



UPPSALA  
UNIVERSITET

UPTEC ES 22018

Examensarbete 30 hp

Juli 2022

# Optimizing sunlight distribution in agrivoltaic systems for the Swedish climate

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## Abstract

Due to a rising land demand for the construction of large-scale PV-systems, there is increasing competition between energy and food production. A new emerging segment within the PV market called agrivoltaics is providing a contributing solution to this issue by co-using the land for both crop cultivation and PV energy. Agrivoltaics is a relatively new application in Sweden, so far there is only one research site in Kärbo Prästgård, Västerås, which was built in 2020. This thesis aims to examine how the basic layout of a PV system affects the irradiance distribution of an agrivoltaic system located in Sweden. With the aim of reaching an effective light sharing to provide the crops with acceptable growing conditions while producing as much electricity as possible. Methodologically, this was done by performing optical light simulations for a big number of different PV layouts. The results show how the module row distance and the array height have the most significant influence on the total irradiance distribution throughout the year. Furthermore, by altering the clearance height and the system azimuth, the irradiance uniformity on the ground can be improved, which results in more similar growing conditions for all the cultivated crops. Arguments are also given for why it is helpful to consider the temporal distribution of the ground irradiance. This thesis has shown that there are PV system layouts that provide low degrees of shading for the crops cultivated on the ground beneath the modules. However, if agrivoltaics is a suitable application for the Swedish climate or not is still an open question. Economic analysis is needed to examine the profitability of agrivoltaic systems in Sweden, and experimental studies on how the shading from the PV modules affect the crop growth in practice would also be useful. In the result section, there are some example layouts given for different degrees of tolerated ground shading which can be used when planning for future agrivoltaic parks.

The results generated in the optical light simulations will be accessible for future research. These data files can be found attached together with this report on the DiVA portal.

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## Populärvetenskaplig Sammanfattning

På grund av de pågående klimatförändringarna finns det en stark strävan mot en omställning i så väl det globala som det Svenska energisystemet, från användning av fossila energikällor till förnyelsebara. Solenergi är en av de förnyelsebara energikällorna som ökat i användning allra mest de senaste åren, men svårigheterna med att hitta mark att anlägga stora solcellsparker på saktar ner utvecklingen. Det finns också en konkurrens på marknaden när det kommer till just markanvändningen, mellan mat och energiproduktion. En ny gren inom solenergi som kallas för agrivoltaics har utvecklats som ett svar på detta problem, och innebär att solelsproduktion kombineras med odling av jordbruksgrödor på samma mark.

Det finns många potentiella fördelar respektive utmaningar med att implementera agrivoltaics i ett svenskt klimat. Solpanelerna bidrar med skugga till grödorna, vilket kan vara bra om det är väldigt soligt eller torrt. Samtidigt som grödorna släpper ut fukt som kyler ner solpanelerna, vilket ökar solcellernas verkningsgrad. Sverige har en relativt låg årlig solinstrålning om man jämför med många andra länder i världen, på grund av att vi befinner oss så långt norrut. Frågan som ska besvaras i detta arbete är om denna låga solinstrålning påverkar det optimala sättet att utforma ett agrivoltaiskt system, och huruvida detta är en lämplig teknik att använda på våra breddgrader. Dessutom ska detta projekt undersöka de enskilda designparametrarnas inverkan på hur det inkommande solljuset fördelas i systemet.

Arbetet utfördes genom att göra ljussimuleringar i programmet SketchUp Deluminare för många olika designalternativ. I programmet beräknades hur mycket solinstrålning som landar på olika delar av systemet; på marken mellan panelraderna, samt på solmodulernas fram och baksida. Mätningen på baksidan av solmodulerna användes för att kunna utvärdera hur systemet skulle prestera om bifacialpaneler används, det vill säga solpaneler som kan utnyttja instrålning från både fram och baksidan av modulerna. Sedan bearbetades datan för att kunna utvärdera hur de olika designparametrarna påverkar hur solinstrålningen distribueras i systemet. Detta för att försöka nå en effektiv ljusdelning mellan grödorna som växer på marken samt hur mycket instrålning som landar på modulerna, för att kunna producera så mycket effekt som möjligt. Designparametrarna som undersöktes i detta projekt är; avståndet mellan modulraderna, höjden på systemet, antalet moduler per rad, modullutningen samt systemets riktning. Vidare beräknades också den tillgängliga effekten för tre olika exemplarsystem.

Det finns begränsat med forskning att hitta på hur den ökade skuggan från solpanelerna skulle påverka skörden, därför har resultaten i denna rapport utvärderas utefter några olika nivåer av markskugga. Resultaten visar hur radavståndet samt modulhöjden (antal moduler staplade på bredden), har den största påverkan på systemets totala ljusfördelning över ett år. Medan systemets riktning, samt hur högt över marken modulerna är lokaliserade påverkar hur solinstrålningen fördelas över marken i systemet. Att rikta modulerna mot någon annan riktning än rakt söderut, samt att höja modulerna gör att markinstrålningen jämnar ut sig över marken, vilket ger alla grödor liknande tillväxtförhållanden. Att ändra lutningen på solpanelerna är ett sätt att optimera effektproduktionen från solcellerna, men en brantare lutning på panelerna leder också till en liten ökning av solinstrålningen på marken. Detta projekt har också argu-

menterat för att det är viktigt att se till hur markinstrålningen är fördelad tidsmässigt, det kan till exempel vara fördelaktigt att se till att grödorna får som mest skugga mitt på dagen, medan skuggningen bör minimeras under morgon och kväll.

Det finns vissa begränsningar i detta projekt på grund av dess utformning. En av dessa är att bara ett avgränsat antal designalternativ har undersökts, medan systemet i verkligheten skulle kunna utformas på ett oändligt antal olika sätt. Alternativ så som användning av semitransparenta solcellsmoduler eller att införa ett avstånd mellan modulerna i en rad skulle förmodligen ge lovande resultat för mängden instrålning som når grödorna, men dessa alternativ är inte inkluderade i denna studie. När man planerar för ett agrivoltaiskt system i verkligheten finns det också många praktiska parametrar att ta hänsyn till. Det måste finnas nog med utrymme för jordbruksmaskiner att kunna passera säkert genom systemet; vilket gör att systemet antingen måste ha ett så stort radavstånd att maskinerna kan passera mellan raderna, eller att systemet monteras högre upp på en ställning så att maskinerna kan passera under.

Slutsatserna som dras i detta arbete är att möjligheten finns att utforma ett agrivoltaic system som resulterar i en relativt låg skugga av grödorna, vilka med stor sannolikhet skulle kunna vara lämpliga för användning i ett svenskt klimat. Men huruvida dessa system skulle vara ekonomiskt lönsamma är fortfarande en öppen fråga och någonting som också beror på hur utvecklingen ser ut framåt i tiden. Ett sjunkande pris på solcellsmoduler och ett ökande elpris skulle kunna förbättra förutsättningarna för utbyggnad av agrivoltaics system i Sverige avsevärt. Mer forskning på grödors anpassningsförmåga till förändrad solinstrålning behöver utföras, då många växter har förmågan att anpassa sig till nya förhållanden, så som en reducerad solinstrålning.

## Executive Summary

Due to the rising demand for available land to build large-scale PV plants on, there is an increasing competition between energy and food production. A new emerging segment within the PV market called agrivoltaics is providing a contributing solution to this issue by co-using the land for both crop cultivation and PV energy. This thesis aims to examine how the basic layout of a PV system affects the irradiance distribution of the agrivoltaic system located in Sweden. The results show how the module row distance and the array height have the most significant influence on the total irradiance distribution throughout a year. But by altering the clearance height and the system azimuth, the irradiance uniformity on the ground can be improved, resulting in more similar growing conditions for the cultivated crops. The result section presents examples of suitable PV layouts for a few different ground shading limits, and the results are evaluated for two cases; the use of monofacial and bifacial PV modules respectively. This thesis has also provided arguments for why it is helpful to consider the temporal distribution of ground irradiance. It can also be useful to consider the trend of the farms electrical load to try and maximize the self-consumption of the system. Adjusting the temporal distribution of the irradiance can be done by, for example, altering the azimuth of the PV system. In practice, there are also other parameters to consider when designing for an agrivoltaic system, such as; the shade tolerance of the selected crop species as well as the dimensions of the farming equipment used. Whether agrivoltaics is suitable for the Swedish climate is still an open question. This thesis has shown how there are PV system layouts that provide reasonable amounts of shading of the crops grown on the ground, but additional research is needed to reach further conclusion. An economic analysis would be useful to examine the profitability of agrivoltaic systems in Sweden, and practical studies on how the shading from the PV modules affect the crop growth is also needed.

## Acknowledgement

The completion of this master's thesis marks the end of my studies at the master of science program in Energy Systems at Uppsala University and the Swedish University of Agriculture. First, I want to thank my supervisor Jonathan Staaf Scragg for the valuable support throughout this project, for leading me onto the right track and for contributing with experience and knowledge. My subject reader Uwe Zimmermann for providing good advice and for valuable input on the report writing. And to Marcos Lana for giving an engineer a crash-course in ecology.

I also want to take the opportunity to thank all of my fantastic friends and classmates, for enriching my life and for always being there. Last but not least, I want to thank my family and my partner for always being my biggest supporters. The last couple of years have been some of the best and most rewarding years of my life, and I could not have done it without you. Now, off to new adventures!

*Uppsala, June 2022*

*Amanda Daniels*

## Glossary

|                         |   |
|-------------------------|---|
| <b>BF</b>               | Bifaciality Factor  |
| <b>kWh</b>              | Kilo Watt Hour  |
| <b>PAR</b>              | Photosynthetically Active Radiation                                   |
| <b>PR</b>               | Performance Ratio   |
| <b>PV</b>               | Photovoltaics: the direct conversion of sunlight into electric energy |
| <b>STC</b>              | Standard Testing Conditions   |
| <b>TMY</b>              | Typical Meteorological Year   |
| <b><math>W_p</math></b> | Output power for a PV module at STC                                   |

## Nomenclature

| Symbol   | Property                | Unit |
|----------|-------------------------|------|
| $\gamma$ | <b>Azimuth</b>          | °    |
| $\beta$  | <b>Tilt</b>             | °    |
| w        | <b>Module Width</b>     | m    |
| L        | <b>Row Distance</b>     | m    |
| h        | <b>Clearance Height</b> | m    |

## Table of content

|          |                                       |           |
|----------|---------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                   | <b>1</b>  |
| 1.1      | Goal . . . . .                        | 1         |
| 1.2      | Framing of Question . . . . .         | 2         |
| 1.3      | System Boundaries . . . . .           | 2         |
| <b>2</b> | <b>Background</b>                     | <b>3</b>  |
| 2.1      | Solar Irradiance . . . . .            | 3         |
| 2.1.1    | Irradiance Theory . . . . .           | 3         |
| 2.1.2    | Optical Theory . . . . .              | 3         |
| 2.1.3    | Typical Meteorological Year . . . . . | 4         |
| 2.2      | PV . . . . .                          | 4         |
| 2.2.1    | Performance Ratio . . . . .           | 5         |
| 2.2.2    | Shading . . . . .                     | 6         |
| 2.2.3    | Bifacial PV Modules . . . . .         | 6         |
| 2.3      | Agrivoltaics . . . . .                | 7         |
| 2.3.1    | Potential Benefits . . . . .          | 8         |
| 2.3.2    | Potential challenges . . . . .        | 9         |
| 2.3.3    | Micro-Climatic Effects . . . . .      | 10        |
| 2.3.4    | Plant Ecology . . . . .               | 10        |
| 2.3.5    | Crop Shading Tolerance . . . . .      | 12        |
| 2.3.6    | Land Equivalent Ratio . . . . .       | 12        |
| 2.4      | Previous Studies . . . . .            | 13        |
| <b>3</b> | <b>Method</b>                         | <b>15</b> |
| 3.1      | Layout . . . . .                      | 15        |
| 3.1.1    | Ground Based . . . . .                | 16        |
| 3.1.2    | Vertical Bifacial . . . . .           | 16        |
| 3.1.3    | Stilt Mounted . . . . .               | 17        |
| 3.1.4    | Integrated System . . . . .           | 17        |
| 3.2      | Design Parameters . . . . .           | 18        |
| 3.2.1    | Clearance Height (h) . . . . .        | 18        |
| 3.2.2    | Row Distance (L) . . . . .            | 19        |
| 3.2.3    | Azimuth ( $\gamma$ ) . . . . .        | 19        |
| 3.2.4    | Tilt ( $\beta$ ) . . . . .            | 19        |
| 3.2.5    | PV Module Dimensions . . . . .        | 19        |
| 3.2.6    | Albedo ( $\rho$ ) . . . . .           | 20        |
| 3.2.7    | Weather Data and Location . . . . .   | 20        |
| 3.2.8    | Time Period . . . . .                 | 21        |
| 3.2.9    | Summary . . . . .                     | 21        |
| <b>4</b> | <b>Simulations</b>                    | <b>22</b> |
| 4.1      | Assumptions . . . . .                 | 23        |
| 4.2      | Simulation Settings . . . . .         | 24        |
| 4.2.1    | Sensor Spacing . . . . .              | 24        |
| 4.2.2    | Model Dimensions . . . . .            | 25        |
| 4.3      | Analyze Results . . . . .             | 26        |
| 4.4      | Calculations . . . . .                | 27        |



|          |  |           |
|----------|--|-----------|
| 4.4.1    | Shading Index . . . . .  | 27        |
| 4.4.2    | Electrical Output . . . . .                                      | 28        |
| 4.5      | Sensitivity Analysis . . . . .                                   | 28        |
| 4.6      | Machine Learning . . . . .                                       | 28        |
| <b>5</b> | <b>Results</b>   | <b>31</b> |
| 5.1      | Design Parameters . . . . .                                      | 31        |
| 5.1.1    | Clearance Height . . . . .                                       | 32        |
| 5.1.2    | Azimuth . . . . .  | 33        |
| 5.2      | Objective Function . . . . .                                     | 35        |
| 5.3      | Optimization - Ground Shading Level . . . . .                    | 37        |
| 5.3.1    | Design Examples . . . . .  | 38        |
| 5.3.2    | 0 - 10 % Shading . . . . .                                       | 38        |
| 5.3.3    | 10 - 20 % Shading . . . . .                                      | 39        |
| 5.3.4    | 20 - 30 % Shading . . . . .                                      | 40        |
| 5.3.5    | 30 - 40 % Shading . . . . .                                      | 41        |
| 5.3.6    | 40 - 50 % Shading . . . . .                                      | 42        |
| 5.3.7    | Ground Irradiance Uniformity . . . . .                           | 43        |
| 5.3.8    | Summary . . . . .  | 44        |
| 5.4      | Optimization - Temporal Distribution of Ground Shading . . . . . | 44        |
| 5.5      | Larger Scale Example Designs . . . . .                           | 45        |
| 5.5.1    | Ground Based . . . . .   | 45        |
| 5.5.2    | Vertical Bifacial . . . . .                                      | 46        |
| 5.5.3    | Stilt Mounted . . . . .  | 47        |
| 5.6      | Sensitivity Analysis . . . . .                                   | 47        |
| 5.6.1    | Module Thickness . . . . .                                       | 47        |
| 5.6.2    | Albedo . . . . .   | 48        |
| <b>6</b> | <b>Discussion</b>  | <b>49</b> |
| 6.1      | Optimization . . . . .   | 49        |
| 6.2      | Practical Considerations . . . . .                               | 50        |
| 6.3      | Project Limitations . . . . .                                    | 50        |
| 6.4      | Further Research . . . . .                                       | 51        |
| <b>7</b> | <b>Conclusions</b>   | <b>52</b> |

# 1 Introduction

The increasing release of greenhouse gases into the atmosphere is the primary cause of the ongoing climate change, which has led to a strive toward increasing the amount of fossil-free energy in the energy mix. Solar power is one renewable source of energy which has seen rapid development lately. At the end of 2021, the total installed PV power in Sweden was above 1500 MW, divided into around 92 000 separate grid-connected solar plants (Energimyndigheten 2022*b*), and the PV electricity production is expected to grow continuously in the upcoming years. A scenario from Energimyndigheten (2022*a*) shows how the PV production in Sweden is expected to increase from a production of 1.0 TWh in 2020 to about 3.0 TWh in 2024.

The development of large PV plants results in a rising demand for available land to build PV plants on, increasing the competition between food production and energy production. A way of trying to avoid this trade-off dilemma is the use of agrivoltaics, a relatively new application within the PV market, which combines energy production with agriculture on the same piece of land. Agrivoltaic systems can also provide benefits to both the PV efficiency and the crop yield. Shading from the PV panels can be beneficial for the plants in sunny climates, and the humidity from the plants can contribute to a cooling effect for the PV panels, which increases the operating efficiency of the cells.

For the Swedish climate, agrivoltaics is a relatively unexplored application. The first agrivoltaic research site in Sweden was built in 2020 at Kärrobo Prästgård in Västerås, and there are now plans to start the construction of the first larger-scale agrivoltaic system in the town of Fellingsbro in the summer of 2022 (MyNewsdesk 2022). This thesis will examine how an agrivoltaic system would perform in a Swedish environment and how the layout of the PV system will affect the ground irradiance. To be able to reach an effective light sharing to provide the crops with acceptable growing conditions. This will be done by studying how the design parameters of a PV system, such as height, orientation, and spacing of the PV modules, affect the energy output and the ground irradiance. Methodologically, this will be done by performing an optical simulation to estimate the system's energy output and ground irradiance depending on the system design.

## 1.1 Goal

This project aims to examine and illustrate how the incoming solar irradiance gets distributed between the PV panels and on the ground, depending on the agrivoltaic system design. From this, some suggestions will be made for how to design a park depending on the system constraints. Another goal of the project is to generate a database showing the resulting system properties depending on the agrivoltaic system design. The generated data can be used in further research and decision-making processes, such as choosing a suitable layout of a PV system for the cultivation of a crop with a certain shade tolerance, visualizing the effects on the ground irradiation distribution depending on the layout, as well as to make calculations for electricity production and crop yield for a planned agrivoltaics park.

## 1.2 Framing of Question

- What are some suitable design alternatives for an agrivoltaic system located in Sweden?
- What is the potential for agrivoltaics in a Swedish climate?
- How do the design parameters of an agrivoltaic system influence the light sharing between the PV panels and the ground?

## 1.3 System Boundaries

The complexity behind constructing an agrivoltaic system requires careful consideration of several different parameters, which are not only technical, but also societal and economical. However, this project aims to perform an in-depth analysis of how the light irradiance distribution of the system depends on its basic layout. To not make the project too broad, some delimitations have been made which are presented below.

- **Solar tracking**

Solar tracking would be an efficient way of optimizing the light distribution for an agrivoltaic system by redirecting the PV modules according to the sun's movement in the sky. However, solar tracking implementation in agrivoltaic systems will be left out from this study for two reasons. Firstly, it was considered too complex to properly simulate such a system in the software used in this study. Secondly, solar tracking is often considered a particularly expensive feature of a PV park, as described by Trommsdorff et al. (2020).

- **Economy**

The system profitability is important to consider when constructing an agrivoltaic system. According to Suuronen (2022), the economy is the most critical parameter the farmers would consider if they were to plan for the construction of an agrivoltaic system on their land. To make the investment in an agrivoltaic system profitable for the farmer, the economic gain from the PV panels has to make up for the potential loss in revenue from reduced crop production. Also, the profitability of different designs depends on the cost of construction. For example, stilt mounted systems are often expensive due to the cost of the material and construction (Sekiyama 2019). However, in this project, the purpose is to analyze the light distribution of an agrivoltaic system rather than the system as a whole. Also, by neglecting economic details, the results of this thesis can be applied to current and future scenarios and is not subject to unforeseen technological or economic changes. Therefore the system profitability will not be considered in this project.

- **Losses**

In practice, when implementing an agrivoltaic system there are several potential causes for loss in PV electricity production. For example, farming activities might cause dust on the PV panels, which reduces their efficiency. This is also true for snow or shading from surrounding objects. These kinds of site-specific losses will not be considered in this thesis.

## 2 Background

*In the following section some background information is provided about agrivoltaics and some adjacent subjects. To begin with, an introduction to solar irradiance and optical theory, after that some basic information about photovoltaic technology, and lastly an introduction to the agrivoltaic technology and a summary of some previous studies made within the research area.*

### 2.1 Solar Irradiance

There is a constant influx of energy flowing from the sun towards the earth. The incoming solar radiation is our most important source of energy. It is the driving force for the photosynthetic process in plants, providing us with heat and also the option of converting irradiance into electrical energy via photovoltaic technology. In the next section, some solar irradiance theory is presented.

#### 2.1.1 Irradiance Theory

The amount of incoming solar irradiance received by a given location depends on the latitude as well as the local climate. For Sweden, the incoming irradiance is relatively low compared to many other places on earth because of the high latitudes. Here, the average incoming solar radiation ranges between about 900 and 1000 kWh/m<sup>2</sup> yearly as measured on a horizontal surface, according to the Swedish Meteorological and Hydrological Institute (SMHI 2019).

The solar irradiance hitting the ground can be divided into several different components; beam radiation which is direct sunlight, diffuse radiation which is sunlight scattered by the atmosphere or reflected by clouds before hitting the ground, and finally, reflected radiation which is sunlight bouncing off surfaces such as the ground or surrounding objects. The diffuse radiation accounts for about half of the available radiation in Sweden throughout one year. All of the three components combined measured on a horizontal surface are summed up by the term global irradiance (Bengtsson et al. 2017).

#### 2.1.2 Optical Theory

Since the incoming solar irradiance is usually measured for a horizontal surface, it is useful for PV applications to be able to compute the incoming irradiance on an arbitrarily oriented surface, such as a solar panel. To do this, a few different solar angles are used. The tilt angle ( $\beta$ ) of a solar module is the angular difference between the panel and the horizontal plane and is a number between 0 ° and 180 °. The azimuth angle ( $\gamma$ ) describes the cardinal direction of a system, where an azimuth of 0 ° refers to south, west lies at 90 ° azimuth, east at -90 ° and north has an azimuth of  $\pm 180$  ° (Widén & Munkhammar 2019). An azimuth of 0 ° then indicates the PV modules are facing south. A figure showing the azimuth angles for all the main cardinal directions can be seen in figure 1 below.

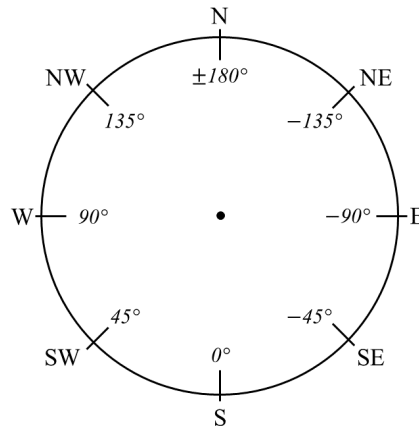


Figure 1: Schematic showing the azimuth solar angles for some of the main cardinal directions.

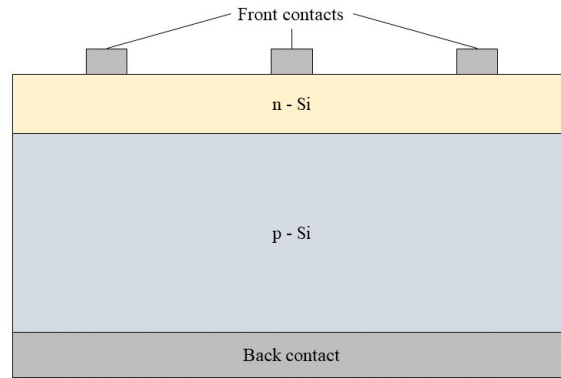
The measurement of ground reflectance is called albedo, and is defined as the share of the incoming light which is reflected by a surface. The albedo is an index between 0 and 1. In this project the albedo is used to determine how much of the incoming irradiance falling on the plants, is reflected onto the PV panels. The albedo of vegetation can vary over a range of values, depending on what type of vegetation is looked at and in what growing phase the plant is in (Iqbal 1983).

### 2.1.3 Typical Meteorological Year

When studying a process which depends on the incoming global irradiance for a specific location it is necessary to find reliable data which resembles the actual irradiance values as well as possible. According to PVEducation (n.d.), the type of data set called Typical Meteorological Year (TMY) is a way of estimating yearly meteorological data for a specific location. The data set is created by selecting data for each month out of several years of measurements, based on which year shows a trend that is most similar to the average for a specific month. All selected months are then merged into a yearly data set with hourly resolution which resembles a typical weather pattern for a specified location throughout a year. So, a TMY is a way of presenting an average yearly data set, but without averaging each hourly value, which would reduce the variability of the data.

## 2.2 PV

According to Mertens (2014) photovoltaics (PV) is described as "the direct conversion of sunlight into electric energy." The most commonly used type of PV cell is made from silicon, a semiconductor material. The silicon is doped to create n-type silicon and p-type silicon, where the n-type silicon has a surplus of electrons and the p-type has a deficit of electrons. When layering these materials on top of each other an electrical voltage is created. Light particles called photons generate free charge carriers in the material, which can be transported into an external circuit by the cell voltage. A sketch showing the construction of a typical silicon solar cell can be seen in figure 2 below. Other materials besides silicon can also be used to make solar cells; one example is thin-film modules made from cadmium telluride (Mertens 2014).



*Figure 2: Schematic showing an intersection of a common type of silicon based PV cell.  
Figure inspired by Mertens (2014)*

To achieve a useful voltage level, several solar cells are connected in series to construct a PV module. The modules are then connected in series and in parallel to form a PV system, in which the output power is controlled by a power inverter. The available output power of a solar cell is measured under STC, which refers to Standard Testing Conditions. These conditions are defined as an incoming irradiance of  $1000 \text{ W/m}^2$ , at a temperature of  $25^\circ \text{C}$  and a light spectrum of AM 1.5. The PV efficiency describes how much of the incoming solar energy can be transformed into electrical power by the PV cell according to equation 3 below. This equation shows that there is a direct proportionality between the output power of a PV system to the incoming solar irradiance (Mertens 2014).

$$\eta = \frac{P_{\text{electricity}}}{P_{\text{irradiance}}} \quad (1)$$

The operating efficiency of commercial solar cells has been increasing steadily over the last few years due to technical improvements within the industry. In 2021, mass-produced silicon solar cells had an efficiency at STC of about 21 - 24 % depending on cell design, and this number is expected to show a continuous improvement in the near future according to the Association of German Mechanical and Plant Engineering (VDMA 2022). The practical efficiency of a solar cell also depends on other factors besides the amount of solar irradiance, such as the light spectrum and the ambient temperature. With increasing ambient temperatures, the cell efficiency gets reduced (Mertens 2014).

### 2.2.1 Performance Ratio

A way of measuring how a PV system is performing in practice is by using the so called *Performance Ratio*. According to the inverter manufacturer SMA (n.d.) this index is independent from the location of a PV park, and therefore makes it possible to compare the performance fairly. The ratio describes how a PV plant performs as compared to the theoretical available power output. The ratio gives a percentage index between 1 and 100 where 100 % means that the plant operates according to the theoretical maximum, which is not possible in practice. The Performance Ratio is defined in the simulation program SAM (system advisor model) as:

$$PR = \frac{\text{Energy Produced Annually (kWh)}}{\text{Total Solar Radiation Incident on Array (kWh)} \cdot \text{Module Efficiency (\%)}} \quad (2)$$

### 2.2.2 Shading

Shading reduces the power output of solar modules, where a uniform shade results in a power reduction proportional to the amount of shading. However, shading of single cells may lead to more significant power reductions, due to the series connection of the cells making the most shaded cell limit the power production of other cells as well. The power loss due to shading varies depending on when during the day the shading occurs and how the system is designed. There are some technical solutions for how to mitigate shading losses in PV cells; by installing bypass diodes to create an electrical path for the current to flow past the shaded cell, and by using MPPT trackers to optimize the power production from the module depending on the amount of incoming irradiance (Bengtsson et al. 2017). Self-shading between the panel rows occurs when one row of PV modules is casting shade on the next row, which often occurs the case if the module row distance is too short. This phenomenon is illustrated in figure 3 below, where the yellow area indicates that the panel area is receiving direct irradiance, while the grey area indicates shading by the first panel row.

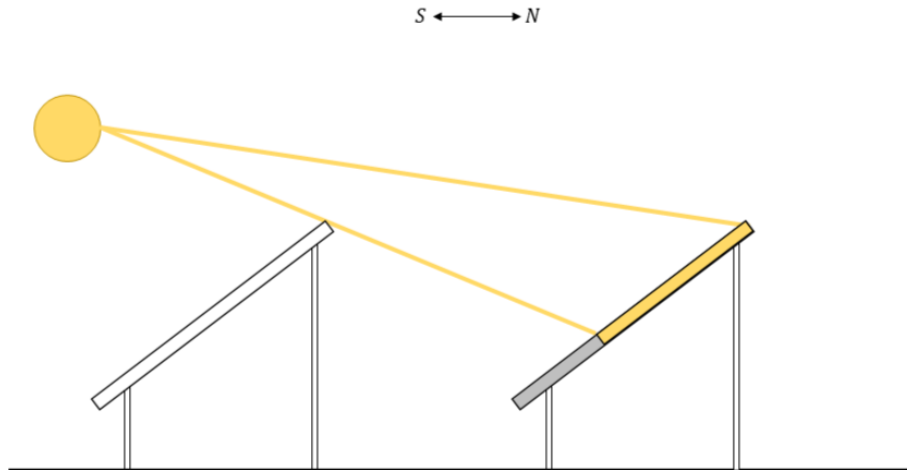


Figure 3: Schematic showing self-shading between two PV module rows.

### 2.2.3 Bifacial PV Modules

The traditional PV module can collect incoming photons from only one side of the module, they are so-called monofacial, while bifacial modules are able to collect light reaching the module from both the front and back. The market share of bifacial modules is expected to increase in the future due to falling prices and standardization of the production process. By using the bifacial technology the output power for a module can be increased by up to 50 %, according to Guerrero-Lemus et al. (2016), due to the ability to collect a bigger share of the incoming light by ground-reflected irradiance.

The bifaciality factor (BF) is computed as a fraction between the efficiency of the rear side to the front side of a bifacial module, and can be used to evaluate the performance of a bifacial module (Janssen et al. 2017).

$$\text{Bifaciality Factor (BF)} = \frac{\eta_{\text{rear}}}{\eta_{\text{front}}} \quad (3)$$

According to VDMA (2022) some typical bifaciality factors of modules produced in 2021 was between 0.70 to 0.90 depending on cell technology.

### 2.3 Agrivoltaics

Agrivoltaics first emerged as a way of reducing the land competitiveness between food and energy production. The concept was first theorized in the 1980s, but the first more proper agrivoltaic experiments were done in Montpellier, France, in 2013 (Dinesh & Pearce 2016). Since then, the installation of new agrivoltaics systems has increased rapidly. As of 2020 there was 2.8 GW<sub>p</sub> installed capacity of agrivoltaic systems internationally, where China had the biggest share of about 1.9 GW<sub>p</sub>. The installed capacity is expected to increase continuously. France for example has plans for the installation of 15 MW<sub>p</sub> agrivoltaics systems yearly going forward (Trommsdorff et al. 2020).

In the report called "Trends in Photovoltaic Applications" from 2020, the International Energy Agency (IEA) identifies agrivoltaics as a new emerging segment within the PV market. It is also described how agrivoltaics can provide another supplemental revenue source for the farmers. IEA also mentions how any PV plant located on agricultural land can not by default be seen as an agrivoltaic system, and are providing a definition of agrivoltaics as:

*'...' a PV plant which allows a combined land use, for agriculture and for PV plants, without putting the emphasis completely on the PV plant (Masson & Kaizuka 2020).*

The above statement implies that the layout of the PV plant has to be modified for the agrivoltaic system, to provide the crops with enough sunlight for acceptable growing conditions. A simple example is to reduce the ground coverage of the PV modules as compared to a conventional PV system to let more light pass to the ground. However, depending on the climate and situation, such as the crop species or type of farming equipment used, different accommodations can be made in agrivoltaic plants to make the overall production of both crops and electricity as effective as possible.

There are several potential benefits as well as challenges that rises from combining a PV system with agriculture, for the PV technology and the crops, but also when it comes to other parameters. Some of these will be presented shortly in the next sections 2.3.1 and 2.3.2.



### 2.3.1 Potential Benefits

- **Land use efficiency**

In many countries, there is a big competition on the market for the available land. And there is often a debate about if we should use the land to produce electricity or food, or else, if the land should remain untouched by either of these. Agrivoltaics would provide a possible solution for this trade-off dilemma by co-using the same land to produce both of these essential resources on the same land and at the same time.

- **Water savings**

According to Dinesh & Pearce (2016) the use of agrivoltaics could reduce the amount of water needed for irrigation of the crops by about 14-29 % due to the increased shading of the plants, which reduces the evapotranspiration from the ground and retains the moisture in the plants and soil.

- **PV efficiency**

The humidity provided by the crop transpiration will result in a cooling effect on the PV modules. Since a lower operating temperature will make the energy conversion in the solar cells more efficient (Adeh et al. 2019).

- **Cooler micro-climate beneath panels**

Shading from the PV modules makes for a cooler and more humid micro-climate beneath the panels, which could provide a better growing climate for the crops, especially in already hot and dry climates. And as the temperatures and extreme weathers continue to increase due to climate change, this parameter might become more prevalent in the future. The cooler climate beneath the panels also creates a better working environment for the farmer who is working there, especially for raised systems with shorter row spacings.

- **Self-consumption**

Combining farming activities with PV electricity production on the same land has the potential to result in a high degree of self-consumption for the system as a whole. Since most of the farming activities presumably takes place simultaneously as when the PV is producing the most electricity, the farmers could charge their electrical equipment during the day to make sure that a lot of the produced power is utilized directly.

- **Income diversification for the farmer**

The operation of a combined system will result in an extra income source for the farmer (Suuronen 2022). This may increase the farmers' total revenue, or at least provide a diversification of their income, making it less sensitive to fluctuations in either of the two income sources.

### 2.3.2 Potential challenges

- **NIMBY**

The *Not in my back yard* (NIMBY) effect describes how people tend to have a negative attitude towards proposed land use in the close proximity to their home, or some place they have an emotional connection to. The opposition is often motivated by that the construction is considered unattractive and therefore destroys the local landscape (Brown & Glanz 2018). Even though the construction, such as a PV system or a wind mill, is something of common interest.

- **Investment cost**

The installation cost of one of the main points of concern for farmers if they were to plan for an agrivoltaic system on their land, according to Suuronen (2022). The extra income from the produced PV electricity has to wight up for the potential loss in revenue due to shading of the crops. Some solution for making sure that the investment in agrivoltaics is profitable could be to make some deal with the company constructing the PV park that they would pay for the loss in crop production, or some other kind of lease agreement.

- **Low electricity prices**

The relatively low electricity prices we have had in Sweden during the last couple of years have made installing PV less profitable (Campana et al. 2021), since the revenue from selling the produced energy increases with the electricity price. However, recently we have seen a trend toward higher electricity prices, which has increased the incentive to invest in large-scale PV parks. If electricity prices continue to rise while the cost of installing PV continues to fall, it will further increase the profitability of both PV and agrivoltaic systems.

- **Geographical location of Sweden**

Since Sweden is located at relatively high latitudes, the incoming solar radiation is lower, and the seasonal variations are larger than in many other countries globally (Šúri et al. 2007). Therefore, the Swedish climate might be less suitable for an agrivoltaic system in several ways; a reduced PV production due to less incoming solar irradiance and reduced benefits for the plants when it comes to the shading effects.

- **Low subsidies in Sweden**

As of today the Swedish government gives out subsidies for the installation of normal, PV only, parks. But the subsidies are still lower as compared to some southern European countries, such as Italy (Campana et al. 2021). And there are yet no subsidies in place in Sweden specifically made for agrivoltaic systems.

- **Soil erosion**

One concern for agrivoltaic systems the cause of soil erosion due to the rain concentrating from the module edges and falling down on the same spot on the ground. However, a study by Trommsdorff et al. (2021) has shown no negative effects on the ground by erosion so far.

### 2.3.3 Micro-Climatic Effects

In an agrivoltaic system, micro-climates are created beneath the panels. Directly below the panels the climate will be shaded, more humid and cooler. The climate in between the panel rows will be sunnier and dryer, almost like with no PV modules present. The wind speed might be affected as well. The micro-climate will affect the plants growing there, and for systems located closer to the ground the micro-climates get more influential (Trommsdorff et al. 2020). The humidity and temperature also affect the PV panels since lower temperatures will increase the module efficiency as described in section 2.2. The micro-climatic effects provide a further dimension for optimizing agrivoltaic systems, however, only the light irradiance parameter will be considered in this thesis.

### 2.3.4 Plant Ecology

Plants use the sunlight as an energy source for the photosynthetic process and an information source. The wavelengths of the photons available for these processes are in the range of 400 - 700 nm, which is called the photosynthetically active radiation (Hernandez Velasco 2021). The PAR is estimated by Meek et al. (1984) to account for about 45 % of the total incoming solar irradiance. The amount of irradiance a plant requires for optimal photosynthesis depends on the plant species, some can do with less sunlight than others. The plant growth does not increase anymore once the irradiance reaches a certain level, where the plant can no longer make use of the available light, and there is even a risk of the plant getting damaged by the sunlight. This point is called the light saturation point, as illustrated in figure 4 below. A plant which has a high light requirement is called a light plant, and a plant that can grow under more shaded conditions is called a shadow plant (Trommsdorff et al. 2020).

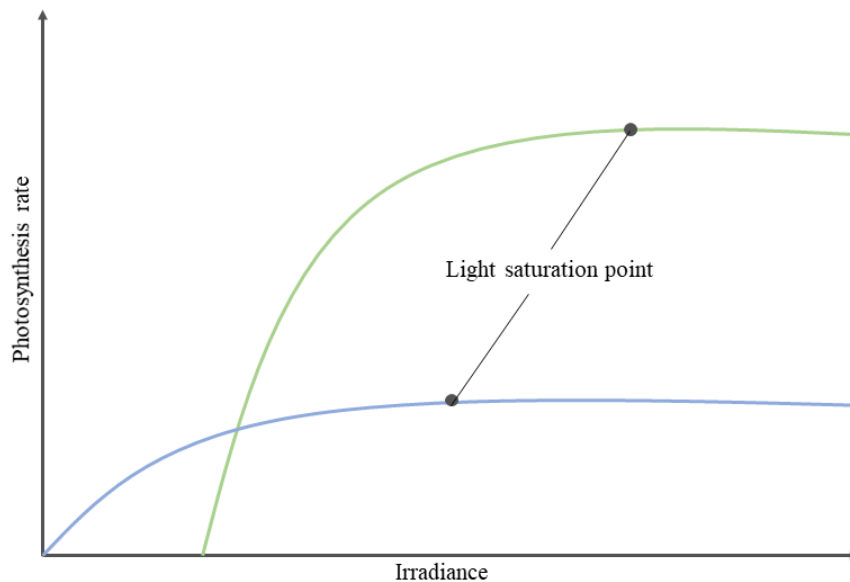


Figure 4: Graph illustrating the concept of the light saturation point for different types of crops. The green line shows a light plant and the blue shows of a shadow plant. Picture inspired by (Trommsdorff et al. 2020).

Another figure showing the relationship between the light irradiance and the crop productivity can be seen in figure 5 below, where it is noticeable how a high incoming light irradiance leads to a lower carbon uptake and a reduced light use efficiency (Durand et al. 2021).

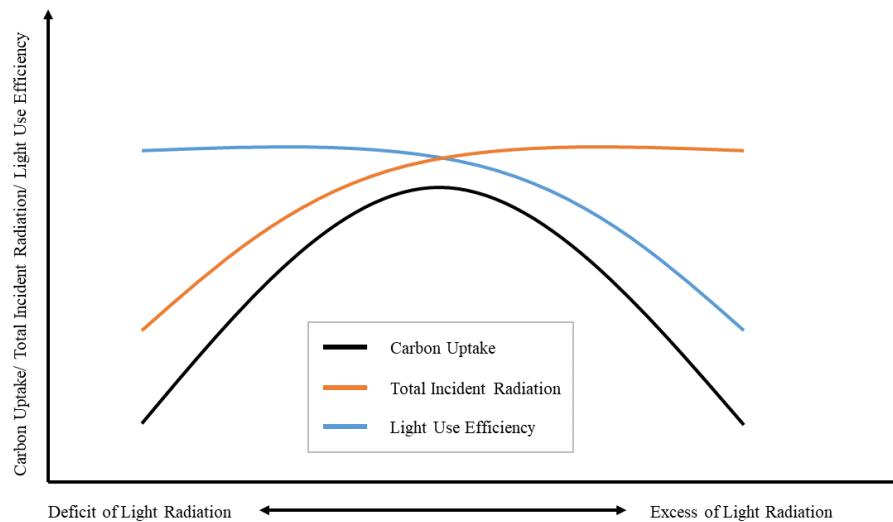


Figure 5: Figure showing the relationship between incoming light radiation and the light use efficiency. Figure inspired by (Durand et al. 2021).

The juvenile phase of a plant's life cycle is the most influential period for the overall crop growth (Marrou et al. 2013a), therefore an increased amount of shading during this period might lead to a more significant loss in the total crop production. This means that it would be suitable to have an agrivoltaic layout that allows for more ground irradiance during the juvenile period of the cultivated plants' growth period. Moreover, the relationship between crop yield and the amount of ground irradiance is not very predictable. Some plant species, such as lettuce, have the ability to adapt to a more shaded environment by, for example, developing a larger leaf area (Marrou et al. 2013b). Because of this, it is hard to predict to what degree the increased shading by the PV modules will influence the productivity of the crops.

From an interview with Marcos Lana, a senior lecturer at the Department of Crop Production Ecology at the Swedish University of Agricultural Sciences, SLU (Lana 2022), it was discussed how an agrivoltaic system should limit the shading of the crops during time periods of lower incoming irradiance, which means during the morning, evening as well as during spring and autumn. While allowing for more shading during mid-day and summertime when the crops might not utilize all the irradiance. This is also a conclusion that could be made based on the rest of the information presented in this section.

### 2.3.5 Crop Shading Tolerance

When designing an agrivoltaic system, it is essential to carefully decide on which crop to cultivate beneath the PV modules. Shade tolerant crops are generally more suitable since they can better deal with the increased shading from the PV panels. Examples of shade-tolerant crops are grass, stone fruits, berries, asparagus, garlic, and leafy vegetables such as lettuce. For example, only 60 - 70 % of the incoming light is sufficient for the apple production to be optimal (Trommsdorff et al. 2020).

In Weihestephan, Germany, there is an agrivoltaic research site, with the PV modules raised on a stilt mounting with a clearance height of 3.6 m, 7 m row distance, which is east/west facing and has solar tracking installed. Tests with Chinese cabbage showed yield reductions due to shading which was between 29 and 50 %, depending on the distance between the modules in a row, where the crop yield is presented as a percentage drop as compared to a reference with no shading (Trommsdorff et al. 2020). The result of this research can be seen in table 1 below.

*Table 1: Table showing the resulting decrease in crop yield depending on the distance between modules in a row. Results from an agrivoltaic system in Weihestephan, Germany (Trommsdorff et al. 2020)*

| Module distance | 0 cm | 25 cm | 66 cm |
|-----------------|------|-------|-------|
| Yield reduction | 50%  | 44%   | 29 %  |

At another German research site located in Heggelbach, wheat, potatoes, celery and a grass/clover mixture was used as test crops in the agrivoltaic system. This research site is also a stilt mounted system with a clearance height of 5 m, a row distance of 9.2 m and facing southwest to increase the uniformity of the irradiance reaching the crops. The research site showed land equivalent ratios of about 160 % for the year of 2017, but for the particularly hot summer in 2018 as high as 186 %. The resulting reduction in crop yield was shown to be about 5.3 % for the grass/clover mixture and 18-19 % for potatoes, wheat and celery in the year of 2017 (Trommsdorff et al. 2020). In warmer and dryer climates, the benefits from shading is expected to increase the yield for certain crop species. For example, in India, the increased shading might increase tomato and cotton yields with up to 40 percent according to Trommsdorff et al. (2019).

In Germany a reduction in the incoming irradiance of about one third is considered acceptable for an agrivoltaic system. In the US there are also several agrivoltaic research sites, and some requirements for how to construct such a system have been developed; the bottom edge of the modules should be at least 2.4 m from the ground. And the system is not allowed to provide more than 50 % shading at any point on the ground (Trommsdorff et al. 2020).

### 2.3.6 Land Equivalent Ratio

To be able to evaluate the productivity of an agrivoltaic system, the *Land Equivalent Ratio (LER)* can be used to weigh the productivity of the two inter-coupled systems. LER is defined by (Mead & Willey 1980) as:

$$LER = \frac{Y_a}{S_a} + \frac{Y_b}{S_b} \quad (4)$$

Where  $Y_a$  and  $Y_b$  are the separate yields of the two components a and b in the inter-coupled system, and  $S_a$  and  $S_b$  are the yields which could be reached by the two different systems operating independently from each other (Mead & Willey 1980). The concept was first used for the cultivation of two crops on the same land, but has also been used in the context of agrivoltaics by for example Trommsdorff et al. (2021) where the PV electricity and the crop yield account for the two different components of the inter-coupled system. Meaning that  $S$  for the PV system would be the potential power output for a corresponding normal (non-agrivoltaic) system designed to maximize the power output, and  $S$  for the agricultural system is the potential crop yield for a standard convectional farmland with no shading from the PV modules present.

## 2.4 Previous Studies

This section will focus on agrivoltaic research made in Sweden firstly and in northern countries close to Sweden secondly. Suuronen (2022) has studied the potential for agrivoltaic systems in Sweden by interviewing farmers about their opinion on installing a system on their land, and by making some light simulations. This study showed that the solar fence system is among the most suitable for light sharing purposes since it provides relatively low shading effects for the ground, is easy and cheap to install, as well as that it is easy to pass with agricultural machines in the spacing between the module rows. But the energy production is low relative to the other tested designs. Some concerns brought up by the farmers in the interviews were uncertainties in effects on the plant yield, if there is enough room for their machines to pass through the systems, worries about extra workload as well as an uneven water distribution.

The first agrivoltaic research site in Sweden is located in Kärrobo prästgård, Västerås, and is constructed as a vertical bifacial system. The crop used in this system is a type of grass. The research results from this facility are yet limited, but it has already been shown that for dryer weather, the production of grass harvested in the agrivoltaic site is larger than for a reference with no PV modules present (Mälardalens Universitet 2021). One of the researchers involved in this project points out the need for national guidelines and strategies for agrivoltaic systems in Sweden, and states that there are Swedish legislation in place today which hinders the construction of PV systems on farmland.

A research paper by Campana et al. (2021) presented the results of an optimization study of a vertical bifacial agrivoltaic system made by looking at solar irradiance, photovoltaic production, and crop yield, with oats and potatoes used as reference crops. This study shows that by decreasing the row distance from 20 m to 5 m, the crop yield will be reduced by approximately 50 %. It also shows how optimizing for the LER reduces the potential power output of the system significantly, and therefore other parameters need to be considered as well. The investigation shows results of land equivalent ratios above 1.2, which legitimates using an agrivoltaic system since the overall output increases. The study also shows how the optimal row distance for oat is 9.2 m, and for potatoes, 9.7 m, indicating that the optimal design of an agrivoltaic system depends on which crop is looked at.

Another study by Trommsdorff et al. (2021) investigated the optimal design for an agrivoltaic site located in Heggelbach, Germany. The layout of the studied system is a stilt mounted design with 5.5 m clearance height,  $20^\circ$  tilt, and south-west orientation. The system is constructed so that the module row distance is 9.5 m, but the distance between the mounting pillars is 19 m to allow bigger machines to pass beneath. Potato, celeriac, clover grass, and winter wheat are used as test crops in this research site. By setting a target of 80 % crop yield compared to the reference with no PV shading, they found that a suitable ratio between the row distance and the width of the PV panels should be about  $L/w = 2.8$ , the design parameters L and w are also illustrated in figure 6. They study also showed land equivalent ratios above 1.5, depending on the specific climate of the year and which crop is used.

### 3 Method

*In the following section the basic methodology for this project will be presented. First, some argumentation leading up to the choice of which layouts to include in the investigation, as well as an introduction to the most common layouts for systems in operation today. And secondly, motivations for which design parameters to vary in the simulations and in what ranges, and also, some information about the irradiance data and the chosen location for the simulations.*

#### 3.1 Layout

When constructing an agrivoltaic system there are some additional factors to consider, as compared to for a conventional PV park. The optimal design of an agrivoltaic system depends on the geographical setting, which species of plant is used as well as what type of farming equipment is needed for cultivating the crops (Zainol Abidin et al. 2021).

According to Zainol Abidin et al. (2021), some design alternatives to consider are:

- Elevating the PV panels by using a stilt mounting. This is beneficial both for letting more light pass through the sides to the crops on the ground, as well as to make room for agricultural machines to safely operate beneath the PV panels without damaging them. However, these types of mounting structures are fairly expensive as of today, which increases the system installation cost.
- Adjusting the spacing between the module rows, to optimize light sharing between the PV panels and the crops.
- Optimization of the tilt, to adjust the power output of the panels, as well as the ground shading.

Additionally there are also other alternatives which might be suitable:

- Adding a tracker to the agrivoltaic system, to allow optimization of the tilt and/or azimuth as the sun changes location in the sky from hour to hour or seasonally. However adding such a tracking system to a PV system is relatively expensive according to for example Trommsdorff et al. (2020). As stated in section 1.3 solar tracking will be excluded from this study.
- Creating space between the modules in a row or between the cells in a module by using semi-transparent modules can allow more light to reach the crops, but will cause a trade-off effect by reducing the overall PV electricity production.

For the goal of investigating the suitability of different agrivoltaic system layouts for an efficient light sharing, it is desirable to examine as many potential designs as possible. Four main constructions of agrivoltaic systems were identified by looking at previous studies and parks in operation today, these are presented in figure 6, 7, 8 and 9 below. In the following figures the different design parameters are indicated with letters. These design parameters are: the distance between the module rows ( $L$ ), the tilt of the PV modules ( $\beta$ ), the clearance height between the modules and the ground ( $h$ ) as well as the width of the PV panels ( $w$ ). The last design parameter which is not shown in these two dimensional schematics is the azimuth ( $\gamma$ ) which describes the cardinal direction of



the system. A further theoretical explanation for this specific parameter can be found in section 2.1.2 above. The ground based, vertical bifacial and stilt mounted systems are all varieties of each other with different design parameter dimensions. While the integrated type system is different in the way that the PV modules are facing opposite directions. The integrated system will be excluded from the light simulations made in this project due to time constraints. But since the integrated system is similar to the other designs in many ways, the results of this thesis might still be applicable for such a system.

### 3.1.1 Ground Based

An agrivoltaic system constructed similarly to a normal, conventional, non agrivoltaic PV park. The system is usually south facing, with tilted panels and raised up only slightly from the ground. Three practical examples of such ground based standard type systems can be seen in the report by Toledo & Scognamiglio (2021), and an illustration can be seen in figure 6 below.

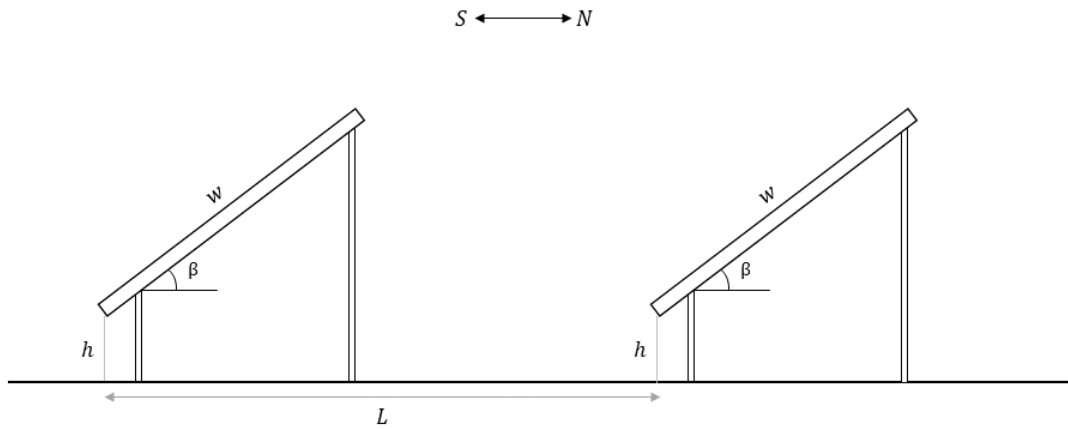


Figure 6: Schematic showing the construction of a standard, ground based agrivoltaic system.  
Figure inspired from Dinesh & Pearce (2016).

### 3.1.2 Vertical Bifacial

The vertical bifacial design, also called a solar fence, has modules tilted at  $90^\circ$  and usually facing east/west, which allows for light collection from both the front and the back of the modules, by the use of bifacial technology. One park which has this type of layout is the first agrivoltaics park in Sweden, located outside of Västerås (Mälardalens Universitet 2021). A schematic showing the construction of this type of system can be seen in figure 7 below.

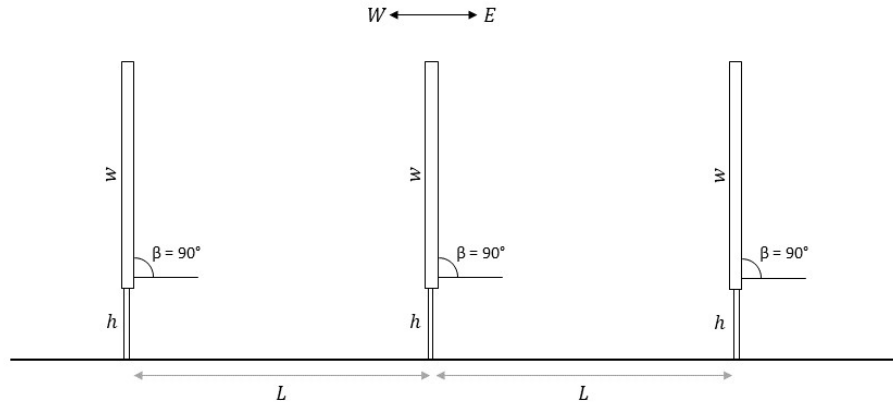


Figure 7: Schematic showing the construction of a vertical, ground based agrivoltaic system. With a 90 degree tilt, and usually facing east/west.

### 3.1.3 Stilt Mounted

This is the type of construction used in the very first experimental agrivoltaic system in Montpellier, France (Marrou et al. 2013a). Which is a standard PV design, but with the modules raised higher from the ground by a stilt mounting system, as can be seen in figure 8 below. Which allows for more space for farming equipment to pass, and also allows for more light to reach the crops on the ground.

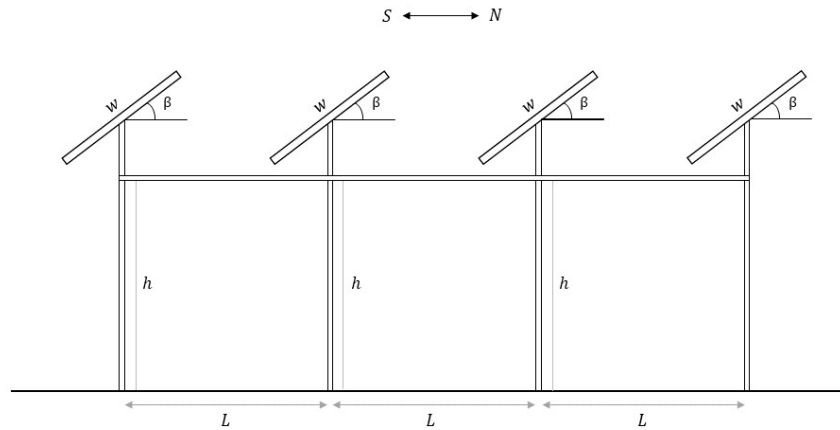


Figure 8: Schematic showing the construction of an agrivoltaic system with the PV panels raised on a stilt mounting. Figure inspired from Dinesh & Pearce (2016).

### 3.1.4 Integrated System

The integrated system is usually used as a type of protection for plants which usually grow under a plastic cover or in a greenhouse. This construction has for example been used for the cultivation of berry bushes (Trommsdorff et al. 2020). The PV system itself is similar to the stilt mounted design, but usually with the modules tilted opposite to each other, facing east/west, as can be seen in figure 9 below.

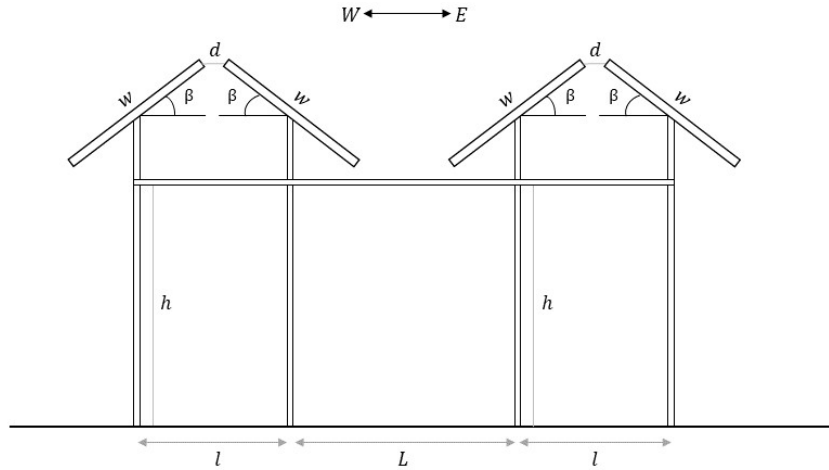


Figure 9: Schematic showing the construction of an integrated agrivoltaic system, with the PV panels are facing opposite directions.

### 3.2 Design Parameters

When deciding which agrivoltaic system designs to include in the simulations, the focus was on including as many systems as possible on a broad scale to try and not miss any design variations. The simulations will include the Ground Based, Vertical Bifacial and Stilt Mounted design, since these are among the most common types of agrivoltaic designs, but also as since they are all variations of each other. By changing the specified dimensions of one of them, it is possible to construct the others. The below section will present which dimensions are simulated for each of the design parameters, as well as some other input data to the model.

#### 3.2.1 Clearance Height (h)

When looking at some stilt-mounted agrivoltaic systems in operation today, some clearance heights can be found in table 2 below. Where one can see that the heights of such constructions range from 3.6 to 5 m, and according to Trommsdorff et al. (2021) the largest harvesters need a clearance height of about 5 m.

Table 2: Table showing examples of the height of different agrivoltaic systems in operation today.

| Location      | Country | Height (m) | Source                    |
|---------------|---------|------------|---------------------------|
| Weihenstephan | Germany | 3.6        | Trommsdorff et al. (2020) |
| Heggelbach    | Germany | 5          | Trommsdorff et al. (2020) |
| Pionlec       | France  | 4.2        | Sun'Agri (2021)           |
| Montpellier   | France  | 4          | Marrou et al. (2013a)     |

For extending the range of the design parameter even further, the simulations will include clearance heights between 0.5 to 8 m, to also include the ground based system which usually has a slight clearance height.

### 3.2.2 Row Distance (L)

For conventional solar parks the distance between the panel rows is often decided by the desire to avoid shading above a certain threshold for the solar angle. There are different ways of doing this, but based on a report by Stridh (2016), the row distance ranged between 4.7 to 9.33 m. Also, a large type of farming equipment called sprayer booms are typically 6 m wide according to Trommsdorff et al. (2021). However, in a stilt mounted system the row distances in some research parks are as narrow as 2 m, to create a higher density of solar panels (Marrou et al. 2013a). Another study by Campana et al. (2021) showed how the crop yield can be doubled by increasing the row distances from 5 to 20 m. So, to include as many scenarios as possible in the simulations the row distance will be varied from 2 to 18 m in the simulations.

### 3.2.3 Azimuth ( $\gamma$ )

The optimal azimuth depends heavily on which type of system is used. A normal ground mounted PV park in Sweden usually has an optimum azimuth of about 0 degrees (facing straight south) since the sun reaches it's highest point on the sky in the south direction. While a vertical bifacial park collects light from both sides, so most of these system are constructed to be east/west facing (90 or -90 ° azimuth), which makes both the front and the back of the modules get approximately the same amount of light.

However, for a south facing system the shading from the panels spreads very homogeneously over the ground beneath, which makes some crops get a lot more sun than others. A solution for this would be to offset the azimuth slightly from zero degrees (to SW or SE), to make the light spread more evenly over the ground level (Trommsdorff et al. 2021). Therefore the azimuth will be varied between -90 through 0 to 90 ° in the simulations, to cover all of these design options.

### 3.2.4 Tilt ( $\beta$ )

According to (Jacobson & Jadhav 2018) the optimal tilt is about 41 ° for Sweden. However due to self-shading, PV systems are often designed with lower tilt angles than that, at about 20 - 30 °, and for an agrivoltaic system it is even more crucial to avoid substantial shading of the ground. Vertical bifacial systems have a 90 ° tilt. To include all of these design options the tilt angle is varied between 20 to 90 ° in the simulations.

### 3.2.5 PV Module Dimensions

From studying some datasheets from common PV manufacturers for some standard size solar panels the conclusion is that a smaller commercial PV module has the dimensions of about 1.7 m times 1 m, see table 3 below. These are the module dimensions which were used in the simulations. The exact size of the modules themselves does not matter that much since the modules are placed right next to each other lengthwise and the panel width is varied in the simulations. Noticeable is how one module is 1 m wide, hence the number of modules is the same as the module width in meters in the upcoming simulation results.

Table 3: Standard dimensions for PV panels from some of the more common manufacturers on the market.

| Manufacturer | Module name               | Dimensions          | $\eta$ ( % ) | Source            |
|--------------|---------------------------|---------------------|--------------|-------------------|
| JA solar     | Deep blue 3.0 light 420 W | 1722 x 1134 x 30 mm | 21.5         | (JASolar n.d.)    |
| Suntech      | Ultra V mini 410 W        | 1724 x 1134 x 30 mm | 21.0         | (Suntech 2022)    |
| Trina Solar  | Vertex S 405 W            | 1754 x 1096 x 30 mm | 21.1         | (TrinaSolar 2020) |

For agrivoltaic and standard PV-only systems, panels are usually stacked width-wise to make for a larger surface area for collecting energy. In integrated systems the modules are usually only one module width high, but for standard and vertical bifacial systems they are typically stacked 2 - 4 modules in a row. So in the simulations the panel width will be varied from 1 - 4 m to simulate these scenarios.

### 3.2.6 Albedo ( $\rho$ )

The albedo for vegetation can vary over a range of values, depending on what type of vegetation is looked at and in what growing phase the plant is in. For vegetation the albedo can range all the way between 0.02 - 0.37 (Iqbal 1983). A study by Robledo et al. (2021) measured the albedo value at a PV project site consisting of farming fields, and found the albedo value to be about 0.17.

Since the albedo has a seasonal variation there are ways to use dynamic albedo values in simulations to get more exact power outputs. However, a study by Nygren & Sundström (2021) proved that the difference between using a dynamic and a static value for the albedo value does not change the configuration of an optimized system, even if it resulted in some deviations in the resulting panel irradiance.

The albedo will be approximated with 0.2 in the upcoming simulations, which is a reasonable value for vegetation, and was also the default value used in the simulation program SketchUp DeLuminae. However, a sensitivity analysis will be performed to investigate how big of a difference the albedo makes for the simulation results.

### 3.2.7 Weather Data and Location

In Sweden the most promising locations for PV production is in the very south, since the yearly incoming solar irradiance is slightly larger there due to the lower latitudes than in northern parts (Šúri et al. 2007). Also the amount of farmland is a lot larger in the south than in the north, because of both climatic reasons and a more suitable type of soil. Skåne has the biggest share of farmland out of all provinces in Sweden, with 45 % of the total land being agricultural (Jorsbruksverket 2021). Therefore the area of Skåne shows the highest probability of installing an agrivoltaic system, and the simulations will be located there.

Data for incoming global irradiance was collected from climate.onebuilding.org (OneBuilding 2021) since the data-base had data from sites close to the chosen simulation location of Skåne, and that some testing of the data showed reliable results. The specific location where the weather data was gathered from is the town of Hörby. The data is validated, checked for quality and derived by using certain standards. The data used is a TMY dataset (further description in section 2.1.1) and in .epw format

(OneBuilding 2021). The data-set contains hourly irradiance data for a whole year, derived from measurements throughout 2004 to 2018.

### 3.2.8 Time Period

The specified period for the simulations will be a whole year in hourly resolution. However, the whole year period is not quite relevant for the available light for crop production since the agricultural season is a lot shorter than this because of the cooler winter temperatures. So the ground irradiance in the results section will be computed over the farming season/vegetation period.

The vegetation period is defined by SMHI (2021) as the time of year when the average daily temperature exceeds a specific limit, and SMHI uses 5 °C as this defined limit. Temperature data for the chosen location Hörby was used to find when this period occurs. The temperature data used ranged between 1996 and 2021. The data was collected from SMHI (2022). From this, the vegetation period for the specified location was computed to be between the 4th of April and the 11th of November, so this time period will be used for all computations of the ground irradiance.

### 3.2.9 Summary

In table 4 the simulated design parameter values are presented as well as the chosen increments. All parameters were varied in all combinations, resulting in a total of 1080 different layouts.

*Table 4: Table showing simulation parameters and increments for the main type of systems.*

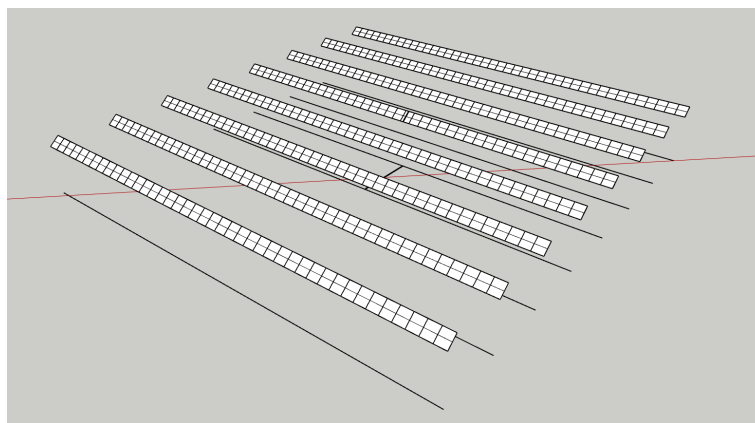
| Parameter            | Range    | Increments          |
|----------------------|----------|---------------------|
| Tilt (°)             | 0 - 90   | 0, 20, 40, 60, 90   |
| Clearance height (m) | 0.5 - 8  | 0.5, 4, 8           |
| Row distance (m)     | 2 - 18   | 2, 4, 6, 10, 14, 18 |
| Width PV panels (m)  | 1 - 4    | 1, 2, 4             |
| Azimuth (°)          | 90 - -90 | -90, -45, 0, 45, 90 |

## 4 Simulations

The simulation program used to analyse how the incoming sunlight is distributed between the PV panels and the ground is called SketchUp DeLuminae, which is a light intensity model based on ray-tracing. The program is most commonly used to study daylight distribution on buildings or in indoor environments (DeLuminae 2022). To start up the simulations a schematic of the PV system is constructed in the program, an example of what this may look like can be seen in figure 10 below. A Geolocation was set up in SketchUp by defining the geographical location of the system as Hörby, Skåne to define the cardinal directions in relation to the Cartesian coordinate system in the SketchUp interface. An explanation to why this specific location was chosen as the location for this project can be found in section 3.2.7.

After constructing the physical design of the PV system in SketchUp, a TMY global irradiance data file for the chosen location was incorporated into the model. From the constructed system and the input data the program was then able to calculate how much irradiance is falling on selected surfaces of the drawn model by using virtual light sensors. To simplify the simulation and following computations the light measurements of the agrivoltaic system were performed on a one dimensional scale in the center of a big PV park. This to locate the measurements in the part of the system which showed a uniform light distribution with no boundary variations, and the result might then be interpolated though out the whole construction area to be able to say something about the light sharing properties for the design as a whole.

Three different light measurements were performed for each of the simulated agrivoltaic designs; on the ground beneath the panels as well as on both the front and back of the PV panels. The sensor configuration can be seen in figure 11 below. The light sensors themselves can be seen as the small black dots in figure 12. The irradiance measurements on the back of the PV panels was included to be able to evaluate how a bifacial solar module would perform as compared to a conventional monofacial one.



*Figure 10: Schematic providing an example of what the simulated system looks like in SketchUp.*

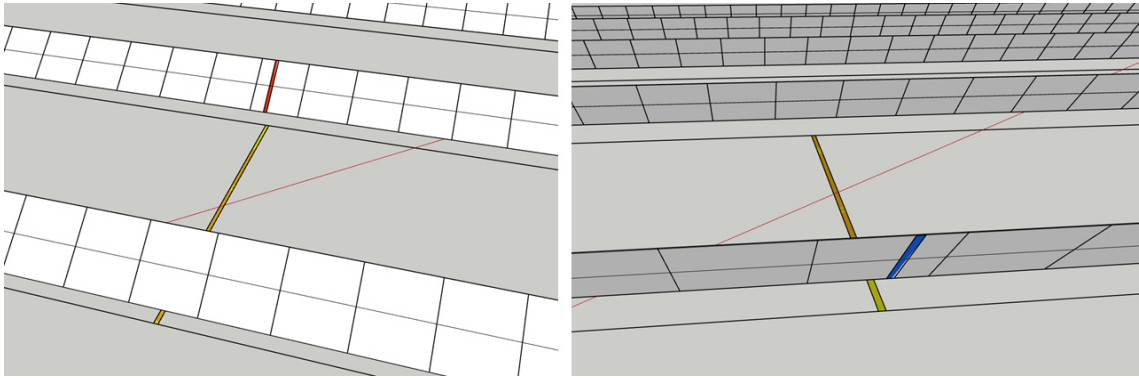


Figure 11: Schematic showing the light measurement sensors as they look like in the SketchUp interface, from the front and from the back respectively.

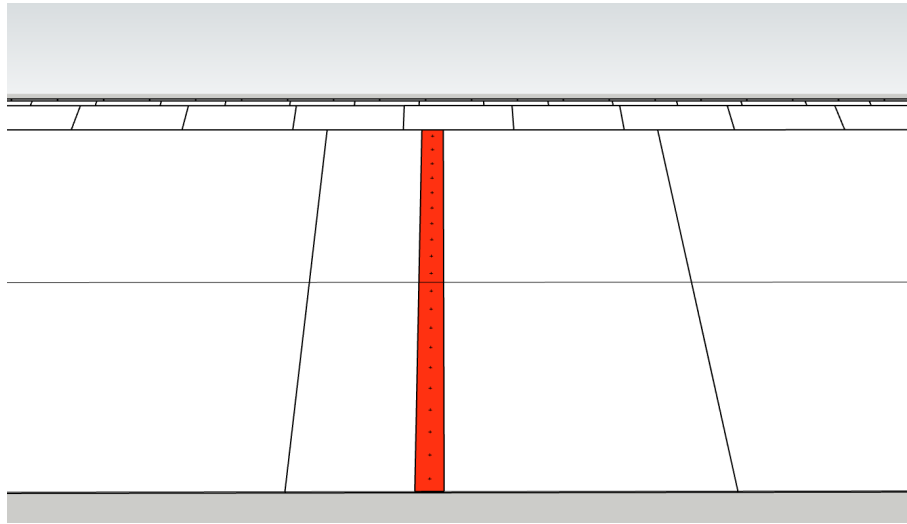


Figure 12: Picture showing the virtual light sensors in SketchUp.

For making the light simulations more time efficient, six different designs were computed simultaneously in the SketchUp interface, with the six different row spacings. Then all of the other design parameters were altered one by one to finally simulate all different combinations of the chosen design parameters in table 4, and the light measurement results were saved and imported into Matlab for further processing. SketchUp DeLuminae was validated as compared to a PV system simulation program called SAM (System Advisor Model), to validate that the irradiance computations could be considered reliable.

#### 4.1 Assumptions

When constructing the physical agrivoltaic system in SketchUp only the panels themselves are considered, meaning that the mounting structure is excluded from the model. This is due to there being so many options when it comes to how to construct the mounting structure for a PV site. Also, the PV mounting would probably contribute only slightly to the ground shading.



In the model the panel thickness was assumed as 10 mm, to separate the back and front panel measurements in the simulations. This is an approximation which assumes that the panel thickness does not matter that much for the output results of the simulations. Therefore the influence of this design parameter will be examined in a sensitivity analysis.

## 4.2 Simulation Settings

In the sections below, some information will be provided about what settings were used in the optical simulation, and some information about how the systems were constructed in the SketchUp interface. Furthermore, an explanation for why some of the performed simulations will be excluded from the final results.

### 4.2.1 Sensor Spacing

The light sensor spacing in SketchUp was defined manually. To be able to make a suitable choice for this parameter a few different sensor spacings were tested, to see how the ground profile and total incoming irradiance throughout a year would be affected. Figure 13 illustrates the light irradiance profile between two panel rows for three different sensor spacings. It is noticeable how a tighter sensor spacing provides a smoother looking profile which better illustrates how the shading is distributed on the ground beneath the panels.

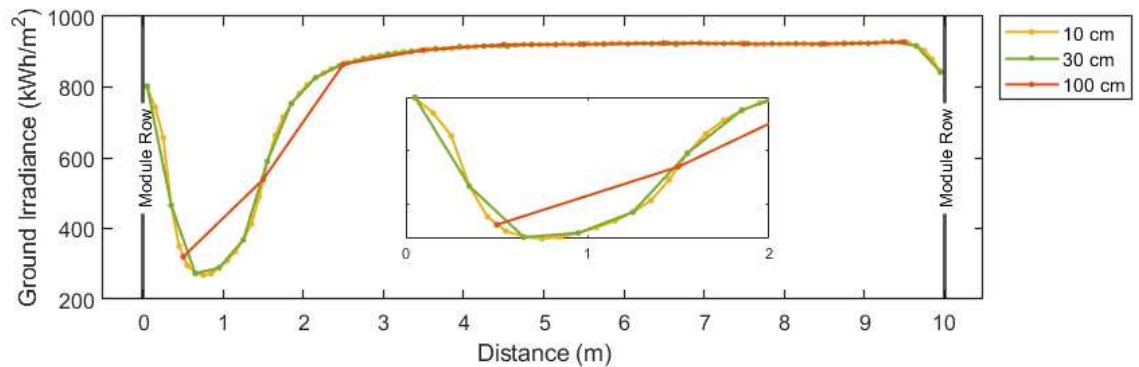


Figure 13: Schematic showing the irradiance profile for the ground beneath two panels depending on the light measurement sensor distance, for an example system.

Figure 14 as well as table 5 shows how the total yearly irradiance per  $\text{m}^2$  varies with the sensor spacing. A smaller sensor spacing results in an improved accuracy in the computations since the irradiance is then measured at more points. In figure 14 it is clear how the accuracy of the light measurement is reduced for sensor spacings above 20 cm.

Table 5: Table providing numerical values for the resulting incoming yearly ground irradiance per  $\text{m}^2$ , depending on the sensor distance, for an example system.

| Sensor Distance (cm)                          | 2     | 5     | 10    | 20    | 30    | 50    | 100   |
|---|-------|-------|-------|-------|-------|-------|-------|
| Ground Irradiance ( $\text{kWh}/\text{m}^2$ ) | 826.4 | 826.2 | 826.5 | 826.3 | 825.7 | 829.6 | 816.7 |

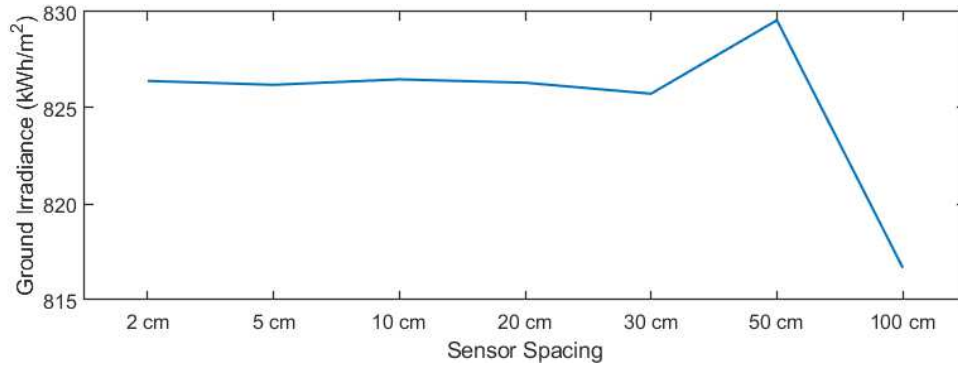


Figure 14: Graph showing the resulting incoming yearly ground irradiance per  $\text{m}^2$ , depending on the sensor distance, for an example system.

It was decided from the above argumentation to set the sensor distance to 10 cm.

#### 4.2.2 Model Dimensions

Since the simulation light measurements were performed on a one dimensional scale in only one location of the simulated system, it was necessary to make sure that the sensor surfaces were located in the uniform part of the agrivoltaic system. Meaning that no boundary irradiance deviations would be included in the measurements. The desired system dimensions were investigated by simulating an example system with the highest clearance height (8 m) from the chosen design parameters, since this is the system which will cast the longest shadows. The result of the shadow test simulation is shown in figure 15 below. From which it can be concluded that there are no significant boundary irradiance influence 28 m in from the south direction boundary, 24 m in from the east and west direction and 0 m from the north direction. Hence all of the simulated designs were constructed with a 30 m buffer distance to every direction from the light measuring sensor, to make sure that they were located in the uniform part of the system.

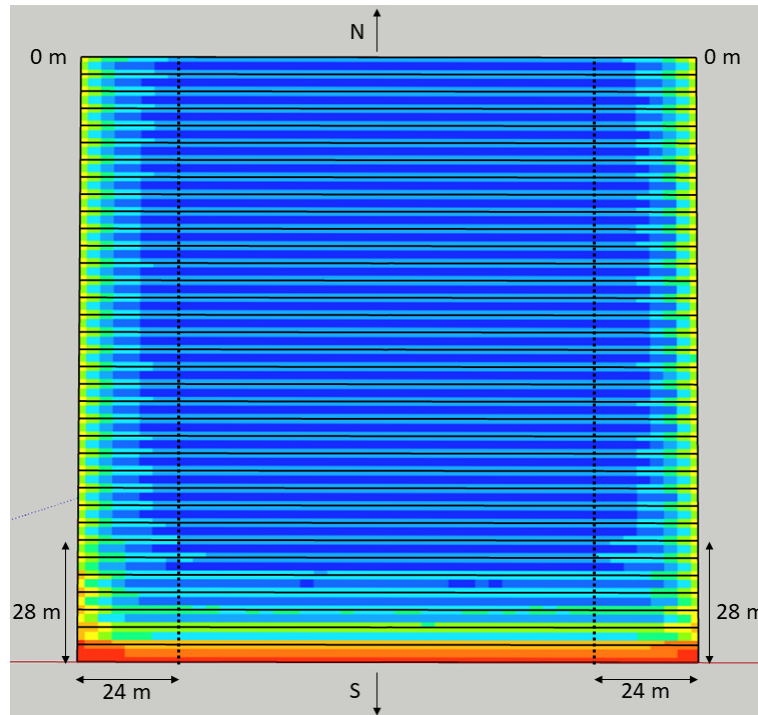


Figure 15: Light distribution for the simulated system with the largest clearance height, to show where the boundaries for a uniform light distribution is at. The colored area is showing the ground irradiance distribution as seen from above, with the PV modules hidden in the program interface.

Not including any irradiance measurements from the system boundaries will mean that the resulting irradiance will be lower than for a real case, since some parts of the system which has a higher ground irradiance will be missed, and thus all of the results show a lower incoming irradiance which is underestimated. However, most of the agricultural companies owned about 5 - 10 ha farmland in 2020 according to Jorsbruksverket (2021). And if only a fraction of this land would be used for an agrivoltaic system, the boundary influence on the irradiance distribution would be negligible.

### 4.3 Analyze Results

Since the incoming light on the PV panels is measured on both the front and the back of the panels, the resulting panel irradiance as well as electricity output is presented as two different cases in the result section, labeled Monofacial and Bifacial respectively. One result for what it would look like if using monofacial panels and one result which adds up the back and the front irradiance, to show how the useful panel irradiance would look like if the system would use bifacial solar panels.

When combining all the chosen design parameters from table 4 it was noticeable how some of the resulting PV designs would be unpractical to construct in real life. Some combinations of parameters resulted in overlaying panel rows as can be seen in figure 16 below. The results from these simulations have been excluded from the result section. Since these designs obviously result in too much self-shading, and would be very hard to practically construct.

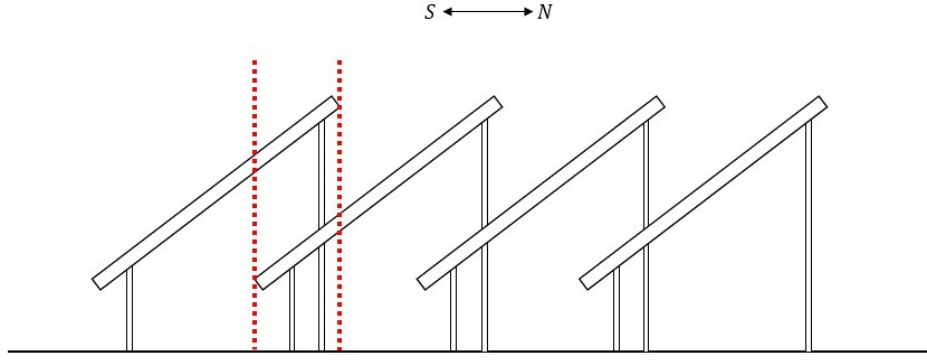


Figure 16: Schematic illustrating overlaying PV panels.

To be able to evaluate the incoming ground irradiance as compared to how it would look like with no shading from the PV panels, a reference case was used for some of the the calculations. The reference computations were made for a horizontal surface in SketchUp with no PV panels present above the ground. The reference values are shown in the results graphs as a black line labeled as *reference*.

#### 4.4 Calculations

MatLab was used to process the simulation results from SketchUp. The result contained hourly values for incoming irradiance for each light measurement sensor in the model. Which made it possible to process the results into total irradiance throughout the year as well as to show different temporal and spatial trends.

Since the total produced electricity in a PV park varies with the number of modules on a specific plant rather than just the panel irradiance per panel area, it was chosen to convert the available panel irradiance into panel irradiance per ground area in some of the results. An equation for how this was done can be seen below. Which means that the available panel irradiance is increased by increasing the number of modules stacked width-wise and reduced with increased row distance.

$$\text{Panel Irr.}/\text{m}^2 \text{ ground} = \frac{\text{Measured Panel Irradiance per m}^2 \cdot \text{Module Width}}{\text{Row Distance}} \quad (5)$$

##### 4.4.1 Shading Index

A daily ground shading index was developed as an indicator to the temporal distribution of the ground shading. This was done by dividing the daily ground irradiance into three parts (morning, mid-day and evening) and then evaluating how much of the shading takes place in the morning and evening as compared to during the middle of the day. The shading index computed by the following equation:

$$Si_{x,day} = \frac{\text{average of } X_{i,morning} \text{ and } X_{i,evening}}{X_{i, midday}} \quad (6)$$

Where the  $X$  values are the ground irradiance for a specific case and for a specific time period divided by the ground irradiance for the reference case.

$$X_i = \frac{\text{Ground irradiance for Agrivoltaic Layout } i}{\text{Ground irradiance for reference case (with no PV panels)}} \quad (7)$$

A shading index above 1 then indicates that a bigger share of the shading is occurring during the middle of the day than in the morning/evening. Which would be suitable for an agrivoltaic system according to what is already described in section 2.3.4.

#### 4.4.2 Electrical Output

The electrical output from the PV panels was computed by estimating a performance ratio using the PV simulation program SAM (System Advisor Model). By which, for example, the temperature dependence of the cell efficiency is considered. The performance ratio was computed with an assumption of no self-shading because this parameter is already included in the results from the optical simulations, since the calculations made in SketchUp includes the reduced available irradiance landing on the modules due to the arrays casting shade on each other.

However, by estimating the shading losses from the optical light simulations, the self-shading is assumed as linear, meaning that the power output is directly proportional to the amount of irradiance. Which means that the potential shading effects by shading of individual cells in a conventional silicon-based PV module, as described earlier in section 2.2.2 will be excluded from the calculations. The performance ratio for the bifacial module was also assumed to be the same as for a monofacial one due to the uncertainty in the bifacial calculations made in SAM. The performance ratio was assumed as 0.84 based on this PV system simulation. Moreover, the module efficiency was assumed as 22 %, based on the presented typical PV efficiencies in section 2.2. Moreover, the bifaciality factor of the PV modules was estimated as 0.8, which is also based on the typical values found in section 2.2.3.

#### 4.5 Sensitivity Analysis

In the sensitivity analysis the albedo and the module thickness were varied to see how these parameters would affect the results. The analysis was done by varying these values in the light simulation model for two different type systems, and investigate their impact on the light distribution of the different layouts.

#### 4.6 Machine Learning

In the simulation the design parameters were varied in rather rough increments, meaning that some optimal designs or result variations could be missed which lay in between the chosen increments. A machine learning model in MatLab was used to be able to approximate results which lay outside of the discrete simulated ones. This was done for the resulting total ground irradiance throughout one year per  $\text{m}^2$  depending on the design parameters of the PV system. The model which best fitted the data was the Rational Quadratic Gaussian Process Regression model, which resulted in an RMSE (Root Mean Square Error) of  $7.43 \text{ kWh/m}^2$  and seems to fit well for designs within

the simulated range of parameters. The machine learning results never ended up being used in the results of this thesis, but it might be useful to know that the generated data can be used in machine learning programs for future research.

The response plots for this machine learning model can be seen in figure 17 and 18 below where the true response show the SketchUp simulation results and the predicted response shows how the model would predict the results based on the true values. Figure 17 Shows the true and predicted total ground irradiance for all of the simulated designs. And figure 18 shows the predicted response plotted against the true ground irradiance.

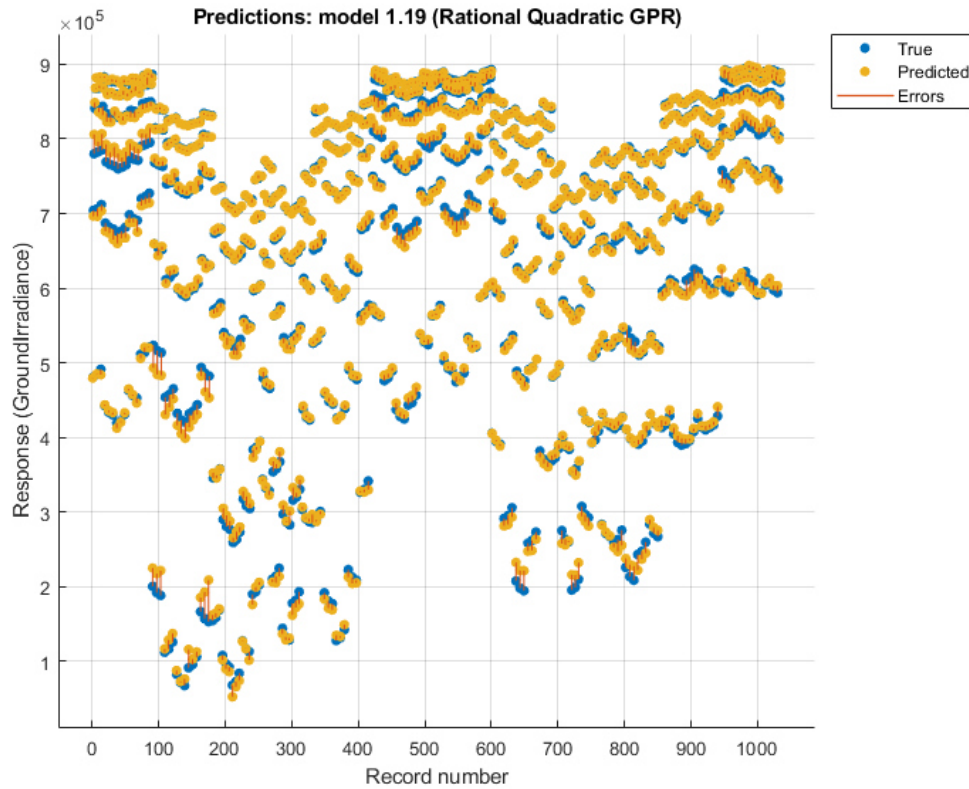


Figure 17: Response plot showing the true and predicted results respectively from the machine learning process. The unit on the y-axis is  $W/m^2$ .

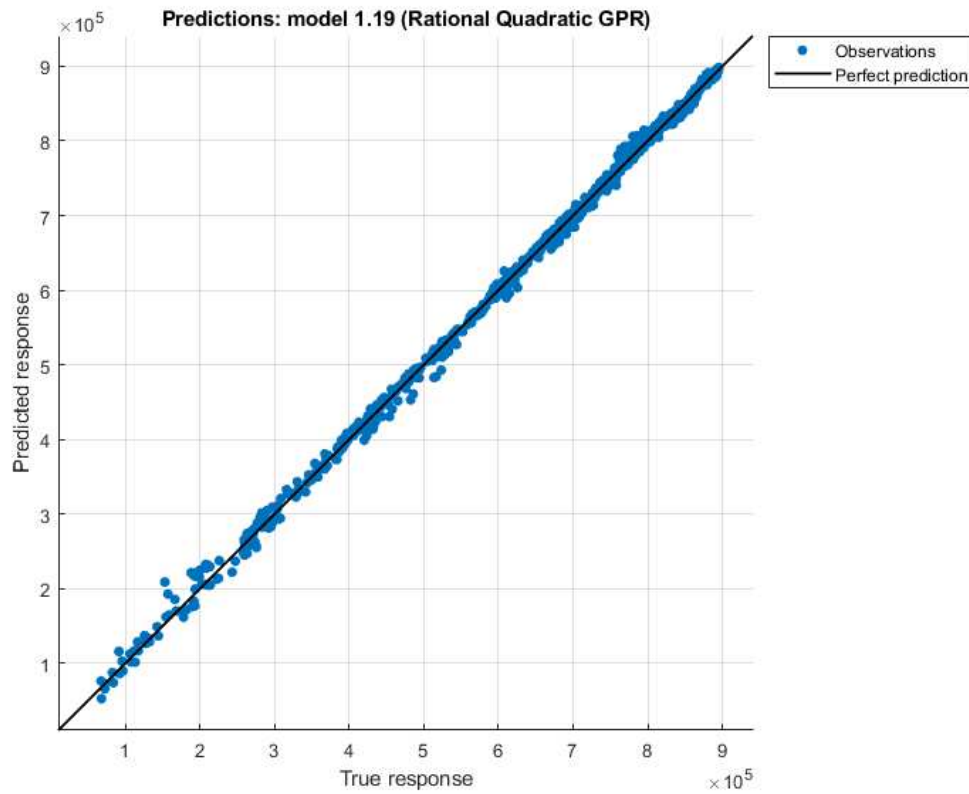


Figure 18: Plot showing the predicted values from the machine learning model as compared to the actual simulated values. The black line is showing how a perfect prediction would look like. The unit for the x and y axis is  $W/m^2$ .

## 5 Results

The following chapter presents the results of the light irradiance simulations. It starts with an overview of each of the design parameters' impact on the light sharing properties of the agrivoltaic layouts. After that, an optimization analysis is made investigating the different function objectives that could be optimized when constructing a design with good light sharing properties. Lastly, some example designs suitable for various degrees of allowed ground shading will be presented, as well as some real scale examples of agrivoltaic system layouts which might be suitable for a Swedish climate.

### 5.1 Design Parameters

In figure 19 the impact on the light sharing properties by each of the five investigated design parameters is presented. The line presented as *Monofacial* shows the incoming irradiance falling on the front of the modules, and the line presented as *Bifacial* is the total irradiance falling on both the front and the back of the panels. Furthermore, the panel irradiance is evaluated as the panel irradiance per  $\text{m}^2$  of ground, a description of what is meant by this can be found in section 4.4. The values in figure 19 are computed by averaging the resulting irradiance for all systems with a fixed design parameter value. For example, in the upper left sub-figure, the values at 10 m row distance are the mean irradiance results for all the design combinations with a row distance of 10 m.

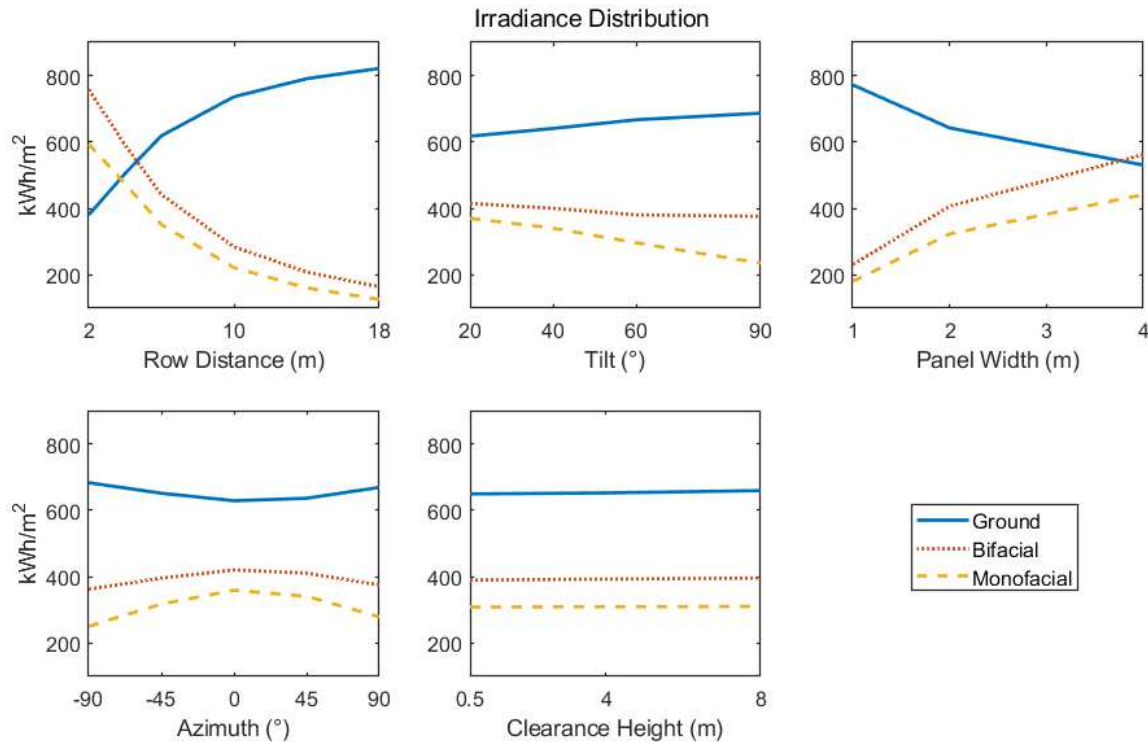


Figure 19: Graphs showing the influence on the incoming irradiance distribution by each of the investigated design parameters individually. The irradiance is averaged values over all of the simulated design, and the panel irradiance (Monofacial and Bifacial) is evaluated as per ground area.



From this, it is noticeable how each of the design parameters influences the irradiance distribution of the model in different ways; below is a short review considering each of the investigated parameters.

- **Row Distance**

The distance between the module rows is the parameter which has the biggest impact on the irradiance distribution of the system. Due to a longer row distance resulting in less shading of the ground beneath the panels and a reduced area for collection of the incoming light by the reduced number of module rows.

- **Tilt**

It is visible from the graph how a tilt angle of 20 - 40 ° is the optimum for maximizing the panel irradiance. An increase of the module tilt angle also results in a higher bifacial irradiance since a higher amount of ground-reflected light can hit the panel from the back. Considering the ground, there is less ground shading present for higher tilt angles since this allows more light flow from the sides of the system.

- **Panel Width**

One can see from the presented profile how a higher module array (more modules stacked) reduces the ground irradiance by stopping more incoming sunlight but increases the area of collection for the PV panels, which results in a higher panel irradiance.

- **Azimuth**

It is visible how the optimal azimuth for maximizing panel irradiance is at 0 ° azimuth. However, a south-facing system results in more ground shading when the sun is at its highest point, reducing the total yearly ground irradiance. For azimuths diverging from 0 ° the bifacial panels are more beneficial since the panel can collect incoming light also from east and west.

- **Clearance Height**

Noticeably, the system clearance height has the smallest influence on the total irradiance distribution out of all design parameters. The following section will further discuss why that is and describe how the system installation height still affects the light sharing of the system in other ways, such as how the irradiance gets distributed on the ground between the panel rows.

### 5.1.1 Clearance Height

As described in the section above, the clearance height is the parameter that has the least influence on the overall light distribution. This is because the increase in ground irradiance due to raising a system higher mainly occurs when the sun is low in the sky and irradiates the least amount of energy. The potential increase in panel irradiance is due to the possibility of collecting more diffuse irradiance from all sides for a higher system. The biggest increase in irradiance over the agricultural season, from raising the simulated designs from 0.5 to 8 m, was 17.3 kWh/m<sup>2</sup> for the ground and 26.9 kWh/m<sup>2</sup> for the panels. These potential increases in total irradiance are negligible for the yearly total irradiance. The system clearance height makes the most significant difference for the irradiance distribution for short row distances and wide module rows.

However, the clearance height significantly impacts how the incoming irradiance gets distributed in space and in time. For example, a raised system results in a smoother irradiance profile for the ground between the panel rows. In figure 20 below the ground irradiance distribution profiles are shown for two example designs. It is noticeable how the shape and the magnitude of the lowest point change with the system height. The design specifications for the two example systems can be found in table 6.

Table 6: Table showing the design specifications for the example layouts shown in figure 20. Where the total ground irradiance of design ex. 1 is less sensitive to the height parameter than design ex. 2, due to the difference in row spacing.

|              | Row Distance $L$ (m) | Tilt $\beta$ ( $^{\circ}$ ) | Panel Width $w$ (m) | Azimuth $\gamma$ ( $^{\circ}$ ) |
|--------------|----------------------|-----------------------------|---------------------|---------------------------------|
| Design ex. 1 | 18                   | 20                          | 1                   | 0                               |
| Design ex. 2 | 2                    | 20                          | 1                   | 0                               |

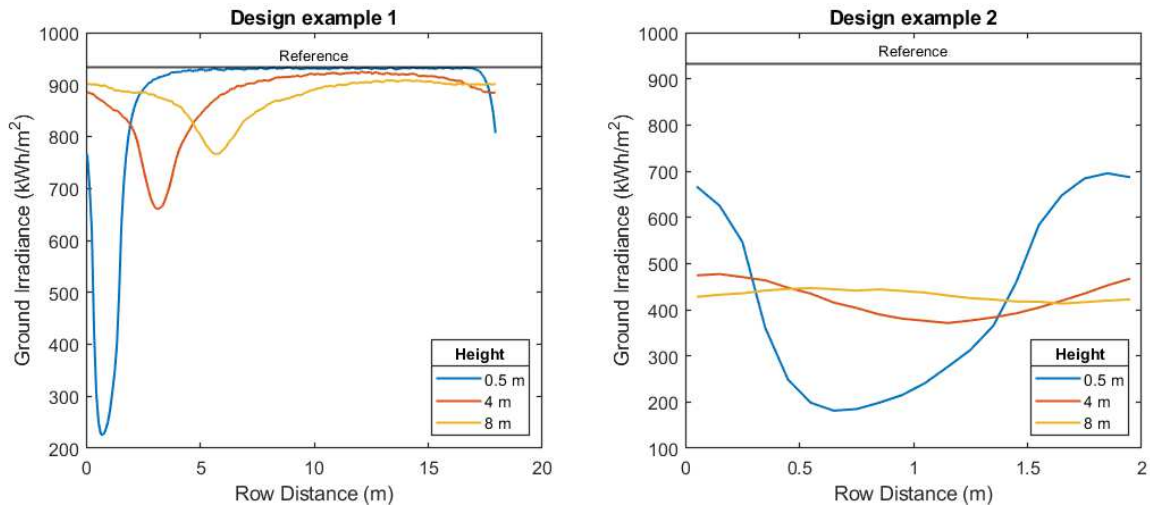


Figure 20: Figure showing ground irradiance distributions of two example systems, depending on the system clearance height. Design example 1 is a system which total yearly irradiance is less sensitive to the clearance height, while Design example 2 is more sensitive to the height. The black line shows the ground irradiance profile for a reference system with no PV modules present.

### 5.1.2 Azimuth

The temporal distribution of the ground irradiance throughout time is heavily affected by the azimuth of the system, as can be noted from figure 21 below. Furthermore, it is clear how an east ( $-90^{\circ}$ ) or southeast ( $-45^{\circ}$ ) facing system allows for more incoming light to reach the ground in the afternoon, while a west ( $90^{\circ}$ ) or southwest ( $45^{\circ}$ ) facing system allows for more light reaching the ground in the morning. A south-facing system allows for a little more incoming light in the morning and the evening but blocks the incoming light during mid-day when the sun is at its highest point.

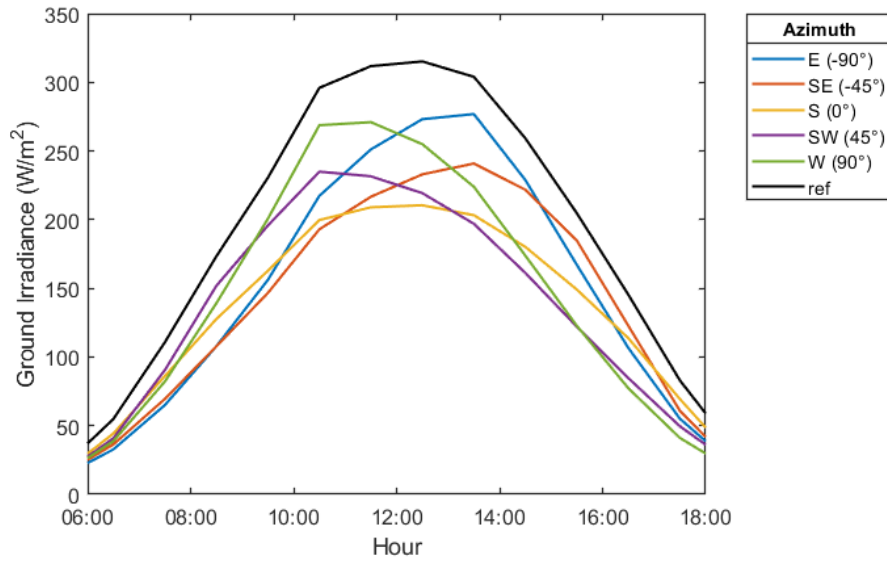


Figure 21: Plot showing how the daily trend of the irradiance profile changes depending on the system azimuth.

The same trend is present for the yearly distribution profile, as can be seen in figure 22 below, even if the trends are a bit less evident from just looking at the graph. An east-facing system gives more ground irradiance later in the year towards autumn, while a west-facing system gives more ground irradiance in springtime.

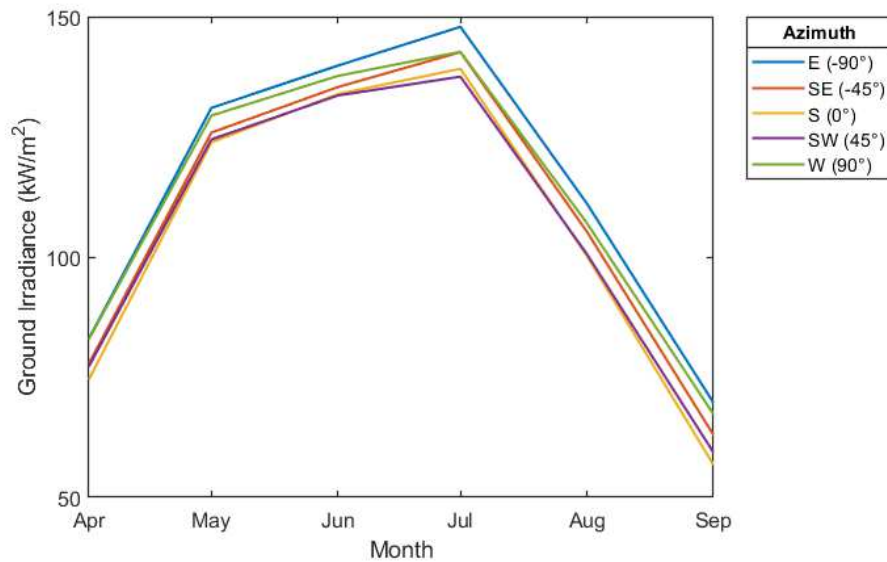


Figure 22: Plot showing how the seasonal trend of the irradiance profile changes depending on the system azimuth. The figure is zoomed in to better illustrate the profiles. The black line shows the daily ground irradiance for a reference system with no PV modules present.

## 5.2 Objective Function

It is not trivial which resulting properties should be used as the objective function when optimizing the layout of an agrivoltaic system. The most intuitive choice is to maximize both the panel and ground irradiance. But as discussed in section 2.3.4, it is also important to look at the temporal distribution of the ground irradiance, which is why a shading index could be used as explained in 4.4.1. The uniformity of the ground irradiance also matters since a more uniform light distribution provides the crops similar growing conditions independent of their location in the system. Therefore, another potential objective function is the standard deviation (STD) of the ground irradiance depending on the location between the panel rows, where a lower value indicates a more uniform light distribution. Figure 23 below shows all of these potential objective functions as well as their mutual correlation.

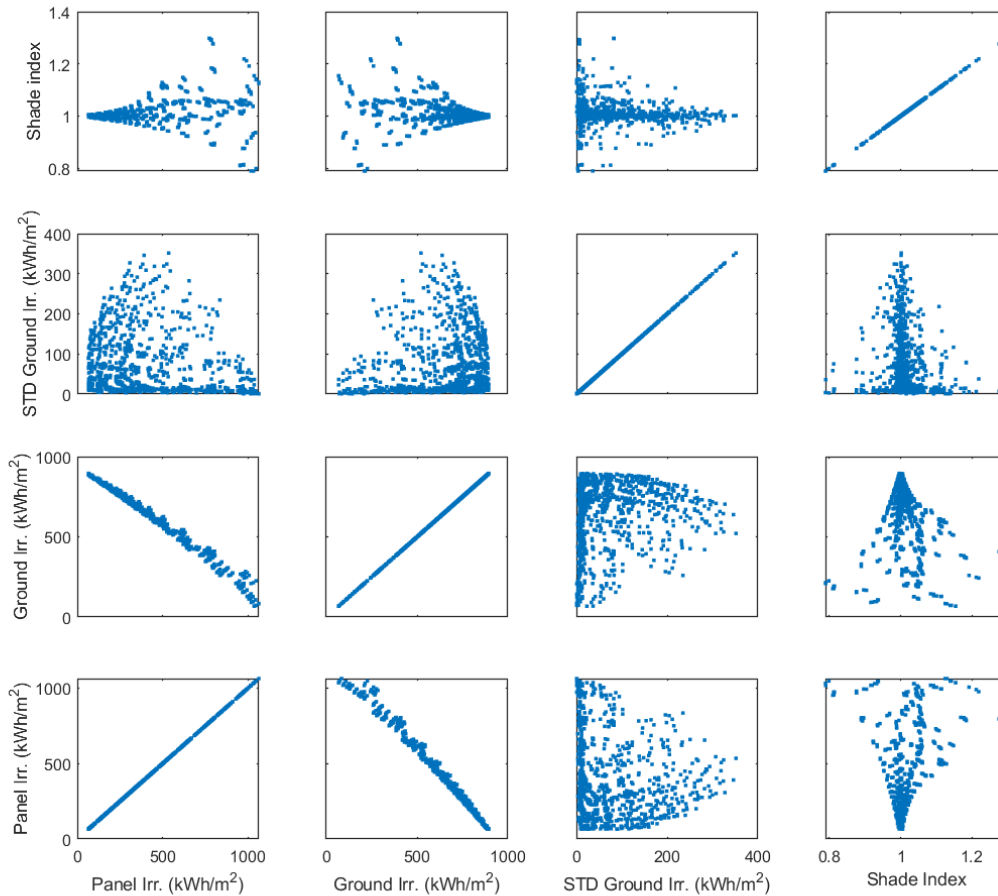


Figure 23: Showing the objective functions and their mutual correlation. The diagonal subplots all look linear since the  $x$  and  $y$ -axis of those are the same parameter. The panel irradiance is presented as the bifacial module irradiance per ground area. The STD of the ground irradiance is the standard deviation of the ground irradiance as distributed on the ground between the panel rows. And the shading index is a ratio between the irradiance coming in during the morning and evening divided by the amount of irradiance during mid-day as defined in section 4.4.1.

From figure 23 above, it is noticeable how the ground irradiance and the panel irradiance show a linear dependence, where an increase in the panel irradiance results in a reduction of the ground irradiance. However, there is no clear correlation between the standard deviation or shading index as compared to the other function objectives. Nevertheless, one can see how the shade index is close to 1 for most of the simulated layouts, which means that the ground shading is approximately the same during mid-day as the morning/evening for most simulated layouts. The standard deviation of the ground irradiance seems to be slightly lower for a low panel irradiance and high ground irradiance.

In figure 24 below, the resulting ground and panel irradiance are shown depending on what objective function is maximized for. By maximizing either the panel irradiance or the ground irradiance the irradiance distribution for the best layout looks similar, with high resulting values for both the panel and the ground irradiance. However, if the system is maximized for the panel irradiance per ground area the shortest row distances are favored, and hence the ground irradiance gets significantly reduced while also increasing the self-shading. Minimizing the STD of the ground irradiance results in relatively low total values for the ground irradiance. While optimizing for the shading index results in values for the panel and ground irradiance which are somewhere in the middle.

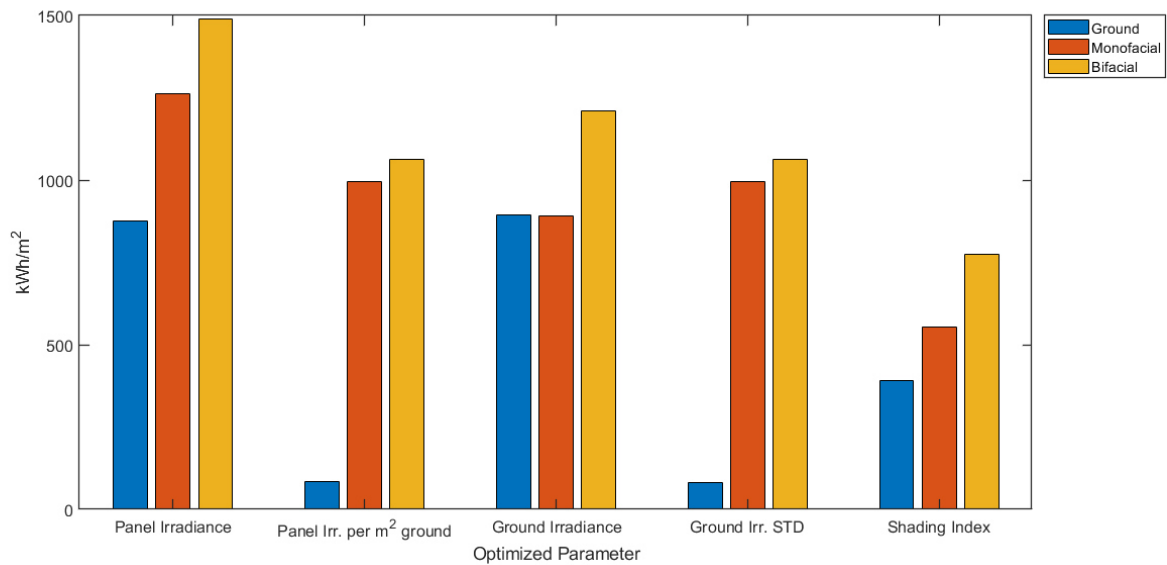


Figure 24: Plot showing the resulting panel and ground irradiance when optimizing for five different function objectives.

### 5.3 Optimization - Ground Shading Level

This section presents one way of optimizing an agrivoltaic system, based on minimizing the shading received by the plants while producing as much PV electricity as possible. This was done by picking out the system designs that meet a certain ground shading level and then finding the layouts which gives a high panel irradiance. The evaluated shading limits are based on the argument given in section 2.3.5. Below, two figures are presented illustrating the evaluated ground shading levels, where figure 25 demonstrates the distribution of the resulting ground shading percentages for all the investigated system layouts. Furthermore, figure 26 shows daily mean irradiance profiles as well as seasonal irradiance profiles for some example systems which are meeting the different ground shading levels.

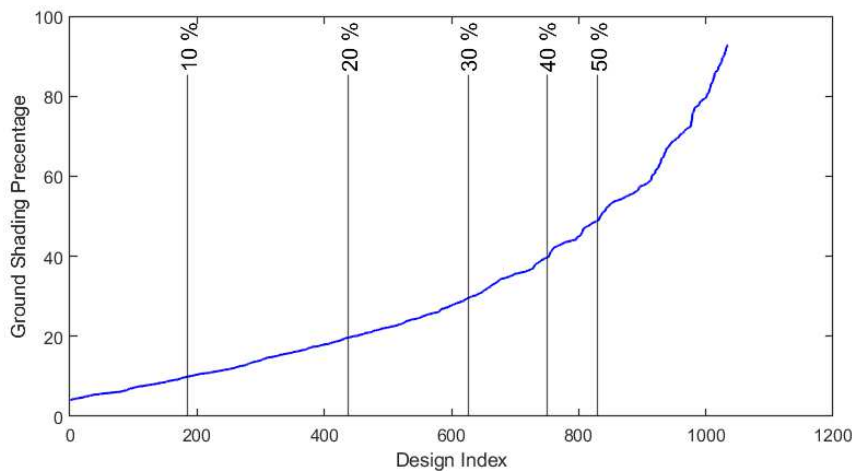


Figure 25: Showing the ground shading percentage results for all simulated system layouts. From this one can see approximately how many of the simulated systems meets a certain shading limit.

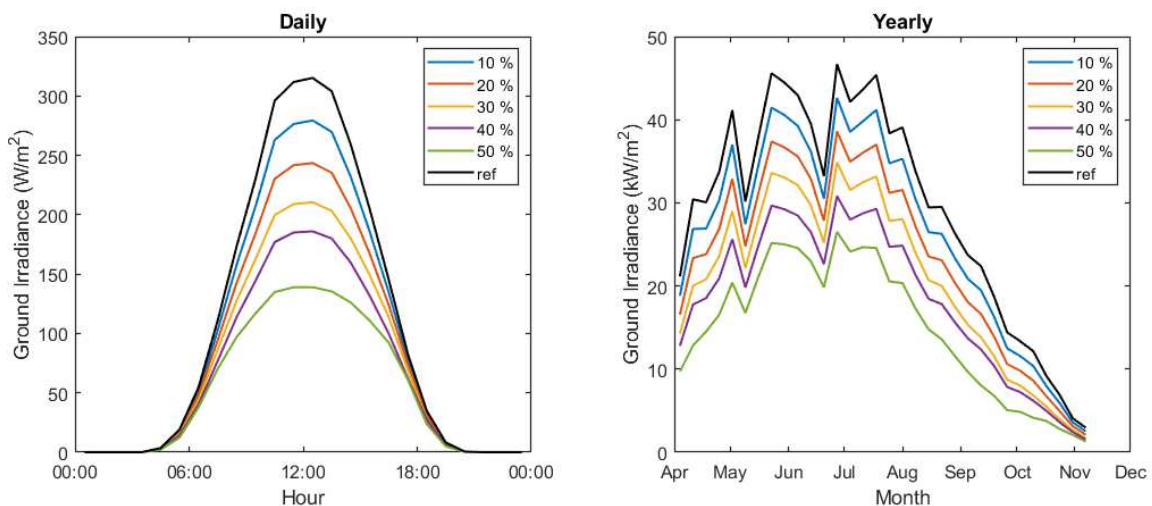


Figure 26: Figure showing examples of daily mean and seasonal profiles for the 5 different shading levels. All the presented systems are south-facing. The black lines shows the daily and yearly ground irradiance profile for a reference system with no PV modules present.

### 5.3.1 Design Examples

The following results show some examples of suitable PV system layouts for some different ground shading levels. The resulting parameters presented are the total ground irradiance throughout the agricultural season, the available yearly electricity output by the modules, and the total panel irradiance throughout a year. The electricity output and the panel irradiance are calculated by including incoming irradiance on both the front and the back of the modules. Noticeable is how the panel irradiance and power output are given as per panel area in the following section. For the ground irradiance, the value in parenthesis is the ground irradiance for the light sensor which gets the highest amount of shading throughout a year. Because of the results in section 5.1.1, that the clearance height results in a negligible difference for the total yearly irradiance distribution, the following section only presents systems with a clearance height of 0.5 m.

### 5.3.2 0 - 10 % Shading

In table 7 below a few different design examples for an agrivoltaic systems with a ground shading of less than 10 % are presented. To archive this minor amount of ground shading the module row spacing has to be fairly big, no shorter than about 10 m. It is also noticeable how the panel width should be no wider than about 1 m. A 2 m row width can meet this shading level if the row distance is 18 m, and the system is east/west-facing with a tilt angle of 90 or 60 °. It is also possible to have an optimal tilt and azimuth for the module power output by having a south-facing system with a 40 degree tilt and a row distance of or longer than 14 m.

Table 7: Design examples for system setups resulting in 0 - 10 % ground shading.

| Row Distance L (m) | Tilt $\beta$ (°) | Panel Width w (m) | Azimuth $\gamma$ (°) |
|--------------------|------------------|-------------------|----------------------|
| 18                 | 60 / 90          | 2                 | -90 / 90             |
| 18                 | 20 / 40 / 60     | 1                 | 0                    |
| 14                 | 20 / 40 / 60     | 1                 | 0                    |
| 14                 | 20 / 40 / 60     | 1                 | -45 / 45             |
| 10                 | 90               | 1                 | -45 / 45             |
| 10                 | 60 / 90          | 1                 | -90 / 90             |

In table 8 some design examples and their resulting properties are shown. The table is showing the specific design parameters to the left and the corresponding simulation results to the right. For system designs meeting this shading level the ground irradiance ranges from 841 kWh/m<sup>2</sup> to 891 kWh/m<sup>2</sup> and the available panel irradiance ranges from 1160 and 1487 kWh/m<sup>2</sup> per module area.

Table 8: Resulting system properties for system designs with 0 - 10 % ground shading. A description of the system property values can be found in section 5.3.1.

| Design Specifics |         |   |          | System Properties ( kWh/m <sup>2</sup> ) |                    |                  |
|------------------|---------|---|----------|--|--------------------|------------------|
| L                | $\beta$ | w | $\gamma$ | Ground Irradiance (min.)                 | Output Electricity | Panel Irradiance |
| 18               | 90      | 2 | 90       | 846 (656)                                | 200                | 1193             |
| 18               | 40      | 1 | 0        | 873 (271)                                | 266                | 1487             |
| 14               | 40      | 1 | 0        | 857 (270)                                | 266                | 1481             |
| 14               | 40      | 1 | 45       | 859 (368)                                | 258                | 1440             |
| 10               | 60      | 1 | -45      | 843 (472)                                | 232                | 1317             |
| 10               | 20      | 1 | 90       | 841 (414)                                | 226                | 1264             |

### 5.3.3 10 - 20 % Shading

For 10 - 20 % ground shading a few example layouts can be found in table 9. To achieve this level of ground shading the module row distance should be no shorter than 4 m. It is also noticeable how the array height is limited to 2 module widths for systems with a shorter row spacing than 10 m. For a row spacing of about 18 m or longer it is possible to stack more panels on top of each other to about a width of 4 m, but then it gets important to carefully consider the system design, only a system with 90 ° module tilt facing SW or SE is able to meet this ground shading limit. A south-facing agrivoltaic system with a row spacing of 18 m and 2 m panel width also meets this ground shading limit.

Table 9: Design examples for system setups which results in 10 - 20 % ground shading.

| Row Distance L (m) | Tilt $\beta$ (°) | Panel Width w (m) | Azimuth $\gamma$ (°) |
|--------------------|------------------|-------------------|----------------------|
| 18                 | 90               | 4                 | -45 / 45             |
| 18                 | 20 / 40 / 60     | 2                 | 0                    |
| 14                 | 20 / 40 / 60     | 2                 | 0                    |
| 14                 | 60 / 90          | 1                 | -90 / 90             |
| 10                 | 20 / 40 / 60     | 1                 | 0                    |
| 10                 | 60 / 90          | 2                 | -90 / 90             |
| 6                  | 20 / 40 / 60     | 1                 | 0                    |
| 6                  | 20 / 40 / 60     | 1                 | -45 / 45             |
| 4                  | 90               | 1                 | -45 / 0 / 45         |

In table 10 some resulting properties are presented for example systems giving between and 10 and 20 % ground shading. For system designs meeting this shading level the ground irradiance ranges from 747 kWh/m<sup>2</sup> to 839 kWh/m<sup>2</sup> and the available panel irradiance ranges from 1100 and 1471 kWh/m<sup>2</sup>.



Table 10: Resulting system properties for system designs which results in 10 - 20 % ground shading. A description of the system property values can be found in section 5.3.1.

| Design Specifics |         |   |          | System Properties ( kWh/m <sup>2</sup> ) |                    |                  |
|------------------|---------|---|----------|--|--------------------|------------------|
| L                | $\beta$ | w | $\gamma$ | Ground Irradiance (min.)                 | Output Electricity | Panel Irradiance |
| 18               | 90      | 4 | 45       | 767 (419)                                | 201                | 1153             |
| 18               | 40      | 2 | 0        | 815 (178)                                | 263                | 1468             |
| 14               | 40      | 2 | 0        | 781 (177)                                | 262                | 1459             |
| 14               | 90      | 2 | 90       | 822 (654)                                | 198                | 1177             |
| 10               | 40      | 1 | 0        | 826 (268)                                | 264                | 1471             |
| 10               | 90      | 2 | 90       | 781 (645)                                | 193                | 1148             |
| 6                | 40      | 1 | 0        | 757 (263)                                | 260                | 1450             |
| 6                | 20      | 1 | 45       | 764 (294)                                | 246                | 1370             |
| 4                | 90      | 1 | 45       | 747 (554)                                | 198                | 1137             |
| 4                | 90      | 1 | 0        | 757 (422)                                | 195                | 1113             |

### 5.3.4 20 - 30 % Shading

In table 11 below a few different design examples for an agrivoltaic systems with a ground shading between 20 and 30 % are presented. For row distances of 10 m and longer it is possible to have four PV modules stacked width-wise and still meet a ground shading level of less than 30 %. For a system layout with 18 m row spacing the panel irradiance per panel area can be maximized by having a south-facing system with a tilt of 20 - 60 degrees. This system design is also the one out of the 18 m row distance designs which gives the highest panel irradiance and the most ground shading, so for higher ground shading levels the 18 m design can no longer be improved and hence will not be included in those results.

Table 11: Design examples for system setups which results in 20 - 30 % ground shading.

| Row Distance L (m) | Tilt $\beta$ (°) | Panel Width w (m) | Azimuth $\gamma$ (°) |
|--------------------|------------------|-------------------|----------------------|
| 18                 | 20 / 40 / 60     | 4                 | 0                    |
| 18                 | 20 / 40 / 60     | 4                 | -45 / 45             |
| 14                 | 60 / 90          | 4                 | 0                    |
| 14                 | 60 / 90          | 4                 | -90 / 90             |
| 10                 | 90               | 4                 | 0 / -45              |
| 10                 | 20 / 40 / 60     | 2                 | 0                    |
| 6                  | 60 / 90          | 2                 | -90 / 90             |
| 6                  | 90               | 2                 | 0                    |
| 4                  | 20 / 40 / 60     | 1                 | 0                    |
| 4                  | 60 / 90          | 1                 | -90 / 90             |

In table 12 some resulting properties of example systems giving between 20 and 30 % ground shading. The table is showing the specific design parameters to the left and the corresponding simulation results to the right. For system designs meeting this shading level the ground irradiance ranges from 658 kWh/m<sup>2</sup> to 746 kWh/m<sup>2</sup> and the available panel irradiance ranges from 1128 and 1437 kWh/m<sup>2</sup>.

Table 12: Resulting system properties for system designs which results in 20 - 30 % ground shading. A description of the system property values can be found in section 5.3.1.

| Design Specifics |         |   |          | System Properties ( kWh/m <sup>2</sup> ) |                    |                  |
|------------------|---------|---|----------|--|--------------------|------------------|
| L                | $\beta$ | w | $\gamma$ | Ground Irradiance (min.)                 | Output Electricity | Panel Irradiance |
| 18               | 40      | 4 | 0        | 700 (120)                                | 258                | 1432             |
| 18               | 40      | 4 | 45       | 707 (159)                                | 250                | 1391             |
| 14               | 60      | 4 | 0        | 660 (180)                                | 242                | 1353             |
| 14               | 90      | 4 | 90       | 723 (586)                                | 186                | 1106             |
| 10               | 90      | 4 | -45      | 664 (433)                                | 177                | 1028             |
| 10               | 40      | 2 | 0        | 722 (173)                                | 259                | 1437             |
| 6                | 90      | 2 | 90       | 691 (606)                                | 181                | 1077             |
| 6                | 90      | 2 | 0        | 706 (339)                                | 188                | 1071             |
| 4                | 40      | 1 | 0        | 670 (253)                                | 256                | 1421             |
| 4                | 90      | 1 | 90       | 745 (692)                                | 188                | 1121             |

### 5.3.5 30 - 40 % Shading

In table 13 below a few different design examples for an agrivoltaic systems with a ground shading of 40 - 50 % are presented. To archive this amount of ground incoming irradiance the module row distance could be as narrow as 2 m. For row distances of 14 m and longer it is possible to have 4 PV modules stacked width-wise and still meet a ground shading level of less than 40 %. For a row spacing of 14 m it is possible to have a south-facing system with 20 or 40 degree tilt and 4 modules stacked width-wise, which is also resulting in a higher panel irradiance and the possibility of producing more PV electricity. For 2 and 4 m row distance only a few specific system designs met the considered shading level.

Table 13: Design examples for system setups which results in 30 -40 % ground shading.

| Row Distance L (m) | Tilt $\beta$ (°) | Panel Width w (m) | Azimuth $\gamma$ (°) |
|--------------------|------------------|-------------------|----------------------|
| 14                 | 20 / 40          | 4                 | 0                    |
| 10                 | 60 / 90          | 4                 | -90 / 90             |
| 10                 | 60 / 90          | 4                 | 45                   |
| 6                  | 20 / 40 / 60     | 2                 | 0                    |
| 6                  | 20 / 40 / 60     | 2                 | -45 / 45             |
| 4                  | 60 / 90          | 2                 | -90 / 90             |
| 4                  | 90               | 2                 | -45 / 0 / 45         |
| 2                  | 40 / 60          | 1                 | -90                  |
| 2                  | 90               | 1                 | -45 / 0 / 45         |

In table 14 some resulting properties of example systems giving between 30 and 40 % ground shading. The table is showing the specific design parameters to the left and the corresponding simulation results to the right. For system designs meeting this shading level the ground irradiance ranges from 562 kWh/m<sup>2</sup> to 652 kWh/m<sup>2</sup> and the available panel irradiance ranges from 977 and 1408 kWh/m<sup>2</sup>.

Table 14: Resulting system properties for system designs which results in 30 - 40 % ground shading. A description of the system property values can be found in section 5.3.1.

| Design Specifics |         |   |          | System Properties ( kWh/m <sup>2</sup> ) |                    |                  |
|------------------|---------|---|----------|--|--------------------|------------------|
| L                | $\beta$ | w | $\gamma$ | Ground Irradiance (min.)                 | Output Electricity | Panel Irradiance |
| 14               | 40      | 4 | 0        | 635 (116)                                | 254                | 1408             |
| 10               | 90      | 4 | 90       | 652 (552)                                | 175                | 1043             |
| 10               | 60      | 4 | 45       | 569 (212)                                | 224                | 1257             |
| 6                | 40      | 2 | 0        | 587 (158)                                | 251                | 1389             |
| 6                | 60      | 2 | 45       | 624 (298)                                | 230                | 1289             |
| 4                | 90      | 2 | 90       | 596 (523)                                | 166                | 986              |
| 4                | 90      | 2 | 45       | 593 (406)                                | 176                | 1009             |
| 2                | 40      | 1 | -90      | 562 (429)                                | 184                | 1039             |
| 2                | 90      | 1 | 0        | 608 (353)                                | 174                | 990              |

### 5.3.6 40 - 50 % Shading

In table 15 below a few different design examples for an agrivoltaic systems with a ground shading between 40 and 50 % are presented. For row distances of 6 m and longer it is possible to have 4 PV modules stacked width-wise and still meet a ground shading of less than 40 %. For a row spacing of 10 m it is possible to have a south-facing system with 20 or 40 degree tilt and 4 modules stacked, which is also resulting in a higher panel irradiance and the possibility of producing more PV electricity.

Table 15: Design examples for system setups which results in 40 - 50 % ground shading.

| Row Distance L (m) | Tilt $\beta$ (°) | Panel Width w (m) | Azimuth $\gamma$ (°) |
|--------------------|------------------|-------------------|----------------------|
| 10                 | 20 / 40          | 4                 | -45 / 0 / 45         |
| 6                  | 60 / 90          | 4                 | -90 / 90             |
| 6                  | 90               | 4                 | -45 / 0 / 45         |
| 4                  | 60               | 2                 | -45 / 0 / 45         |
| 4                  | 20               | 2                 | -90 / 90             |
| 2                  | 60               | 1                 | -45 / 0 / 45         |
| 2                  | 20               | 1                 | -90 / 90             |

In table 16 some resulting properties of example systems giving between 40 and 50 % ground shading. The table is showing the specific design parameters to the left and the corresponding simulation results to the right. For system designs meeting this shading level the ground irradiance ranges from 562 kWh/m<sup>2</sup> to 652 kWh/m<sup>2</sup> and the available panel irradiance ranges from 977 and 1408 kWh/m<sup>2</sup>.

Table 16: Resulting system properties for system designs which results in 40 - 50 % ground shading. A description of the system property values can be found in section 5.3.1.

| Design Specifics |         |   |          | System Properties ( kWh/m <sup>2</sup> ) |                    |                  |
|------------------|---------|---|----------|--|--------------------|------------------|
| L                | $\beta$ | w | $\gamma$ | Ground Irradiance (min.)                 | Output Electricity | Panel Irradiance |
| 10               | 40      | 4 | 0        | 521 (100)                                | 246                | 1362             |
| 10               | 40      | 4 | 45       | 535 (135)                                | 238                | 1322             |
| 6                | 60      | 4 | 90       | 481 (310)                                | 167                | 952              |
| 6                | 90      | 4 | 45       | 510 (332)                                | 162                | 927              |
| 4                | 60      | 2 | 0        | 476 (180)                                | 224                | 1247             |
| 4                | 60      | 2 | 45       | 491 (250)                                | 215                | 1203             |
| 2                | 60      | 1 | 0        | 474 (237)                                | 224                | 1246             |
| 2                | 60      | 1 | 45       | 489 (333)                                | 215                | 1201             |

### 5.3.7 Ground Irradiance Uniformity

When it comes to the uniformity of light distribution on the ground, some layouts, such as a south-facing one will result in more shading beneath or behind the module row. One indicator of the uniformity of the ground irradiance is the minimum point of irradiance between the panel rows, which is shown in the tables above. By increasing this minimum irradiance, the ground irradiance profile will be more uniform, which allows for more similar growing conditions throughout the park. Two ways of improving the ground irradiance uniformity are to raise the system higher on a stilt mounting or to divert the azimuth from 0 °. As an example, one layout which gives less than 10 % ground shading, with a minimum point of ground shading at 271 kWh/m<sup>2</sup> is a south-facing system with 18 m row distance, 40 ° tilt, and 1 m panel width. Figure 27 shows how the minimum point of ground irradiance can be increased by changing the height or the azimuth of the system.

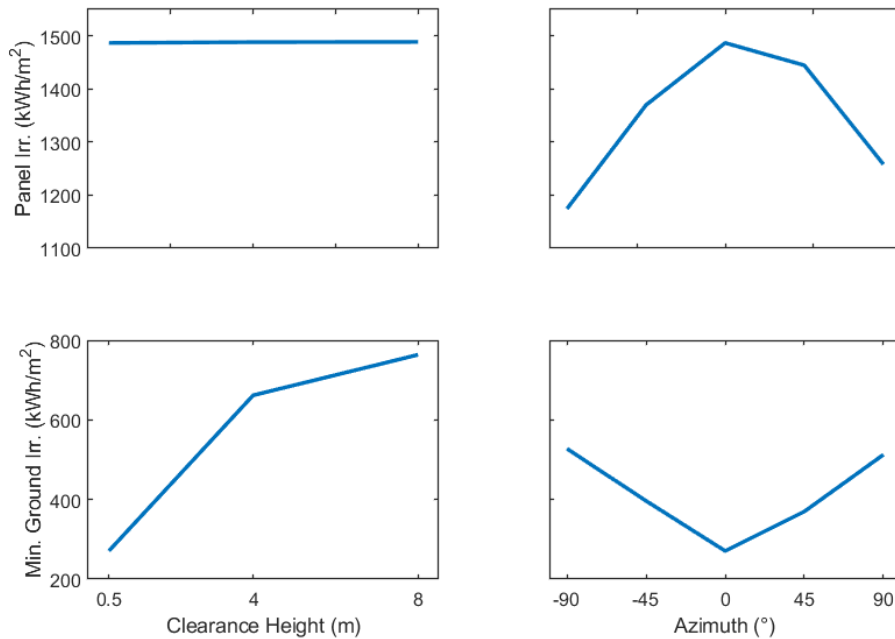


Figure 27: Showing how the minimum ground irradiance and the panel irradiance changes with the system azimuth and clearance height.

### 5.3.8 Summary

Some takeaways from the previous section are presented below:

- To reduce the ground shading from the PV modules to a minimum, long row distances, and low array heights are required.
- To increase the uniformity of the ground irradiance throughout the agrivoltaic system, the azimuth could be deviated from zero °, or the clearance height could be increased.
- A vertical bifacial system generally results in a higher degree of total ground irradiance falling on the crops, than a standard south-facing system with a 20 - 40 ° tilt.

In figure 28 a summary of the resulting design properties based on the different ground shading levels are shown. This bar diagram shows the maximum resulting values acquired for the different ground shading levels. A higher level of ground shading is mostly due to an increased ground coverage of the PV modules, which also increases the amount of self-shading in between the module rows, hence the module irradiance is also reduced for systems which gives a higher degree of ground shading.

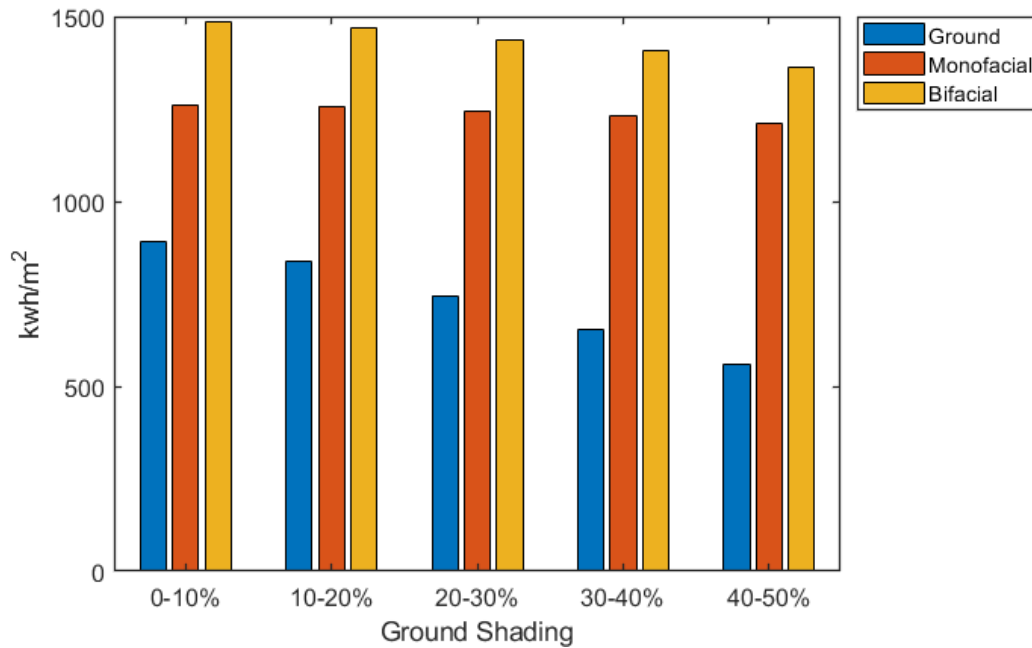


Figure 28: Showing how the irradiance distribution changes with the degree of ground shading.

## 5.4 Optimization - Temporal Distribution of Ground Shading

In this section some design examples are presented, which are resulting in less ground shading during morning/evening and more shading during mid-day. A reason for why it is good to investigate the temporal distribution of the ground irradiance is motivated in section 2.3.4. The following example designs shown in table 17 are some of the simulated layouts which resulted in a high shading index.

Table 17: Resulting system properties for system designs which allows for more ground irradiance during the morning/evening as compared to mid-day, based on the daily shading index.

| Design Specifics |         |   |          |     | System Properties ( kWh/m <sup>2</sup> ) |                    |                  |
|------------------|---------|---|----------|-----|--|--------------------|------------------|
| L                | $\beta$ | w | $\gamma$ | h   | Ground Irradiance (min.)                 | Output Electricity | Panel Irradiance |
| 2                | 90      | 2 | 45       | 0.5 | 390 (289)                                | 135                | 773              |
| 4                | 60      | 4 | 90       | 0.5 | 369 (274)                                | 138                | 787              |
| 2                | 40      | 2 | 0        | 0.5 | 128 (72)                                 | 181                | 995              |
| 2                | 90      | 1 | -90      | 0.5 | 594 (513)                                | 162                | 984              |

As can be noted from this, optimizing for the shading index does not result in a very good agrivoltaic system, since the systems with the highest shading indexes are some of the systems which results in the highest ground shading overall. However, the shading index might still give an indicator to how the temporal distribution of the ground irradiance looks like.

## 5.5 Larger Scale Example Designs

The following section presents three examples of actual size agrivoltaic designs. The land area in which the systems are constructed, is assumed to have an area of 5 ha (50 000 m<sup>2</sup>), from the information about the typical size of farmland which can be found in section 4.2.2 above. It is assumed that the farmland considered is square-shaped and that the PV modules can be oriented in an arbitrary direction. All of the designs were chosen to result in between 20 - 30 % ground shading, based on the recommendations made in Germany that an agrivoltaic system should have no more than one third irradiance reduction, as already discussed in section 2.3.5. The total produced electricity values for the following example layouts are a rough estimate based on several assumptions, which can all be found in section 4.4.2.

### 5.5.1 Ground Based

The first design example is a south-facing system with 18 m row spacing, 40 ° tilt, 0.5 m clearance height, and 4 modules stacked width-wise. Using this agrivoltaic layout on a 5 ha farmland, one could fit approximately 12 module rows with 524 modules in each row, which results in a total of 6288 modules. And these modules could produce approximately **2.75** GWh annually. The ground irradiance distribution of this layout can be seen in figure 29 below, where one can see that there is some more shading present directly behind the module row.

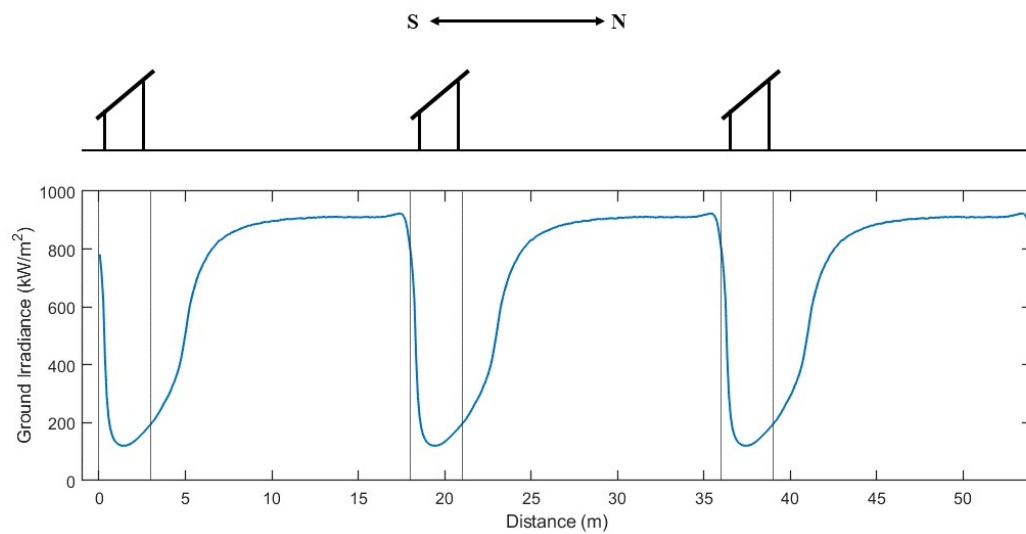


Figure 29: Showing the ground irradiance profile for a ground based agrivoltaic layout.

### 5.5.2 Vertical Bifacial

A design example with vertical modules is an east/west-facing system with 6 m row spacing, 90 ° tilt, 0.5 m clearance height, and 2 m module width. With the use of this agrivoltaic layout on a 5 ha farmland, one could fit approximately 37 module rows with 262 modules in each row, which is 9694 modules in total. This agrivoltaic park could then produce approximately **2.98 GWh** electricity annually. The ground irradiance distribution of this layout can be seen in figure 30 below, where it is noticeable how there is slightly more shading directly behind and in front of the module rows.

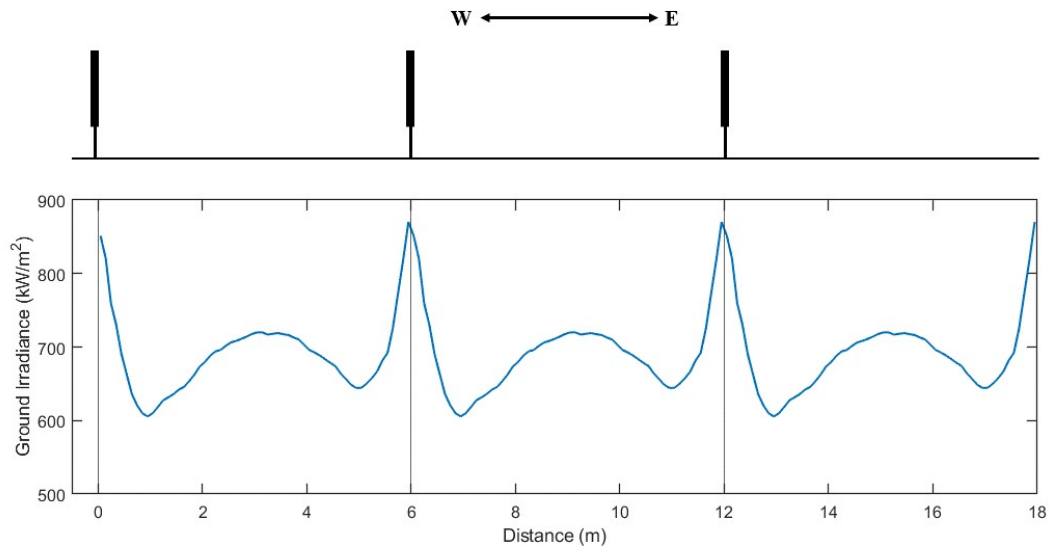


Figure 30: Showing the ground irradiance profile for a vertical agrivoltaic layout.

### 5.5.3 Stilt Mounted

An example of a stilt-mounted design is a south-west facing system with 4 m row spacing, 40 ° tilt, 4 m clearance height, and 1 m module width. By the construction of this agrivoltaic layout on a 5 ha farmland, one could fit about 55 module rows with 131 modules in each row, which is 7205 modules in total. And these modules could produce approximately **3.0 GWh** annually. The ground irradiance distribution of this layout can be seen in figure 31 below. It is visible how the light distribution of this type of system is very uniform, this is partially due to the clearance height of the system but also that the system azimuth is deviated from 0 °.

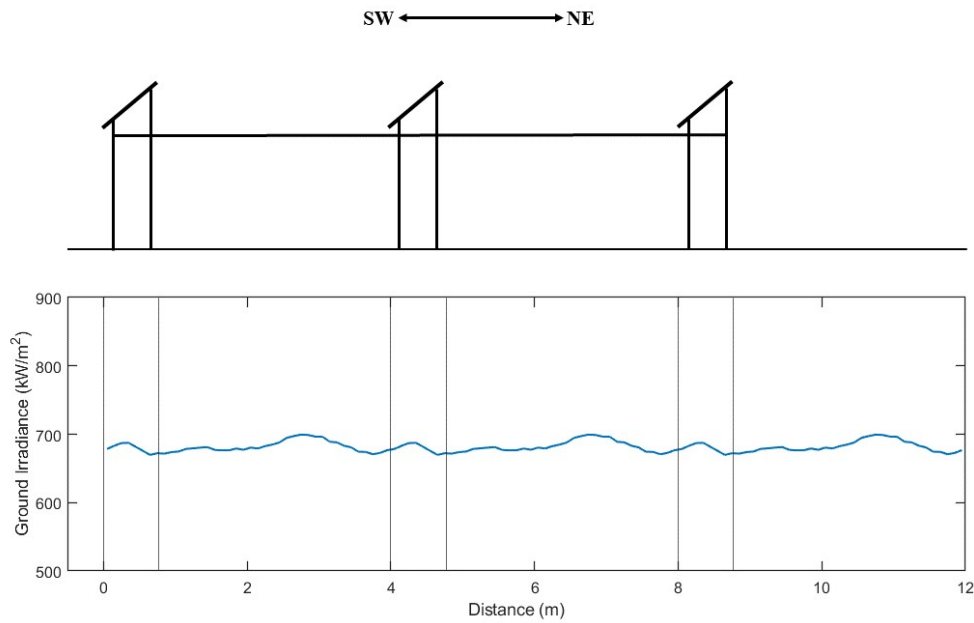


Figure 31: Showing the ground irradiance profile for a stilt mounted agrivoltaic layout.

## 5.6 Sensitivity Analysis

A sensitivity analysis was performed for some selected variables which were fixed in the simulations; the module thickness as well as the ground albedo. The sensitivity analysis was performed by changing the value of the parameter in question, and then investigate the influence by the change on the resulting irradiance distribution.

### 5.6.1 Module Thickness

The module thickness was fixed at 10 mm in the simulations, based on the assumption that this module dimension have no significance for the overall light distribution. A PV module is usually about 30 mm thick, as shown in table 3. But depending on the type of protection material used, the modules might get slightly thicker. Hence, the thickness was varied between 10 to 80 mm in this analysis. The results are given in figure 32 below, with the module thickness on the x-axis and the percentage change in ground irradiance on the y-axis. As visible from the figure, the module thickness only makes a slight difference in the ground irradiance, but for shorter row distance the difference



is more significant. The system used for this sensitivity analysis is south-facing, with  $40^\circ$  tilt, clearance height of 0.5 m, and a module width of 1 m.

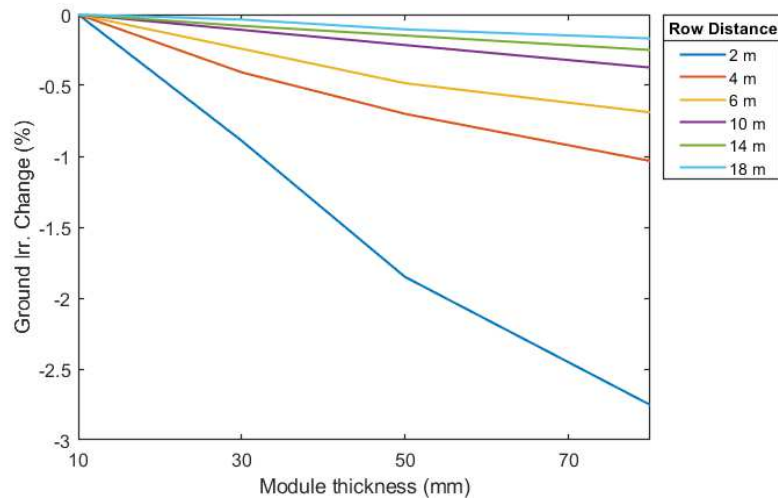


Figure 32: Showing the results of the sensitivity analysis for the module thickness.

### 5.6.2 Albedo

The ground albedo was fixed at 0.2 in the simulations. However, the albedo varies a lot with the crop's growth stage and what crop species is considered. This value was varied between 0.1 and 0.3 in the sensitivity analysis, which is based on some example values for vegetation found in section 3.2.6. The results of the sensitivity analysis can be seen in figure 33 below, and shows how the panel irradiance changes slightly with the ground albedo. It increases for higher values, and decreases for lower values. The albedo makes a smaller difference to the panel irradiance for shorter row distances, than for longer ones. The system layout chosen for this sensitivity analysis is an east/west-facing vertical bifacial system, with a module width of 1 m. Based on the assumption that vertical modules gets affected the most by the ground albedo.

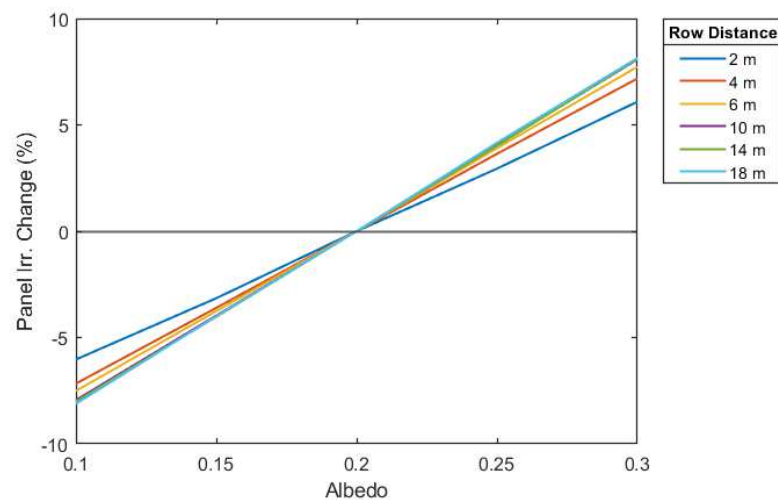


Figure 33: Showing the results of the sensitivity analysis for ground albedo, with the change in panel irradiance (both front and back) on the y-axis and the albedo value on the x-axis.

## 6 Discussion

*Below follows a discussion based on the simulation results shown in the section above. First, some conclusion and discussion points when it comes to the layout of an agrivoltaic system and how each of the design parameters influences the light sharing properties of the system. Secondly, some practical considerations. And lastly, about some limitations to this type of study and some thoughts about what to focus on in future research.*

### 6.1 Optimization

A challenge with performing an optimization analysis is often that there are no right or wrong regarding what to optimize for, since the best result can vary significantly depending on what is considered the most important parameter. For this project, the suitable layout of the PV modules in an agrivoltaic system depends on many different parameters and circumstances, and this project only provides results for two distinct cases; optimizing the yearly light distribution between the modules and the ground as well as optimizing for when the majority of the light distribution take place.

Another challenge is that there are no clear indicators or data for how the crops would be affected by the increased shading by the PV modules. The light measurement for the amount of the incoming irradiance that the crops can utilize for photosynthesis is PAR, which is not equal to the energy content in the incoming irradiance, which has to be considered. It is also hard to compare the shade tolerance for crops between research made in different countries, since the plants tend to adapt to the environment and climate where they are grown. Because of this uncertainty, a number of thresholds for various degrees of ground shading were used in this project, to be able to provide a range of suitable layouts for different degrees of allowed ground shading, which can then be used in the projecting processes for a future agrivoltaic system.

One thing to comment on in the results is that it is clear from figure 22 and 27 how the east facing system allows for slightly more ground irradiance, while a west facing system results in a higher module irradiance. This is due to the nature of the weather data used in the project. At the chosen locations the local weather is probably slightly sunnier in the evening when the sun is setting in west, than in the morning when the sun is rising in east.

The design examples shown in the result section can give an indicator of what to think about when deciding how to layout an agrivoltaic system. For longer row distance and fewer modules stacked width-wise, one can get plenty of ground irradiance, which means the plants can get better growing conditions. Raising the PV system using a stilt mounting or deviating the system azimuth from  $0^\circ$  can improve the ground irradiance uniformity, which means that all plants get more alike growing conditions. A standard, non-agrivoltaic PV system is usually south-facing to optimize for the power output, but by deviating from  $0^\circ$  azimuth, the uniformity can be significantly improved. By adjusting the module tilt is possible to optimize the power output or control the amount of self-shading between the module rows, but a higher tilt angle also increases the yearly ground irradiance slightly.

## 6.2 Practical Considerations

It can be expected that some adjustments will have to be made to the layout of the PV park to make room for agricultural equipment to pass safely through the agrivoltaic system. But also, some minor adjustments may have to be made by the farmer, such as adaptations to the machines or which route the farmer is taking when driving over a field. For short row distances, the PV modules might need to be raised on a stilt mounting to make room for machines to operate beneath the PV module. For a stilt-mounted system, there is also an option of having a longer distance between the pillars than between the module rows, which provides more space for the machines. An example of such construction is the agrivoltaic research site in Heggelbach, Germany, which is further described in section 2.4. Moreover, for the shortest row spacings, it might be suitable to choose a smaller size PV module to allow for more ground irradiance and less self-shading. Depending on the circumstances and the purpose of the agrivoltaic systems, plenty of alterations could be made to the PV system to account for special needs.

Something else to consider when designing an agrivoltaic system is the load profile of the farms electricity consumption, to try and adjust the PV power production to fit with the load, and hence maximize the self-consumption of the system. This can be done by, for example, changing the azimuth of the park. The same goes for the light requirement for the crops. Depending on the crop species, it might be useful to optimize for more ground irradiance during specific time periods. Practical parameters which influence the development of agrivoltaic technology are economy and regulations. The economic uncertainty of building an agrivoltaic system will likely slow down the development but lease agreements by companies and subsidies would likely speed up the process. Clear regulations and strategies for how to construct agrivoltaic systems, as well as what to consider when doing so, is also needed to improve the conditions for agrivoltaic development in the future.

## 6.3 Project Limitations

Due to the nature of this study, the potential layouts of an agrivoltaic system investigated in the thesis project are limited. In reality, there is an infinite number of options for how to design a PV park; for example, the module rows do not have to be straight, the module themselves can be curved if using thin-film technology, and the design does not have to be uniform throughout the system. Hence, the results of this thesis do not have to serve as a design manual for what exact measurements to use for an agrivoltaic system but rather an indicator of how tweaking some of the design parameters will affect the resulting light sharing of the system.

The light calculations performed in SketchUp were only made in the uniform central part of a big square shaped PV system, but at the system boundaries more light will be able to reach the ground from the sides and less self-shading will be present for the PV panels. Hence, depending on the dimensions of the land area used for an agrivoltaic system in practice, the light distribution might look slightly different. The ground irradiance measurements were also only performed on the very ground ( $h = 0$ ) in this thesis. However, crops growing taller will be able to collect more irradiance also from the sides. This is also something to consider when looking at what crop to cultivate in an agrivoltaic system.

## 6.4 Further Research

The theoretical nature of this project and other similar ones will eventually have to be backed up by practical studies in the Swedish climate, to be able to know more about how the agricultural crops would be affected by the increased shading from the PV modules.

An economical analysis would be necessary to be able to estimate the profitability for agrivoltaic systems. It is still an open question if an agrivoltaic system could be a profitable investment in Sweden. The electricity production from the PV system would have to make up for the potential loss in revenue to decrease in crop production, as well as the land used for mounting of the modules which can no longer be used for agriculture. The system profitability is also sensitive to several external factors, such as the electricity price.

Furthermore, some design alternatives for an agrivoltaic system were excluded from this thesis. Such as the integrated system layout, and also cell or module spacing. Further research about how these designs might be suitable for an agrivoltaic system would be useful. It was also shown in this thesis how the optical light simulation data generated in this project could be implemented in a machine learning model, to be able to estimate the resulting properties for agrivoltaic layouts which was not directly investigated in this study. Future research might be able to utilize this knowledge to perform further analysis.

## 7 Conclusions

The suitable agrivoltaic layout for a Swedish climate depends on many parameters such as the shading tolerance of the cultivated crop, which agricultural equipment is used in production, and economic considerations. This thesis has shown that some agrivoltaic designs which could be suitable in a Swedish climate are ground-based systems with relatively long row distances, vertical bifacial systems, as well as stilt mounted systems with slightly shorter row distances.

The question about whether or not agrivoltaics is a suitable application in a Swedish climate is still open-ended, however. This project has shown ways of designing an agrivoltaic system which results in minimal shading of crops cultivated on the ground beneath the modules. But if these types of layouts could be made economically profitable still have to be examined, and the conditions affecting the profitability of such a system might change in the future due to for example fluctuations in the electricity price and PV module cost. Practical experiments are also needed to validate the results produced in this report and see how the crops would be affected in reality with increased shading effects from the PV modules.

In general, the row distance and the panel width make the most significant difference for the total irradiance distribution of an agrivoltaic layout, while the clearance height and the azimuth can provide ways of increasing the uniformity of the ground irradiance to provide more similar growing conditions throughout the park. The module tilt has a minor effect on the ground shading, but by altering this parameter it is possible to optimize the electricity production from the modules and control the level of self-shading between the module rows.

The results generated in the optical light simulations will be accessible for future research. These data files can be found attached together with this report on the DiVA portal.

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