cultivation, grazing and native habitants of the area, under and between the PV module rows. The idea of agrivoltaics originates back to Germany in the 1980s when Prof. Adolf Goetzberger developed the concept together with Dr. Armin Zastrow (Trommsdorff et al. 2022). The concept of agrivoltaics was not implemented in actual research projects until 2004 by Akira Nagashima who built the first agrivoltaic prototype in Japan and called the concept solar sharing. Having studied biology Nagashima learned that the rate of photosynthesis increases as the irradiance level is increased, up to a light saturation point from which further increase in irradiance level does not affect the crops growth rate. Using this as a basis for the concept of solar sharing Nagashima studied the effects of his prototype on cultivated crops using different shading intensities. (Nagashima & Takashi 2020).

Agrivoltaics have already been implemented in multiple locations around Europe and other parts of the globe. With the costs of PV modules and components decreasing in recent years, researchers have been innovating with new PV solutions accelerating the development of agrivoltaics systems. Some projects conducted are solely for research purposes while others have already been constructed with commercial goals. This chapter reviews some of these projects with a goal of finding relative information on the state-of-the-art of APV systems, their challenges and opportunities and what systems are most suitable to be implemented into Nordic environment of Finland.

2.1 Heggelbach, Germany

APV-RESOLA, Agrivoltaics: contribution to resource-efficient land use is a German Federal Ministry of Education and Research funded project which investigates the economic, technical, social and environmental aspects of agrivoltaic technology in real-world conditions, with the aim of demonstrating its basic feasibility. The project is conducted with 8 different partners, and it resulted in a pilot project at Heggelbach farm near Lake Constance in Germany. (Trommsdorff et al. 2022.)

The APV system installed was implemented as an overhead system. This means that the solar PV modules were installed 5 meters high over the field using specifically designed substructures illustrated in figure 1 below. This allows the farmers to use large machinery such as a combine harvester with only minor restrictions. The system takes up 0.3 ha of land and the PV modules used were 270 Wp Bi-facial double-glass modules by SolarWorld. The system was built with a fixed mount facing south-west with a tilt angle of 20°. The system has a total of 194.4 kWp with an approximate yearly production of 256 000 kWh in 2020 (Trommsdorff et al. 2022.)

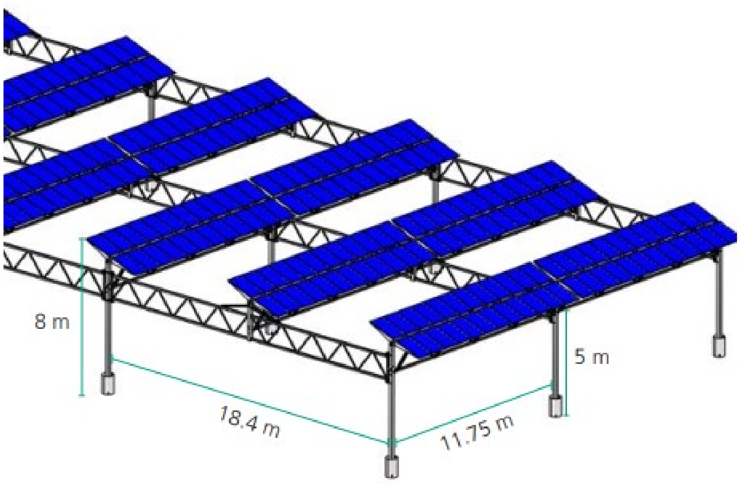

Figure 1. Illustration of the agrivoltaic system in Heggelbach (Trommsdorff et al. 2022).

The module row width in this system is 3.4 meters and the spacing between the PV module rows is 6.3 meters which is larger than the typical ground mounted system to let enough sunlight through for the crops below. The planted test crops consisted of potatoes, winter wheat, celery and clover grass. The researchers on the project collected data on crop development, yield, harvest quality and microclimatic conditions, both under the agrivoltaic system and on a reference plot near the system, project layout illustrated in figure 2. (Trommsdorff et al. 2022.)

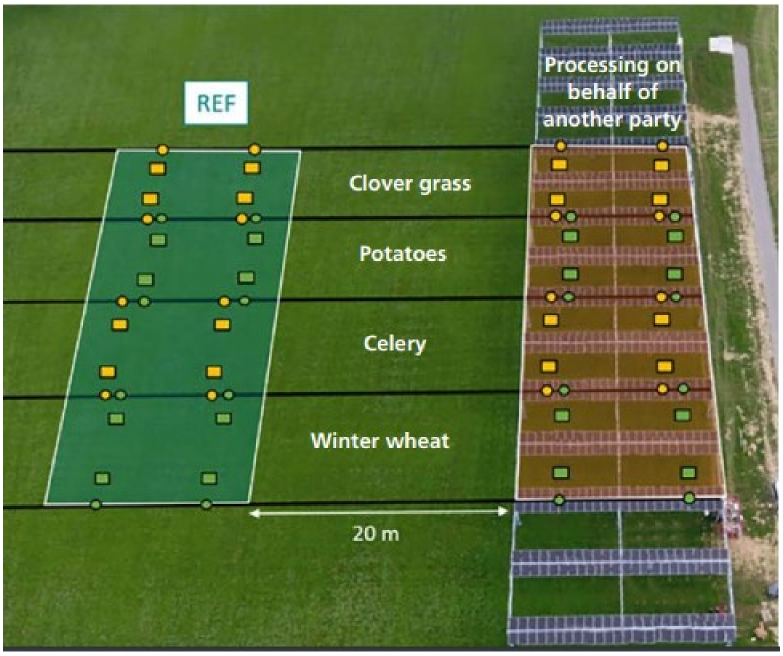

Figure 2. Field plan for the 2017 research site (Trommsdorff et al. 2022).

The most significant result that shows the practical viability of agrivoltaics is the increase in land equivalent ratio (LER) up to 160 percent during the first year of the project, Illustrated in figure 3 below. The yield of crops compared to reference areas without PV modules remained over 80 percent mark, which is a critical number considering commercial viability. Electricity generation from the agrivoltaic system per kWp in the first 12 months was a third more than the average for Germany. Reasons for this were relatively high solar radiation in the region and additional yields from the bifacial PV modules. (Trommsdorff et al. 2022.)

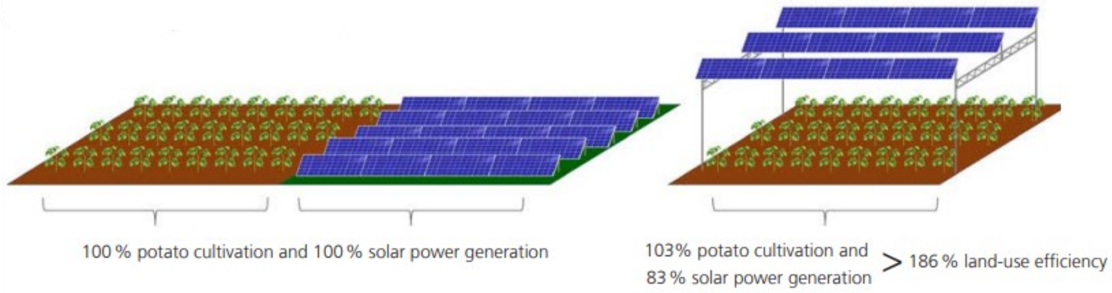

Figure 3. Illustration on land-use efficiency on the Heggelbach test site (Trommsdorff et al. 2022).

Yields of the second year significantly exceeded the previous results. During summer heat waves of 2018 the partial shade under the PV modules increasing crop yields combined with high levels of solar radiation increasing electricity generation the project saw improvement of 86 percent in LER in parts where the potato crops were being tested. The researchers believe that the crops were able to compensate for the summer's lack of rain because of the additional shading provided by the PV modules. (Trommsdorff et al. 2022.)

Data revealed that photosynthetically active solar radiation (PAR) under the agrivoltaic system was around 30 percent lower than on the reference plot. Other effects from the agrivoltaic systems were primarily on the soil temperature and distribution of precipitation. (Trommsdorff et al. 2022.) Mean temperature of the soil under the APV system was on average 1.2 °C lower in 2017 and 1.4 °C lower in 2018 on almost every day throughout the whole summer from early March until mid-October in 2017 and 2018 the daily mean temperature was lower by around 1.1 °C on average. Also, the air humidity was higher during both years on several days, on average being 2 % higher on 60 days in 2017 and 44 days in 2018. The differences happened mainly in wintertime from October 2017 until April 2018. (Weselek et al. 2021.)

2.2 The Brouchy agricultural canopy, France

The Brouchy project is an innovative agrivoltaic canopy that was created to answer the critical dual need of the agricultural and energy sectors, create resilient solutions to adapt to climate change and to develop new renewable solar energy production capacities. The Brouchy canopy is the second agrivoltaic demonstration completed by TSE within a span of a year. TSE, formerly known as Thirdstep Energy is a leading solar energy producer in France, with expertise in photovoltaics and a leading position in APV systems. The project received 2.7 million euros in funding from the EU Innovation Fund, due to its low-carbon innovative technology. ''The EU innovation Fund is one of the world's largest funding programmes for the demonstration of innovative low-carbon technologies.'' The project aims to create a new versatile solution, that offers synergy between agriculture and renewable energy production and sets the stage for expansion in the growing agrivoltaics market. (European Commission 2023.)

The canopy is a 5-meter-high shade house structure held together by cables and poles with a width of 27 meters, system illustrated in figure 4 below. This makes it suitable for large field crops and allows the use of large machinery. The biggest challenge of this wide cable structure was technical structural strength. The system has integrated an innovative control of each row of PV panels, which limits the effects of wind vibrations, TSE also claims this system to be able to withstand windspeeds of up to 44 m/s. The system has 2.9 MWp power and the steel structure of the canopy is lighter than other solutions in the market. This is based on the use of cables to support PV module rows instead of steel beams. The system's dynamic shading capability offers crops shield from hot temperatures and reduces plants stress while generating solar power. The canopy also has an integrated irrigation system that helps reduce water consumption by up to 30 percent. (European Commission 2023.)

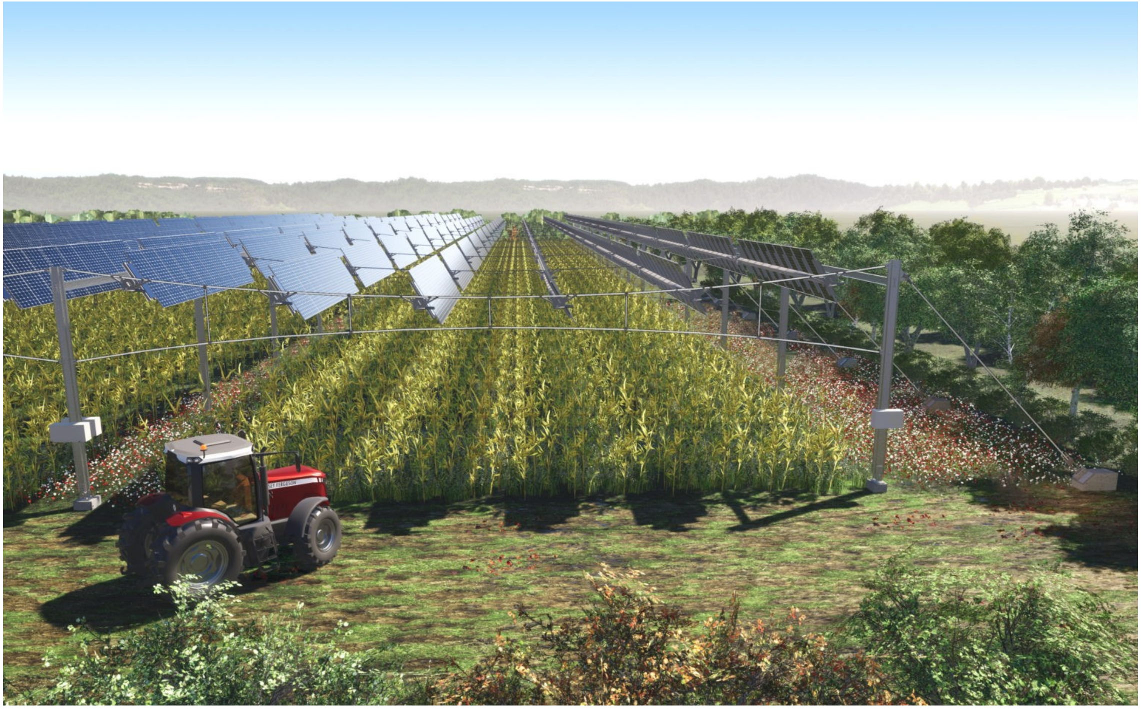

Figure 4. Illustration of the solar canopy by TSE (Deboutte 2022).

This system is adaptable to a large variety of plant species and can be changed to better suit the needs of the farmers field management. Thanks to the tiltable PV modules, controlled by an automated computer system using a large number of sensors, the system will automatically orient the PV modules according to weather forecasts. This way the system is able to meet the specific needs of the crops as well as optimize energy production. While the detailed results from this project are not available, it aims to avoid 6982 tons of CO2 equivalent of greenhouse gas emissions during the first 10 years of operation. Other objectives of this project are to quantify and analyze the improved plant yield and quality of food as well as the decreased need for irrigation. The project also has direct economic benefits to farmers through improved profitability and additional revenue. (European Commission 2022.)

2.3 Montpellier agrivoltaic study, France

A research project conducted at an experimental agrivoltaic site near Montpellier France, with the aim of assessing the effect on crop yield of two different densities of PV modules installed 4 meters above ground. As shown in figure 5, the array of PV modules was mounted using wood as the main construction material, which makes this experiment have unique structural material compared to other studies. Research on the emissions effect of the wooden substructure are not published. Half of the agrivoltaic system was installed with module row spacing of 1.6 meters or full density and the other half had 3.2 meters or half density between each row. Two other control plots were set up 10 meters apart from the system on the eastern and western sides, to be far enough not to be shaded by the system but close enough to be on similar soil. This experiment focused on lettuce cultivation. (Marrou et al. 2013.)

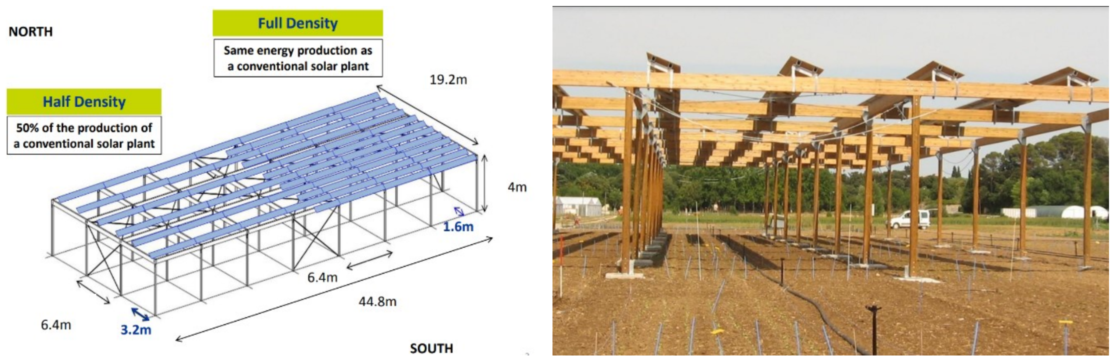

Figure 5. On the left technical dimensions, and on the right a picture of the agrivoltaic system under study in Montpellier (Marrou et al. 2012).

The project simulated the amount of radiation available to the plants using a ray-tracing algorithm on a 3D scene. The scene represented the PV module strips with the same size and orientation as used in the experiment, but the supporting structure was not taken into account by the model. The results for the available radiation at plant level during the cropping season averaged 53 percent in full density simulations and in half density simulations it varied from 68% in summer 2010 to 72% in spring 2011. (Marrou et al. 2013.)

Results for the yield in 2010 showed that full density shading from the PV modules reduced all lettuce varieties down to 58% of the reference control plot. Half density shading from the PV modules reduced the yield only to 81% of the control yield. Results also revealed large differences between different years. In 2011 yield reductions averaged 79% for full density shading and 99% for half density shading. This shows that the crops under half density shading were hardly impacted at all. (Marrou et al. 2013.)

2.4 Interspace agrivoltaics, Belgium and Sweden

There are mainly two different types of interspace APV. Fixed modules and dynamic single-axis tracking modules. Fixed mounts are usually more affordable but offer less electricity generation and customization. In Grembergen, Belgium a study comparing the two mentioned systems was conducted. Three rows of vertically mounted fixed PV modules were installed and other three rows of dynamic single-axis tracking systems, shown in figure 6. The study considered various performance indicators such as crop yield, quality, energy yield, cost, and spatial efficiency. The research involved theoretical modeling as well as field measurements gathered during two growing seasons in 2021 and 2022. The cultivated crop in this research was sugar beet. (Willockx et al. 2023.)

In Sweden a similar APV research was conducted with an aim of highlighting advantages and disadvantages of APV systems at northern latitudes. The research was conducted by building an APV system in Sweden and monitoring its performance from an energy and agricultural standpoint and developing new techno-economic models. Data from the APV system was used to better understand the effects of northern latitudes on the efficiency of the solar modules, crop productivity and the financial return for ground mounted PV systems. (Campana et al. 2023.)

Figure 6. The setup used in the research in Grembergen, Belgium (Kahana 2023).

At the research site in Belgium the distance of 9 meters between rows of PV modules was selected to allow the use of required farming machinery. The modules were also left with 0.5 meters of spare space on each side. The height of the system was limited to 2.6 meters due to it being near a residential area to minimize visual impact. The size of the system was also limited by the local electrical grid capacity. This way the project avoided excessive costs associated with grid reinforcement. Both the fixed and dynamic systems were installed using a pile drilling technique. The method is commonly used in ground-mounted PV system foundations due to its time efficiency and reversibility allowing for quick and easy removal without permanent soil damage. (Willockx et al. 2023.)

Electricity production results for the first year of operation revealed that the dynamic single-axis tracking system outperformed the fixed vertical system by an increase of 35% in monthly electricity production. The specific yield for the dynamic system was 1305 kWh/kWp, while the fixed system achieved a specific yield of 915 kWh/kWp. Comparing these systems to a typical ground mounted fixed system with the same bifacial PV modules and a tilt of 20° would have a specific yield of 1045 kWh/kWp. Comparing these systems using electricity yield per ha the agrivoltaic system would have only 450 kWp/ha compared to 1140 kWp/ha in a typical ground mounted system. The dynamic system has a 45% lower yield per ha and the vertical would have 60% lower compared to a typical south-facing installation. LER is a typically used term in agrivoltaics calculations, which expresses the spatial efficiency of the system. According to the study the vertical system in 2021 achieved a LER of 0.95 which indicates that no improvement in spatial efficiency was achieved. Dynamic tracking system achieved a LER of 1.15. The first year's results started from the end of July which affects the low LER numbers of this experiment. In 2022 the LER for both systems increased up to 1.21 for vertical and 1.47 for the dynamic tracking system. (Willockx et al. 2023.)

Due to the volatility of the energy market prices, a fixed power purchase agreement (PPA) between a large off-taker and the owner of the agrivoltaic site is recommended and used on economic evaluations in this study. The levelized cost of electricity (LCOE) is a value used to determine the financial feasibility of renewable energy projects, since it is a metric that calculates the per-unit cost of producing electricity over the entire lifetime of the project. The study achieved an LCOE of 100 €/MWh for the fixed vertical system and an LCOE of 73 €/MWh for the dynamic tracking system. Due to the small scale of both systems used in this research they achieved the same capital expenditures which affects the comparability of LCOE results. (Willockx; Lavaert & Cappelle 2023.) The LCOE of photovoltaics in 2021 ranges from 30 €/MWh to 110 €/MWh according to a study by Fraunhofer ISE (Kost 2021).

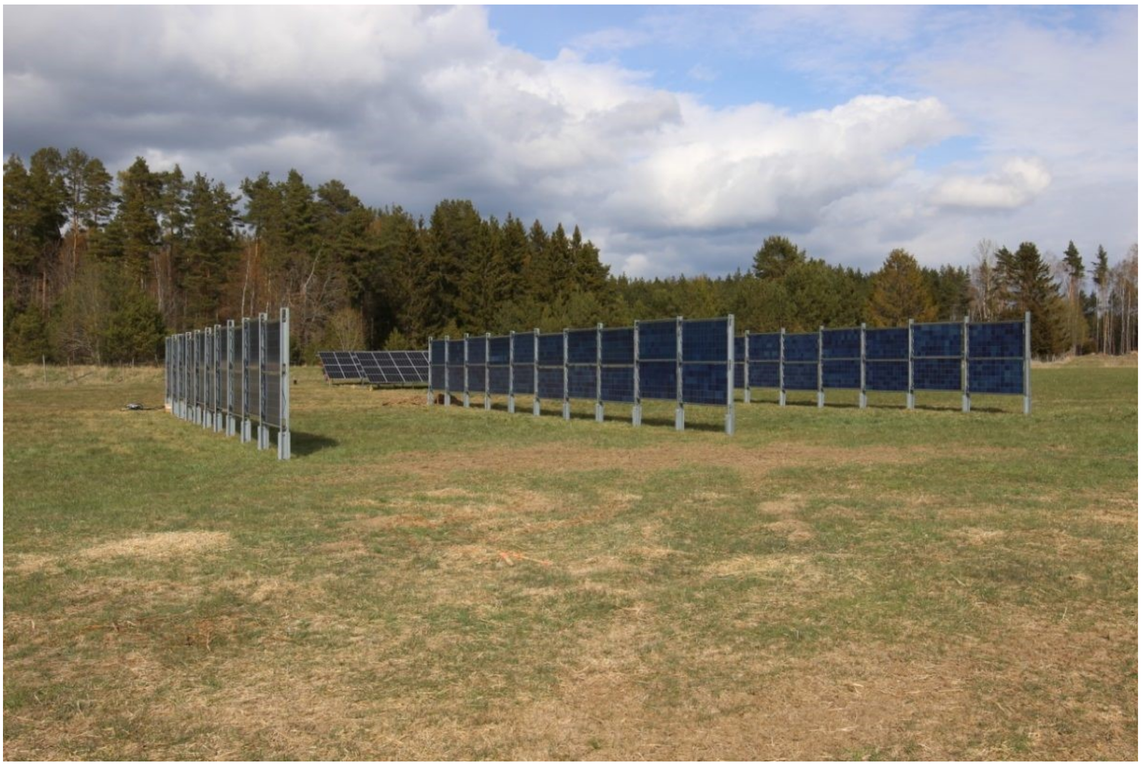

Figure 7. Agrivoltaic research site at Västerås, Sweden (Bellini 2021).

The Mälärdalen APV site was the first of its kind built in Sweden, the site is shown in figure 7 above. It was built on permanent ley grass field at Kärrbo Prästgård, Västerås and the research activities mentioned were conducted during 2021 and 2022. The researched areas on the site had three rows of vertical bifacial system with peak power of 22.8 kWp, two rows of PV modules with a fixed tilt of 30° and a peak power of 11.8 kWp and a reference area with no PV modules affecting the ley grass grown. Distance between the rows of vertical PV modules was 10 meters to allow the use of harvesting equipment such as tractors. The site had more than 20 sensors for weather, microclimate, power and agricultural parameters. (Campana et al. 2023.)

The research calculated specific electricity production for a typical meteorological year for the APV system and the reference ground mounted system. The APV system amounted to 1067 kWh/kWp/year and the ground mounted system 1116 kWh/kWp/year. Economic analysis of the research site analysed a situation where the farmer was leasing the land for a third-party company that owned and managed the APV system. Comparing the APV system to the reference ground mounted system, the APV system showed significantly lower Net Present Value (NPV). The main factors that caused this were the assumed lower electricity production and higher investment costs. The analysis compared two different crop rotations in mind, in which the APV system is combined with permanent lay grass and in the second it is combined with a conventional crop rotation. From the farmers perspective the combination of APV system with crop cultivation could lead to an increase in 30-year profit of about 30 times for the crop rotation to more than 600 times for permanent grass, when compared to the agricultural production with EU farmer support. From an agricultural perspective a vertically mounted APV system on permanent grass field does not affect productivity except for land loss due to the PV modules supporting structures, which is around 10% of the arable land. (Campana et al. 2023.)

2.5 Agrivoltaics in orcharding, France and Germany

There are many agrivoltaic projects conducted with different orchards. In Mallemort, France at the La Pugère experimental station an agrivoltaic experiment with apple tree orcharding was conducted. The experiment consisted of 3 different growing seasons between 2019-2021. The aim of the experiment was to evaluate the impact of fluctuating shading on water relations, leaf characteristics and yield determinants. (Juillion et al. 2022.) Other examples of agrivoltaics in orcharding can be found in Germany. APV-Obstbau is an experimental pilot project site in Gelsdorf by BayWa r.e and Fraunhofer Institute for Solar Energy Systems ISE. The system was first of its kind in Germany which started in 2020 and the project is ongoing until 2025. This project is investigating to what extent agrivoltaics can replace protective measures against extreme weather events in apple cultivation. It also considers which system design makes sense for apples and in which way the agrivoltaic system affects crop yields. (Fraunhofer ISE 2023.)

At La Pugère The orchard had seven rows with 4 meters between each row. Trees had 1.25 meters distance between each other within rows. Tree density for this experiment was 2000 trees/ha. Also, a white anti-hail net was installed above the whole orchard each year from May to October. This net reduced the incident radiation by 9 %. The agrivoltaic system was installed to the north part of the orchard in February 2019. The PV modules were installed at the height of 5 meters, which left 1.5 meters between the apple trees and the modules. The module width over the apple row is 1.7 meters, which covered 735 m^2 over the orchard. The rest 1482 m^2 of the orchard was left as a reference area and no PV modules were installed above, the system is illustrated in figure 8. The PV modules were installed with a tracking system and between February 2019 and July 2021 the modules rotated maximizing their solar radiation interception. The system was configured to minimize light interception after raining to allow the vegetation to dry quickly. In cases of possible frost, the system was placed into a horizontal position to stop heat from escaping the orchard. (Juillion et al. 2022.)

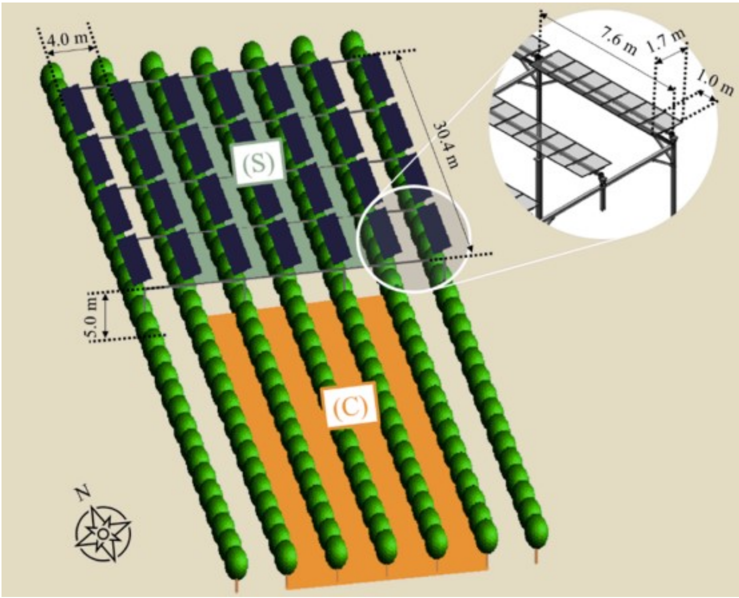

Figure 8. Agrivoltaic system at La Pugère experimental farm in Mallemort, France (Juillion et al. 2022).

From July 2021 the experiment adopted a new shading strategy. The plan was to provide shade to the trees only during the sunniest and warmest hours of the day. The system was configured to track the location of the sun unless incident radiation and air temperature were below 870 W/m^2 and 30 C°, respectively.

Under these conditions the module rows would turn so the amount of sunlight intercepted would be as low as possible. The tracking hours during the day decreased from 15 hours per day to 5.8 hours per day after adopting the new strategy. (Juillion et al. 2022.)

The experimental pilot site at Gelsdorf was specially designed to meet the practical requirements of commercial organic fruit farming with minimal restrictions on efficient farming. One reason for the specially designed modules was to not exceed shading below the modules by more than 30% which is based on a study on shading caused by hail nets. The agrivoltaic canopy in this case was also designed to replace traditionally used protective structures in fruit cultivation, such as hail protection nets and foil roofing. The project is also examining possible reductions in plant protection products. This agrivoltaic systems goal in fruit growing is not primarily to maximize crop production, but to increase the security and quality of the apple yields with additional solar power production. The experimental site at Gelsdorf is working with five experimental variants for the apple trees. Two of them are control variants, one of which has standard hail protection nets and the other has foil roofing. Three of the variants have agrivoltaic systems installed above, one has fixed system with PV cells spatially separated zebra design, another has a tracking agrivoltaic system with PV cell array block design and the last one has fixed agrivoltaic system with PV cell array in block design. The fixed mounted systems consist of 8 rows and 106 modules each and the tracking system has 3 rows with 100 modules each. This amounted to a combined capacity of 258.3 kWp. The special design of the PV system can be seen in figure 9 below. (Fraunhofer ISE 2023.)

Figure 9. The agrivoltaic site at Gelsdorf, Germany (Fraunhofer ISE 2023).

At the La Pugère experiment the shading caused by the agrivoltaic system did not impact the phenology of the apple trees over the whole three seasons of experimentation. Full bloom occurred on all occasions in early April within 3 days of each other on both the control plot and on the plot affected by the PV module shading. The harvest for each season also occurred on the same date for both reference areas during mid-September, which implies the fruits reaching physiological maturity at the same rate. (Juillion et al. 2022.)

Microclimatic conditions under the PV modules were acquired via simulations and measurements. The transmitted radiation under the agrivoltaic system was simulated using AVstudio model. Two sensors were placed within the tree canopy and connected to a datalogger for each modality around 2 meters above ground level, to get air temperature and relative humidity data. The measurements were logged every 30 seconds. The simulation results for transmitted radiation at 2 meters height under the PV modules indicated that the trees received between 4% and 88% of incident radiation over the PV modules with little variation on different days. The commonly used constant reduction of photosynthetically active radiation is between 15% and 30% but in this experiment the average daily shading was 42%. In the central row of the agrivoltaic system the mean shading intensity was on average 40-50% throughout the season. The temperatures and relative humidity did not see large impact during the night but during the day temperatures were cooler and relative humidity higher. Large seasonal variability was also noticed. The largest average daily differences for each season occurred during July. Temperature decreased under the agrivoltaic system on average by 1.2 C° and the relative humidity increased by +1.9%. (Juillion et al. 2022.)

The agrivoltaic systems impact on the yield considering all trees in each modality indicated a negative impact by reducing the yield during 2019 by 32% and 2020 by 27%. However, the yield from 2021 season saw an increase of 90% in the trees under the agrivoltaic system compared to the control plot. Although the yield amount was significantly lower compared to the earlier seasons being 10 t/ha for the control plot and 19t/ha for the shaded plot, compared to yield from 2020 being 51 t/ha for the control and 37 t/ha for the shaded plot. The agrivoltaic system also reduced the irrigation requirement each year by 31% in 2019, 6% in 2020 and 35% in 2021. (Juillion et al. 2022.)

The results for Gelsdorf pilot project are not yet available during the writing of this thesis but there are some findings and practical observations. During construction the soil was heavily compacted which required the soil to be loosened a second time before planting the apple trees. The modules edges are also offset by about a third between the rows of trees which results in rainwater falling exactly into one of the two lanes of an electric narrow-track tractor used in this farm. (Fraunhofer ISE 2023.)

The economical results for the project are also not yet available due to the research being incomplete but they have estimated operating costs to be around 16-18 €/kWp each year. The yield of the agrivoltaic system in the first year of operation was calculated to be around 276 MWh. The yield per kWp varies for each module and elevation from 1006 to 1199 kWh/kWp and the average resulted in 1068 kWh/kWp. (Fraunhofer ISE 2023.)

2.6 Agrivoltaics in herding

Agrivoltaics have been combined with grazing cattle and sheep in multiple locations. The idea is to provide shelter for the grazing animals and at the same time produce renewable energy and increase land use efficiency. At the University of Minnesota, a study evaluating solar photovoltaics systems to provide shading for cows in a pasture-based dairy herd was conducted. The system was installed in 2018 and it has a peak power of 30 kW. The PV modules were installed with a tilt of 35° facing south. Also, the system was lifted 2.4 meters to 3 meters high above ground so that the cattle cannot get on the PV modules, the system installed is shown in figure 10 below. The study was conducted in 2019 from June until September. The effect of the shade had been studied by comparing the behavior and effects on milking of the cows on a herd that was grazed on the pasture with the APV system and on a herd with access to no shading. The study had grazing periods of 7 days and 5 days that had around 30 days between them to allow the pasture to regrow. Weather data was also recorded during the study and used for the evaluation of the results. (Sharpe et al. 2021.)

Figure 10. Agrivoltaic system used in research by University of Minnesota (Sharpe et al. 2021).

Another study considering the life cycle analysis of integrated sheep agrivoltaic systems was conducted by Sustainable Futures Institute in Michigan Technological University. The study investigated agrivoltaics potential producing a combined output of electricity and agricultural goods and compared them to conventional methods for producing the same quantify of service in both categories. In this study an agrivoltaic system was designed around a model agricultural site of around 30 acres or around 12 ha, over a time period of 30 years. A 6.7 MWp agrivoltaic system was assumed by a guideline of 4.5 acres per MW density for the life cycle assessment. The study accounts for electricity generation mix in three different states in USA which makes the effects on greenhouse gas results of this study to be not as relevant in European countries, since the amount of fossil fuels and other methods used in electricity production are different in each country. The study uses the IPCC 100a global warming potential method to evaluate the effect of greenhouse gas emissions produced during the whole life cycle of the agrivoltaic system. The IPCC 100a measures the cumulative CO2-equivalent greenhouse effect of all climate-active gas emissions involved in the life cycle. (Handler 2022.)

A study comparing lamb growth and pasture production on an agrivoltaic site and a traditional open pasture over the course of two years was conducted by the Department of Animal and Rangeland Sciences and the Department of Biological and Ecological Engineering of Oregon State University. The experiment was carried out in spring 2019 and 2020 at the Oregon State University in Corvallis. The agrivoltaic system in this project was built on an area of 2.4 ha and it has a peak power of 1.4 MW, system shown in figure 11 below. PV modules used are 1.65 meters wide and installed oriented towards south with a tilt angle of 18°. The lowest edge of the PV module tables is 1.1 m above the ground. The soil on the experiment site is a combination of Woodburn silt loam, Amity silt loam and Bashaw silty clay. Three different replicate areas were assigned on the experiment site. The replicate areas were 0.2 ha blocks and they were fenced and compared to a 0.6 ha pasture paddock which was under the solar panels. Each plot was further divided into 0.1 ha subplots which where assigned to grazing in open pasture fields and grazing under the solar panels. (Andrew et al. 2021.)

Figure 11. Experimental agrivoltaic site studied by Oregon State University (Burns 2022).

The results from the study by University of Minnesota show that no harmful impacts on the dairy cows were noticed. The research used Boluses and an ear tag sensor to monitor internal body temperature, activity and rumination on all cows, respectively. The research also revealed no differences in many key factors such as fly prevalence, milk production, fat and protein production or drinking bouts between the researched shaded and no shade treatment groups. Minor effects noticed in the comparison between the groups show an increase in ear flick per 30 seconds in shaded cows, during afternoons the shaded cows had lower respiration rates and a slightly lower body temperature between 12:00-00:00. Assumption that agrivoltaic systems may reduce the heat stress of dairy cows and increase the wellbeing of cows along with increasing land use efficiency can be made. (Sharpe et al. 2021.)

Results from the life cycle assessment study showed that the most significant cause of greenhouse gas emissions is electricity production, being around 10-100 times higher than the meat production service that is provided in the scenarios studied. Also, the results show solar PV systems having 10 times less impact than conventional electricity production. This amount is based on the electricity production of the 6.7 MWp system during its whole estimated 30-year lifetime of 288 400 MWh. To produce the same amount of electricity from conventional sources referenced in this study, the overall emissions profile is around 9 times worse. When comparing agrivoltaic sheep grazing and conventional sheep grazing the emissions impact of agrivoltaic systems are around 25% better, which is mostly due to not cultivating corn and soybean feed with the agrivoltaic combination. Other benefits include the reduced need for mowing and herbicide applications with agrivoltaic systems, but they only amount to around 70 000 kg of CO_2 equivalent on the course of the whole lifecycle. (Handler 2022.)

Measurements for herbage dry matter production were studied during spring, summer and autumn under fully shaded, partial shade and no shade conditions. Over the entire course of the experiment, the agrivoltaic pastures produced 38% lower herbage than open pastures due to low pasture density of fully shaded areas under the PV module tables. But the results also indicated that lower herbage mass was offset by higher forage quality which resulted in similar spring lamb production to open pastures. Water consumption by the sheep for open and agrivoltaic pastures was similar in early spring of 2019 but during late spring the sheep in open pasture consumed more water than those grazed under agrivoltaic systems. (Andrew et al. 2021.)

2.7 Summary of reviewed research studies

In table 1 below a summary of all main results of the research reviewed in this thesis are listed. Overhead agrivoltaic studies show that keeping shading factor intensity below 30% allows the negative effects on crops to stay within acceptable limits of 80% of normal yield. Also, the results suggest that overhead systems are able to compensate abnormal weathers effects on yield, specifically during warm or dry periods. Overhead systems also benefit from tracking capabilities, being able to adjust the tilt of PV modules according to weather and the need of cultivated crops.

The results from interspace agrivoltaic research show that the systems positive and negative effects on crops is minimal compared to overhead systems. Most challenges with these systems come from the power per area being considerably lower than conventional PV plants and additional challenges to farming due to the PV modules being additional obstacles on the fields. Interspace APV offer the possibility for farmers to diversify their income by utilizing land lease payments for the installed system. Also, when compared to overhead APV the CAPEX is significantly lower which makes interspace APV more appealing for investors and PV developers. This could make acquiring land for solar power generation easier and more environmentally acceptable by sharing land already in commercial use for two purposes instead of replacing forests and fields completely.

APV research in orcharding proves that they are a viable alternative for hail nets in protecting the trees. PV modules have to be specifically designed to not decrease the amount of sunlight available under the modules too much. Research in APV grazing proves no negative effects on grazing animals and decreases the environmental impact of said practice.

Table 1. Summary of results from reviewed studies.

Research project	Effects on yield compared to a field without APV	Land Equivalent Ratio (LER) & Photosynthetically Active Radiation (PAR)	Electricity production and Levelized Cost of Electricity (LCOE)
Heggelbach, Germany. Overhead	The yield remained over 80%. During warm periods yield was higher under APV.	LER increased up to 160%. PAR reduction around 30% under APV.	1 316 kWh/kWp/yr
Montpellier, France. Overhead	2010 yields under full density 58% and half density 81%. 2011 yield 79% & 99%	PAR 53% of normal under full density and 68% under half density	Information not studied in this research.
Grembergen, Belgium. Interspace	Information not studied in this research.	LER of single-axis tracker 147%, Fixed vertical system 121%.	Single-axis tracking 1305 kWh/kWp/yr, fixed vertical system 915 kWh/kWp/yr, LCOE 73 €/MWh and 100 €/MWh
Västerås, Sweden. Interspace	Around 10% loss of arable land due to APV system.	Information not studied in this research.	Fixed vertical 1067 kWh/kWp/yr fixed tilted 1116 kWh/kWp/yr
La Pugère, France. Orcharding	The yield was 70% under APV, during abnormal year 90% higher than without APV.	PAR reduction of ~40%	Information not studied in this research.
Multiple locations, USA. Herding	38% lower herbage. Higher forage quality offset results.	Comparing APV sheep grazing and conventional sheep grazing the emissions impact of APV systems are around 25% better.	

3 Potential of arable land in Finland

The first part of implementation into northern latitudes is to figure out the potential of different crops for agrivoltaics in Finland. There is 2.3 million hectares of arable land in use in Finland, which divides into cereals, grasses, fallows and other crops, illustrated in figure 12 (The Finnish Cereal Commitee 2023). The land area is significant and with successful implementation of agrivoltaics, opens large potential for renewable energy production. Three main types of APV systems from the research done on previous studies are overhead systems, interspace systems and canopy systems for berries and orchards designed to replace protective hail nets which use specially designed PV modules with larger cell spacing to allow more light to pass through. Different crops work well with different APV systems. This chapter considers the potential of crops for each APV installation method.

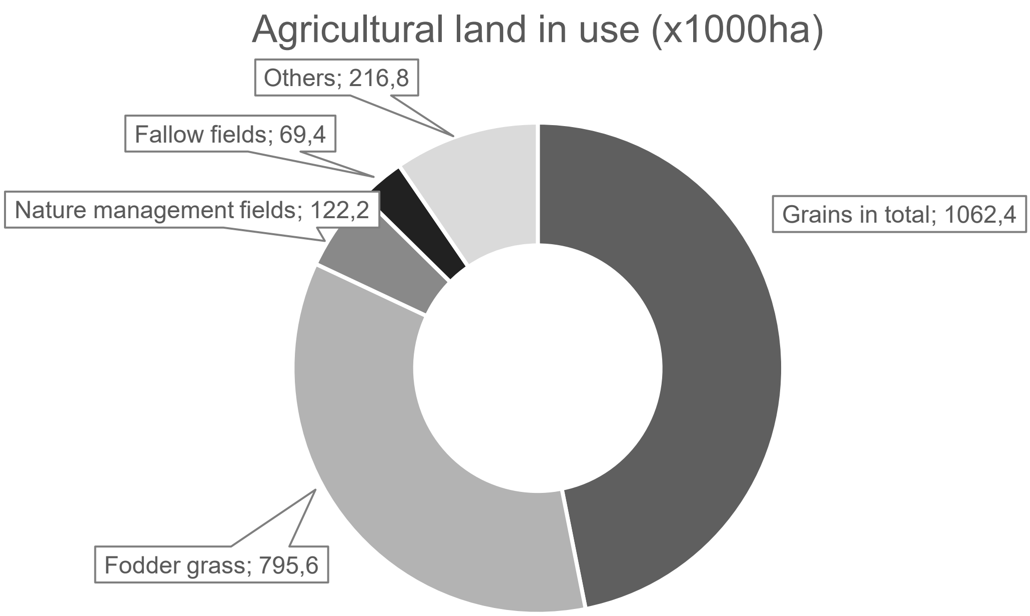

Figure 12. 2022 Agricultural land in use in Finland (Natural Resources Institute Finland 2022).

3.1 Crops for interspace agrivoltaics

Interspace agrivoltaics cause much less shading than other kinds of APV systems since they are not installed directly above the crops. When considering crops for these systems, shade tolerance does not have to be accounted for, at least on the same level as the other systems. Commonly used and researched crops with interspace agrivoltaics are grains and fodder grass (Campana et al. 2023; BayWa r.e. 2023). Fodder grass and grains amount to most of the arable land in Finland with 1 062 000 ha of grains and 795 600 ha of fodder. Permanently cultivated areas of fodder grass by national law of Finland require at least 5% of all arable land to be fodder and in 2018 it amounted to 175 000 ha which is 7.5% of all arable land in use (Finnish Food Authority 2023). In Finland cultivated grains consist mostly of rye, oats, barley and wheat, from which rye and wheat are mostly bread cereals and oats and barley are mostly feed grains which are used as nutrition for animals (Martat 2023). Most of the grains in Finland are cultivated in southern parts which furthers the large potential of APV systems installed to increase the efficiency of agricultural land. One of the reasons for this is the growth season of grain being around 180 days in southern Finland and around 105 days in northern Finland (The Finnish Cereal Committee 2014). Implementing interspace APV systems with grass fields could be a first area to start commercial projects considering the low effect on the crop production (Campana et al. 2023). Interspace APV systems affect grass fields mainly by lowering the area of the arable land by taking space away from the crops, according to earlier research a vertically installed or single-axis tracking APV system takes around 22% of the arable land (Willockx et al. 2023). Due to the electricity generation, land equivalent ratio still stays over 1.0 which means the efficiency is higher than conventionally.

3.2 Orchards and berries

The cultivated area of berries in Finland stayed over 7000 ha on the course of 2019 to 2021 according to natural resource center of Finland. Strawberries accounted for around 4500 ha of the total amount. (HML 2022.) From the total area of cultivated berries in Finland most are on open fields, but outdoor tunnel berry production has been increasing steadily in Finland. In 2021 the outdoor tunnel production area increased to 107 ha (Natural Resources Institute Finland 2022). The majority of the tunnel area was used for strawberry cultivation, 71 ha in 2022. The growing tunnels used are mostly made out of thin plastic and they are not built to last multiple growing seasons. By replacing the tunnels with permanent agrivoltaic systems the area could be utilized more efficiently and possibly further increase the amount of tunnel farming in Finland. In Netherlands an agrivoltaic system by BayWa r.e. is already in commercial use (BayWa r.e. 2023). The 2.7 MWp system is used to replace the traditional plastic tunnels and the system is done with traditional land lease agreement with the farmer. The investment cost amounted to around 1150 €/kWp which is higher than conventional ground-mounted systems of 500-800 €/kWp. The agrivoltaic systems would require the utilization of specifically designed glass-glass PV modules with larger cell spacing that let light through to the crops by just the right amount to optimize electricity production and crop cultivation or just focus on the other.

Orcharding in Finland is not very common due to the short growing season. Utilizing APV systems to offer optimal conditions throughout spring and fall might offer opportunities to increase the popularity and feasibility of orcharding by increasing the growing season and offering additional revenue from the APV system. The most cultivated fruit are apples, which is mostly cultivated in southwest Finland and Åland. In 2019 apples were cultivated on an area of 687 ha from which 201 ha was done in Åland (ProAgria 2020). Apple trees require a lot of warmth which is why it is mostly cultivated in southernmost parts of Finland. Also, sub-zero winters might damage the apple trees specifically if the ground is without snow (HML 2019). APV systems could be utilized to prevent these types of damage during winter.

3.3 Crops for overhead agrivoltaic canopies

Overhead agrivoltaic canopies could be utilized with almost any given crop. For example, research projects and commercial projects done in Europe have included potatoes, celery, winter wheat, lettuce, Vinyards and berries (Trommsdorff et al. 2022; Baywa r.e 2023). Overhead APV systems have the advantage of allowing modifications to the shading patterns and shading intensity which allows them to be optimized for use with most crops. Main challenges with these systems are the excessive substructures required and the large quantity of raw materials they consume. Another advantage these systems provide is the ability to protect crops from extreme weather events. Crops that are sensitive to being damaged by hail or heat waves are ideal crops to implement with overhead systems. These systems also work well in dry areas by lowering the need for precipitation and increasing soil moisture under the system (Weselek et al. 2021).

Common negative weather events in Finland include abnormally warm temperatures, rainy or abnormally cool summer or temperate and rainy winter. Warm and dry summers affect crops in the following ways. Late summers high air moisture along with short periods of warmth increase crop diseases and lessens the quality of the harvest. Garden plants like lettuce and some berries suffer from droughts by affecting the taste or size of the harvest. High temperatures also make it more difficult to time the harvest from lettuce as well as cauliflower or broccoli. Abnormally warm seasons also make some plants ripen more quickly which makes the growth season shorter. Rainy and cool summers are commonly cloudy which makes the growth of crops slower. This might cause some vegetable crops to have smaller yield than average. Some plants that are heavily dependent on warmth like cucumbers, melons and pumpkins provide weak yields. Temperate and rainy winters might cause the runoff of nutrients from fields. Rainy winter might also weaken perennial vegetables wintering since in the worst cases the roots can suffer from the lack of oxygen. (Natural Resources Institute Finland 2023.) Overhead systems might provide solutions to preventing the impacts of abnormal weather events as listed above.

4 Modeling of an agrivoltaic site

After deciding which crops to cultivate on an agrivoltaic site, comes designing of the said site. There are many differences between a typical utility scale ground-mounted and an agrivoltaic system when it comes to technical properties. When designing a typical ground-mounted PV plant the external variables taken into consideration mostly comprise of geographical location, availability of sufficient grid connction and what kind of soil or land the plant is built upon, these affect the panels tilt and orientation and the supporting structure required. In the case of an agrivoltaic site the variables for each location are unique. The PV module technology, height and alignment of the system, the supporting structure and foundation all need to be carefully planned for farming on the specific site so that the required farming equipment and machinery can be utilized. Also, depending on the APV system type the amount of light interception and water management needs to be adjusted accordingly in order to ensure that negative effects on yield stay to a minimum. The PV modules used in the simulations and modeling are 400 Wp bifacial modules by Solyco. The dimensions of the modules are 1723mm x 1134mm x 30mm (Secondsol 2022).

4.1 Overhead APV research site

In order to decide what dimensions the agrivoltaic system has above a field, the type of module has to be decided. If the system is planning to use more common PV modules that are used in typical ground-mounted systems, the module rows must have larger distances in relation to each other to allow enough light to pass through to the crops. This would result in less protection for the crops and less efficient power generation per ha used, but at the same time decreased component costs compared to other solutions. Utilizing single-axis trackers for these modules would allow for the module rows to be installed with less space between rows. This way the PV module tilt could be optimized to meet the time specific requirements of the crops, depending on the need for shade, light or protection from extreme weather events but would bring up the initial cost of the system. Another option is to use PV modules that are specifically designed for agrivoltaic systems. PV modules designed for agrivoltaics are typically glass-glass modules which have front and back panels made of glass and have more space in between the cells in each module to allow more light to pass through while still offering protection for the crops grown below. This could allow the system to function without tracking systems and many companies are already developing and researching said modules.

The initial design for the research was made with the goal of maximizing data gathered for different densities of APV systems and their effects on crops. The hail-nets used in orcharding typically block around 15-30% of incident solar radiation (Juillion et al. 2022). This amount could be the same for hailnets and growing tunnels used for berries. According to the results of several research projects, designing an agrivoltaic system with capabilities to intercept solar radiation within these limits should allow the yield of the field to remain relatively normal. (Marrou et al. 2013; Fraunhofer ISE 2023.) To put this into practice a research site with four different shading factors will be designed. The proposed site location is a research farm in Viikki Helsinki (66N, 39E ETRS-TM35FIN) and it is run by University of Helsinki. The planned area for the research project is around 1.8 ha of which around half is used for the APV system. The overhead APV system designed has PV modules installed in patterns with a goal of causing 10%, 20%, and 30% shading from direct solar radiation between 6-18 a clock in summer months respectively. These areas are then compared to a control plot that is located on the same soil but does not suffer any shading caused by the APV system. Under each shading factor a control plot with homogenous shading will be delimited so that the different shading factor on the edges of the APV system do not affect the results. Area planned for the system is shown in figure 13 below.

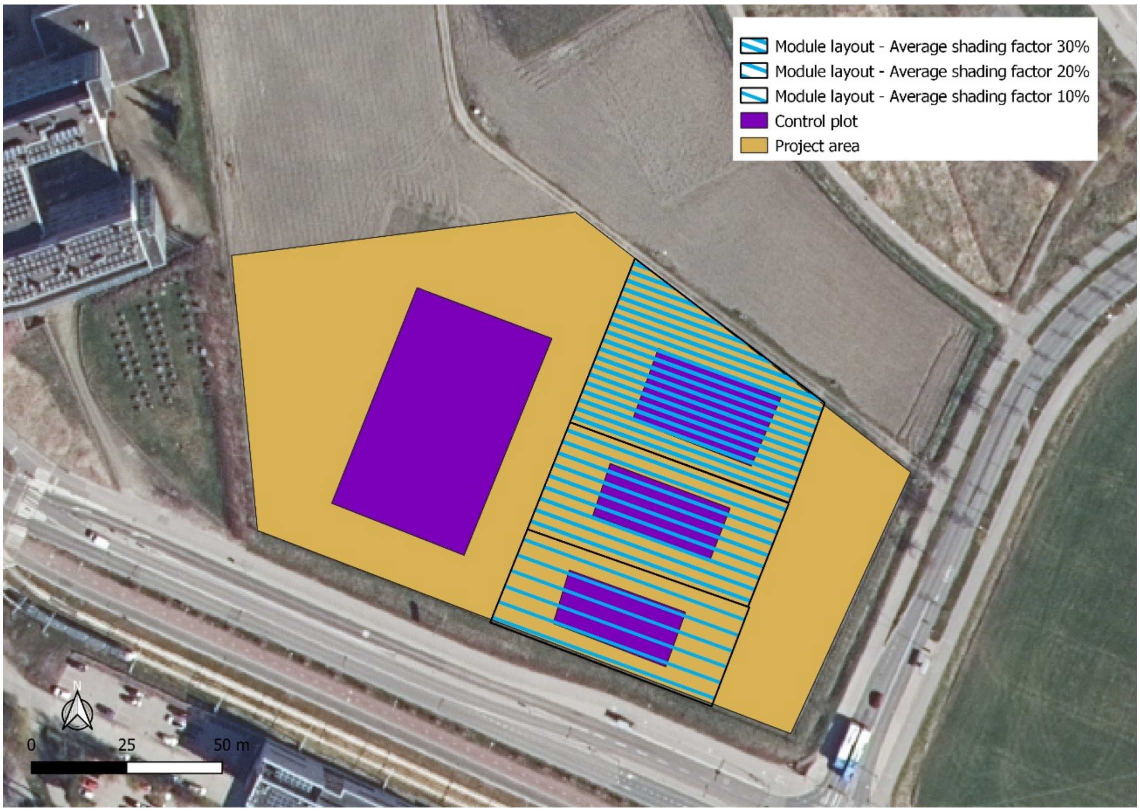

Figure 13. Initial layout of the planned overhead APV research site at Helsinki, Finland.

The four control plots, shown in figure 13 above in purple all have the same four different crops cultivated. Crops suitable for overhead systems could be wheat, potatoes, lettuce and strawberry. The proposed crops are chosen for their potential in Finland. This is to maximize the data gained considering effects caused by the APV system on different kinds of crops. The data researched in this proposed project is the effect of three different shading intensities to three different cultivated crops harvest yields. This will increase the knowledge of APV functionality with agriculture and further helps to clear the question of feasibility in Nordic environments. The other research area of this project site is to study the substructure required to install an overhead APV system. This site should be used to study the optimization of the substructure and shading patterns and the substructure should be built in a way that allows modifications to the system, so that other parameters for further studies can be applied.

By using PVsyst to calculate the shading factors for different patterns of installation, a rough estimate for intercepted direct irradiation can be measured. The shading factor calculated using PVsyst shows the percentage amount of a certain area that is under shade caused by the PV system above at a given time. To accomplish this with PVsyst the system can be modeled normally but in addition the control area on the ground has to be made of PV tables. The reason for this is that PVsyst calculates the shading factor only for the PV table areas and in this case the shading factor needed is an area on the ground in which the crops would grow.

After gaining the shading factor from PVsyst the table is then exported into an excel sheet where the data is easier to manage. Since the azimuth angle from the shading factor table is given in an accuracy of 20° the values between are created as averages of the two values. Also, the height angle values are filled with average values between the values retrieved from the shading factor table. Using PVsyst to estimate the angle of the sun on a given date the hourly estimated shading factor can be found from the shading factor table. This way the average shading factor for an example day of a given month can be measured. Calculating the average shading factor for one day for each high irradiance months through summer in Finland the average amount of sun light intercepted can be calculated. This can then be used to create example agrivoltaic system parameters and get rough estimates for each pattern and how much shade they provide for the plants below. PVsyst software is not designed for this kind of use, which is why the shading factor provided can only be estimated for PV modules that completely intercept sunlight. Also, the shading data PVsyst calculates is only for direct irradiation which does not take diffuse radiation into accord.

For initial research studies considering agrivoltaics in Finland, there should be as much data to be researched as possible. This means that on the agrivoltaic research area there should be multiple control plots with different shading factors, but all the control plots should have the same crops grown underneath. For the design in this thesis the intercepted direct irradiance levels chosen are 15% (A), 20% (B) and 30% (C). By having three different shading levels covering the plots data can be recovered on different outcomes and used to optimize future agrivoltaic systems for different crops.

Table 2. The average area under the APV system in constant shade at a given date for each pattern of PV modules installed, when substructure is accounted for.

Date for solar angle	Shading factor Pattern A	Shading factor Pattern B	Shading factor Pattern C
16.4.2016	0.20	0.23	0.37
16.5.2016	0.17	0.20	0.33
16.6.2016	0.16	0.20	0.31
16.7.2016	0.16	0.20	0.32
16.8.2016	0.19	0.22	0.35

In table 2 above the results for shading factor estimations are shown for each pattern. The values do not take diffuse radiation into calculations and the modules chosen for this research should allow a certain amount of light to pass through which decreases the shading factor of each pattern in the APV system. The goal of achieving 0.1 shading factor for pattern A is difficult since the substructure of the system has a large effect on the shading factor. This can be seen when comparing the results of table 2 and table 3. Based on the comparison a conclusion can be made that less dense APV systems have most of the shading effect caused by the substructure rather than the PV modules themselves.

Table 3. The average area under the APV system in constant shade at a given date for each pattern of PV modules installed, when substructure is not accounted for.

Date for solar angle	Shading factor Pattern A	Shading factor Pattern B	Shading factor Pattern C
16.4.2016	0.07	0.12	0.23
16.5.2016	0.08	0.11	0.20
16.6.2016	0.06	0.12	0.20
16.7.2016	0.06	0.11	0.20
16.8.2016	0.06	0.11	0.22

In figure 14 below, designed patterns to achieve above mentioned shading factors are shown. The patterns were chosen with water and light distribution in mind. By creating patterns of PV tables that consist of one or two PV modules, the rainwater should spread more evenly than if the APV system comprised of larger tables of multiple modules. Earlier research showed that APV systems cause erosion in the sides where rainwater flows and this might lead into issues such as, washing out of seedlings or nutrient discharge and eutrophication of surface water (Trommsdorff et al. 2022). The patterns chosen also even out light distribution which is important considering the results for the research into the effects of APV systems on cultivated crops. The downside of APV systems with chequered patterns is the increase in size of substructure by making the system need more horizontal layers.

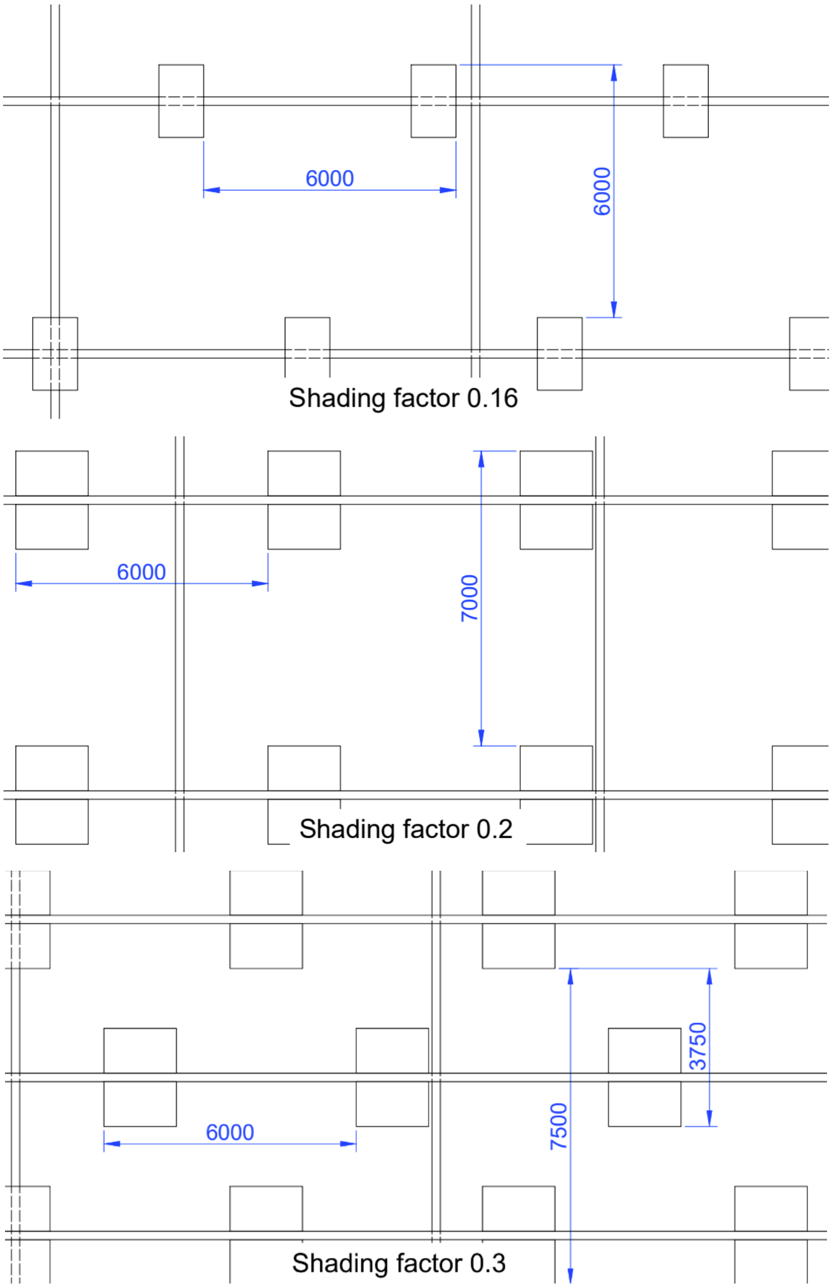

Figure 14. AutoCAD illustration of the patterns for each shading factor intensities planned for the research project.

The final system is designed in an area of 0.7 ha, illustrated in figure 15 below. The design of the research site allows for the use of farming equipment from north-west to south-east directions. The substructure has 10-meter gaps between supporting pillars. The system is designed with height of 4 meters but the height and gaps in substructure should be developed with the used farming equipment in mind. Material used for the substructure impacts the distance needed between pillars and the required refortifications to reach the needed structural resistance levels. Also, the lowest shading factor pattern is designed with the same substructure as the others but in actual implementation optimization should be reconsidered. The substructure to PV module ratio is a lot lower than in the other densities which results in unnecessary costs and shading.

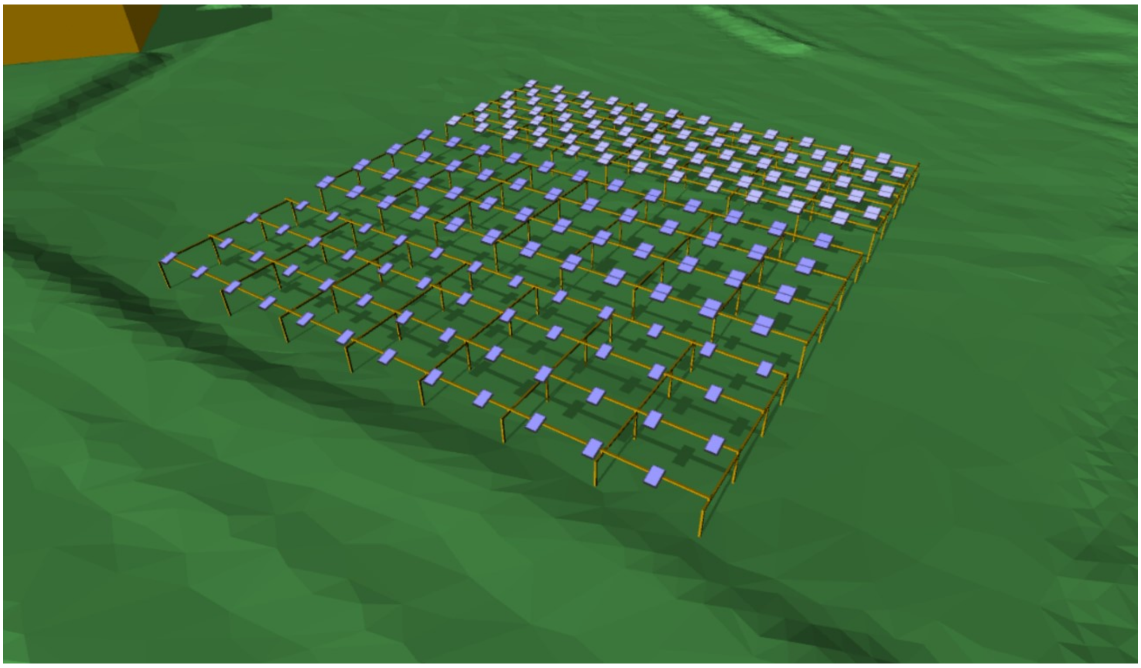

Figure 15. Final design of the overhead agrivoltaic site in PVsyst.

The amount of diffuse and albedo radiation with elevated PV systems is considerably larger than compared to regular ground mounted systems which is the reason why bifacial modules should be utilized in overhead APV plants (Rodríguez 2022). The whole system has an azimuth of 25° so that it is parallel with the property limits. PV module tilt is 15°, which is to even out shading caused by the system. With higher tilt angles the system would cause considerably more shade during the peak hours of solar irradiation and in this design the shading factor has been strived to equalize for every hour of the day.

4.2 Interspace APV research site

Utility scale agrivoltaics in the Nordics are most likely going to be interspace APV systems. The benefits from overhead APV systems are mostly against extreme weather events such as droughts, hail and abnormally warm periods (Juillion et al. 2022; Trommsdorff et al. 2022). These events are not yet common in the Nordics or in Finland which is why feasibility is a challenge. Substructure needed in overhead agrivoltaics increases capital costs significantly and makes using farming equipment more challenging. Interspace agrivoltaics effects on crops are less than overhead systems and the raw material needed for substructure is not substantially more than conventional ground mounted PV systems. The installation options for interspace APV systems are fixed vertical, single-axis tracking and fixed tilted systems. Vertical and single-axis trackers require the use of mounts that are not the most commonly used in utility scale PV plants but take up less of the arable land. Fixed tilted systems could utilize commonly used mounts but take up larger portions of arable land.

The modules themselves should be bifacial PV modules that can generate electricity from light hitting the back panel as well. Usually, APV systems are also installed higher than conventional ground mounted systems, since the shading caused by the growing crop has to be compensated which would increase the efficiency of the said back panel of bifacial modules. In the case of vertically installed APV systems, having two sided PV modules should be the industry standard since the PV modules get a lot of electricity production from diffuse radiation and when installed so that the panels are facing east and west the back side of the panel has to be able to produce electricity almost as effectively as the front panel.

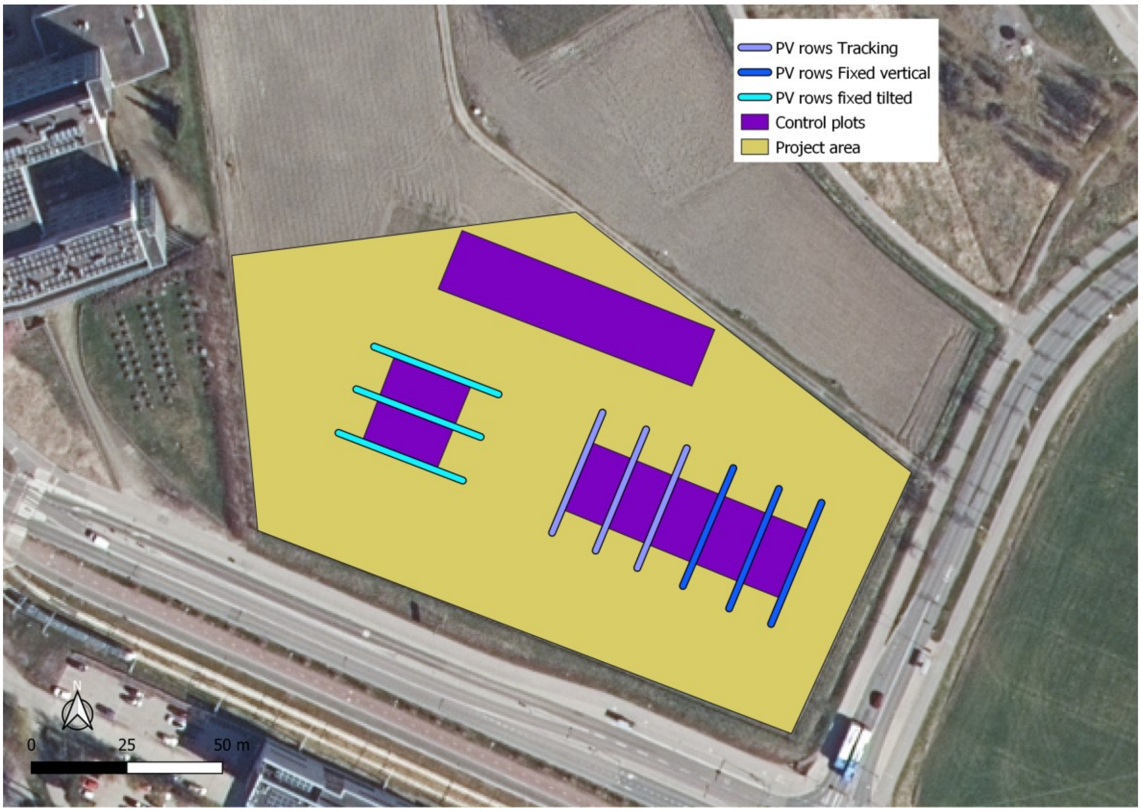

Figure 16. Initial layout of the interspace APV research site for Viikki, Helsinki.

The APV tables are oriented to go parallel with the project areas limits, since the vertically installed fixed system does not have significantly lower electricity production efficiency by having an azimuth of -70° instead of -90°. The azimuth for the fixed 60° tilted system is 25°. This should make it easier to modify the field with farming machinery and for the initial design around 10.5-meter gap is left between the rows of PV tables to allow the use of combine harvesters and other farming machinery. This gap should always be optimized for the farming machinery used in a specific field by the farmer. For the initial design, nine rows of PV tables are planned with the said 10.5-meter row distance. Three different types of systems are installed to gain data for different types of interspace APV systems, fixed vertical, fixed tilted and single-axis tracking system. This way data determining which method is most feasible can be collected and compared.

Initial hypothesis for comparison are that the fixed vertical system takes the least amount of space away from arable land but requires the use of specifically designed substructure which increases capital costs. Shading caused by the fixed vertical system is also lower than the other systems due to the tilt angle not being optimal for electricity production. Single-axis tracking system could maximize electricity production while taking away same amount of arable land as vertical system by turning the PV modules away from farming equipment while harvesting. Installing PV modules with trackers are more expensive and has not yet shown to be feasible when compared to fixed installations in Finland. Fixed tilted system with high tilt angle could use conventional substructure used in large utility scale PV plants which should decrease capital costs significantly.

Installing PV modules with fixed over 45° tilt angle reduces the area needed for the modules while keeping electricity production high and capital costs to a minimum. The area taken away from arable land is calculated with the assumption that the substructure of the APV systems are 0.2 meters wide to which a 0.5-meter buffer zone per side is added. This is used for fixed vertical and single-axis tracking systems. The fixed tilted system uses the width of the system added with the buffer zones for each side. When optimizing fixed installation PV modules to have the highest efficiency in Finland throughout the year, the tilt angle should be around 45° and azimuth 0° facing directly south (Caruna 2023). Most utility scale solar plants use a tilt angle that is less than 45° to allow the PV module rows to be closer to each other without causing shading to the row behind and so increase the peak power and land use of the whole site by allowing more PV modules to be installed. When optimizing the system for APV sites the PV module rows have to be installed further apart to allow the use of farming machinery which then allows the use of higher tilt angles and so increases the efficiency of the PV modules. In northern latitudes the PV modules can be installed with large tilt angles due to the sun shining from relatively low angle throughout the year. Installing PV modules with a tilt angle of 60° achieves around the same electricity production as installing with a tilt angle of 30°. The optimal 45° could also be used for APV sites but the amount of space the width of the rows would take increases considerably from 1.164 meters for 60° tilt angle to 1.646 meters for 45° tilt angle. Also, a 0.5-meter buffer zone for each side of the PV tables should be considered so that the risk of hitting the substructure of the APV system during harvest would be as low as possible. Vertical and single-axis tracking systems only take up the amount of substructure and buffer areas out of the arable land.

The goal for this research is to confirm the results from earlier research done in Sweden and Belgium considering interspace APV systems and their low effects on crop growth and to gather data for future feasibility studies on the APV systems efficiency, production, expenditures and challenges on the installation (Willockx et al. 2023; Campana et al. 2023). Data on effects to crops should be gathered utilizing at least two control plots for each APV system type. Sensors gathering data for example on temperature and moisture from the soil and air, as well as irradiance levels between the PV table rows should be installed on the plots. These values are then compared to a reference plot located next to the APV systems on the same soil but far enough to not be affected by the systems. Crops that have potential with interspace systems should be planted and studied in this research. Fodder grass or grains could be potential for commercial projects in the future which makes them ideal for this research. The arable land in use in Finland for these are also among the highest which increases the relevancy of the crops.

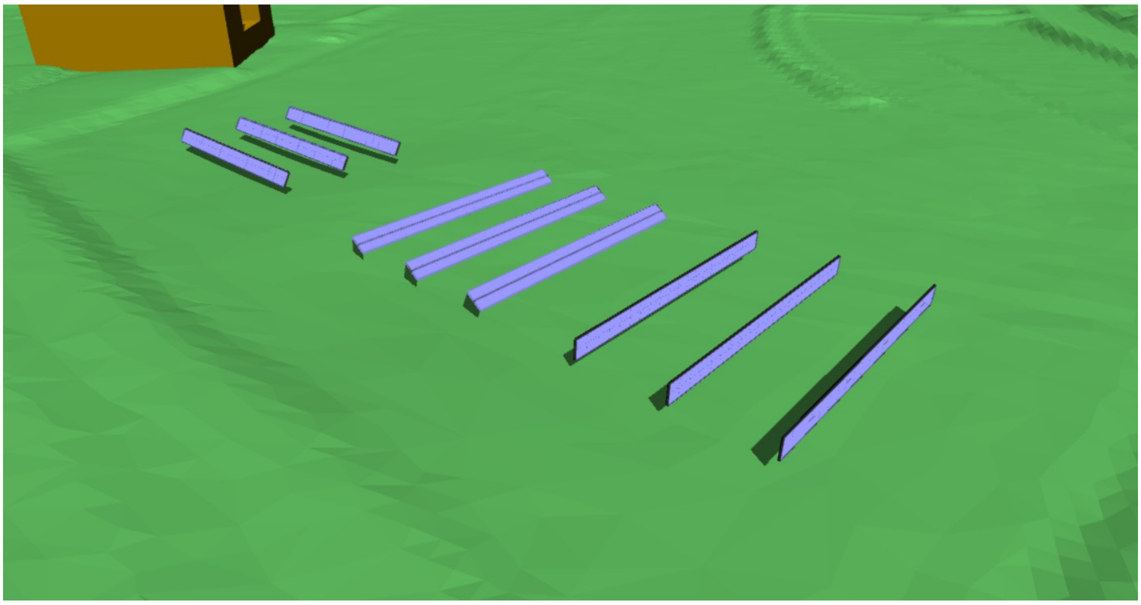

Figure 17. PVsyst model of the interspace APV research site planned for Viikki, Helsinki.

By modeling the site with PVsyst software, the specific electricity generation can be simulated and used to evaluate the feasibility of each system. Also, the peak power of the system as well as the number of PV modules able to fit inside the project area can be estimated. The results for the final model can be seen in figure 17 above. The fixed tilted system has a tilt angle of 60° to take up around 1 meter of arable land without counting the buffer area and still achieve good yearly electricity production. When simulating east-west facing vertically installed PV modules with PV syst, accurate results are difficult to achieve. PVsyst simulation software cannot calculate direct radiations effect on electricity production on the backside of the PV panels. To estimate the electricity production with PVsyst a PV table that has a bit less power is placed close to the back side of the correct PV table facing the opposite direction, thus acting as a back panel with a bit less electricity production when compared to the original PV table.

4.3 PVsyst simulation results

The designed overhead APV system with three different densities of installed PV modules reached a simulated total peak power of 125 kWp. The power density for each intensity of PV modules from lowest to highest are 0.11 MWp/ha, 0.24 MWp/ha and 0.39 MWp/ha respectively. According to a study in PV power density the average power density for fixed ground mounted PV plants is 0.87 MWp/ha (Bolinger & Bolinger 2022). The simulated electricity production for the whole system amounted to 115 MWh annually. Comparison of the overhead and interspace APV systems main simulation results is listed in table 4 below. The design for the interspace system has nine rows of PV tables on the project area with enough area to allow the farming machinery to maneuver around the PV modules. The resulting system has 360 PV modules that amount to 144 kWp. The different installation methods simulated each generate electricity annually by up to 44.3 MWh for fixed vertical, 42.5 MWh for fixed tilted and 53 MWh for single-axis tracking system. Performance per kWp for each system type is 988 kWh/yr for fixed vertical, 948 kWh/yr for fixed tilted and 1204 kWh/yr for single-axis tracking respectively.

The amount of arable land each interspace APV table in this design take away from crop cultivation is 41.4 m^2 for fixed vertical and single-axis tracking systems and 74.8 m^2 for fixed 60° tilted system. The area taken from arable land if all of the 9 rows of PV tables were fixed vertical systems or single-axis tracking systems amount to 372 m^2 or 324 m^2/ha with PV table row distance of 10.5 meters and 25 meters area around the whole APV system so that farming machinery is able to turn around the outside. For a fixed tilted system, the same area is 673 m^2 or 585 m^2 per ha. The fixed vertical and single-axis tracking APV systems take around 3.2% away from arable land and fixed tilted system with 60° tilt takes up around 5.8%. The overhead APV system takes away 104 m^2 of arable land when assuming each of the supporting pylons take away 1 m^2 of space. Per ha the same area is 185 m^2 or 1.85%. If whole strips of land between the pylons have to be taken away from farming, the area grows up to 1118 m^2/ha.

Table 4. PVsyst simulation main results of both simulated agrivoltaic research sites.

	Overhead research site total	Interspace Fixed 90° vertical	Interspace Fixed 60° tilt	Interspace Single-axis tracking
System prod. (MWh/yr)	115	44.3	42.5	57.8
Specific prod. (kWh/kWp/yr)	921	988	948	1204
Perf. ratio	0.85	-	0.83	0.84
Norm. prod. kWh/kWp/day	2.52	2.7	2.60	3.3
Array losses (kWh/kWp/day)	0.37	0.40	0.43	0.51
Area taken from arable land (m^2/ha)	185	372	673	372

5 Economic evaluation

The economic evaluation is done mainly using results from the simulations combined with estimations from earlier research. Key evaluation values such as capital and operating expenditures, LCOE, return of investment and land equivalent ratio are estimated for each APV system. The results are used to compare the different APV installation methods planned in this research to estimate which might be most feasible and what benefits they might have over the other. Utility-scale PV plants have many different financing solutions which all have different performance considering economic feasibility. In this evaluation all of the systems will have the same financing parameters but different electricity production and capital costs. This way the results for each system will be comparable with each other but not with results from other studies or real cases.

5.1 Capital and operating expenditures

The initial capital (CAPEX) and yearly operating (OPEX) expenditures are important factors considering economic evaluation. Feasibility is not possible to evaluate without knowing the costs of the system. On the other hand, estimating the initial costs is also challenging without actual data on the costs of installing a specific PV or APV system. The CAPEX and OPEX also vary by large margins depending on the size of the proposed system. For the economical evaluations done in this thesis estimations for CAPEX and OPEX are based on estimations on utility scale PV plants published by various companies and websites. The results for CAPEX and OPEX estimations as well as LCOE calculations are listed in table 5 below.

Table 5. CAPEX and OPEX estimations for all simulated systems in this research.

System Type	CAPEX (€/kWp)	$CAPEX_{total}$ (€)	OPEX (€/kWp/yr)
Fixed 60° tilt	600	28 800	13.3
Fixed 90° vertical	700	36 700	13.3
Single-axis tracking	1219	58 512	19.5
Overhead APV	1000	125 000	13.3

The fixed 60° tilted system is assumed to share the CAPEX and OPEX of conventional ground mounted systems. These are estimated at around 600 €/kWp for CAPEX and 13.3 €/kWp for OPEX. The amounts are based on a study by Fraunhofer ISE on levelized cost of electricity (Kost et al. 2021). A PV module manufacturing company Next2Sun specializing in fixed vertical agrivoltaics reveal their systems turnkey costs are around 700 €/kWp or around 20-25% higher than the conventional ground mounted systems (Next2Sun 2023). Operating costs on fixed vertical systems could be larger annually due to a possible need of mowing grass growing directly in front of the PV panels. For the calculations on this thesis OPEX are the same for fixed vertical as they are for fixed tilted system. (Next2Sun 2023.) The single-axis tracking system has the highest CAPEX per kWp aswell as OPEX with the advantage of high electricity production efficiency per kWp. According to the National Renewable Energy Laboratory the average CAPEX for utility-scale single-axis tracking systems in 2023 is 1 219 €/kWp and OPEX 19.5 €/kWp. These are the values estimated in the USA and the amounts are changed from US dollars to Euros. (NREL 2023). The overhead APV systems CAPEX and OPEX are based on a guideline on agrivoltaics made by Fraunhofer ISE. The CAPEX from the guideline suggests that initial costs amount to around 1000 €/kWp. The guideline for OPEX of agrivoltaics suggests that compared to conventional ground mounted PV plants OPEX for APV systems might be lower since the usual maintenance works done could be performed by the farmer on the site. (Trommsdorff et al. 2022.) Based on this the overhead APV uses the same OPEX for the calculations as the fixed systems. Estimated CAPEX for projects designed for the research area total at around 125 000 € for both overhead and interspace systems and OPEX for a 30-year project lifetime would be around 66 000 € for interspace system and 50 000 € for overhead system.

5.2 Levelized cost of electricity

LCOE is an important metric used to calculate feasibility, since it can be used to estimate the costs of the electricity produced. LCOE can be estimated for all electricity sources which makes it possible to compare between different methods of producing electricity. The LCOE of a renewable energy project is calculated using the following formula (Corporate Finance Institute 2023):

$$LCOE = \frac{NPV\ of\ Total\ Costs\ Over\ Lifetime}{NPV\ of\ Electrical\ Energy\ Produced\ Over\ Lifetime}, \qquad (1)$$

where

$NPV\ of\ Total\ Costs\ Over\ Lifetime$ is the net present value of CAPEX and OPEX on the whole project over the estimated lifetime in €

$NPV\ of\ Electrical\ Energy\ Produced\ Over\ Lifetime$ is the net present value of all produced electricity sold over the course of project lifetime in €.

The resulting LCOE values were calculated with having costs only from CAPEX and OPEX. In actual project development cases there are many hidden expenses that are challenging to estimate from simulation results alone. This results in lower LCOE values for each system than what might be in actual implementation. LCOE values from calculations ranged from 35 €/MWh to 50 €/MWh. The fixed tilted system had the lowest LCOE of 35 €/MWh, which is mainly due to the low capital costs of the system. Fixed vertical had second lowest with an LCOE of

39.7 €/MWh. Single-axis tracking system had a similar LCOE to the overhead system of 49.9 €/MWh compared to overheads 50.6 €/MWh. CAPEX had the most effect on the LCOE results on system of this scale. The increase in yearly production that single-axis trackers achieve is not enough to bring down the LCOE due to the high CAPEX. Simulating a single-axis tracking system with bifacial PV modules using PVsyst also gives inaccurate estimations and could impact the results for electricity production and feasibility calculations.

5.3 Feasibility

The feasibility of each type of APV system is evaluated by using payback period and return of investment (ROI) over the course of the systems assumed 30-year lifetime. The results for each system are listed in table 6 below. Due to the volatility of the energy market, the price for the produced electricity which is fed into the grid is determined by the average power purchase agreement (PPA) values in Europe for 2023. A 55 €/MWh is used for feasibility calculations based on PEXA EURO Solar PPA Price index, which has been a little over 50 €/MWh on the course of 2023 (Steinecke et al. 2023). A 30% taxation according to Finnish capital taxation laws is assumed for profits. Also, the ROI and payback period are calculated with no loan interest so that all CAPEX is assumed to be paid for instantly on the plants completion.

Table 6. Feasibility evaluation and LCOE results of each system.

System Type	ROI (30-year lifetime)	Payback period (years)	NPV (x1000 €)	LCOE (€/MWh)
Fixed 60° tilt	+66%	16.5	19.2	35
Fixed 90° vertical	+41%	21.3	15.1	39.7
Single-axis tracking	+6.4%	28.2	3.8	49.9
Overhead	+8.4%	27.7	10.5	50.6

During the estimated 30-year lifetime ROI for the interspace systems were around +66% with a payback period of 16.5 years for fixed 60° tilted system, +41% with a 21.3-year payback period for fixed vertical and +6.4% with a payback period of 28.2 years for single-axis tracking system. The overhead system resulted in a ROI of +8.4% with a payback period of 27.7 years. Net present values for each interspace system after 30 years were around 19 200 €, 15 100 € and 3 800 € respectively and 10 500 € for the overhead system. Fixed interspace systems are clearly most feasible from an investors perspective based on the results.

5.4 Land equivalent ratio

Land equivalent ratio is an important metric to evaluate the efficiency of arable land used. It can be used just for agricultural purposes but with agrivoltaics it is used to estimate the effect of said agrivoltaic system on the cultivated crops and if the agrivoltaic system increases the efficiency of land use. Land equivalent ratio is calculated using the following formula (Trommsdorff 2020):

$$LER = \frac{CropYield_{APV}}{CropYield_{normal}} + \frac{ElectricityYield_{APV}}{ElectricityYield_{Normal}} - LandLoss, \qquad (2)$$

where

$CropYield_{APV}$ is the yield with an APV system installed on the field

$CropYield_{normal}$ is the yield on the same field without APV installed

$ElectricityYield_{APV}$ is the electricity production of an APV system on a said field

$ElectricityYield_{Normal}$ is the electricity production yield of a typical ground mounted system in place of the APV system

$LandLoss$ is the percentage of arable land taken away from crop cultivation due to substructure.

The land equivalent ratio for the interspace system is calculated with the assumption that they do not affect the cultivated crop at all. The overhead system is calculated with the assumption that the effect on crops would be a 10% decrease in yield for average shading of 30%, 5% decrease for average shading of 20% and no effect for average shading of 15%. This is based on the overhead system having three different intensities of PV modules installed which all affect the crops differently. The reference conventional ground mounted system is a 30° tilted system with 5-meter row distance. The reference system has the same area as the overhead system and has around 650 kWp with a yearly production of around 610 MWh. The interspace systems yearly production is doubled for the LER calculations since around six rows can fit within the limits of the overhead system.

Table 7. Land equivalent ratio of each different installation method planned for the research project in Viikki, Helsinki.

Interspace APV	LER	Overhead APV	LER
90° vertical	1.11	10% in shade	1.07
60° tilt	1.08	20% in shade	1.10
single-axis tracker	1.15	30% in shade	1.18

The land equivalent ratio for all of the systems is very similar to each other as seen in table 7 above. Evaluating LER based on simulated results is highly affected by electricity production, since data for crop yield differences are not available until the project is realized and studied. Yearly differences in crop yield have large effects on LER as was seen by APV-RESOLA research project in their research done in southern Germany, since during abnormally dry seasons the APV system might increase crop yield compared to the reference area and thus increasing LER by a large margin (Trommsdorff et al. 2022).

6 Conclusion & Discussion

As a conclusion all of the different agrivoltaic implementations have their own unique advantages. When considering their appliance into the Nordic environment of Finland, most feasible systems from an economic perspective would likely be interspace agrivoltaics. They offer increased land efficiency with relatively low investment costs when compared to other APV implementations. Agrivoltaics combined with grazing animals might prove to be very feasible projects as well since they can utilize conventional ground mounted PV systems. Most challenges considering them would be land quality and will the areas used for grazing be suitable for PV plants. Reasons for overhead APV not yet being as ideal for Finland is that they mostly offer protection for crops from heat and droughts which are not as of today as common in Finland as they are in Central to Southern Europe where the overhead systems have been studied. In the near future these might become more common events in Finland and so makes it also important to research. Overhead APV could also be adapted for berry cultivation which could replace commonly used growth tunnels and hail nets while increasing growing season.

Interspace and overhead APV systems should be chosen for the subject of research projects in Finland. Interspace APV research should focus to confirm earlier research results that they do not affect crop growth and to study their feasibility when scaling them up to the size of utility scale PV plants. These could offer solutions for the location of future PV plants to not take away land entirely from active agricultural use or having to deforest areas to make space for PV sites. Overhead systems impact on crops are yet to be studied in northern latitudes which would be important considering climate changes effect on food production and coming up with ways of securing consistent crop yields. Earlier studies on overhead APV show that around 30% decrease in PAR should allow the yield to stay within acceptable amounts considering feasibility. Northern climates already have lower average PAR amount which could prove the 30% decrease to be too intense for the cultivated crops. Also, the economic feasibility of overhead APV should be researched more thoroughly and further develop the substructures used to mount the PV modules over the field.

For the research project planned in this thesis to be implemented in Finland, both interspace and overhead APV systems are proposed. The scale of each system should be determined by the funding granted for the project and the final area provided for the research. The area planned is a research field owned by the University of Helsinki and both of the systems designed have the same initial capital expenditures of around 125 000 €. The simulation results show that the interspace systems are more efficient in electricity production but take away more land from farming. This is mainly due to the overhead system having a tilt angle of 15° which is not as optimal for maximizing electricity production as the tilt angles used by the different interspace applications. The lowest LCOE was achieved by a fixed 60° tilted interspace APV system. CAPEX had the most impact on the LCOE of each system as the electricity production difference was not enough to make single-axis tracking system more feasible. More research in the feasibility of single-axis tracking systems is required since the simulation results for electricity production and the CAPEX estimations could be inaccurate. Fixed vertical interspace system results do not differ by large margins from the fixed tilted system which makes it a great contender for them, especially since it takes half the space per ha when compared to the fixed tilted system. Also, the vertically installed PV modules could prove to be more efficient in northern latitudes since the angle of sun is lower by average and during summer the sun remains above the horizon for almost entire day.

The results from the simulations should be used only as a preliminary guide to give initial expectations for each system and help in deciding what kind of APV research site should be implemented first in Finland. The actual effects on crops by each system has a large impact on the feasibility of each system, since if they offer too many disadvantages for agricultural practices, farmers will not be interested in having them in their fields. The research site should also be used to create standard methods and guides for farming alongside APV systems to help convince farmers that having another source of income from the field this way has more benefits than challenges.

There are many challenges that APV causes for farmers as well as PV project developers. The APV systems make farming more difficult since maneuvering around the substructures might prove difficult and requires more focusing. Also, when creating a profitable PV project from a project developers perspective the site has to be of large scale. APV has lower power density per ha than conventional ground mounted systems and thus require larger land areas to make them profitable. This could bring up challenges in the project development when the land is in constant agricultural use. Also, some legal issues such as eligibility for EU agricultural subsidies might surface when using agricultural land for two different purposes at once. Further research should include interviews with landowners and farmers to hear their thoughts and questions about the subject. Also, deeper research into the viable crops should be done to further the knowledge of which crops have the most potential and what effects APV have on the crops on a more detailed level. The substructures used for APV systems also need to be further developed to advance the competitiveness of APV when compared to conventional ground-mounted systems.

Even though there are still many challenges and questions regarding the feasibility and functionality of agrivoltaic systems, they do show large potential in driving the world towards a more environmentally sustainable energy footprint. APV could help farmers secure consistent income through diversification and have more secure seasonal crop yields. Also, the benefits of not having to deforest areas or remove agricultural practises from fields completely, show the potential of agrivoltaics over conventional PV systems in the future of renewable energy production.

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