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Possible implementations of agrivoltaics in Sweden

With focus on solar irradiation and electricity production

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Possible implementations of agrivoltaics in Sweden – With focus on solar irradiation and electricity production

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Abstract

With a need for rapid growth of renewable energy sources like photovoltaics, there will also be a competition of land. Agriculture and solar energy share the same optimum conditions of land to produce. But with a combination of the two on the same surface, a concept called agrivoltaic, that issue can be solved. This projects has investigated the possibilities of implementing an agrivoltaic system in Sweden in the near future with a focus on solar irradiation, energy production and crop selection. The decrease in solar irradiation under the panels was simulated because it is an important parameter in making these kinds of systems profitable from a crop and energy perspective. The annual energy production and energy yield was also simulated for various system designs for a comparison between the two important parameters of an agrivoltaic system.

One solar fence system, a single axis tracker system and an integrated PV system was chosen for the simulations. In general, all results of agrivoltaics is location dependent due to important differences in solar irradiance and climate. The solar fence system had the best results regarding the solar irradiance, with a decrease in the range of 3-5% and 20-28 % depending on the design. Single axis trackers had a minimum 3-8 % and maximum 40-59 % and integrated PV had a minimum 42-60% and maximum 50-75 % reduction. When the annual energy was compared with a row spacing of 12 m, the solar fence has an annual energy of 1738 kWh and single axis trackers got 2812 kWh. The results indicate that depending on what is most important for the system, the recommendations are different. If energy is more important, then the single axis tracker system can be a good fit but if it is solar irradiance, the solar fence is better. Both systems should be suitable for shade tolerant crops but if experimenting with others such as field bean and barley, the solar fence is more appropriate. The results for the integrated panels designs indicates that these designs are not a good first fit for Sweden since the reduction is greater than 50 % for most designs. Since there is only one agrivoltaic system in Sweden with results on one type of crop, there is a need for more systems with different designs and crops to be able to tell the real potential of agrivoltaics is Sweden.

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Populärvetenskaplig sammanfattning

För att nå nationella mål om förnybara energikällor i den svenska energimixen behövs en snabb tillväxt. Regeringen har efterfrågat en strategi för att öka de förnyelsebara energikällorna fram till 2040. Det skulle innebära en ökning av solenergin och därmed också öka konkurrensen av markytor. Agrivoltaics är ett koncept som kombinerar solceller och jordbruk på samma yta och därmed är konkurrensen av markyta inte ett problem vid implementering av sådana projekt.

Detta projekt har undersökt möjligheten att implementera ett agrivoltaic system i Sverige eftersom det har blivit ett hett ämne inom solcellsindustrin. Syftet med denna studie är att ta fram ett underlag för Svea Solar som kan vara till hjälp för att avgöra vilket agrivoltaic system som är bäst för en första implementering i Sverige beroende på solinstrålning, energiproduktion och val av grödor. Detta inkluderade att föra en förstudie av olika befintliga agrivoltaic system och intervjua tidigare jordbrukskunder till Svea Solar. Den största oron bland bönderna var hur ett sådant system skulle påverka skörden, energiproduktionen och därmed ekonomin. Detta var anledningen till att solinstrålning valdes som en viktig parameter att simulera. Solceller och fotosyntesen i växter behöver solinstrålning för att producera och därför är det en viktig faktor i utformningen av ett agrivoltaic system.

Solinstrålningen under utvalda system och solpaneler simulerades. Energiutbytet simulerades också för att kunna jämföra de båda viktiga faktorerna av ett agrivoltaic system. Ett system med vertikala paneler (Solar fence), ett enaxlat spårsystem (Single axis tracker system) och ett integrerat system valdes för simuleringarna. Ett integrerat system definieras genom att en del material i ett system/objekt ersätts med ett annat, i detta fall solceller. Till exempel plasten som använda i odlingstunnlar för produktion av bland annat bär.

Generellt är resultaten för agrivoltaic system plastsberoende på grund av viktiga skillnader i solinstrålning och klimat. Resultaten visade hur mycket solinstrålningen och därmed också den årliga energin minskade beroende på systemdesign. De vertikala panelerna visade på bäst resultat vad gäller solinstrålningen med en minsta minskning på 3-5 % och som mest 20-28 % under hela dagen beroende på design. Enaxlade spårare hade minst 3-8 % och som mest 40-59 % och integrerade systemet hade minst 42-60 % och mest 50-75 % minskning av solinstrålningen. När den årliga energiproduktionen jämfördes med ett fast radavstånd på 12 m hade de vertikala panelerna ett årligt resultat på 1738 kWh i jämförelse med det enaxlade systemet som producerade 2812 kWh.

Resultaten, från simuleringen av solinstrålning, indikerar att ett vertikalt system är bäst lämpat för att experimentera med olika grödor, skuggtåliga men också mer känsliga grödor såsom korn och åkerböna. Enaxliga spårare är ett bra alternativ med skuggtåliga grödor om elproduktionen är den viktigaste delen av systemet, då den gav goda resultat i energisimuleringen. Resultaten för de integrerade systemen indikerar att dessa konstruktioner inte passar lika bra för Sverige eftersom minskningen av solinstrålning är markant större.

Executive summary

The results from this study shows that the solar fence system is a good option for experimenting with crops and designs since it had the highest amount of solar irradiation along the test surface compared to the other suggested systems and still procced a fair amount of electricity. The solar fence system had a minimum decrease of 3-8 % and maximum 20-28 % of solar irradiation. To truly tell the potential of this, there is a need for more results and evaluations and solar fence systems in Sweden could be a good fit for doing so. But if the project is focused on producing the most electricity, then the single axis tracker system is more suitable since it had an annual electricity production of 2812 kWh compared to solar fence 1738 kWh. It is clear after this study that the results of agrivoltaic systems are location dependent. For Svea Solar to continue the expansion of solar energy in a sustainable way, this kind of systems may be a part of the solution that can solve the competition of land and promote further development.

Acknowledgement

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Nomenclature

PV – Photovoltaics
AV – Agrivoltaics
Ha - Hectare
kWh – Kilowatt hour
MW – Megawatt
GCH - Ground clearance height
CS - Cell spacing
LER – Land equivalent ratio
AVS – Agrivoltaic system

1 Introduction

In 2020, 0.7 % of Sweden's total electricity production consisted of solar energy (Stridh, 2021). Although, at the request of the government, the Swedish energy agency has come up with a strategy to increase the share of solar energy to 2040. To 2040 there is a possible scenario where 5-10 % of the total electricity production could come from solar energy, but to achieve such a goal, various actions are needed. According to the Swedish energy agency, 5-10 % would correspond to 7-14 TWh (Energimyndigheten, 2016). As a natural consequence of this rapid growth of solar, the competition for land will increase.

Ground mounted PV systems requires flat with minimal wetlands and preferably close to three-phase power (OYA Solar, 2021). In Sweden, there are in general five types of categories for land and they are; 69 % of woodland, 8 % agricultural land, 3 % built up land and 20 % of mountain areas, natural grassland and mires (SCB, 2021). Of these five, the agricultural land is best suited for ground mounted PV parks due to the mentioned requirements. It is mostly flat, cleared and with minimal wetlands. Agricultural activities and solar energy both share the need for these optimal conditions (Mälardalens högskola, 2021a).

Traditionally you either have solar or agriculture because both require land to produce. Having a combination of solar energy and agriculture on the same surface is one way to avoid this competition of resources and researchers in Italy, France, Germany, USA and Japan has already proven that this is the case. This type of solution is called Agrivoltaics and as the name suggests it is a collective name for systems that combine agriculture and photovoltaics. Agrivoltaic systems can results in efficient land use (Campana, et al., 2021) and open new possibilities for the solar energy expansion in Sweden but also in the rest of the world (Mälardalens högskola, 2021b).

Sweden's annual electricity consumption in 2020 was 140 TWh (Energimyndigheten, 2020). If assumed that an Agrivoltaic system produces 30 kWh/m^2, to reach a production that matches Sweden's annual electricity consumption from solar, 15 % of Sweden's agricultural land must be covered. As mentioned earlier, 8 % of Sweden's land area consists of agricultural land and these 8 % corresponds to 3 013 000 ha and this is divided into 2 549 500 ha of arable land and 463 500 ha of pasture land. 15 % of this is approximately 450 000 ha (Stridh, 2021).

There is potential for Agrivoltaics in Sweden, but so far there is only one agrivoltaic park installed on a ley field in Västerås (Solkompaniet, 2021). Apart from that park, there is no concrete information on how agrivoltaic affects crops in Sweden. The challenge with agrivoltaics is to find the best solution for the geographic location and test the system, before that there is difficult to estimate the real potential. But the interest in agrivoltaics has started to grow among Svea Soar's customers and within the company. To continue the expansion of solar energy in a sustainable way, this may be a part of the solution that can solve the competition of land and promote further development.

1.1 Research aim

Agrivoltaics is a hot topic in the solar energy industry and as Sweden’s largest installer of solar cells, Svea Solar wants to be a part in the development of Agrivoltaic systems. The purpose of this study is to produce a basis for Svea Solar that can be helpful in deciding which agrivoltaic system is best suited for implementation in Sweden depending on solar radiation, energy production and crop selection. Based on information collected from former agriculture customers and researchers on the agricultural side, as well as a technical literature study, agrivoltaic system designs will be compared and evaluated.

To be able to suggest a system solution that is interesting and feasible for both installers and farmers, the parameters from which the systems are analyzed will be based on the interests and uncertainties that Svea Soar’s previous agricultural customers had about the systems and wanted answered but also parameters that are crucial for Svea Solar as an installer. Because this study has taken potential customers into account, this can hopefully generate enough interest and curiosity for some customers to be willing to test this type of system.

To operationalize the purpose and reach the goal of this study, the following task were to be conducted:

- Do a pre-study of different agrivoltaic systems.
- Interview previous agricultural customers to get their opinion about a combination of agriculture and photovoltaics.
- Compare agrivoltaic system designs in the world and give suggestions that would suit Svea Solar and Sweden’s climate and agriculture.
- Analyze the suggested systems based on relevant parameters.

2 Theory

2.1 Agriculture in Sweden

Arable land, mowing field and pastureland are all included in the concept of agricultural land. To be defined as arable land, the area must be used for crop production or be suited for crop production with only the preparation of agricultural machinery and agricultural processes. For example, the cultivation of energy forests and fruits and are included in arable land, but not land with, for example, too much stone. Land with too much stones is not suitable for crop production and would need to be prepared with methods other than the usual agricultural methods to possibly be used for crop production. Therefore, it is not included in the category of arable land but will possibly be categorized as mowing field or pastureland instead. (Jordbruksverket, 2020).

Out of the total 3 013 000 ha of agricultural land in Sweden in 2020, 85 % were arable land and 15 % mowing fields and pastureland. Of the arable land categories, cultivation of ley and pasture grass holds the biggest share at 38 % which corresponds to 1 138 800 ha in 2020, see table 1. Cereals occupied 1 006 700 ha, where wheat took up the largest shares of 45 % of the total cereal area. The next largest crop share was barley at 30 % closely followed by oats at 18 % (Jordbruksverket, 2020).

Table 1: Specific hectares for the different categories of agricultural land in Sweden during 2019 and 2020 (Jordbruksverket, 2020)

Category	2019 [ha]	2020 [ha]
Cereals	993 200	1 006 700
Pasture grass and ley	1 163 700	1 138 800
Rapeseed	105 600	98 300
Leguminous plants	44 200	47 900
Sugar beets	27 300	29 800
Potatoes	23 600	24 100
Other crops	51 300	54 800
Unspecified arable land	10 900	11 300
Fallow	131 700	137 600
Pastureland and mowing fields	461 300	463 500

2.2 PV modules

There are different kinds of PV modules and some has characteristics that could be more suitable for an agrivoltaic system than others. Monofacial modules have a non-transparent backsheet which prevents light to pass through between the cells and prevents them from taking advantage of the light from at the rear side. A bifacial module has a glass or transparent material as backsheet which enables the module to take advantage of the light hitting the rear side as well as for some light to pass through. In a study done by Jang et al. they assumed a fixed cell spacing of 5 mm as reference (Jang, et al., 2021) and a material from Trina Solar states their traditional modules have 2-3 mm (Posrunna, 2021). Cell spacing in modules varies a lot depending on manufacturer and design. The common modules used by Svea Solar has a cell spacing that differs from 2 mm to 5 mm depending on type of module.

A bifacial module has a characteristic called bifaciality factor and that is a ratio of the efficiency at the rear side and front side. See equation:

$$Bifaciality\ factor = \frac{n_{rear}}{n_{front}}$$

Where n_{rear} is the efficiency of the rear side at STC conditions and n_{front} is the efficiency at the front side (PVsyst, n.d.). Example, if n_{rear} is 15.5 % and n_{front} is 21 %, then the bifaciality factor is ≈ 74 %.

2.2.1 PV profitability

In Sweden, there are in general low electricity prices and lower subsides for solar systems compared to the rest of Europe. There is also less and seasonal solar irradiation and these are factors that has an impact on the profitability of all PV systems in Sweden. Despite this, there is a rapid growth and development in the PV market. This might be a difference from other countries but conventional PV systems in Sweden are still profitable. But to increase the growth of the PV market and reach the national goals, Campana et al. suggests a development of new business models and new solutions (Campana, et al., 2021).

2.3 Agrivoltaics

2.3.1 Definition

Agrivoltaics (AV) is defined as a combination of agriculture and photovoltaics in the same area. Although the concept has become a hot topic in recent years, the idea of agrivoltaics was proposed in 1982. This integrated solar PV solution is becoming more popular and there are both research- and commercial agrivoltaic systems (AVS) all around the world showing potential. The idea is simple and derived from an agricultural method where the goal is to get a beneficial interaction between two productions. The agricultural method was based on intercropping to gain revenue and increasing the land equivalent ratio (LER) by mixing two crops in the same area. In the agrivoltaic systems the same beneficial interactions are possible but instead of two different crops there will be agricultural- and energy production (Zainol Abidin, et al., 2021).

There are three categories of agrivoltaic systems; cropland, greenhouses and grassland (Fraunhofer Insitute For Solar Energy Systems Ise, 2020). The idea of agrivoltaics is to remove the competition of land between the two parts of production but still care about both sides and making compromises that can benefit both (Zainol Abidin, et al., 2021).

2.3.2 Land equivalent ratio

One method that can be used to determine the efficiency of land use is land equivalent ratio, shorted LER. The method can be applied for agrivoltaic system because it can include more than one production source (Zainol Abidin, et al., 2021). The equation for LER is:

$$LER = \frac{CY_{APV}}{CY_{AC}} + \frac{E_{APV}}{E_{PV}}$$

Where CY_{APV} is the crop yield [t/ha] in an agrivoltaic system and CY_{AC} is the crop yield [t/ha] in the reference case without an agrivoltaic system. E_{APV} is the electric production [kWh/m^2/year] with an agrivoltaic system and E_{PV} is the reference without (Campana, et al., 2021). LER is a popular method to determine if it would be possible to have a synergy between two systems. If the LER is greater than 1, it means that a combination of the suggested systems/productive sources are more efficient that having them separately. To reach a value above 1 it is important to have both systems in mind when designing it. LER in the agrivoltaic field is dependent on finding a match between crop selected and the PV system design (Zainol Abidin, et al., 2021).

2.3.3 Research and results

Agrivoltaic research facilities and commercial systems are developing fast around the world in the recent years. In 2021, there was an installed capacity of 14 GW of agrivoltaic systems globally in comparison to the 5 MW in 2012. Even though the agrivoltaic systems market is growing there is a funding program for the PV design in five countries. In 2020, China alone had an installed capacity of 1.9 GW making them the largest shareholder. Chinas largest system has berries cultivated underneath and an installed capacity of 700 MW. Even though Japan does not have a system as big as in China, Japan has 1800 smaller systems instead (Fraunhofer Insitute For Solar Energy Systems Ise, 2020). Some of Sweden's neighboring countries that also developed agrivoltaic systems that has been evaluated will be described briefly in the next chapters below.

2.3.3.1 In Sweden

In 2021 in Sweden, there is only one agrivoltaic system installed and that was in Västerås. The project is led by Mälardalens Högskola together with partner companies and universities. It is a solar fence system, which means the system has vertical bifacial PV modules (Mälardalens högskola, 2021b). It is a smaller research facility and the installed capacity is 22.8 kW. Because it is a research facility and it was installed a year ago, the results from the research are yet limited. The crop selected for this system was pasture grass and clover because it was available in that field but there are plans to test other crops as well in the future (Campana, 2021b).

There are indications of results for the cultivations months of 2021 for the park system in Västerås. According to Mälardalens högskola agrivoltaic researchers, for 3 out of 5 months the results were positive for pasture grass and clover with an increase in crop yield. The two months had a decrease in the crop yield when the drought index was higher. The results indicated a decrease but not as significant, still a good result that could be acceptable for the farmers and installers (Campana, 2021a).

2.3.3.2 In Germany

In Heggelbach in south Germany, an agrivoltaic system was installed in 2016. The system was an elevated module system with a ground clearance height of five meters. During the upcoming two years, the increase of the LER was 60-84 % and better tolerance during drought periods. Four different crops grew under the modules as a test including winter wheat, potatoes, celery and pasture grass/clover mix. The crop yield stayed above 80 % and the PV modules increased the electric production due to the increased height combined with bifacial modules. The results from this system shows that the agrivoltaic LER will depend a lot on the weather. For example, the potatoes in Heggelbach increased the crop yield by 11 % in the warm summer of 2018 but during 2017, the crop yield of the potatoes decreased 20 %. The crop yield of the pasture grass and clover decreased by 5.3 % 2017 and the wheat and celery were reduced by 18-19 %, but for 2018 the wheat has a yield of 3 % higher than the reference and pasture grass/clover dropped 8 % below the reference (Fraunhofer Insitute For Solar Energy Systems Ise, 2020).

In 2013, a system with an east-west single tracker system was installed and tested with Chinese cabbage growing under. The system had a height of 3.5 m to the middle of the modules and a 7 m row spacing. With 0 m between the modules the results showed a decrease of 50 % for the crop yield. With 66 cm between the modules, there was a 29 % decrease instead.

The results from a solar fence system has been compared to a conventional ground mounted PV system, both systems located in Germany, see table 2. Although, the overall profitability depends on the relative profits of the crop and the electricity.

Table 2: The comparison between the two systems (Stridh, 2021).

System	Energy [kWh/m^2]	Land use [ha/MW]	Energy yield [kWh/kW]
Conventional ground mounted PV	60-70	1.5	900-1100
Solar fence	29-48	2.1-3.1	900-1000

2.3.3.3 In the Netherlands

Different integrated systems have been installed in the Netherlands. The facility has five pilot projects with integrated panels, all with different designs regarding cell spacing and transparency. Under these systems there are berries growing, like blueberries, raspberries, strawberries and black berries. The idea is to substitute the regular plastic covers used for cultivating in berries in tunnels with solar modules on top instead, making this an integrated system. The results have showed that the temperature under the module rows is 5 degree lower in the days and 2 degrees warmer at night because the modules create a microclimate underneath that can retain the warmth which is a benefit and could increase the quality. The research has showed that raspberries can handle the shade from the designs (Bellini, 2020b).

2.3.4 The different systems

Unlike conventional ground mounted systems, agrivoltaic systems needs to adjust to the agricultural and its processes. This means that new parameters become important when designing the systems. Light management is one of the most crucial ones when designing because the effect on the crops is of great significance. This is the reason why an east-west alignment is preferred because in general it obtains a more homogenous lightning for the crops (Fraunhofer Insitute For Solar Energy Systems Ise, 2020).

2.3.4.1 Elevated modules

Because of the need for extra material for the elevated construction, this design is a bit more expensive, see figure 1 (Sekiyama, 2019). The typical height of these systems is 3-5 m and depends mostly on the machinery operating underneath but also energy yield. The row spacing is still a bit wider than for ground mounted systems, to make sure the crops underneath gets enough and homogenous light. Even when elevated, the system in Heggelbach has a row spacing of 9.5 m, but the choice of height depends on the shade tolerance of the selected crop (Fraunhofer Insitute For Solar Energy Systems Ise, 2020).

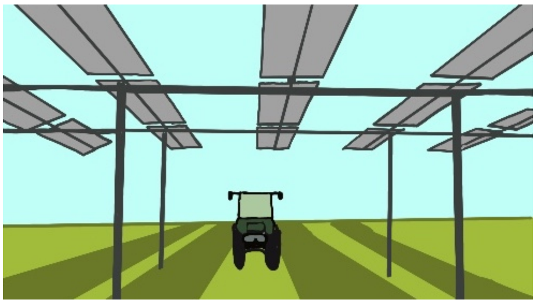

Figure 1: An example of an elevated system.

2.3.4.2 Integrated PV

Cultivating berries is often done under plastic covers in tunnels to keep the plants from getting burnt by too much sun and extend the harvest season. It also protects the plants from extreme weather, insects and some diseases (Scientia, 2020). It is also possible to cultivate apples under covers. With integrated PV, some material gets replaced by PV instead which in this case would be the plastic covered tunnels, see figure 2 (Fraunhofer Insitute For Solar Energy Systems Ise, 2020).

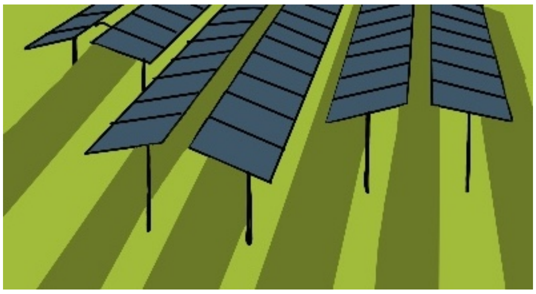

Figure 2: An example of an integrated system.

2.3.4.3 Single axis trackers

The single axis trackers track the suns movement throughout the day, keeping a perpendicular angle. This tracking system has a positive effect on the energy yield and can increases the electricity production (Fraunhofer Insitute For Solar Energy Systems Ise, 2020). There is an agrivoltaic single axis tracker system in Harre Jylland in Denmark, and an agrivoltaic system like the one in Jylland is planned to be built soon in Sweden as well. When it is time to do any agricultural process, the thought is to tilt away the modules from the row to the opposite row, making a clear path in between so the machinery can operate close to the mounting structure, see figure 3 (Braun, 2021).

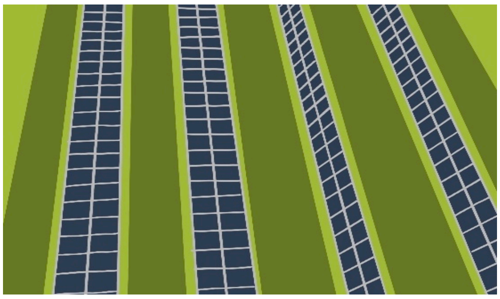

Figure 3: An example of a single axis tracker system.

2.3.4.4 Solar fence

A solar fence system is rows with modules like a conventional ground mounted system but with a vertical tilt, see figure 4. Because the height is lower and with no moveable parts, it is one of the cheapest agrivoltaic options. With a vertical tilt, the modules do not take up much land and the solar fence can be used as a real fence for animals if desired (Fraunhofer Insitute For Solar Energy Systems Ise, 2020).

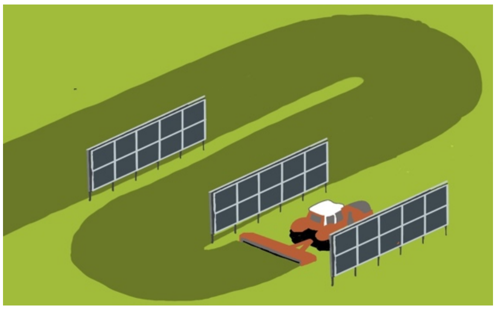

Figure 4: An example of a solar fence system.

2.3.4.5 PV systems with grazing animals

For some fields, cultivating crops is not suitable but can still be used as pastureland. On pastureland, farmers often have grazing animals that can also be combined with PV. PV systems with grazing animals is a category of agrivoltaic systems and the most common one. In these systems, the optimization of PV is prioritized and the module rows act as shelter for the animals. Sheep and chickens are best suited for this because they are small and calm (Fraunhofer Insitute For Solar Energy Systems Ise, 2020). However there has been tests with having cows combined with vertical modules in Germany (Next2sun, n.d.).

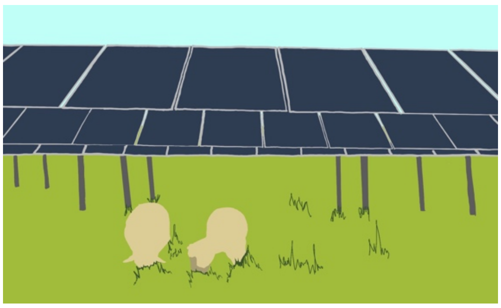

Figure 5: An example of a system with grazing animals.

2.3.5 Solar radiation

Solar radiation is important to the photovoltaics and for the photosynthesis and thus an important factor when designing an agrivoltaic system (Zainol Abidin, et al., 2021). PAR stand for photosynthetically active radiation, which wavelength is 400-700 nm. It is the light with best suited wavelength for the photosynthesis in plants and crops (ENGIE Solar, 2020). PAR is measured in $\mu mol/m^2/s$ and that is called Photosynthetic Photon Flux Density, shorted PPFD. But it can also be measured in W/m^2, called photosynthesis radiation flux density (Zainol Abidin, et al., 2021).

Another important factor is the solar irradiation which is the total radiant flux incident on a surface and it depends on numerous factors like altitude, latitude and the weather. The solar irradiation also depends on the angle of the sun and that is why it differs throughout the day. It is also higher at the equator and lower in the north. The unit is W/m^2 (Zainol Abidin, et al., 2021).

There is no way of changing the absorption spectra of the photosynthesis because it is set by the photosynthetic pigments, but the radiation absorbed by the photovoltaics can be changed. The relation between the need for radiation and the generated biomass in crops and plants is not linear due to the complexity of several metabolic steps. For a PV module, however, the solar radiation absorbed is linear to the electrical output (Zainol Abidin, et al., 2021).

The average solar irradiation in the Uppsala and Stockholm area in Sweden has been estimated at 1000 kWh/m^2 (SMHI, 2018). During the five winter months of October-February that are not included there is, according to SMHI, under 50-100 kWh/m^2 of irradiation in Sweden (SMHI, 2021).

2.3.6 Crop selection

Crops which yield it not significantly affected negatively by a decrease of PAR are defined shade tolerant crops. The range between a shade tolerant crop and a sensitive crop is big and the results in crop yield depends heavily on the amount of shade (ENGIE Solar, 2020). Some examples of shade tolerant crops are lettuce, grass/clover mix, tomatoes, stone fruits, berries, soft fruits, wild garlic, asparagus and hops (Fraunhofer Insitute For Solar Energy Systems Ise, 2020). Some tests on these crops have showed that some can tolerate a 50 % reduction of light (Zainol Abidin, et al., 2021). In a test done in Heggelbash, the leafy vegetables like lettuce has positive results up to a 30% reduction of light (Fraunhofer Insitute For Solar Energy Systems Ise, 2020).

The grass and clover mix being shade tolerant seems to be true even for Sweden since it was pasture grass and clover that showed some positive results in Västerås and a study in Oregon also had positive results with pasture grass and barley (Bellini, 2020a). Regarding that barley is doing well with agrivoltaics, more sources has gotten good results and barley seems to be more shade tolerant than wheat (Arenas-Corraliza, et al., 2019).

Potato is also known to be a shade tolerant crop and has been included in many tests of agrivoltaics (Schulz, et al., 2019). In an APV-Resola facility in Germany, the light decreased by 30 % but the potato yield still increased by 3 %. At the same conditions, the clover yield decreased by 8 % (ENGIE Solar, 2020). Another test in southwest Germany showed that potato can handle up to 26 % of shade but at 50 % it showed significant changes (Weselek, 2019).

All these percentages in decreased sun light needs to be thought of as individual and connected to a specific location since the solar irradiance depends on the location. But it can still give a good idea of which crop that is more shade tolerant and which ones are not.

2.3.7 The European Union agricultural policy

A farmer with agriculture is eligible for direct payments from the European Union as part of its agricultural policy. The requirement is having land that is used primarily for agriculture. The definition says "primarily for agricultural" but it is not clear whether or not that does include agrivoltaic systems. If the agriculture is not significantly limited due to the PV system being included as an activity in parallel, there are good chances that the owner of the field where the agrivoltaic system is can receive the direct payment from EU. But this require that the agrivoltaic system is planned and designed carefully so that the agriculture is just effected to a minor extent. In 2021, this is still very system specific since there is no concrete term for when the system is granted direct payment and when not. Until there are such terms, a conversation might be needed under the planning process to make sure (Fraunhofer Insitute For Solar Energy Systems Ise, 2020).

2.3.8 Advantages and challenges

For the farmers, having a combined system will equal an extra income, whether it is from a leasing deal with a company or if the farmers own the agrivoltaic park themselves. An increase in revenue can be a great motivation to install this kind of systems for many farmers around the world (Zainol Abidin, et al., 2021). One important advantage that separates an agrivoltaic system from a regular fixed tilt solar park is that this concept takes away the competition of land between the two production sources which means a better utilization of land. Because of the dual productions it also means that a solar energy system investment gets an increase in profitability (Mälardalens högskola, 2021b).

From a society perspective, an agrivoltaic systems expansion can provide even more new jobs in the already growing solar industry. It will also speed up the ongoing change to phase out fossil fuels because it gets replaced with renewable energy sources like solar. This will lead to a decrease in CO_2-emissions (Zainol Abidin, et al., 2021). The agrivoltaic systems have a positive impact on 14 of the 17 sustainable development goals set by the UN (Agostini, et al., 2020). It is also in line with the Food-Energy-Water nexus (Zainol Abidin, et al., 2021).

When cultivated under rows of solar modules, the crops create a microclimate underneath and that microclimate can be a benefit in many ways. For example, the crops can help lower the temperature under the modules and that can lead to an indirectly decrease in the PV modules temperature. The crops can lower the temperature by 1-2°C and because of that, increase the solar modules efficiency (Zainol Abidin, et al., 2021). In countries with a warmer climate, this cooler microclimate under the modules have showed an impact on the need for irrigation. When shaded, the soil moisture can increase, hence leading to less need for irrigation which means more water efficient system (Mälardalens högskola, 2021b). Saving water or reduce the need for irrigation can be a safety for many farmers when dealing with climate change and potential dryer periods. If or when the modules need to be cleaned, that water can be used by the crops underneath (Zainol Abidin, et al., 2021).

Some crops like shade and some does not, so the shading created by the PV modules will in some cases be a benefit and in others a challenge. It all depends on which crops that is selected (Zainol Abidin, et al., 2021). Another challenge with an agrivoltaic system is that both the PV system and the agricultural process needs to be adjusted to each other. Depending on the agrivoltaics system design the adjustment from both parts can differ, but it will require some extra maneuvering of the machinery and for some cases it also limits their efficiency by a decrease of the working width. If driven manually, the machinery cannot come all the way in to the PV structure and that can also affect the crop yield. When it rains, hails or snows, the PV modules can be a cover for the crops underneath and that can be a good thing. But them being there can, for some system designs, also cause an uneven water distribution, moist patches and soil corrosion (Weselek, 2019). The change in wind speed and how that effect the crop growth is also something to keep in mind when designing the systems to avoid negative impacts (Fraunhofer Insitute For Solar Energy Systems Ise, 2020).

2.3.9 Fixed tracks and GPS trackers

In an agrivoltaic system there will be some areas where it will be tricky for the machinery to reach. It will require some precise maneuvering and probably a small area untouched. This area need to managed somehow to avoid potential unwanted spreading of plants like weed. The first step is trying to the designing the system to reduce these areas and then try getting the machineries as close to the structure as possible without risking doing some damage.

There are GPS trackers available that can make perfect tracks and help with precise positioning. Most farmers in Sweden already uses this. It is more common than uncommon. A computer generates perfect routes and can be adjusted to obstacles like trees, stones or like in this case, rows of PV modules (Lana, 2021). This could be a solution to driving close to the PV structure.

2.4 Lease agreement

Svea Solar already offers land lease agreements when building solar parks. If the land is bigger than 5 ha, Svea Solar can do a land lease agreement to be able to use the ground for the solar parks. In the land lease agreement, the landowner is secured a long term revenue for the duration of the lifetime of the solar park. In these cases, Svea Solar maintains and monitors the parks during its lifetime and handles the finance (Svea Solar, 2021a).

For the agrivoltaic systems this can also be possible but instead of Svea Solar just leasing the land and installing a park there, the landowner, which in these cases will be a farmer, can continue using the land during the lease agreement. The idea is also that the allowance for the lease shall cover the possible lost in crop yield due to the panels. The goal is for the farmers to make a profit with an agreement like this (Solar, 2021b).

3 Summary of interviews

10 farmers were interviewed during this study where 8 of them were Svea Soar's previous agriculture customers. Two of the farmers that were interviewed did not have PV panels yet but both considered installing roof mounted PV soon. Because the concept of agrivoltaics is still in the developing phase in Sweden, none of the farmers were familiar with the system solution and therefore when asked about what they thought were the next step for their farm all 10 of them answered they would consider some type of storage system if the battery prices were to decrease.

To get a broad perspective, different kind of active farmers with cultivation of crops were interviewed. The only requirement was that they had to have agricultural land that they used actively for crop production. In figure 6, the different types of agricultural activity are shown.

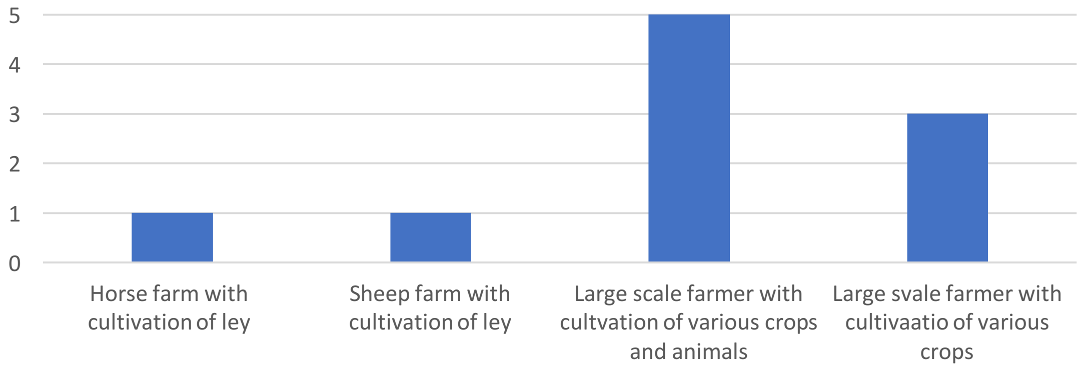

Figure 6: Different types of agricultural activity.

3.1 Opinions on suggested agrivoltaic systems

The different agrivoltaic systems discussed were 50/50, elevated panels, ground mounted systems with single axis tracker, solar fence, integrated PV and solar combined with grazing animals. When the farmers were asked which system(s) they saw the most potential in, there were very scattered answers, but all of them saw great potential in combining grazing animals with solar energy, see figure 7.

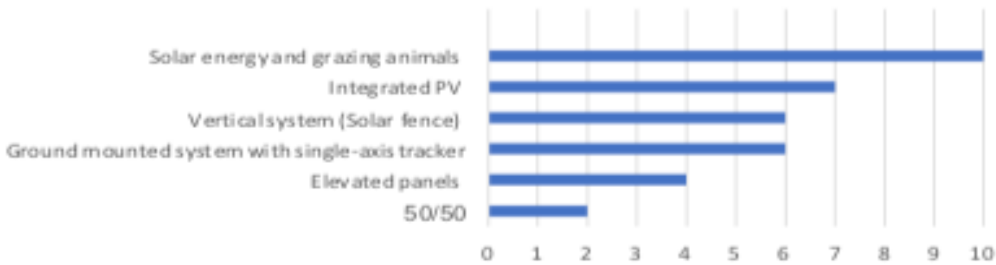

Figure 7: The farmers answer to the questions of which system they saw most potential in.

When the potential lease agreement was mentioned and discussed, 9 out of 10 farmers became much more positive about most of the systems.

A part from this, some of the farmers also has their own ideas of where the panels could be installed. 6 out of 10 farmers themselves suggested that panels could be placed in the outer edges of agricultural land. In the outer edges, there are naturally unused land that the farmers do not use and all 6 of them would consider having panels there.

3.1.1 Issues to investigate from a farmer's perspective

Although the general perception from the farmers was that they thought it was an interesting concept that could solve the food or energy issue and they were positive about contributing with renewable energy, they saw some obstacles and problems. When asked to think about all the negative aspects that came to mind while hearing about the systems for the first time, the following issues presented in table 3 were raised.

Table 3: The table shows the thoughts from the first impression and how many of the farmers that mentioned it.

Issue	How many?
The panels taking up too much space	7
Uncertainties regarding the affect in crop yield	8
Do not want to buy new machines for this:	3
How to handle the weed growing right under the panels.	5
Do not want higher workload	6
Less flexibility for driving machines	4
Not enough light due to shading from the panels	10
Uneven water distribution	3

3.1.2 Challenging processes

During one year, a lot of different operations take place on active agricultural land. The number of operations depends on the crop being grown. Some of these operations are easier to adapt the solar park to than others. The operations mentioned by the interviewed farmers depending on crop are presented in table 4.

Table 4: These were the processes mentioned during the interviews for each category of crop.

	Ley	**Cereals**	**Berries (grown in tunnels)**
Step 1	Plowing	Plowing	Sow
Step 2	Harrow	Crop spraying	Harvest
Step 3	Sow	Harrow	
Step 4	Adding manure and fertilizers	Adding manure and fertilizers	
Step 5	Harvesting	Harvesting	
Step 6	Strings and turn it over*		
Step 7	Press and collecting**		

*The machine strings the ley turns it over to make it dry

**Another machine presses the ley to balls at a certain moist content and then the balls gets collected.

The processes for growing berries are very simple as it does not require much when grown in tunnels. These processes are also performed by hand and without machines. Berry cultivation therefore does not have any processes with machines that could be disturbed by the solar panels and the processes will not affect the panels either. Ley cultivation has 7 steps but only step 4-7 are repeated annually. Because ley is a perennial crop, it does not need to be sown every year. The interviewed farmers plow and sow the land every 4-7 year. The challenging processes are mainly the harvesting, spraying of crops and the adding of manure and fertilization.

The farmers want to spray the crops for, among other things, weed control to avoid weeds spreading in the harvest. The problem with spraying the crops from an agrivoltaic perspective is that the panels will be there as well. The machines used for spraying are also one of those machines, together with the fertilizer machine, that has the largest working width. The working width the interviewed farmers had was either 12 m, 24 m or 36 m. This would possibly mean that the row spacing between the panels must be as wide. Some of the farmers thought it might be possible to spray above the panels and some did not think so because their machines have the ramp that sprays 0,5 m above the ground, which would then collide with the panels if there was not enough space between. Even if it were possible to spray above the panels, this will end up on them and possibly cause corrosion on the metal construction or stains on the panels that does not come of when it rains. Although, in organic farming, spraying the crops is not allowed.

As already mentioned, the manure and fertilize spreader also has a very wide working width, from 2.5 m to 24 m, which can pose a similar problem. But when it comes to fertilization, most farmers were more optimistic because there are various ways to do this and some fits better for Agrivoltaics systems than others. There is solid and liquid manure and artificial fertilizer. Solid manure can contain gravel and if spread above or around the panels there are risk for chipping of the panels. It depends on how much manure is left. The liquid manure however does not contain any gravel and it spreads with a ramp. There is also meat bone meal used in organic farming. It spreads close to the ground and does not splash. Liquid fertilizer is spread with a ramp spreader or thrower. If you use a thrower, there is a risk that this will hit the panels and cause corrosion if it sticks.

When the field is harvested, there is a risk of dust and small stone shots. However, some harvesters have splash guards that could ensure that is does not happen and not risking hitting the panels. The solutions to these challenges will probably have to be very individual and case by case by compromising from both sides.

3.1.3 Parameters

The parameters the customers wanted answered before a possible collaboration or investment when asked are presented in figure 8.

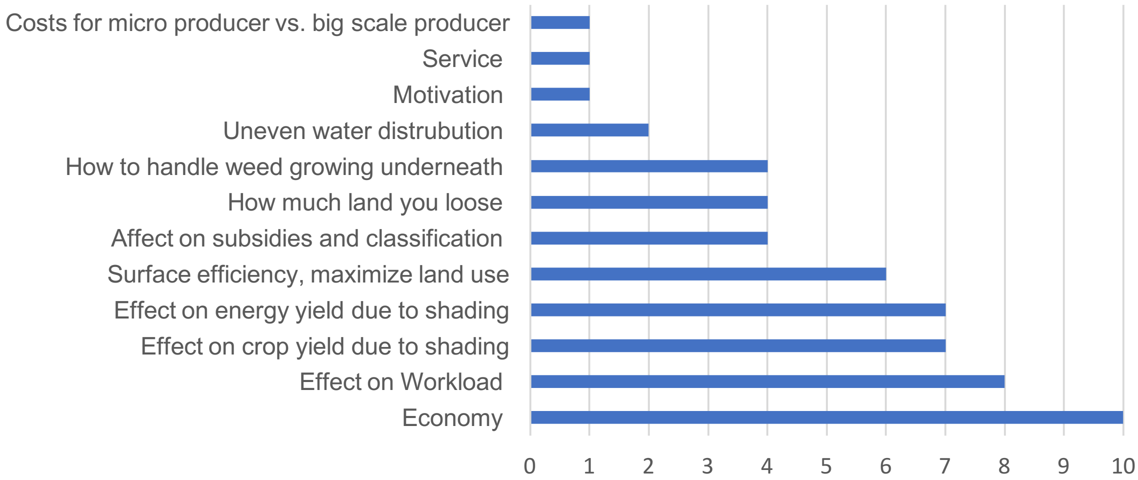

Figure 8: Interesting parameters that the farmers wanted answered and how many of them that said the same.

4 Implementation

4.1 Overview of the systems

4.1.1 Parameters to analyze

Like mentioned in the research aim, the parameters that will be analyzed are based on the farmers and Svea Soar's interests. According to the farmers' answers to the question in chapter 3.1.3, the economy is the most important one as all 10 answered this. Then in the top there is also concerns about workload and effect on crop- and energy yield. These parameters are interesting for Svea Solar as well. But after the literature study it is also clear that the critical parameter for agrivoltaics systems is the solar radiation and the compromises that the agriculture and PV system needs to do for a successful system that benefits both economically. That is why simulations was done on solar irradiance and the electricity production.

4.1.2 The area

The area were the simulations are based is a field located in Funbo Uppsala, and the area is owned by the Swedish University of Agriculture Sciences. To be able to compare the different system designs properly, a set area was needed. That is why an area of 5 ha (50 000 m^2) were chosen for all the simulations. When having a fixed area, it is easy to see how, for example, different row spacing or setbacks will impact the annual energy.

Regarding the setbacks, seen in figure 9, they were set to be as wide as the row spacing which was the easiest way to implement them in the simulations. For example, at a 12 m row spacing, the setback is 12 m as well. That is because a machinery that potentially require a 12 m row spacing to operate in between the rows will in most cases also need at least 12 m at the edges to be able to turn around and go into the next row, and that is called the setback area.

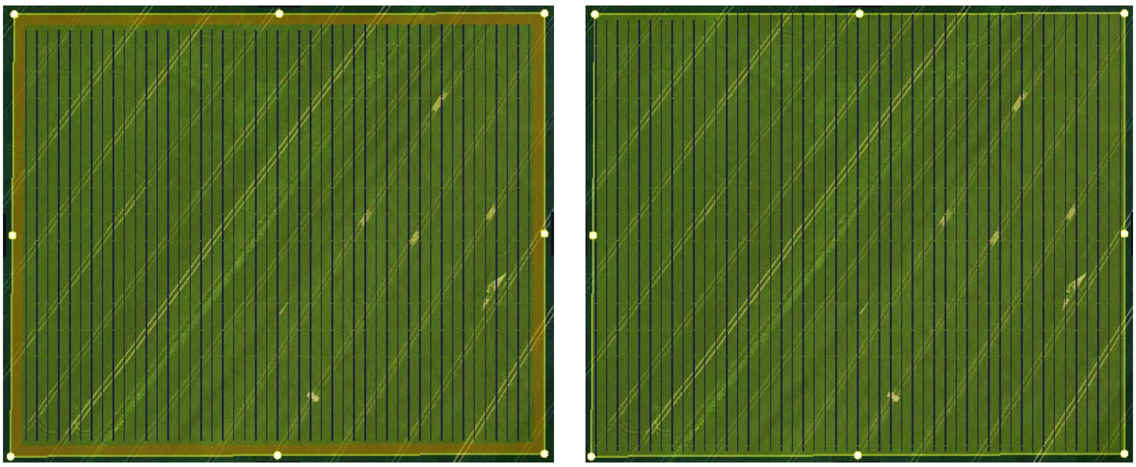

Figure 9: A solar fence system design with setbacks (orange) to the left and without on the right.

For all systems, the idea is that the machinery will follow a switchback like illustrated in figure 10. This will automatically generate a requirement of fixed tracks for the field.

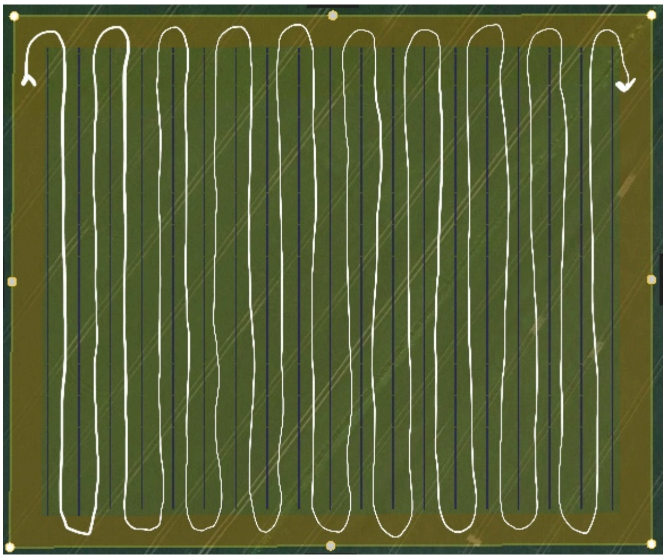

Figure 10: The suggested switchback for a solar fence system with setback.

4.1.3 The systems

Based on the theory and the interviews, three different system designs were chosen for the simulations. The chosen system designs were a single axis tracker system, a solar fence system and an integrated system. The PV and grazing animals' system does not need any simulations done because there are no crops to have in mind and the PV system can be prioritized when designing the system. All the farmers were positive to the system as well during the interviews and it does not need any further investigations like these simulations. Due to the probability mentioned in 2.2.1, the most expensive system, which is the elevated system, is also not included in this. The interviewed farmers were also skeptical to the elevated system.

4.2 The software

4.2.1 SketchUp

All the irradiance simulations were done in SketchUp and with an extension called DeLuminae Light. SketchUp is a 3D modelling tool that also have a lot of extensions to add. DeLuminae is one of the extensions and is used to simulate natural daylight. It can simulate average, total or maximum irradiance.

4.2.2 Helioscope

Helioscope is a web based software used for designing PV systems. It is used at Svea Solar and it is a leading software in the industry. It is a powerful tool that simplifies the designing process and it generate performance reports of the systems. However, it does not have an option for bifacial modules and that is why this project also needed another software with that quality.

4.2.3 SAM

SAM stands for system advisor model and is a software used in the renewable energy industry. It is not only for solar energy; it also has options for other renewable sources. The purpose of this software is to make the decisions of renewable energy projects easier due to the results of the simulations that can be done with SAM. There is an option for bifacial modules in SAM and that is the main reason why it was chosen.

4.3 Method

4.3.1 Interviews

The first part of the work involved interviewing some of Svea Soar's former agricultural customers to gather their opinions on the concept of a combined system but also expertise in agricultural. To not put words in the farmer's mouths, the interviews started with a broad perspective of possible future combinations of solar and agriculture, to avoid an already existing concept and get their thoughts of what they need and are missing with their existing systems before mentioning agrivoltaics. The goal was to talk to them and get an idea of what functions the systems needs to fulfill and which parameters are relevant to analyze and answer before they would be interested in a possible collaboration or an investment in any of the proposed systems. To obtain a more nuanced basis, researchers who are familiar with agricultural processes and researchers involved in agrivoltaic research in Sweden were also interviewed. These interviews where held over phone or Zoom and all recorded.

4.3.2 Designing the systems

After the literature study and the interviews with the customers, the appropriate systems were considered and designed in Helioscope. Even if Helioscope lack the bifacial option for simulations it is still a great PV designing tool. For comparison, it was important to have a fixed area and it is easy to keep the exact same size of the area in Helioscope for multiple designs while switching systems and parameters. The size was set to 50 000 m^2 which is 5 ha and it was used in all the PV simulations done for this project. The same goes for the albedo which was set to 20 % and the AC/DC ratio were kept around 1,20 for all systems as well. This is default settings in all the software's and suitable for this project.

Because 5 m is a common value for row spacing for fixed tilt and single axis tracker systems and because for some farmers with smaller equipment and less land, 5 m could be feasible as a row spacing that could match the working width of the machinery. That is why the simulated row spacing will start at 5 m. The chosen PV module for this project was a module with 650 W and 20.9 % efficiency. The dimensions were 2384×1303×35 mm and it is a common model used in Svea Soar's regular installations of utility scaled projects.

4.3.3 Base case

For comparison, a base case for the simulations was needed. When the parameters were changed in the simulations they all had a base case from which the values were changed one at a time, see table 5 for the set values.

Table 5: Base case values for each system.

System	Cell spacing [mm]	Row spacing [m]	Ground clearance height [m]
Solar fence	3	12	0,5
Integrated	3	12	3
Single axis trackers	3	12	1,5

For the Solar fence system, the distance between the modules was also simulated with as base case of 3x5 mm. The integrated systems had a space on top between the modules that was also changed in the simulations, see figure 13. The base case was 0,3 m between. The reason why the single axis tracker system did not have any similar simulations done were because for the other two it would be easy to change the distance because there is a natural space there anyway.

4.3.4 Weather data

The weather data was downloaded from EnergyPlus (EnergyPlus, n.d.) and the location chosen was Arlanda, Stockholm. The weather can differ much in Sweden from south to up north but because the area where the simulations are deigned upon lies in Uppsala it was reasonable to keep all the parameters to match that area. Arlanda is the closest weather measuring point.

4.3.5 Energy simulations

When the system had been designed in Helioscope the simulation was executed just to use as a comparison with the results from SAM. The values of installed capacity and number of modules in each designed system from Helioscope was used in SAM to keep the same area of 5 ha and the GCR was adjusted in SAM to match the row spacing. Then because of lack of consideration for the bifaciality and bifacial gain in Helioscope the rest of the energy simulations were complemented and executed in SAM. The bifacial module that was used in Helioscope and is used frequently in Svea Soar's utility scale projects was not among the options to choose in SAM but the values from that models datasheet was put in manually instead.

The integrated system was not included in the energy simulations because it is a difficult system to design in a good and real way and compared to the other system designs this system will probably not have a negative impact on the generated electricity since the row distance can be kept narrow and there is no machinery going in between any rows.

4.3.6 Irradiance simulation

SketchUP were used to simulate the total irradiance during a set period. The period was chosen to the agricultural half of the year in Sweden because the other months are irrelevant for this project. To simulate a PV module, components were made in SketchUp with the same dimensions as the components in the chosen PV module, like the PV cell and the glass back sheet. Then materials from a database in the SketchUp extension DeLuminae was assigned to the components to give the correct characteristics. DeLuminae gets its data from online databases for material. From those databases, a cell called Sunpower E20 Solar Panel Cell was chosen for the characteristics of the cell and a glass called clear_glass_4. See the other settings for the simulation in table 6.

Table 6: The irradiance simulation settings.

Sensor density	25 cm grid (spacing: 0,25, edges: 0,25)
Period	1^{st} of April to 31^{st} of October
Analysis	Total in kWh/m^2
Reflection	Direct only

For the irradiance simulation, a specified test surface is needed so that the system can calculate the irradiance on something specific. The test surfaces needed to be a general surface that would represent all possible results for the system. To do so it needed to be placed in such a way that if you make it wider or longer, the pattern is just to repeat itself. That can be seen in figure 11, 12 and 13, all of them represent all possible results.

4.3.6.1 Single axis trackers

Because this system has trackers it was a bit tricky to simulate it because in SketchUp the irradiation simulations are done at fixed objects. The solution was to simulate fixed angles to represent the trackers movement throughout a day. The fixed tilt angles were set to 10°, 40° and 90°. In figure 11 the system is shown as it was set up in SketchUp with the test surface underneath and between the modules.

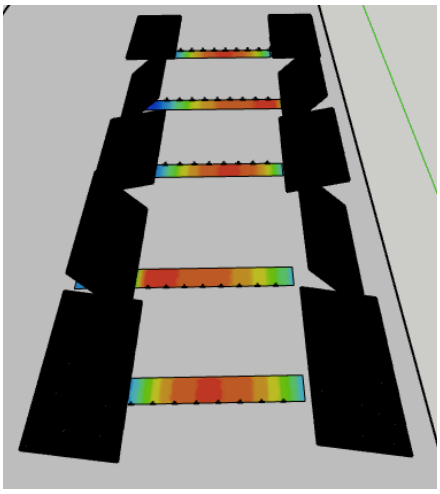

Figure 11: The single axis trackers system set up in SketchUp.

4.3.6.2 Solar fence

The solar fence set up was very similar to the regular fixed tilt designs but with a tilt of 90° making them vertical. In figure 12 the system is shown as it was set up in SketchUp with the test surface underneath and between the modules.

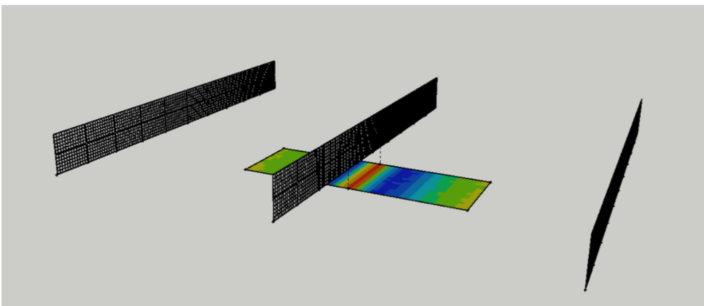

Figure 12: The solar fence system set up in SketchUp.

4.3.6.3 Integrated system

Integrated systems are a broad concept with many different designs, but the one chosen for this project is the integrated system that can be seen in figure 13.

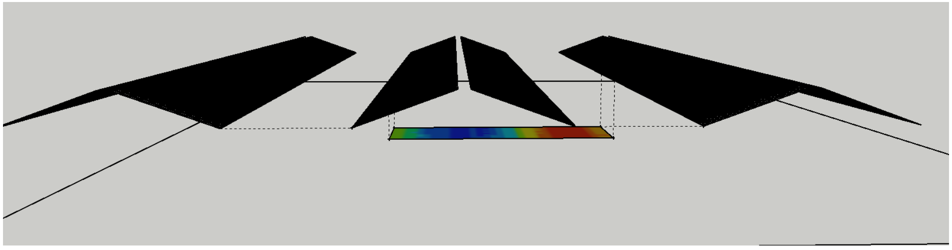

Figure 13: The integrated system set up in SketchUp.

5 Result

5.1 Energy simulations in Helioscope and SAM

5.1.1 Annual energy

Different agrivoltaic system solutions and row spacing affects the annual energy produced and the energy yield. In SAM, a single axis tracker system and a solar fence system were compared with and without setbacks and for different row spacing, see figure 14 for the result connected to annual energy in MWh and in figure 15, the energy yield.

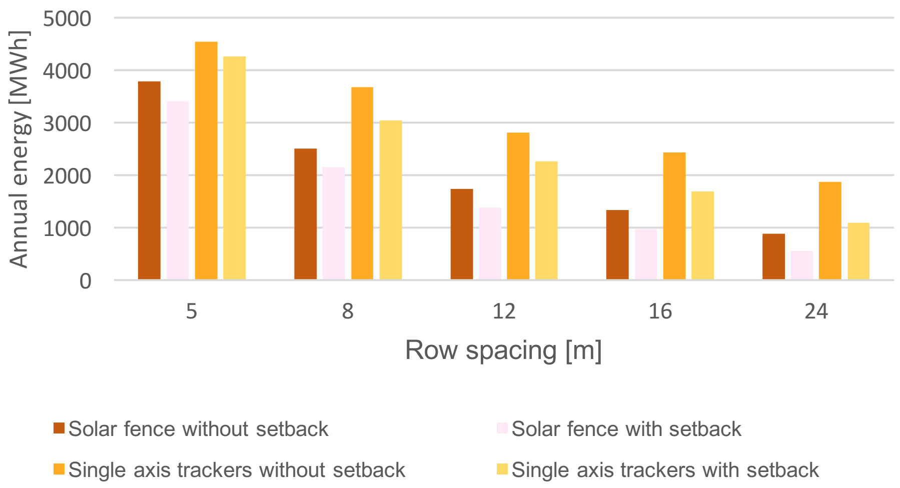

Figure 14: Result of annual energy in MWh for a solar fence system and a single axis tracker system with different row spacing simulated in SAM.

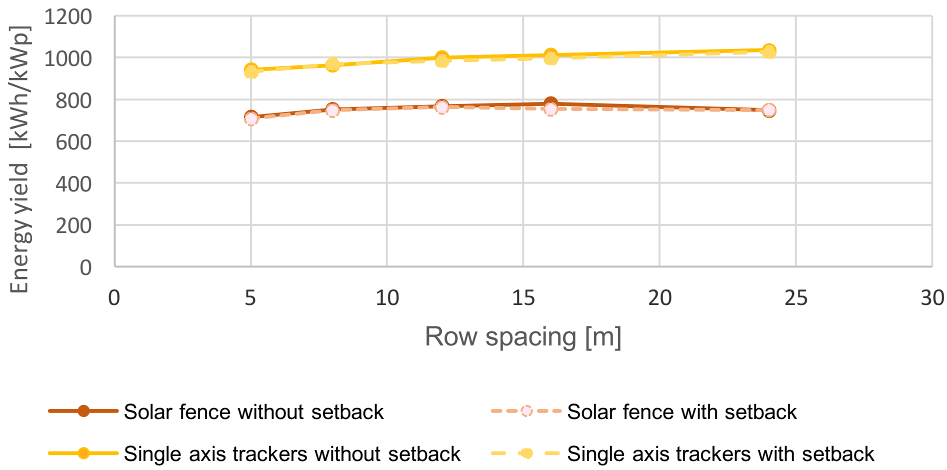

Figure 15: Result of energy yield in kWh/kWp for a solar fence system and a single axis tracker system with different row spacing.

As seen in figure 14, a single axis tracker system will generate more energy in a year than a solar fence system. The setbacks for each system is equal to the row spacing so that the potential agricultural machinery could turn properly at the edges. For some systems, there will naturally be space left at the edges but for those where the agrivoltaic park is planned in a narrow area, this need to be taken into consideration because it affects the annual energy production significantly. The difference in annual energy for a system with or without setbacks increases with increased row spacing. That is not the case for the energy yield. The energy yield, as seen in figure 15, is relatively constant with or without setback for both systems and that is because the energy yield is measured in kWh/kWp.

To validate these results, a comparison between the annual energy for a specific system in SAM and Helioscope was made, see figure 16 and 17. Because Helioscope lacks the ability to implement bifacial modules in the simulations (Helioscope, 2021), the results for the Helioscope simulations for annual energy should generate lower values compared to the simulations made in SAM.

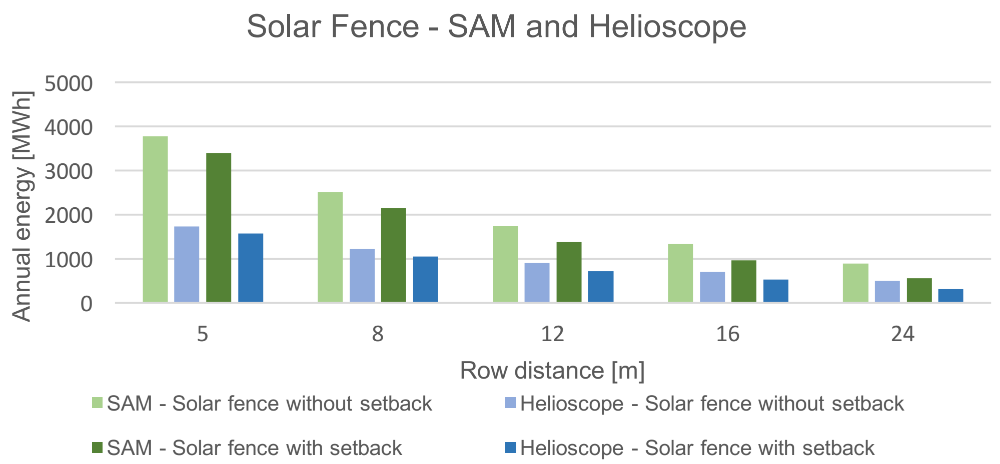

Figure 16: Result of annual energy in MWh for a solar fence system with different row spacing in both SAM and Helioscope.

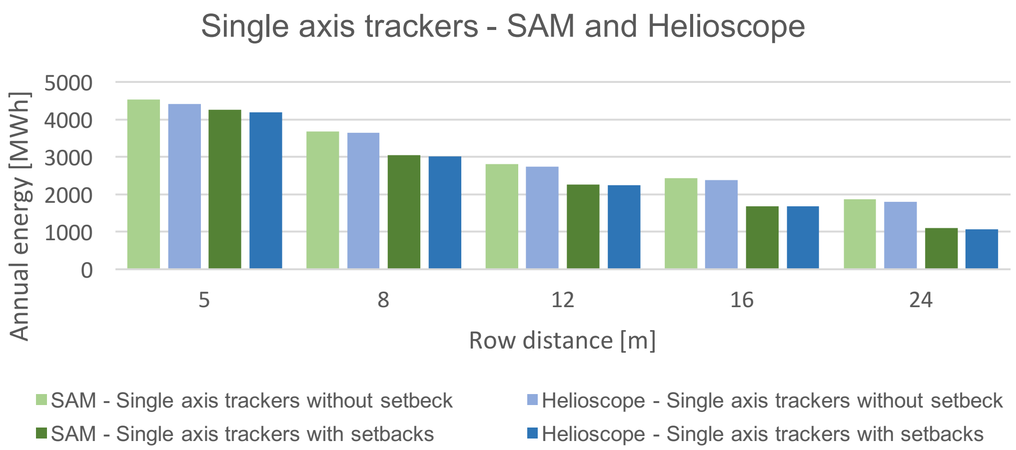

Figure 17: Result of annual energy in MWh for a single axis tracker system with different row spacing in both SAM and Helioscope.

Because the solar fence solution is positioned west to east and has a vertical tilt, it needs to have bifacial panels because otherwise the results will be like in figure 16 for the simulation in Helioscope. To validate the results of the solar fence solution, the results can be compared to the theory stated in 2.3.2.2 where a Solar fence system with a row spacing of 8-12 m had 29-

48 kWh/m^2 and in the results from this project the solar fence system generated 34.76-50.20 kWh/m^2. This seems reasonable because in the example from the theory they had 400 W modules and in this the modules are 650 W.

5.1.2 Installed capacity

Below in figure 18 and 19, the difference of installed capacity is shown with and without setbacks. The systems with setback has been shorted to "w SB" and the ones without setbacks just states the row spacing.

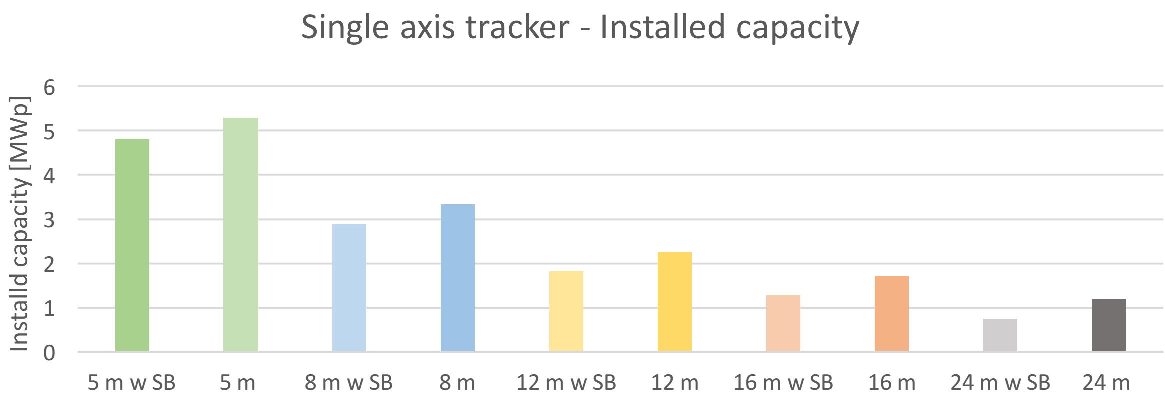

Figure 18: Result of installed capacity MWp for a single axis tracker system with different row spacing.

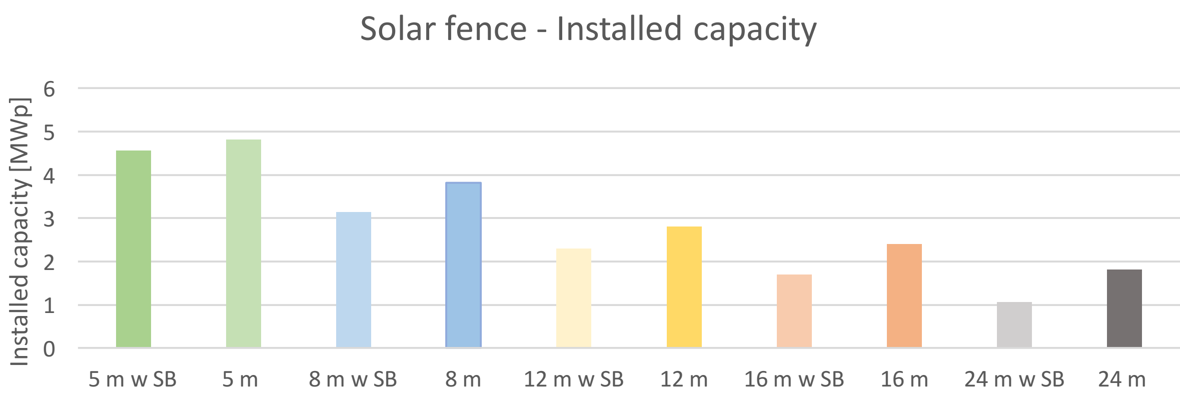

Figure 19: Result of installed capacity MWp for a solar fence system with different row spacing.

5.2 Irradiance simulation in SketchUp

5.2.1 Reference case

The reference case results were between 817 kWh/m^2 and 821 kWh/m^2 during the period of 1st of April and 31st of October, see figure 20. As mentioned in the theory, 2.3.4, the average solar irradiation in the Uppsala and Stockholm area in Sweden has been estimated at 1000 kWh/m^2 and during the five winter months that are not included, there is under 50 kWh/m^2 of irradiation which makes the reference case results reasonable. Since there is some rounding error the reference value is set to an average. Most of the surface gets at least 819 kWh/m^2 so the reference value is set to 818 kWh/m^2 for comparison.

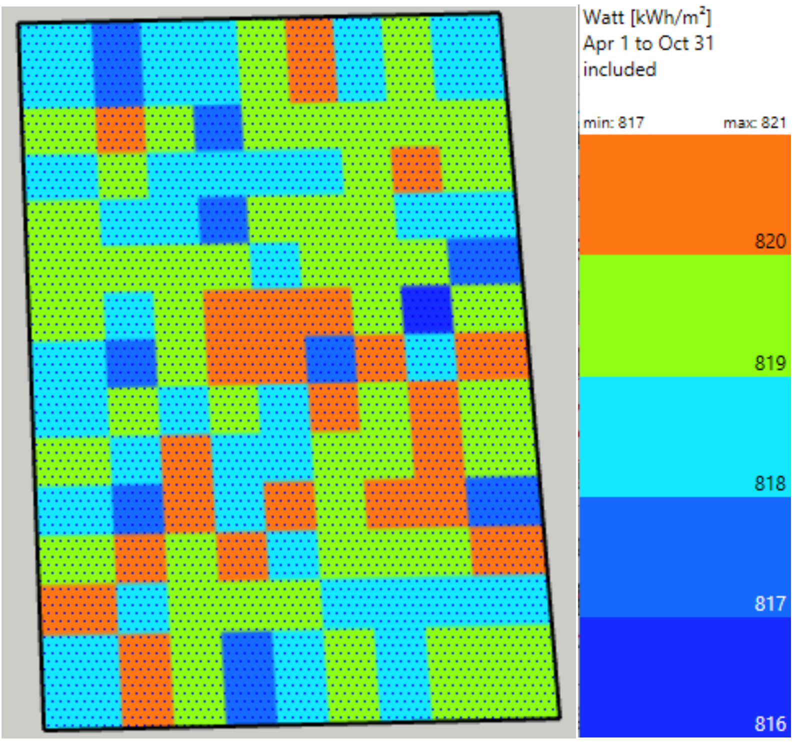

Figure 20: To the left, the test surface is shown with the squares being formed by the density of the sensors. To the right is the colored scale with a maximum of 821 kWh/m^2.

5.2.2 Solar fence

The results from the irradiation simulation in SketchUp, where solar fence systems were simulated, is shown in figure 21, 22, 23 and 24. The base case for all of them being 3 mm cell spacing, 0.5 m in height, 3x5 mm distance between the modules and 12 m row spacing.

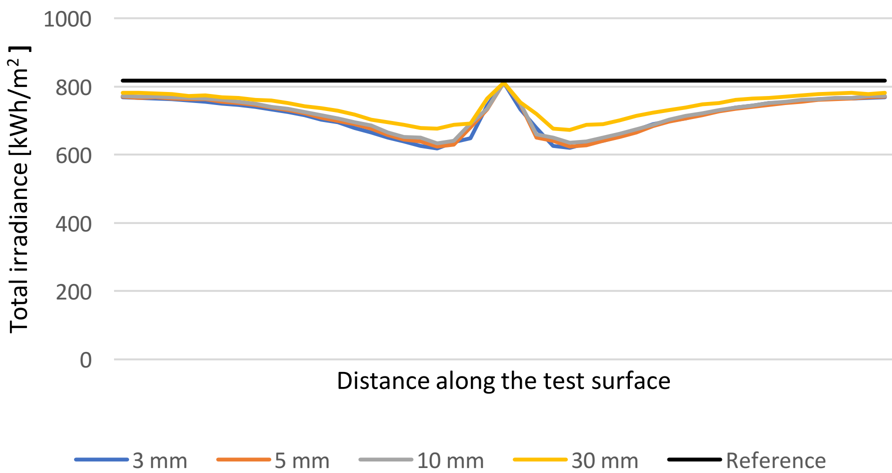

Figure 21: The result of changing the cell spacing between the cells in the modules from 3 mm to 30 mm.

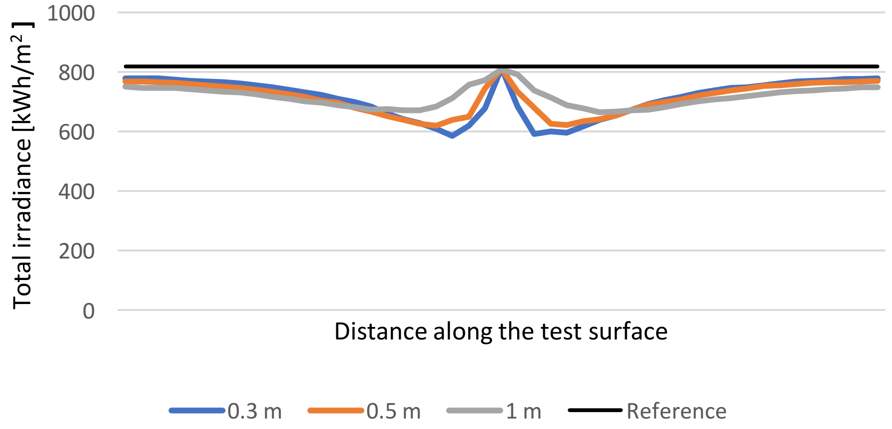

Figure 22: The result of changing the ground clearance height of the system from 0.3 m to 1 m.

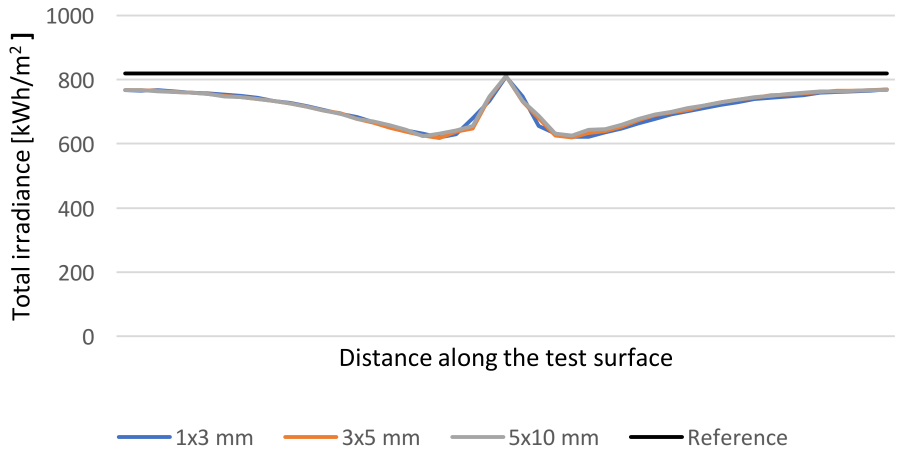

Figure 23: The result of changing the distance between the modules in the system from 1x3 mm to 5x10 mm.

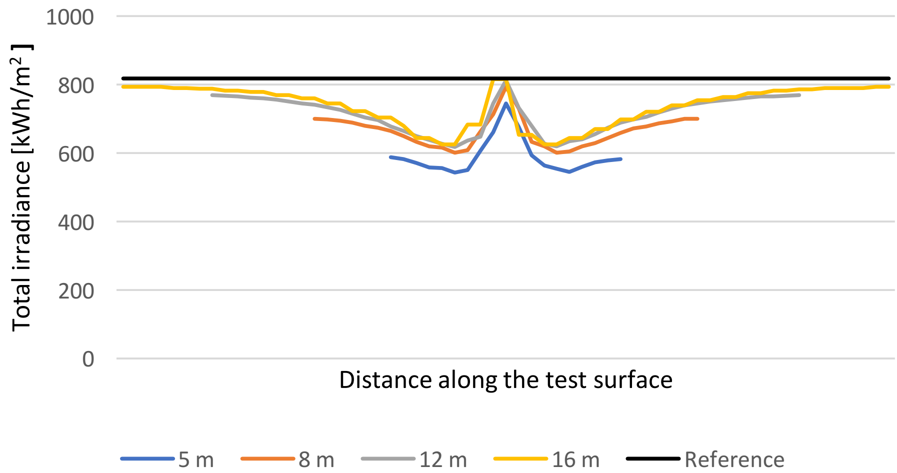

Figure 24: The result of changing the row spacing from 5 m to 16 m.

Out of the four parameters changed, the case where the distance between the modules were changed made the least impact on the results and changing the row spacing and ground clearance height is an easy way to increase the irradiation. If you increase the height by 0.7 m from 0.3 m to 1 m the irradiance minimum increases with 14 %, see table 7. Naturally the irradiance will increase when the row spacing increases, as can be seen in figure 24. Although, after an increase of row spacing above 8 m the difference is minimal for the solar fence system. Most the increase of irradiance happens between 5 and 8 m.

Table 7: The increase in solar irradiance after changing a parameter in a solar fence system. The increase in percent is calculated from the lowest value in both cases.

Parameter	Change	Increase
Distance between modules	1x3 mm to 5x10 mm	1 %
Row spacing	5 m to 16 m	13 %
Cell spacing	3 mm to 30 mm	10 %
Ground clearance height	0.3 m to 1.0 m	15 %

5.2.3 Single Axis trackers

Because single axis trackers are difficult to simulate in Sketch Up due to the movement of the trackers throughout the day, a base case were needed for a couple of fixed angles. Figure 25, 26 and 27 shows that it is a clear decrease of irradiation under the modules compared to the less shaded area between the rows. It is also the same area that will lack irradiation just because of the tracking. Even if the angles do not represent the movement for the whole day, it is roughly half of the day represented. After 90° there will be similar results as the 10° and 40° tilt just with the peak on the contrary. This can be seen in the results in figure 28, where 130° and 170° tilt are included to get a clearer picture of the impact that the modules and the single axis trackers have on the total irradiance throughout a day and along the test surface.

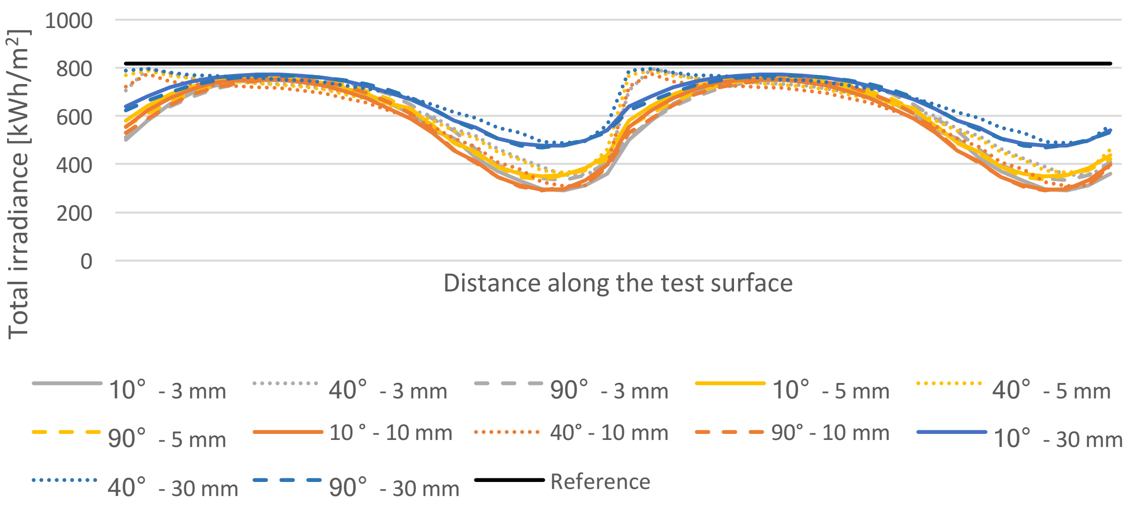

Figure 25: The result of changing the cell spacing for the solar fence system from 3 mm to 30 mm at different angles.

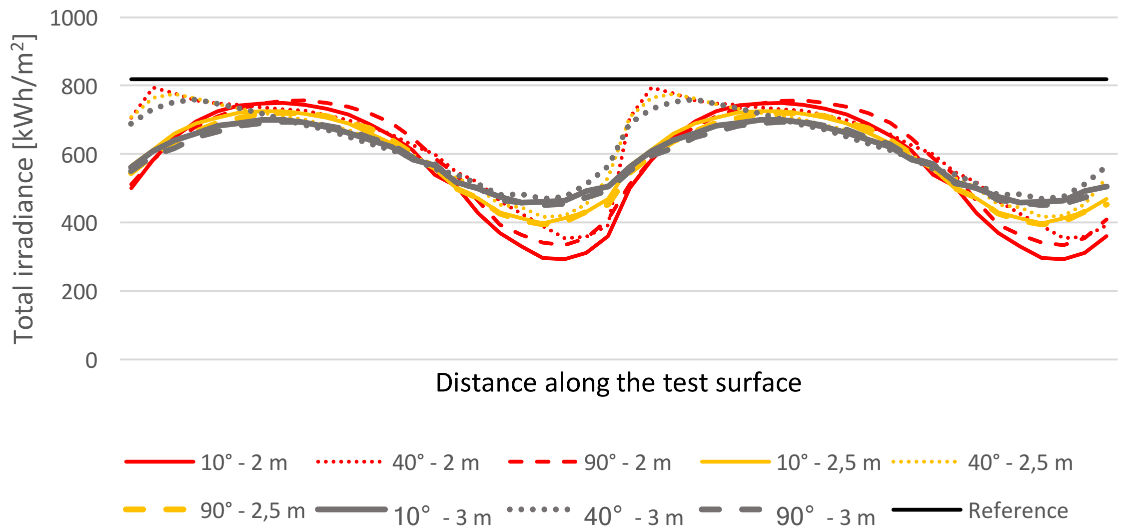

Figure 26: The result of changing the ground clearance height from 2 m to 3 m for different angles.

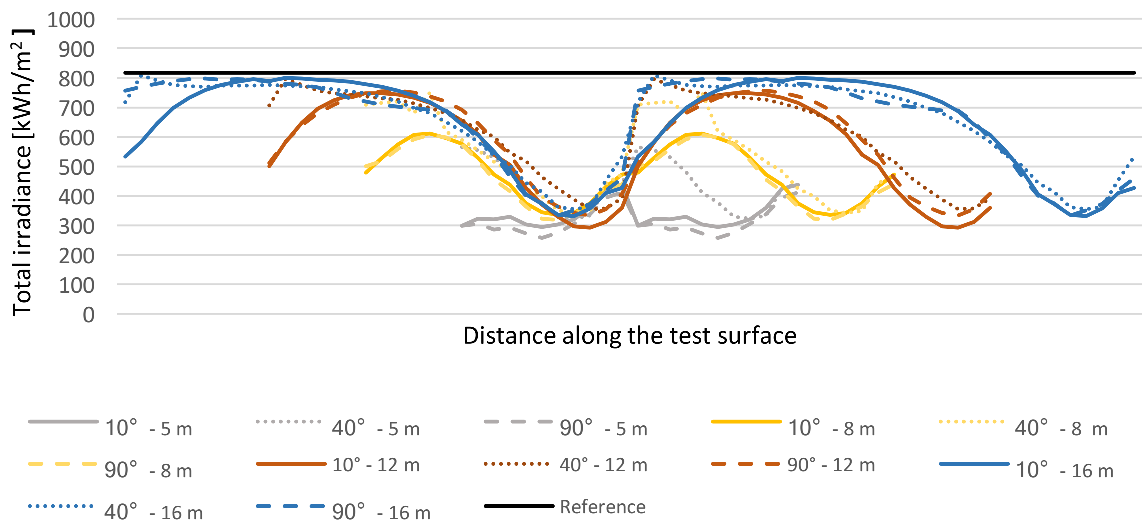

Figure 27: The result of changing the row spacing from 5 m to 16 m for different angles.

In figure 28, the change along the test surface is represented. This is for the base case of the single axis trackers. The test area is 12 m long and with sensors for every meter. At 5 m in there is irradiation above 600 kWh/m^2 but then after 10-11 m it drops below 600 kWh/m^2 again.

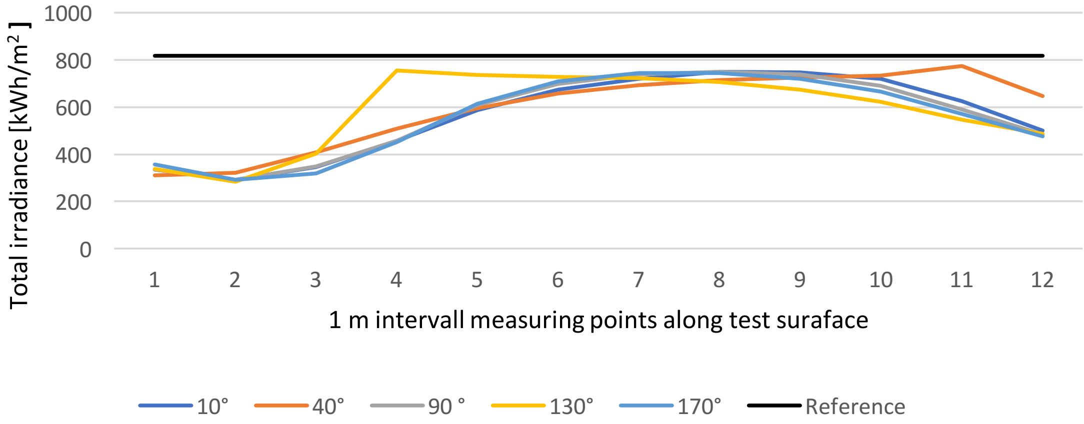

Figure 28: The test surface is 12 m long and these results show how the irradiance change along that surface with 1 m intervals and with two more tilt angles to represent the movement of the day.

The increasing of cell spacing in single axis tracker system has the biggest impact on the result as it increases with 65 % when changed from 3 mm to 30 mm, see table 8. The lowest impact is changing the row spacing with 29 %.

Table 8: The increase in solar irradiance after changing a parameter in a single axis tracker system. The increase in percent is calculated from the lowest value in both cases.

Parameter	Change	Increase
Row spacing	5 m to 16 m	29 %
Cell spacing	3 mm to 30 mm	65 %
Ground clearance height	2 m to 3 m	55 %

5.2.4 Integrated system

For the integrated system, the results were very different to the single axis trackers and the solar fence system. The values are significantly lower but that is something to expect, see figure 29, 30 and 31. When comparing the system designs, the integrated panels are much closer together and they also have panels in both directions all the time because they have a fixed position and tilt facing both east and west.

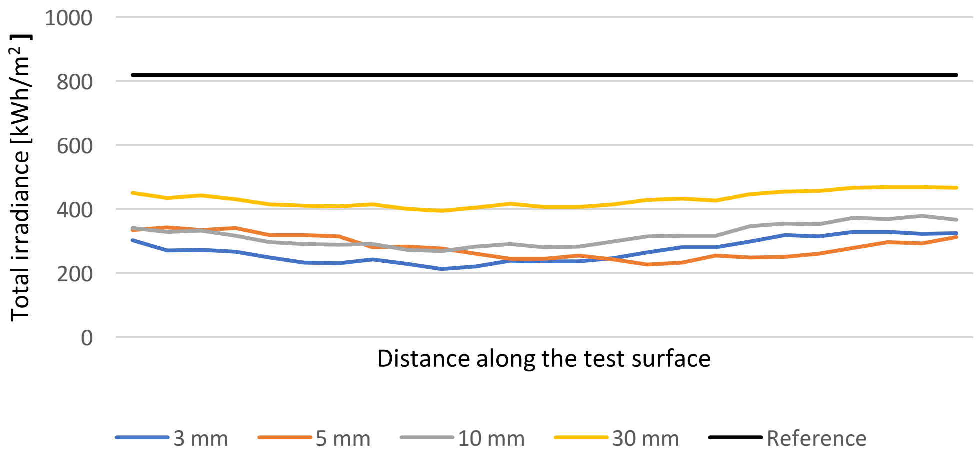

Figure 29: The result of changing the cell spacing for the integrated system from 3 mm to 30 mm.

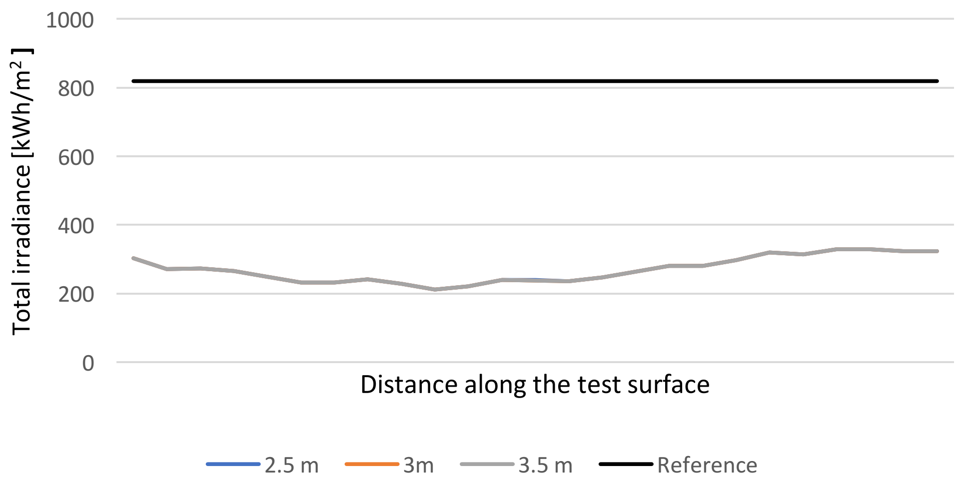

Figure 30: The result of changing the ground clearance height for the integrated system from 2.5 m to 3.5 m.

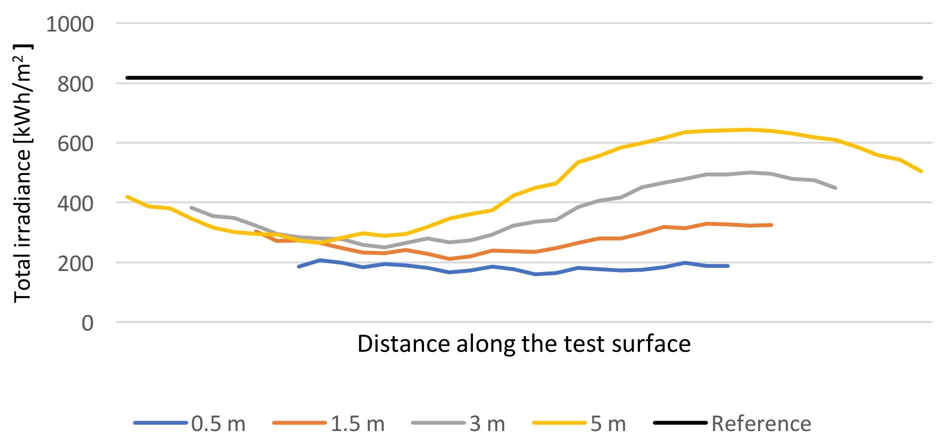

Figure 31: The result of changing the row spacing for the integrated system from 0.5 m to 5 m.

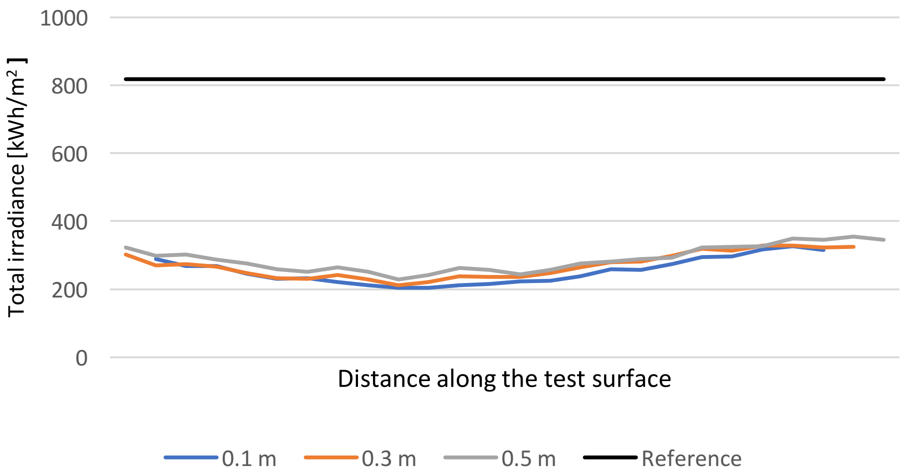

Figure 32: The result of changing the distance between the modules on top for the integrated system from 2.5 m to 3.5 m.

The parameter that had the biggest impact on the result when changed was the cell spacing. The lowest irradiation value for the cell spacing increased from 212 kWh/m^2 to 395 kWh/m^2 when changed from 3 mm to 30 mm. In table 9 there is a list to show the impact in percent of each parameters changed.

Table 9: The increase in solar irradiance after changing a parameter in an integrated system. The increase in percent is calculated from the lowest value in both cases.

Parameter	Change	Increase
Distance between modules on top	0.1 m to 0.5 m	8 %
Row spacing	0.5 m to 5 m	65 %
Cell spacing	3 mm to 30 mm	86 %
Ground clearance height	0.3 m to 1.0 m	0 %

5.2.5 Comparison

For a comparison of the three systems see figure 33 and table 10 for change in percent from the reference case of 818 kWh/m^2. The different system designs lowest and highest total irradiance are compared. The results show that the two designs that has the lowest total irradiance both is an integrated system and the two designs with the highest values are both a solar fence system. The single axis trackers are in between.

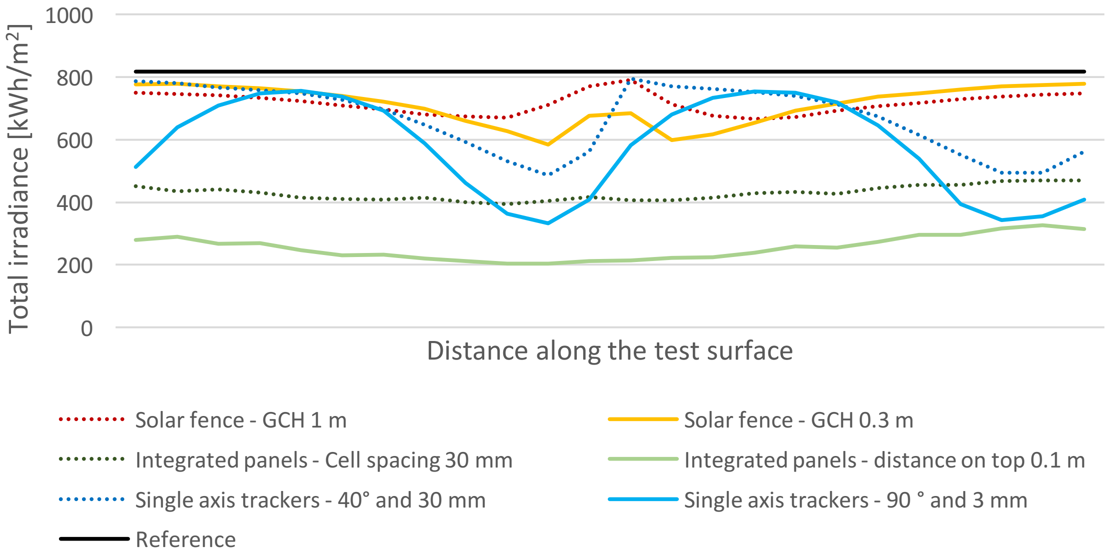

Figure 33: A comparison between all 3 systems, solar fence, single axis trackers and an integrated system.

Table 10: The decrease in solar irradiance in percentage from the reference case.

System and parameter	Decrease [%]
Solar fence – GCH 1 m	3–20
Solar fence – GCH 0.3 m	5-28
Integrated panels – Cell spacing 30 mm	42–50
Integrated panels – distance in top 0.1 m	60–75
Single axis trackers – 40° and 30 mm	3-40
Single axis trackers – 90° and 3 mm	8–59

6 Discussion

6.1 The systems

In general, the solar fence system is showing great potential in the solar irradiance simulation with a minimum result of 545 kWh/m^2 and a maximum of 816 kWh/m^2 which is very close to the values from the reference case, 818 kWh/m^2. It is also the design of the only agrivoltaic system in Sweden in 2021 and it showed some positive results. Since this system showed a smooth curve with around 20 % reduction of solar irradiation, this would be a suitable system for confirmed shade tolerant crops such as ley, berries and vegetables but also for barley which according to some studies proved to be a durable cereal crop. This is not a difficult system to install either and it is also the cheapest. The thing with the solar fence is to evaluate if the decrease in annual energy is worth it economically.

Compared to the single axis trackers both with a row spacing 12 m, the solar fence had an annual energy of 1738 kWh and the single axis trackers got 2812 kWh. Single axis trackers on the other hand had less solar irradiance under the modules than the solar fence. In figure 28, it can be seen that out of the 12 m test surface, around 5-6 m gets less solar irradiance than the solar fence lowest result and that is an important difference. The results for the single axis trackers has a span from 333 kWh/m^2 to 795 kWh/m^2. This means that a significant amount of the surface will have a greater reduction of solar irradiance then 20 %. An advantage with this system is that it is a commonly installed system that just needs to be adjusted to an agrivoltaic design.

The integrated system is a bit different from the other two and not as easy to compare. The results from the irradiance simulation is also lower than for the other two with 204 kWh/m^2 to 469 kWh/m^2. The reduction of solar irradiance is at minimum 42 %, which is close to the 50 % reduction that was the maximum reduction of solar irradiance that the shade tolerant crops could tolerate, according to one study in Germany. The solar irradiance is not the same in southern Germany as it is in Sweden which is something to keep in mind.

Changing the height did not make a difference for the base case and that is probably because the rows were too narrow for that to have an impact. The reason for this row spacing was to mimic the tunnels that the system was supposed to replace. If they were further apart, changing the height should make a difference. For these simulations, the change in cell spacing had the biggest impact on the results. In Germany, they do experiments on different cell spacing for these kinds of systems and that might be a solution to increase the irradiance.

As the grazing animals combined with PV systems are the most common one and it seems accepted among the interviewed farmers, it is a good option for agrivoltaics in Sweden. Like mentioned in the theory, there is also a great potential for this because in Sweden there is around 460 000 ha of pastureland and mowing fields.

In Sweden, there is lower solar irradiation, like mentioned in the theory the solar irradiation is lower up north. One of the agrivoltaic systems challenges is whether the crops can benefit from shade and get enough PAR. Most results so far of agrivoltaic systems are from places south of Sweden and those places have different climate and solar irradiation. Because of this one of the most shade tolerant crop might be suitable for a Swedish agrivoltaic system in the beginning. Like the system in Västerås that has pasture grass and clover which is a shade tolerant crop and has showed some positive results.

6.2 Suggestions

During the interviews, some challenges surfaced regarding an implementation of an agrivoltaic system in the Swedish agriculture that should be addressed. Most of them have possible answers and ideas in the theory. The second most important topic according to the farmers was if there would be any additional labor for them. To avoid any additional labor, the system needs to be designed with that in mind. For example, when the single axis tracker system needs to be tilted away so that the machinery could go in between the rows, that needs to be done automatically. It must be an easy solution that does not require them to do some extra work going in and around the system. Like for instance, if the modules get dirty, maintenance responsibilities need to be sorted out.

Because you are not allowed to spray the crops for weed control in organic farming there needs to be another solution. Like mentioned earlier, there is a possibility of untouched areas between the PV system structure and where the machinery can reach. To avoid unwanted weeds there needs to be a solution to how that could be done. Some options could be a robotic lawnmower that is programed to go directly under the PV system or having something cover the area underneath, like gravel or plastic sheeting. For some crops, maybe it could be a solution to have grazing animals on the field during the winter months to clean up.

One on the challenges mentioned in the theory is the uneven water destitution. It is not an issue for the solar fence systems because they have vertical modules and thus no risk for meddle in that. For the single axis trackers, it might be a good idea to have the option to tilt them vertical as well when it rains if needed.

This is only suggestions to the challenges and as the research and development of agrivoltaic system continues in Sweden and the rest of the world things will get clearer. Agrivoltaics is just in the beginning of a possible great expansion.

6.3 Software limitations

In figure 16, it is clear that Helioscope does not take bifacial modules into consideration and the result indicates that it is a monofacial module without any bifaciality or bifacial gain. That is why in figure 17, the solar fence solution is just generating about half the energy it could have with bifacial panels, like in the simulation done in SAM. Which is reasonable because the rear side should contribute and generate about half the energy in vertical tilt and west/east azimuth. For the single axis tracker system, the difference is smaller than for the solar fence systems and that is because with solar axis trackers, the modules track the sun and therefore the bifacial gain is smaller and so is the impact on the results.

In the irradiance simulations when the period for the simulation was chosen, 2017 weather data was used. This is just for one year but because the reference is simulated with the same file the decrease in irradiance under the modules are still valid. It was only the direct reflection and not with interreflections included in the simulations.

6.4 General

For the future when fossil fuels will continue to be replaced with other sources, it will be a greater need of electricity. A lot of the farmers' equipment could be electrical and that is a good motivation to have PV generated electricity close. Machines driven with the electricity produced on the same area would be a sustainable kind of agriculture. It could also be good for the south parts of Sweden, where most of the agriculture is, to have some more renewable energy sources.

After doing this study and project, it is clear that agrivoltaics are location independent and in 2021 there is no exact guidelines for when to do what. There is still so many possibilities for improvement and more research, and that is what makes agrivoltaics so interesting and a hot topic in the solar industry. These agrivoltaic systems might need some time to become accepted in the agricultural society, even if there is interest and curiosity. With just one smaller system in Sweden today and a new system solution where the results are very location dependent some might be skeptical about the benefits. But if both the agricultural and PV system installers work together and include one another and each other's expertise, there is potential for great synergy system.

7 Conclusions and further studies

After this project, it is clear that the results are location dependent and difficult to apply to other latitudes as the solar irradiation and the climate varies and both parts has a great impact on the results. Agrivoltaics is also a relatively new system solution and even if there are some commercial installations, those are different designs and different crops. The agrivoltaic development in Sweden, could benefit from some official agrivoltaic guidelines regarding crop selection per system and location. Even though all systems are very individual, some official recommendations would benefit the agrivoltaic growth. Now there are many interesting studies and research but official guidelines are still needed in the future for easier implementations.

In general, more studies on systems with different crops should be done in Sweden. There are some shade tolerant crops that could be suitable for first tries and evaluation at Sweden's geographic location and climate. Both a single axis tracker system and a solar fence system would be suitable in Sweden. The result of this study indicates that the solar fence system is suitable for shade tolerant crops, but also more sensitive ones like barley and field beans due to its 3-28 % reduction span of solar irradiance. But if the energy production is more important the single axis tracker system is a better option. The single axis tracker system should keep it to just the shade tolerant crops like ley, potatoes, leafy greens, berries and vegetables. The designs tested for the integrated panel system is not suitable for Sweden since the reduction of solar irradiance spans from 42-75 %. If this is to be considered, the design parameters must me adjusted more.

As a big company in the solar industry in Sweden, it would be interesting for Svea Solar and other companies in the industry, if Svea Solar went ahead with this and installed its first agrivoltaic system. No matter the which system or crop, it is important to keep the farmers included because they have a lot of experience and ideas from their expertise from the agriculture.

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