SHADING ANALYSIS OF AGRIVOLTAIC SYSTEMS

The shading's effect on lettuce and potato from elevated agrivoltaic system in Sweden

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ABSTRACT

The world is progressing towards a more sustainable society, where renewable energy sources, including solar energy, play a crucial role. This study aims to address the conflict between agriculture and energy production by exploring the installation of solar panels on farmland. Four scenarios are considered, with varying parameters such as latitude, azimuth, slope, and row distance between photovoltaic (PV) modules. The study focuses on two different crops, lettuce and potato, which have varying tolerances to shading. The objective is to understand how the shadows cast by solar panels affect the growth of these crops. To analyze the impact of shading, the PVsyst software program is utilized to obtain PAR values for each scenario. The calculations are performed using Excel equations. The literature review encompasses scientific sources that provide insights into both PV technology and agriculture, bolstering the research findings. To ensure realism and manage simulation time, certain delimitations were made. These include limiting the study to two cities in Sweden, comparing only two crops, and conducting simulations during the summer period. The results reveal a significant potential for growing potatoes under PV modules. However, lettuce faces difficulties due to its high requirement for solar intensity (PAR), making it less adaptable to shade. The findings of this study indicate that crops like potatoes, which have a lower requirement for PAR, can be successfully cultivated in conjunction with photovoltaic (PV) systems. However, it is not advisable to implement AV systems in areas where sensitive crops like lettuce, which necessitate a significant number of sun hours with high solar intensity.

Keywords: Photosynthetically Active Radiation, agrivoltaic system, elevated system, crop yield, agriculture, Shade tolerance crop, shading factor, PVsyst.

PREFACE

With the completion of this degree project, we have successfully concluded our studies in the master's program in Sustainable Energy Systems at Mälardalen University. The program consists of 120 credits, and this degree project accounts for 30 credits.
The chosen topic for this report revolves around the AV system, a relatively new technology that has demonstrated numerous advantages over conventional agriculture, including increased crop yield and water savings. However, it is important to note that the shading caused by the photovoltaic system may impact certain crop types. Hence, this thesis focuses on the effects of PV system shading on potato and lettuce cultivation in Sweden.
We would like to express our gratitude to everyone involved in this project. Special thanks go to Sebastian Zainali, our supervisor, who has provided invaluable support and assistance throughout the course, and special thanks to our examiner Mohammed Guezgouz

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SUMMARY

This study investigates the coexistence of solar panel installation and agriculture by exploring the impact of shading on crop growth. The focus is on lettuce and potato crops, which have varying tolerances to reduced solar intensity. Four scenarios are considered, incorporating different parameters related to solar panel installation on farmland. The analysis is conducted using the PVsyst software program and Excel to calculate PAR values for each scenario.

The literature review supports the research findings by examining the benefits and challenges of solar energy production and previous studies on the impact of shading on crop growth. The study acknowledges certain delimitations, such as focusing on two cities in Sweden, comparing only two crops, and conducting simulations during the summer period. These delimitations ensure realism and enable the study to provide context-specific results.

The results of the study indicate that potatoes show significant potential for successful cultivation under PV modules. The reduced solar intensity caused by shading does not severely hinder potato growth, suggesting that solar panel installation on farmland can coexist with potato cultivation. The findings reveal that potatoes can adapt to lower levels of solar radiation, making them suitable for cultivation in shaded areas.

However, lettuce, as a high-intensity solar crop, faces challenges under shading conditions. The study demonstrates that the shade cast by solar panels adversely affects lettuce growth due to its high requirement for solar intensity. Lettuce is more sensitive to reduced solar radiation, and the study advises caution when implementing solar panel systems in areas where lettuce or similar high-intensity solar crops are cultivated. Such crops necessitate a significant number of sun hours with high solar intensity, which may not be provided in shaded conditions.

The study's methodology, which incorporates the PVsyst software program and Excel, provides a replicable framework for future investigations. The analysis of PAR values and the utilization of scientific tools enhance the accuracy and reliability of the research findings. The literature review conducted as part of the study strengthens the credibility of the results by integrating previous knowledge and scientific insights.

Overall, this study contributes to the ongoing discourse on sustainable agriculture and renewable energy production. It sheds light on the potential for coexistence between solar panel installation and potato cultivation while emphasizing the challenges faced by high-intensity solar crops like lettuce under shading conditions. The findings provide valuable insights for policymakers, farmers, and researchers seeking to strike a balance between renewable energy generation and food security. By understanding the impact of shading on different crops, future initiatives can be designed to maximize the benefits of solar energy while minimizing potential disruptions to agricultural activities.

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NOMENCLATURE

Symbol	Description	Unit
PAR_{tot}	Total photosynthetically active radiation	W/ m²
Dir_R	Direct solar radiation	W/ m²
$Diff_R$	Diffuse solar radiation	W/ m²
PAR_F	The value is between 0.3 to 0.5	Used for converting from [µmol /m²/s] to [W/ m²]
Dir_F	Direct solar radiation ratio	%
$Diff_F$	Diffuse solar radiation ratio	%

ABBREVIATIONS

Abbreviation	Description
PVG	Photovoltaic greenhouse
PV	Photovoltaic
AV	Agrivoltaic
STC	Standard test condition
LER	Land equivalent ratio
FD	Full density
HD	Half density
PAR	Photosynthetically active radiation

DEFINITIONS

Definition	Description
Azimuth	Azimuth or orientation is the angle of the PV module relative to the direction south. -90 ° is east, 0 ° is south and 90° is west.
Standard test condition (STC)	Refers to a set of standardized conditions used for testing and rating PV modules or panels. These conditions are defined to provide a consistent and uniform basis for comparing the performance of different PV modules from various manufacturers.
Approved hours	In this study, the hours that meet the necessary PAR value are referred to as approved hours, which are essential for the growth of crops. Each crop has its unique PAR value requirement.
Percentage of approved hours	The percentage of approved hours is calculated by comparing the number of hours that meet the approved criteria to the total number of solar hours during the summer period.
Juvenile phase	The early stage of a plant's life is sometimes called the juvenile phase. During this time, plants are not able to produce flowers. When plants grow from seeds, they go through a juvenile phase and need to mature before they can start flowering.

1 INTRODUCTION

As the world transitions away from fossil fuels and traditional energy sources towards cleaner and more sustainable options, solar energy has emerged as the most prevalent source of power in current times. Despite the availability of other eco-friendly sources like wind and hydro energy, solar energy has experienced widespread adoption in recent years. This can be attributed to its ease of use by individuals, who can install solar panels on their rooftops, as well as large-scale government projects such as the construction of massive solar panel parks.
The utilization of solar energy has seen significant growth, increasing from 64 terawatt-hours (TWh) to 1002 TWh over the past decade. According to the International Energy Agency, the projections indicate that this number will surpass 7400 TWh by the year 2030 (IEA, 2022). During the same period, solar panel-generated electricity production reached 19.6 gigawatts in Europe and 48.2 gigawatts in China (Kumpanalaisatit.M, et al. 2022).

In terms of solar panel installations, China's Tennger Desert solar park stands out as it covers an extensive land area of approximately 43 square kilometers (Wengeler, U, 2020). The International Energy Agency (IEA) predicts that solar power production will contribute around 16% to the total global energy production by 2050 (Dinesh, H, 2016). However, the growing global population and the increasing demand for food pose a significant challenge as agricultural land becomes increasingly essential. This situation fuels the ongoing debate on whether to prioritize land use for agriculture or allocate it to solar energy projects (Kumpanalaisatit, M, et al., 2022).

The competition for land between agriculture and energy has been an ongoing issue since the 1970s. During that time, the emergence of bioenergy led to an increased demand for agricultural land to be used for energy purposes rather than farming. To address this challenge, the invention of conventional oil quickly gained momentum, establishing it as the dominant industry and primary energy source (Erick Galante et al., 2013).
Agrivoltaic systems (AV) are the solution to this problem, where electricity production is combined with agriculture. The potential exists to increase the number of agricultural lands that works hand in hand with solar panels, a good example that increases the hope to invest more in this type of installations is Sweden's largest AV park in Solvallen in Sweden. (Stridh.B, 2022).

1.1 Background

The Earth is currently facing a pressing issue known as climate change, which poses significant dangers to both the planet and all living beings, including humans. This global phenomenon is already impacting the entire world, leading to more frequent and severe extreme weather events such as droughts, storms, and heavy rainfall. The melting of ice in the polar regions has caused rising sea levels, resulting in the disappearance of numerous islands, and putting many more at risk (NASA, 2019). If adequate measures are not taken, the consequences of climate change will be irreversible and catastrophic. Scientists have conducted research indicating that a temperature increase of 1.5 to 2 degrees Celsius would lead to heatwaves affecting around 14 percent of the global population at least once every five years (NASA, 2019). The primary cause of these issues is the significant increase in carbon dioxide emissions, with the energy sector accounting for 73.2% of these emissions (OurWorldInData, 2020).

Recognizing the severity of the situation, political leaders from various countries gathered in Paris to sign a climate agreement. The agreement aims to limit global temperature rise to below 2 degrees Celsius, with most countries committing to reducing their emissions. European nations have set ambitious targets, aiming for zero emissions by 2050. However, achieving these goals poses significant challenges, requiring a fundamental shift in energy consumption patterns and the development of green technologies for electricity generation.
To combat climate change, it is crucial to transition towards sustainable and renewable energy resources, which represent the path to a greener future. This includes increasing investments in solar panels, wind power, and other clean energy solutions (United Nations, 2015). Numerous measures can be implemented to address climate change effectively and mitigate its impacts on the planet and its inhabitants. Due to global warming, the world now wants to reduce the use of fossil fuels as an energy source, but at the same time the need for energy increases. In order to meet global energy demands, the need for renewable energy is increasing as well. Photovoltaic (PV) system is a technology that uses solar radiation and produces clean and renewable electricity. Solar panels can be installed on the roof of villas, terraced houses, and other types of buildings. But to meet global energy demand, the need for land-based PV farms increases. The fact is that implementing solar parks requires a large land area. Using large tract of land for solar farms will increase competition for land resources as food demand and energy demand are both growing and vie for the limited land resources (Dianesh.H, 2016).

Plants have a maximum threshold for utilizing sunlight known as the light saturation point. Beyond this point, additional sunlight does not enhance photosynthesis or contribute to the plant's growth. Instead, it increases the plant's water requirements, causing it to transpire more and become thirstier (Chen.J, 2022). Solar panels perform optimally under standard test condition temperature of around 25 °C, which allows for maximum electricity production. Higher temperatures can reduce the efficiency of solar panels and result in lower electricity output. However, the presence of plants can help mitigate this issue by evaporative cooling, thus reducing the temperature of the solar panels and enhancing their electricity generation.
By strategically positioning solar panels to provide plants with the appropriate amount of sunlight, a synergy known as AV system can be achieved. A study conducted in France on an AV system demonstrated that lettuce cultivation experienced a 30% increase in production compared to traditional agriculture where shade from PV systems was not present. This type of installation is particularly beneficial for growing shade-tolerant crops. Additionally, investing in AV systems for lettuce agriculture in the USA could lead to a significant increase in electricity production, estimated to be between 40-70 GW (Dinesh, H, 2016).

The advantage of the AV system is that it is a combination between solving the global food problem in terms of increasing agricultural yields, and at the same time producing electricity, whose demand has increased in recent years. These two features apply at the same time and place. This system solves problems, including desertification, which is caused by the exposure of agricultural lands to high solar radiation, which leads to the inability of the land for cultivation. Another advantage is the reduction of evaporation resulting from the sun's rays, which decrease the need for irrigation. When solar panels have a suitable height and an appropriate distance between the panels, then this system can protect agricultural crops and reduce the need for water. (Valle. B, 2017). AV systems can be disadvantageous for certain types of plants, that need high amounts of solar radiation to have a complete growth. A study from Middlesex University research, where 14 different gardens were planted in PVG with different degrees of coverage, the result showed that all different species had grown well under 25% degree of coverage, above 50% degree of coverage the plants growth started to be negatively affected (Cossu.M, 2020).

Shading from PV system can impact specific crop types. Therefore, this report examines a shading analysis to understand how the PV system influences crops in order to increase crop yield and generate higher revenues. By comprehending the shading percentages based on latitude, panel density, row distance, and the control strategy for AV systems in Sweden, it would facilitate crop yield calculations and decision-making processes for optimal AV systems.

1.2 Purpose/Aim

The purpose of this work is to simulate an AV system and study how shading of the solar panels affects agriculture through various factors. Furthermore, investigate the possibility of growing potatoes and lettuce in combination with solar modules in Sweden.

1.3 Research questions

- How does the shading of PV modules impact agricultural land in Sweden, considering variations in latitude, azimuth, tilt, and row distance?
- How does the approved percentage of solar hours vary for lettuce and potato in an elevated AV system, considering variations in latitude, azimuth, tilt, and row distance?
- What is the growth potential of lettuce and potatoes in an AV system in Sweden?

1.4 Delimitation

This degree project will encounter several limitations. The research will be conducted in two distinct cities in Sweden, namely Lund and Jokkmokk, which are located at different latitudes. Considering the focus of this study on the impact of PV shading on agriculture, it is appropriate to restrict the investigation to a single type of AV system, specifically the elevated system with a constant height. Additionally, the shading factors will be derived from three specific days during the summer: June 15, July 15, and August 15. These dates are chosen based on the assumption that solar radiation does not undergo significant changes within a 15-day interval. Moreover, this study does not consider the electricity generation potential of PV modules. Additionally, other factors that can influence crop growth, such as soil nutrition and temperature, are also not considered in this analysis.
Lastly, potato and lettuce have been chosen as the crops for examination, with the objective of assessing the shade tolerance of both plants.

2 METHOD

Various methods were employed in this degree project, specifically chosen to facilitate a more accessible resolution to the research questions. To initiate the study, an extensive review of relevant literature was conducted to comprehend the functioning of AV systems. Additionally, the PVsyst software was utilized to design and simulate an elevated AV system. Moreover, a sensitivity analysis was performed to assess the impact of shading from the PV system on agricultural land.

2.1 PVsyst software

The primary purpose of this project was to model and simulate an elevated AV system on agricultural land with an area of 420 m^2. The selected PV modules was polycrystaline-silicon from Jinko Solar, each with a power output of 320 W.
Two different cities in Sweden, namely Jokkmokk and Lund, were chosen due to their distinct latitudes. The purpose was to assess the impact of the AV system on crops in different latitude. Another investigation was to explore the differences in result varying parameters such as azimuth, slope, and row distance. This analysis aimed to compare the results with those obtained from conventional agriculture methods because it would facilitate crop yield calculations and decision of making processes for optimal AV systems.
To conduct the simulations, we employed the software PVsyst, which offers various components to aid in PV system design and can measure different shading factors experienced in the field.

2.2 Literature study

Deep literature study has been done to increase the knowledge of the concept and to explain the main questions around the topic. Moreover, to obtain knowledge about how the simulation model can be used and to find out if they had some limitations. Another goal to achieve with literature study was to give an understanding about how the AV system works and which types of the AV system are existed and how they can be developed. As well as how the light saturation point for agriculture is affected by shading from PV's panels.

3 LITERATURE STUDY

3.1 AV system

The competition between solar panels and agriculture has been present due to their shared requirements of equipment, land, and sunlight for production. To address this issue, the concept of AV systems emerged. The idea of combining agriculture with solar cells was theoretically proposed by Adolf Goetzberger in 1981, envisioning the utilization of land for both electricity generation and crop cultivation (Goetzberger.A, 1982).

In the early 2000s, Europe conducted several studies exploring the potential of AV systems, initially focusing on replacing greenhouse roofs with solar cells. Experiments were conducted in countries like Austria, Italy, France, and Germany. As the 2010s approached, the term "agrivoltaic" gained official recognition and began appearing in publications. Initially, only a handful of researchers possessed sufficient knowledge in this field, leading to terms like "Agrophotovoltaics" in a German report and "Solar Sharing" in Japan being used to describe this combination (Movellan.J, 2013).

The increase in population has led to a rise in both energy and food demand, which has driven the growth of renewable energy sources. Among these, the PV system is one of the fastest-growing technologies for generating clean electricity. However, like any renewable energy source, it has its own advantages and disadvantages. (Movellan.J, 2013).

Solar parks, which require large land areas for electricity production, often face the challenge of balancing the land used for crops and PV system. In terms of electricity generation, using the land exclusively for PV system typically yields more electricity compared to an AV system, where crops are cultivated alongside solar panels. (Movellan.J, 2013).

However, the advantage of an AV system lies in its efficiency. Numerous studies have highlighted various advantages that both crops and PV system provide to each other. For instance, the presence of crops creates a microclimate that slightly lowers the temperature for the PV system, improving their efficiency. Additionally, many studies have explored the use of pivotable frames for the PV system, offering flexibility in managing electricity generation by adjusting the tilt of the panels to maximize shade, electricity production, or provide shelter, among other factors. (Movellan.J, 2013).

3.2 Different AV systems

There are different types of AV systems, the most common are the system with grazing animals, solar fence, a single axis tracker and the chosen system in this degree project is elevated system. Each of these systems offers unique advantages over the others. Take, for instance, the solar fence system, a straightforward setup where solar panels are arranged in the form of a fence surrounding the agricultural land. While its utilization efficiency may be lower compared to other systems, it stands out for its ease of installation and cost-effectiveness. Another example is the system involving grazing animals. In this approach, certain animals like chickens and sheep are allowed to graze alongside the crops. They are provided with shelters to seek refuge in during high temperatures. These animals, being small and docile, do not pose any problems or disruptions to the solar panels.

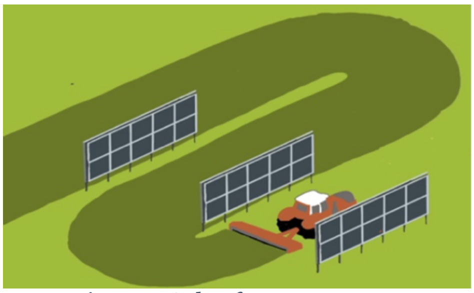

Figure 1:Solar fence AV system

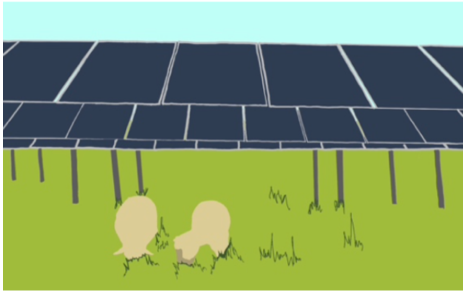

Figure 2:Grazing animal AV system

The single-axis tracker system is commonly employed to adjust the position of solar modules, ensuring optimal capture of solar radiation while minimizing its impact on the plants throughout the day. The spacing between the solar panels still allows for sufficient radiation to reach the plants, enabling them to carry out photosynthesis and grow. This approach results in increased electricity production. The market for single-axis tracking systems has experienced significant growth in recent years, with Brazil observing higher prices for this system compared to the previous two. The long-term profitability of the system, driven by increased electricity production from the panels, has motivated more domestic companies to export this system within the country (Lassio.J, 2022).

The development of the single-axis tracker system originated in a garden with solar panels in Denmark and holds great potential for similar experiments in Sweden. What sets this system apart is its ability to accommodate the movement of farmers and the necessary cultivation equipment, as the panels are positioned at a considerable distance, allowing for unrestricted movement (Brown, 2021).

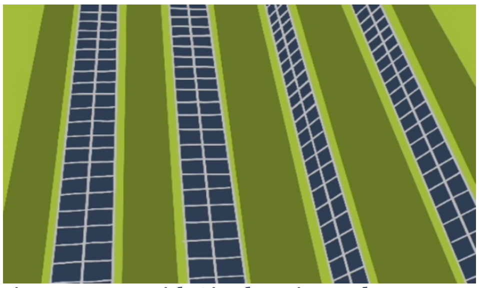

Figure 3: AV with Single axis tracker system.

The elevated agrivoltaic system chosen to carry out this study has various advantages, first is the simplicity of the installation process, since the panels are directed in a specific direction, considering the side most exposed to sunlight. Another advantage is its low cost, compared to single axis tracker systems, which require sensors to capture the sun's rays, but it is also more expensive compared to solar fence, which is easier to install. The elevated has the average cost and average output compared to other systems. The standard height for this elevated system is between 3 and 5 m, different factors play a role in being able to decide what height they should have depends on the electricity production and how farmers need the height to be able to work under the panels and use the machinery. The physical distance between the panels for elevated systems is wider compared to the usual installation of PV, this is due to the need for crops that are under the panels to have access to the sun. Figure 4 below shows how elevated agrivoltaic systems are assembled. (Fraunhofer Institute for Solar Energy Systems Ise, 2023).

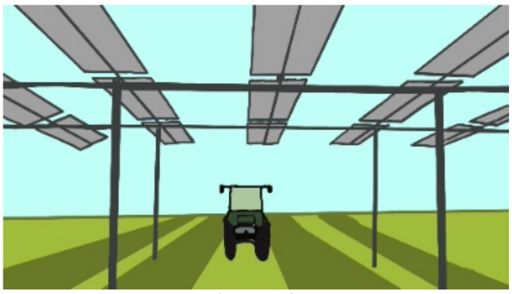

Figure 4: Elevated AV system.

3.3 Potential of AV system in Sweden

3.3.1 Agriculture in Sweden

The land for agriculture is categorized in 2 different parts, the first part is called arable land which is most suitable for crop production, the second part is mowing field and pastureland where land with too many stones are also included. Sweden has a total of 3 013 000 Ha agriculture land in 2020 where 85% is arable land and the rest is mowing fields and pastureland. Cultivation of pasture grass and ley has taken the biggest part that corresponds to 1 138 000 Ha. The table below shows how the agriculture land is used for different crops in 2019 and 2020. (Jordbruksverket, 2020).

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

Category	**2019 [Ha]**	**2020 [Ha]**
Cereals	993 200	1 006 700
Pasture grass and ley	1 163 700	1 138 000
Rapeseed	105 600	98 300
Leguminous plants	44 200	47 900
Sugar beets	27 300	29 800
Potatoes	23 600	24 100
Other crops	51 300	54 800

3.3.2 AV system

There is a lot of research and improvement in AV systems in recent years. In 2021, there has been a total capacity 14 GW of AV systems in the world. In 2012, this number was only 5 MW. However, the AV system market is growing all over the world. China alone stands for 1.9 GW installed AV capacity in 2021. (Trommsdorff.M et al, 2022)
Another giant AV project which has started from 2020 in Ningxia province in China. The total power capacity of this system will be 1 GW and 640 MW have so far been grid-connected. (Bellini.E, 2020).

Installation of Agrivoltiac system has also increased in Europe. Some of Sweden's neighboring countries have already projects ongoing, for example Vattenfall started in the beginning of 2023 an AV project in a small city called Tützpatz in north of Germany. The total power capacity of this system is 76 MW and takes an area of 95Ha. (Wiese.L. (2023)
Another AV system has been installed in the city of Heggelbach in south Germany. The system is an elevated module with a ground clearance height of five meters. The system was installed in 2016 and since those four different crops has been cultivated, the system showed better tolerance in summer periods and an increasing in LER up to 60-84 %. (Ketzer.D, et al, 2020)
Since the weather condition of northern Germany is similar to southern Sweden, it can be concluded that the potential of the AV system is also existing in Sweden. At the moment, only one fence AV system containing a vertical bifacial module has been installed in Västerås Sweden. The installation has been done in 2021 under the leadership of Mälardalen University and collaboration with other universities and the Swedish energy authority. The system has a power capacity of 22.8 kW, and the objective of this small facility is to do experiment on different crops cultivation under the shade of PV system. At the moment, the result from research is still limited but according to Mälardalens university, the experiment that has been done on pasture grass showed a positive result for 3 months out of 5 months. They claim that the crop yield increased, but in 2 months it was a decrease in production. The result they got is still acceptable for farmers and installers because the reduction in crop yield was not as significant. (Bellini. E, 2021)

3.4 Land equivalent ratio

The objective of incorporating a combination of PV systems and agricultural crops is to achieve an optimal balance between utilizing arable land and generating electricity from solar panels. To assess the performance of this integrated system, the Land Equivalent Ratio (LER) is employed as a measure. The LER quantifies how effectively the land area is utilized in AV compared to using the land exclusively for either PV system or agriculture. A LER value greater than 1 indicates that the combination outperforms utilizing the land separately. For example, an LER of 1.3 implies that an additional 30% of area is required to achieve the same production as on two separate plots. In general, the amalgamation of agriculture and PV systems yields an LER higher than 1, indicating increased overall production on the occupied land area. A report by Dupraz et al. (2011) suggests that the land equivalent ratio can reach up to 1.4 in AV systems (Dupraz.C et al, 2011).
The formula below is used to calculate the land equivalent ratio. This formula is extracted from a report Toledo and Scognamiglio (2021):

$$LER = \frac{Y_{agri\_APV}}{Y_{agri}} + \frac{Y_{APV}}{Y_{PV}} \qquad Equation\ 1$$

In this formula $Y_{agri-APV}$ is the yield under an AV system and Y_{agri} is the yield if the land is used only for agriculture crops. Y_{APV} stands for electricity production from solar panels in an AV system and Y_{PV} is the electricity production from PV farm without agriculture crops. However, Toledo and Scognamiglio claims that this equation is insufficient because it doesn't consider many parameters such as morphology, crop yield, quality of the crop and water usage. Furthermore, Toledo and Scognamiglio suggest another formula which can be used to calculate the water usage efficiency. This parameter is important to know if the AV system constructs in a dry land where water availability is low. The water usage efficiency, WUE can be calculated with formula below (Toledo.C et al, 2021):

$$WUE = \frac{WUE_{PV} - WUE_{control}}{WUE_{control}} \qquad Equation\ 2$$

Where WUE_{PV} is the water usage under the PV-panels and $WUE_{control}$ is the water usage on pure farmland. Since water usage as well as land mass use is important to take into consideration both out of economic viewpoint and a sustainable one, the formula for water usage efficiency is a good addition to the evaluation of an AV system. (Toledo.C et al, 2021).

3.5 Crop yield & crop selection

The AV system has both positive and negative impact on the crop. But in general, there exists risk for crop yield to decrease on AV system. The shading from solar panels adding to crops will slow down the crop growth and in turn decreasing the amount of crops production which would be higher without solar panels (David.R, 2021).
In fact, the implementation of AV system has also many benefits such as providing protection against various weather conditions. For instance, heavy rain, hail, droughts, frost, and high solar intensity which appears in the middle of the day. Solar panels in AV system can open small holes to allow the plants to receive solar radiation to absorb carbon dioxide for their photosynthesis and allowing water to escape from their leaves and that will create a cooler microclimate for the plants (Charline.D.S, 2020).
There are some parameters which is important to be taken into consideration in order to succeed with the implementation of an AV system. One key aspect is to select the most suitable crops for the project and the parameters such as crop shade tolerance, water stress, irrigation, crop rotation, height of the crop, crops lifetime etc. AV system is a new technology and there are researches ongoing on how different systems can be installed with specific crop and how the crop yield is affected. A report from Laub M (2022) claims that most crops tolerate reduced solar radiation up to 15% and berries, fruits and fruity vegetables benefited from reduction in solar radiation up to 30% (Laub.M et al, 2022).
Another parameter which affects the crop is the row distance between the solar panels, a study which has been done by researchers Campana, P. Stridh, B (2022) at Mälardalens university showed that 9 m is an ideal distance when the selected crop is oats and 8.5 m is suitable distance for potatoes. This study has been done in a specific location in Sweden, in Västerås, and this value would be something else depending on which type of the system is used and the selected location also plays a major roll (Compana.P et al, 2022).
Dinesh.H (2016) has done a simulation model by PVsyst and Simulateur multidisciplinary Les Cultures Standard (STICS) crop model to measure the technical potential of scaling AV system. This simulation software was originally developed in France. The simulation and study result showed that that a combination of PV system and shade tolerant crop will increase the economic value of the production up to 30%. Furthermore, the simulation result showed that Lettuce is a good shade tolerant crop where the crop yield under full sun during summer was around 50.5 ton/Ha and with combination of ground mounted AV system, the yield was about 50 ton/Ha. By model and simulate an AV system in STICS will make it possible to crop yield in the unit [Tons/Ha] through the formula below:

$$Y = \frac{W * d}{100} \qquad Equation\ 3$$

Where,
W = Weight of lettuce in gram

d = Plant density per square meter

The table below shows the simulation result, where the full density (FD) AV system has the best result from economic point of view. But if both crop and energy production is important, then the ground mounted Av system is more suitable (Dinesh.H, 2016).

Tabel 2: The simulation result for Lettuce production with and without different agrivoltaic system. (Dinesh 2016)

Lettuce growing condition	Yield (ton/Ha)	yield value ($/Ha)	PV value ($/Ha)	Total value ($/Ha)
Full sun summer without AV	50.5	134 000	0	134 000
Ground mounted AV farm summer	50	133 000	74 612	207 612
FD Av system summer	29.3	77 900	135 238	243 138
HD Av system summer	27.8	73 945	44 071	188 016

Another study done by Kumpanalaisatit.M et al (2022) showed that vegetables like spinach and basil has also good shade tolerant and the experiment result showed that the production value for both crop yield and PV production increased 18% and 13% respectively (Kumpanalaisatit.M et al, 2022).

An experiment has been done by (Fu et al., 2009) to test the shade tolerance for 24 types of maize. The maize was conducted under 50% shading and the following parameters have been compared, the plant height, stem diameter, left net photosynthetic rate, specific leaf weight, and the dry matter accumulation. The result showed that 14 species of maize were shade tolerant and 10 of them were shade sensitive. However, the shading didn't have any impact on the crop yield (Fu.J et al, 2009). For some types of plants, the shading doesn't affect the growth rate, but it mostly decreases the growth during the juvenile phase (Charline.D.S, 2020).

3.5.1 Light saturation points for crops

The plants need light for the photosynthesis and optimum growth and development and there exist 3 different light aspects, quality, quantity, and duration. All these three aspects have a big impact on the crops. Every single crop has a light saturation point where the PAR over that point will not increase the plant photosynthesis or growth. By determining the light saturation point for a crop will make it possible to understand how shade-tolerant a crop is. The diagram below shows the net co2 uptake over the PAR where the light saturation point in this case is 1000 PAR (Lopez.J, 2022).

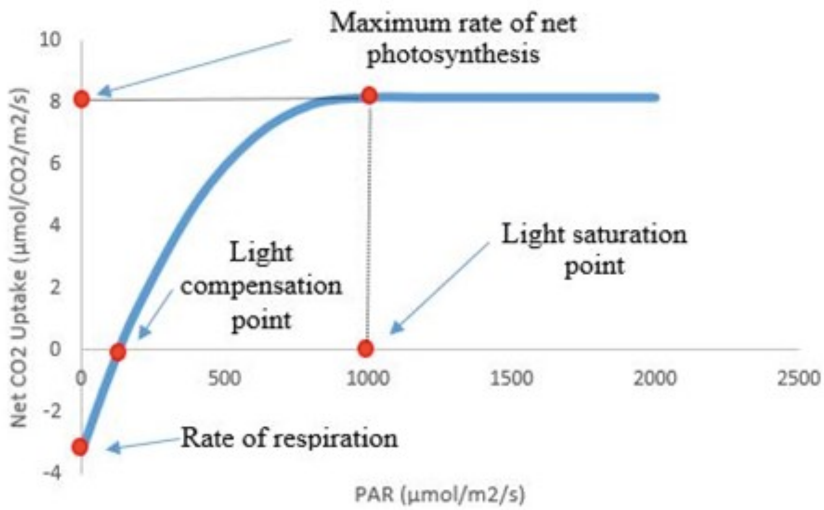

Figure 5: net co2 uptake over the Photosynthetically active radiation (PAR) for a specific plant. (Promix 2022)

Table 3: Different light saturation point for some plants.

Type of plant	Light saturation point (μmol /m^2/s)	PAR [W/m^2]
Apple	900-1000	195 - 217
Lettuce	860-932	186 – 202
Spinach	200-400	45-87
chard and kale	884-978	192 - 212
Potato	400	87
Tomato	600	130

The recommended list of the most shade tolerance vegetables and herbs which can be cultivated in an AV system are: arugula, endive, lettuce, sorrel, spinach, collards, kale, mustard greens, swiss chard, beets, carrots, potatoes, radishes, rutabaga, turnips broccoli and cauliflower, brussels sprouts, cabbage, mint, chervil, chives, coriander/cilantro, oregano, and parsley (Curl.L, 2017).

3.5.2 PAR for crops

PAR which stands for PAR is the type of light that plants need for photosynthesis. PAR is important for plant and plays a huge role for plant grow because it is solar radiation which has the wavelengths range from 400 to 700 nanometers. Plants use this range of solar radiation to convert light to energy. This light is absorbed by chlorophyll in plant cells, and it leads to glucose production and in plants at the same time, oxygen is released. PAR quality leads to better grow for plants and affect their leaf size, flowering, and fruit production. Right amount of PAR will lead the plant to grow better and consequently, increases the crop yield and improve plant health. Different crops have specific requirements of PAR in order to grow well. Leafy greens like spinach need moderate levels of PAR, usually between 200 and 400 ($\mu mol/m^2/s$), to support their leafy growth. Fruit-bearing plants like tomatoes and peppers requires higher PAR when they are flowering and producing fruits, typically between 400 and 600 $\mu mol/m^2/s$. Some other crops like herbs and strawberries, benefit from even higher levels of PAR, ranging from 600 to 800 $\mu mol/m^2/s$ (Lopez, 2022).

Lettuce and potatoes have different PAR requirements because of their unique growth characteristics. Potatoes usually requires a low amount of PAR to grow well. During the leafy growth stage, the PAR levels is around 400 $\mu mol/m^2/s$. On the other hand, lettuce has a higher

PAR requirement. The required PAR levels are between 860 and 932 μmol/m²/s throughout its growth cycle. Providing the right amount of PAR helps both potato and lettuce plants grow strong and gives better yield (Lopez, 2022).

Potatoes typically require a minimum of 6 to 8 hours of approved solar hours per day to grow well. However, it's important to note that the specific solar hours required for potatoes may vary depending on factors such as the variety, local climate, and the stage of growth. (Volente.G, 2023). On the other hand, lettuce needs at least 5 to 6 hours of approved PAR. However, this requirement is mainly for iceberg lettuce, whereas other lettuce types with darker leaves need less sunlight (Almanac, 2023).

3.5.3 Water stress & irrigation

The shade created by PV modules offers protection to crops from excessive solar radiation and reduces evaporation from the plants. This is particularly beneficial for crops that require high levels of irrigation and for plants that are not tolerant to water stress. The presence of shade helps these plants by minimizing water loss and providing a more suitable growing environment (Charline.D.S, 2020).

3.5.4 Crop Height

Another factor to consider when choosing a crop is its height, as the plants located beneath the solar modules should not exceed a certain height throughout their lifespan. The solar modules can be installed at various heights, typically ranging from 3 to 5 meters for elevated systems (Charline.D.S, 2020).

3.5.5 Crop rotation

Crop rotation involves cultivating different crops on the same plot of land within a year. The primary objectives of crop rotation are to preserve soil fertility and maintain a balanced distribution of nutrients in the soil. Crops can be categorized into two types: exhaustive crops and less exhaustive crops. Exhaustive crops are those that require higher amounts of soil nutrients. When selecting crops for an AV system, crop rotation becomes a crucial factor to consider. It plays a vital role in ensuring the long-term sustainability of agriculture by managing nutrient levels and maintaining soil health (Charline, D. 2020).

3.5.6 PV modules lifetime

Solar modules used in AV systems typically have a lifespan of approximately 30 years. However, as time goes on, the efficiency of the solar modules and electricity production gradually declines. This means that the solar panels remain in place for the entire 30-year period, making it impractical to plant crops such as trees that require greater height beneath the PV modules. Long-term planning is essential before initiating the installation of an AV system to account for this limitation (Charline.D.S, 2020).

3.6 Optimization of parameter

The main issue that comes up when installing agrovoltaic systems is the distance between the panels, what height the panels are and so on. The purpose of the research on this question is to reduce the shading of crops and to maintain the production from solar cells. This is done by having the right height, the height is determined based on the height of the crops, so that the modules do not interfere with the growth of the crops. The height of the agricultural machine is also an important factor, and it must be taken into account, so the panels are not an obstacle of the movement of the farming equipment. Otherwise, the modules will be a problem when planting crops and irrigation. The more the modules are raised, the more costs due to more material required to hold the modules as they need to be more robust for the modules to withstand the wind (Charline.D, 2020).

The distance between the modules is as important as the height. The distances must be large enough to ensure that the farming process takes place without disturbances, since the PV modules must not be an obstacle for the farming equipment. At the same time, the distance between the PV panels should provide the opportunity for the crop islands to be able to receive enough solar radiation that is needed for the crops to grow without hindrance. It may happen that the number of PV modules is reduced, with the intention that sufficient distance between the panels is needed, this causes the electricity production to be reduced. The question then becomes, is the priority to agriculture or to electricity production? (Charline.D, 2020).

The spokesperson of Italy's Rem Tec said that there are many crop yields that have low shading efficiency, such as the lettuce, which facilitate the installation of PV panels around the agricultural land. But this requires clear and careful planning at installation regarding the height and distance between the panels in order to keep the average output to a maximum. In this way, AV will contribute with the shade that minimizes the need for water in the soil (BELLINI.E, 2022).

The height and spacing of PV modules in an AV system allow for the optimal growth of various crop types, taking into account factors such as temperature, light, and humidity required for photosynthesis. While agricultural production may not be negatively affected, it does not guarantee that the quality of the yield will be optimal. The arrangement of PV modules has a significant impact on crop yields. Under the PV panels, there are three distinct zones where crops are grown, each with its own characteristics and resulting in different quality of production. Zone 1, directly beneath the PV panels, has high air humidity and low radiation. Zone 2, located in the semi-shaded area depending on the direction of sunlight, experiences regular soil moisture and light exposure. Zone 3, which remains unshaded, has low humidity and high radiation (Toledo.C et al, 2021).

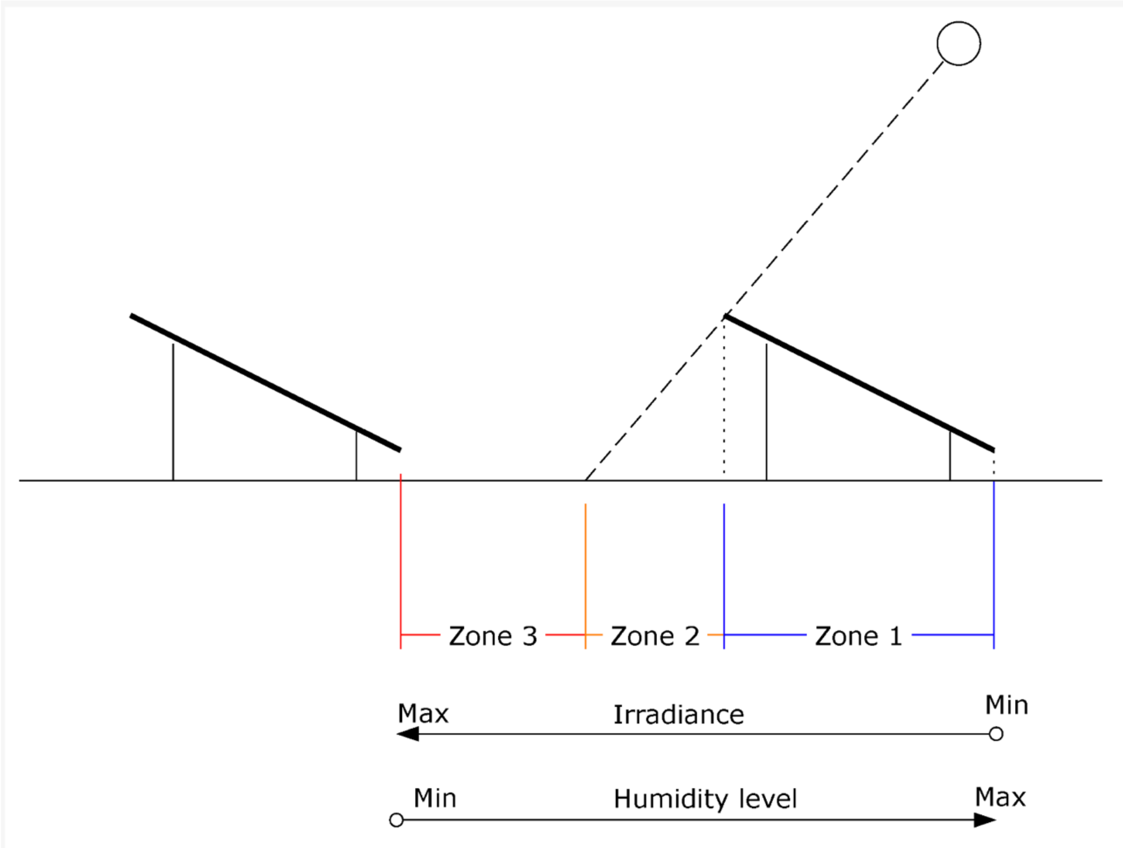

Figure 6: different zones created under AV system.

The studies showed which quality aspects of crops were affected by PV installation due to shading, even that the total production has not decreased, for example crops color, taste and growth. When tomatoes were grown under PV panels and are shaded about 10%, it corresponds to the negative impact on tomato color and size, but still the total crop yield is at the same amount compared to when the cultivation takes place without PV modules. Regarding grapes, the results of a study in Korea showed that the weight of grapes has decreased, as well as sugar content. It also led to the harvest time being 10 days later than the normal time (Toledo.C et al, 2021).

3.7 Advantages & disadvantages

The primary benefit of combining PV technology with agriculture is the ability to reduce farmers' electricity demand without negatively impacting crop yield. This financial advantage extends not only to farmers but also presents a promising opportunity for significant investments in both PV and agriculture sectors, leveraging existing PV parks. Numerous experiments have demonstrated the profitability of such investments, encouraging more individuals to pursue similar ventures (Zainol Abidin, et al., 2021).
A notable advantage of AV systems is their potential to address the longstanding conflict between agricultural land and energy production. These systems effectively transform land competition into a harmonious blend of agriculture and solar cell energy production. This symbiotic relationship is highly advantageous, as it combines energy generation with sustainable renewable agriculture, thereby enhancing the overall potential. Moreover, the growing global emphasis on renewable energy sources further amplifies the importance of this integrated approach in most countries (Zainol Abidin, et al., 2021).

A study conducted in the United States examined the cultivation of various crops, including aloe vera, tomatoes, lettuce, and biogas maize, under solar panels. The findings revealed that the combination of PV technology and certain lettuce varieties resulted in increased production compared to lettuce grown without PV. Conversely, no significant differences in production were observed for other crop types, except for an increase in electricity generation. The explanation behind these outcomes lies in the beneficial microclimates created by the crops, which effectively lower the temperature of the PV modules. This temperature reduction positively impacts module efficiency, allowing them to approach their STC even in warm climates. Additionally, crops grown beneath the shaded modules require reduced irrigation as the soil moisture levels naturally increase (Elnaz, H et al., 2019). The reduction in irrigation is particularly significant as it addresses water resource conservation, which is a critical concern.
A study conducted in Arizona, USA, demonstrated that the microclimate formed beneath the modules had a positive influence on irrigation practices and resulted in substantial water savings. This effect was particularly noticeable in the warm climate of Arizona during the summer season. Despite the presence of climate variations, the results strongly indicated that AV systems played a significant role in reducing water requirements. The researchers who conducted this experiment highly recommend implementing AV systems in regions facing water scarcity or experiencing warmer climates (Reasoner.M et al, 2022).
AV systems offer a significant financial advantage by providing farmers with dual income streams. Firstly, farmers can generate their own electricity through AV systems, meeting their own energy needs and even selling the surplus power. Secondly, they can continue to earn income from crop production. This dual-income approach has proven to be highly beneficial, as it has reduced the average payback time for crop yields from 8 years to just 5 years (Kumpanalaisatit.M et al, 2022).
AV is a highly effective approach for bolstering the energy production sector, particularly in response to the growing global demand for electricity. Notably, AV systems facilitate electricity generation from renewable energy sources, aligning with the crucial objective of reducing reliance on high-emission energy sources like fossil fuels. By embracing AV, it becomes feasible to enhance energy security and support countries, especially those in the developing world, in becoming self-sufficient and reducing their dependence on neighboring nations (Kumpanalaisatit.M et al, 2022).
One of the advantages of the AV system is its ability to prevent the excessive expansion of solar energy infrastructure, which would encroach upon agricultural land. This expansion could potentially undermine food sufficiency in many regions. The rapid development and increased adoption of solar energy, along with other renewable energy sources, can inadvertently contribute to food insecurity. However, AV serves as a crucial solution to mitigate this problem, offering a pathway to achieve both food security and energy security. The potential for finding suitable solutions that benefit both farmers and energy sector stakeholders is substantial, leading to a successful coexistence between the two (Kumpanalaisatit, M et al., 2022).
Moreover, PV panels serve as a protective barrier for crops against heavy rains and hail. However, they can also pose challenges by causing water to accumulate in specific areas of the ground, resulting in uneven distribution of water across the crops. Another drawback arises when PV modules hinder farmers' movement with their equipment or vehicles if proper considerations regarding installation height have not been made. Therefore, it is crucial to design an efficient system that minimizes these disadvantages for both agriculture and PV. Adequate pre-installation planning is essential to ensure the seamless integration of both systems (Suuronen.J, 2022).

4 CURRENT STUDY

This section offers a detailed explanation of the work undertaken in this degree project. It includes a deeper exploration of various aspects, such as the latitude (cities), azimuth, selected system, chosen crops, scenarios, equations, and the software program employed. The purpose is to provide a more comprehensive understanding of the research conducted and to delve into the specific details and components of this degree project.

4.1 Studied System

4.1.1 Latitude variation

The study focuses on two selected cities, namely Jokkmokk and Lund. These cities were chosen to explore the potential of AV systems in both southern and northern regions of Sweden. The selection was motivated by the desire to investigate the impact of different latitudes on weather conditions and solar radiation. Jokkmokk, with a latitude of approximately 66.6°, represents the northern region, while Lund, with a latitude of about 55°, represents the southern region. By examining these two cities, the study aims to compare the varying conditions and solar energy availability in different parts of Sweden.

4.1.2 Periods

In this degree project, the simulation period is limited to three months: June, July, and August. We have chosen these months because they represent the summer season when there are longer daylight hours. Winter periods, with shorter daylight hours, have not been included in this study. By focusing on the summer season, we aim to reduce the simulation time while gaining a complete understanding of how the system performs during the cultivation season in Sweden, which is during the summer period.

4.1.3 Selected system

The system chosen for this study is an elevated AV system, where PV modules are installed at a height of 3 meters. Various parameters, including slope, azimuth, and row distance, have been adjusted to explore and determine the optimal AV scenario. The total land area occupied by this system is 420 square meters.

4.1.4 Selected crops

The objective of AV systems is to combine PV energy generation with sustainable agricultural practices. Therefore, selecting crops that can tolerate shading and thrive under PV modules is essential. In this study, lettuce and potato have been specifically chosen to compare their shading tolerance and determine which crop performs better under PV modules. This analysis will help identify the crop with the highest potential for successful cultivation in AV.

4.2 Equations

The following equation has been utilized in Excel to calculate the total PAR that reaches the agricultural field. It is crucial to consider this value as it aids in determining the crops that can be cultivated under the PV module. (John.C,et al, 2017)

4.2.1 With AV

$$PAR_{tot}[\frac{w}{m^2}] = (Dir_R * Dir_F + Diff_R * Diff_F) * PAR_F \qquad \textit{Equation 4}$$

- PAR: Photosynthetically active radiation
- Dir_R $[\frac{w}{m^2}]$: radiation captured directly from the sun.
- $Diff_R$ $[\frac{w}{m^2}]$: radiations that have spread in the atmosphere because of clouds or dust...etc.
- Dir_F [%]: is the direct factor.
- $Diff_F$ [%]: is the diffuse factor.
- PAR factor is around 0,3 – 0,5, the chosen value in this work is 0,4. (Rodríguez. A, et al, 2020)

4.2.2 Conventional agriculture

$$PAR_{tot} = (Dir_R + Diff_R) * PAR_F \qquad \textit{Equation 5}$$

$$1\ PAR\ \left[\frac{W}{m^2}\right] = 4.6\ \mu\text{mol}\ /\text{m}^2/\text{s}$$

4.3 Software

This section presents the software utilized in this research project. The data was obtained using PVsyst, a software tool that incorporates the appropriate inputs, such as the chosen latitude and installed system, to generate accurate information. The data obtained from PVsyst was subsequently transferred to an Excel file to facilitate the calculation of the desired parameters.

4.3.1 PVsyst

PVsyst is a software program used to design PV parks by engineers and architects. It contains huge library of components and detailed tools that are useful to be able to provide results of the production and the mode of the modules. It also contains guide for executing projects. At the end of the planning, a complete report is given with several graphs, data and tables in PDF form to be able to see the result in different forms. Upon inputting the necessary parameters, including system specifications, latitude, slope, row distance, azimuth, and height, the simulation was executed in PVsyst. The output obtained from PVsyst includes hourly data on direct and diffuse radiation in watts per square meter (W/m^2), along with corresponding direct and diffuse factors. The simulation results are presented in an Excel file by PVsyst.

4.3.2 Excel

The output generated by PVsyst is provided in an Excel file, encompassing a total of 8,766 hours. This dataset includes information on direct and diffuse radiations measured in watts per square meter (W/m^2), accompanied by their respective factors. Utilizing equations 1 and 2, it is now possible to calculate the PAR values. For this particular analysis, the focus is on the period from June 1st to the end of August. Furthermore, the required number of PAR hours for the selected crops is determined. Additionally, graphical representations in the form of diagrams are employed to illustrate the variation in PAR values throughout the summer period.

4.4 Scenarios

The conventional agriculture's scenario is used as a reference for comparing traditional cultivation practices with land that incorporates PV module installations. The objective is to examine how crops in both cities react to the shade of PV installations. This analysis helps assess the impact of PV integration on agricultural land and allows for a comparison with conventional agriculture methods.

4.4.1 Exploring latitude variation

In the first scenario, certain parameters such as azimuth, slope, and row distance (with the same number of PV modules) remain constant, while the latitude is varied by changing the cities while keeping the surrounding conditions consistent. This approach allows for a comparison between a city in the northern region of Sweden and one in the southern region, highlighting the differences. By analyzing the shading patterns resulting from the change in latitude, we can observe how the shading analysis varies across different latitudes.

4.4.2 *Exploring azimuth variation*

In the second scenario, the distance between the modules is kept constant at 5 meters, and the tilt (slope) remains at 10 degrees. The modules are arranged in four rows, with each row consisting of 20 modules in series. The varying factor in this scenario is the azimuth, which refers to the direction the modules are oriented. Initially, the azimuth is set to 90°, pointing towards the west (see to Figure 7). Subsequently, the azimuth is changed to 0 degrees, facing the south (see to Figure 8). The reason for selecting these two different azimuths is that, with a 90° azimuth, the modules have a minimal shading impact on the crops. On the other hand, with a 0° azimuth, the crops are subject to the most shading. However, a 0° azimuth maximizes electricity production since the modules are directed towards the south. This is why the azimuth of 90° was chosen for comparison.

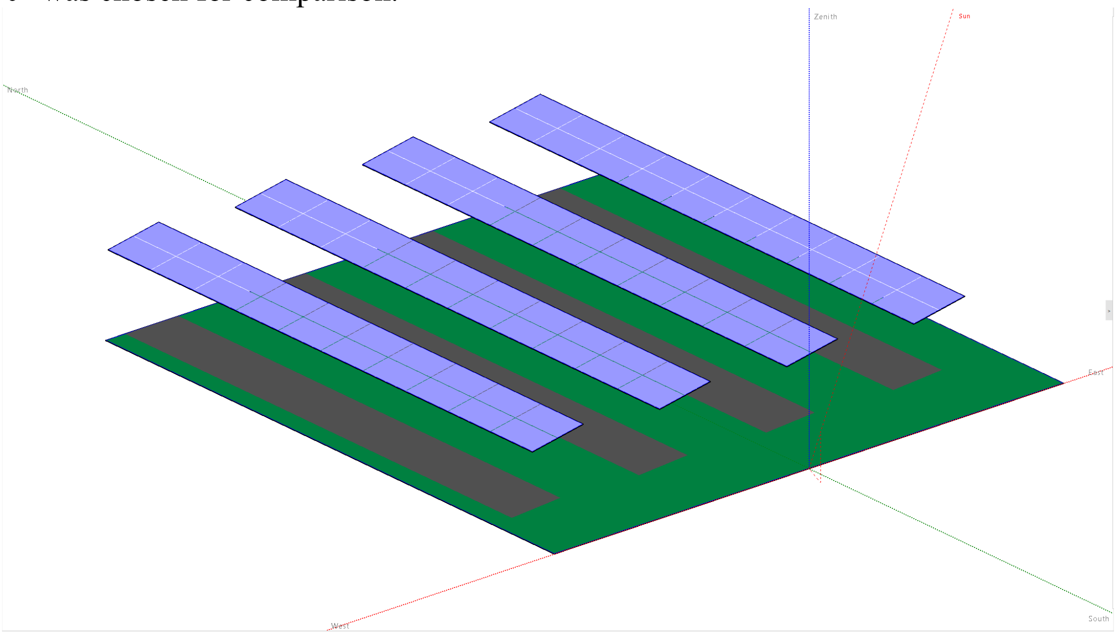

Figure 7: AV system when azimuth is 90°, tilt 10° and 5 m distance between the rows.

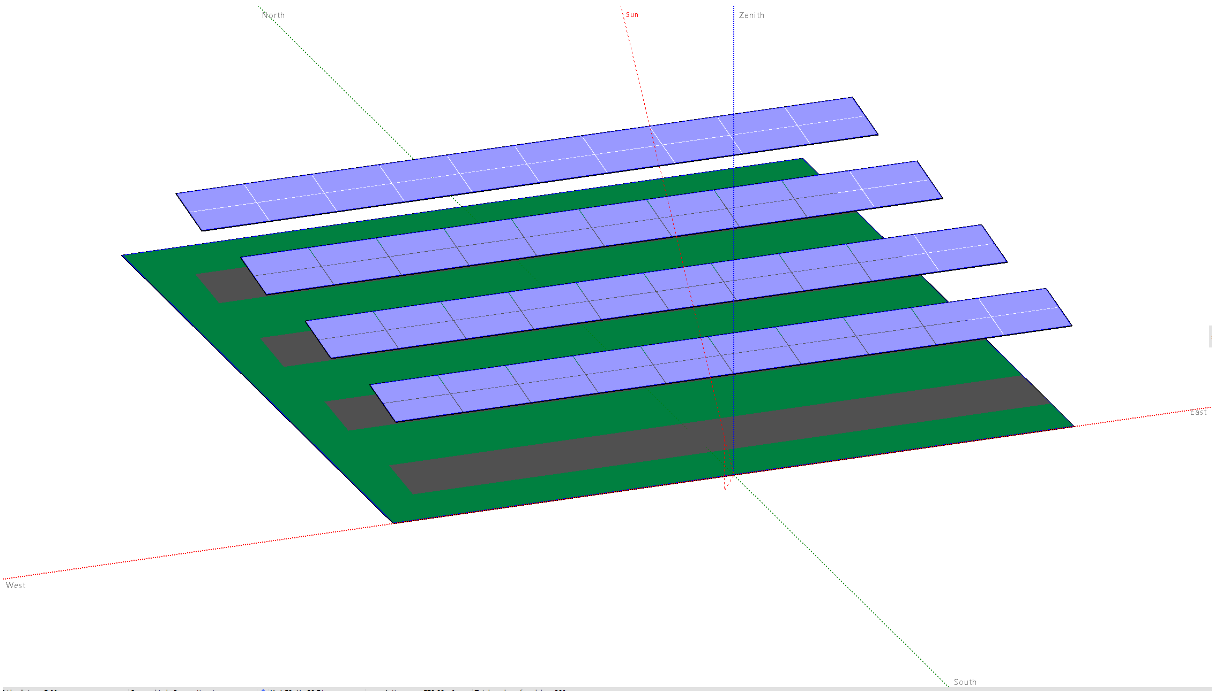

Figure 8: AV system with azimuth 0°, tilt 10° and 5 m distance between the rows.

4.4.3 Exploring distance variation

The third scenario of this study focuses on a constant latitude, specifically the city of Lund. The azimuth remains constant at 0°, and the slope is set at 45°. The only parameter that varies in this scenario is the distance between the rows. In one case, the distance between the rows is set to 2 meters, resulting in an increased number of rows, specifically 10 rows, with 20 PV modules in each row. This configuration covers the field with a total of 200 PV modules (refer to Figure 9). In the second case, the distance between the rows is set to 7 meters, which results in 3 rows containing a total of 60 PV modules (see to Figure 10).

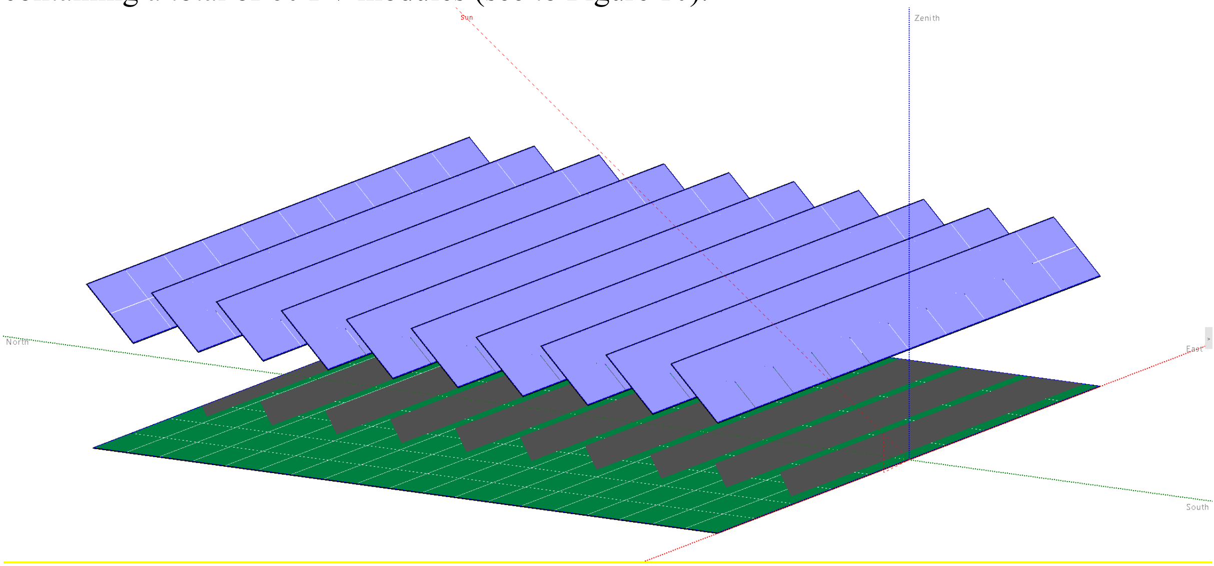

Figure 9: AV system with 2 m distance between the rows, azimuth 0°and tilt 45°.

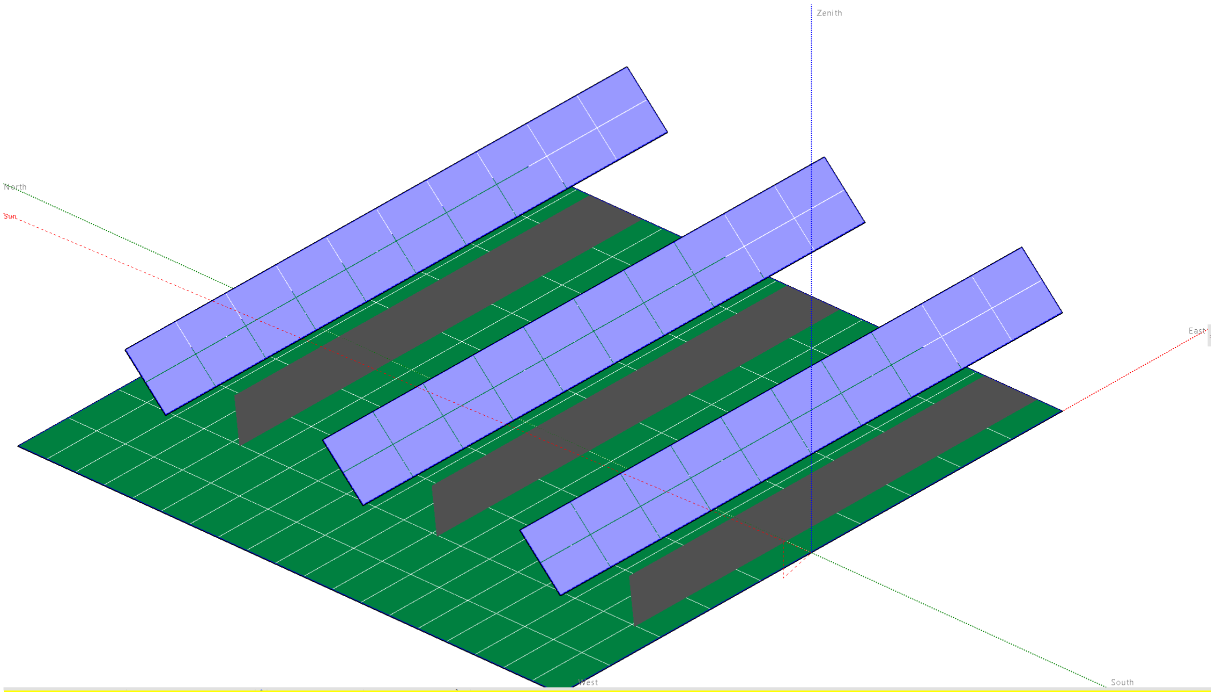

Figure 10: AV system with 7 m distance between the rows, azimuth 0°andt tilt 45°.

4.4.4 Slope (Lund, azimuth 90°. 5m)

The final scenario in this study investigates the impact of slope variations on the shadow cast on the field. Two different cases are considered: one with a slope inclination of 10 ° (almost horizontal, refer to Figure 11) and another with a slope inclination of 45° (refer to see 12). The remaining parameters, including latitude (Lund), azimuth of 90°, and 5 meters between rows, are kept constant throughout these cases. The purpose is to examine how changes in slope angle influence the shadow patterns observed in the field.

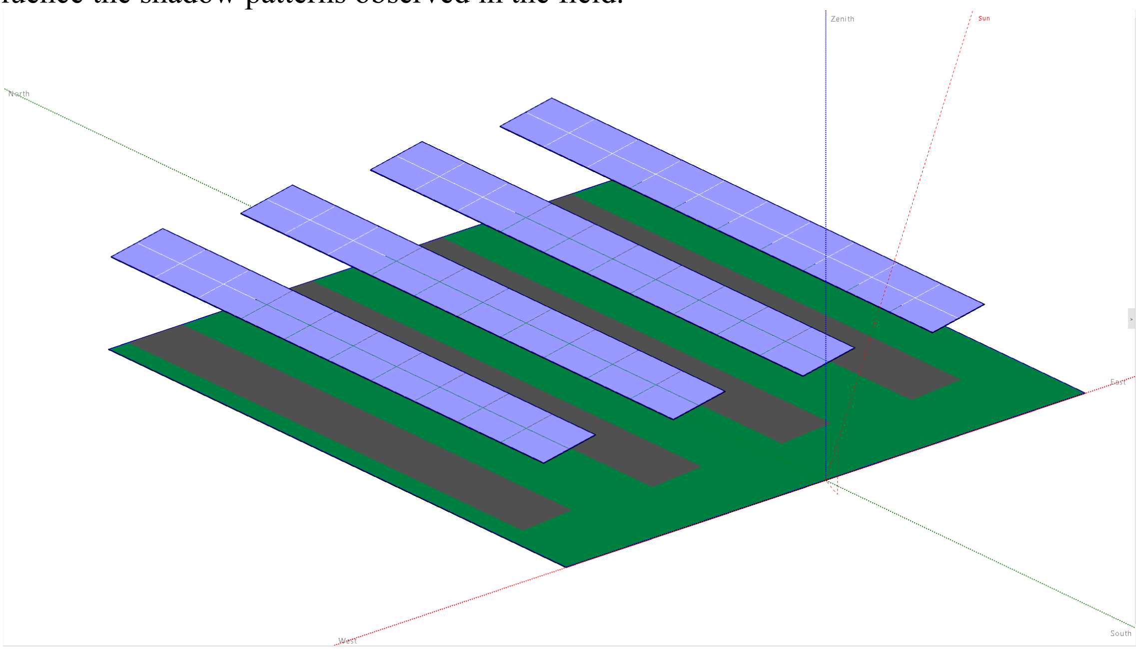

Figure 11: AV system with 10° slope, 5 m distance between the rows, azimuth 90°.

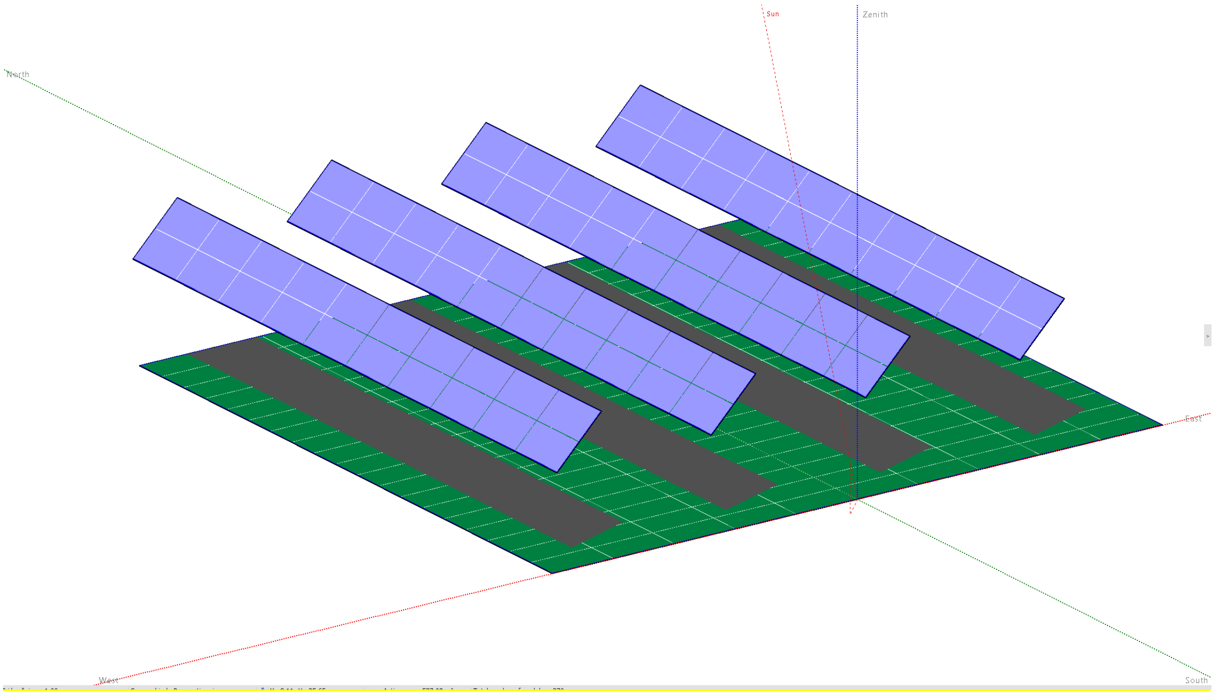

Figure 12: AV system with 45° slope, 5 m distance between the rows, azimuth 90°.

5 RESULTS

In this section, the result obtained from Excel is presented in four different scenarios, including the result of the conventional agriculture. The tables present the Excel results for lettuce and potato crops. Each table displays the total number of approved hours for the crops during the summer, along with the corresponding percentage of approved hours. This percentage is calculated by dividing the approved hours for each crop by the total solar hours during the summer. Furthermore, the tables indicate the number of approved hours per day and the average PAR value for each month.

The diagrams in the results section display the outcomes for each scenario. The x-axis represents the time in hours, ranging from the first of June to the 31st of August. The y-axis represents the PAR in units of watts per square meter [W/m^2]. Each diagram includes two fixed values: the required PAR value for lettuce, which is 186 PAR and is represented by the color green, and the required PAR value for potato, which is 87 and is represented by the color light brown.

Conventional Agriculture

The tables below show the result for conventional agriculture which has been used to compare the PAR values between conventional agriculture and AV for different scenarios.

Tablel 4: Result for average PAR and approved hours for conventional agriculture in Jokkmokk.

	Lettuce	Potato	Unit
Approved hours during summer period	362	1008	h
Percentage of approved hours	**29**	**80**	%
Approved hours per day	**4**	**11**	h
Average PAR in June	142.5	142.5	W/m^2
Average PAR in July	132.5	132.5	W/m^2
Average PAR in August	101.8	101.8	W/m^2

Tablel 5: Result for average PAR and approved hours for conventional agriculture in Lund.

	Lettuce	Potato	Unit
Approved hours during summer period	468	956	h
Percentage of approved hours	**37**	**76**	%
Approved hours per day	**5.2**	**10.6**	h
Average PAR in June	159.0	159.0	W/m^2
Average PAR in July	148.9	148.9	W/m^2
Average PAR in August	124.9	124.9	W/m^2

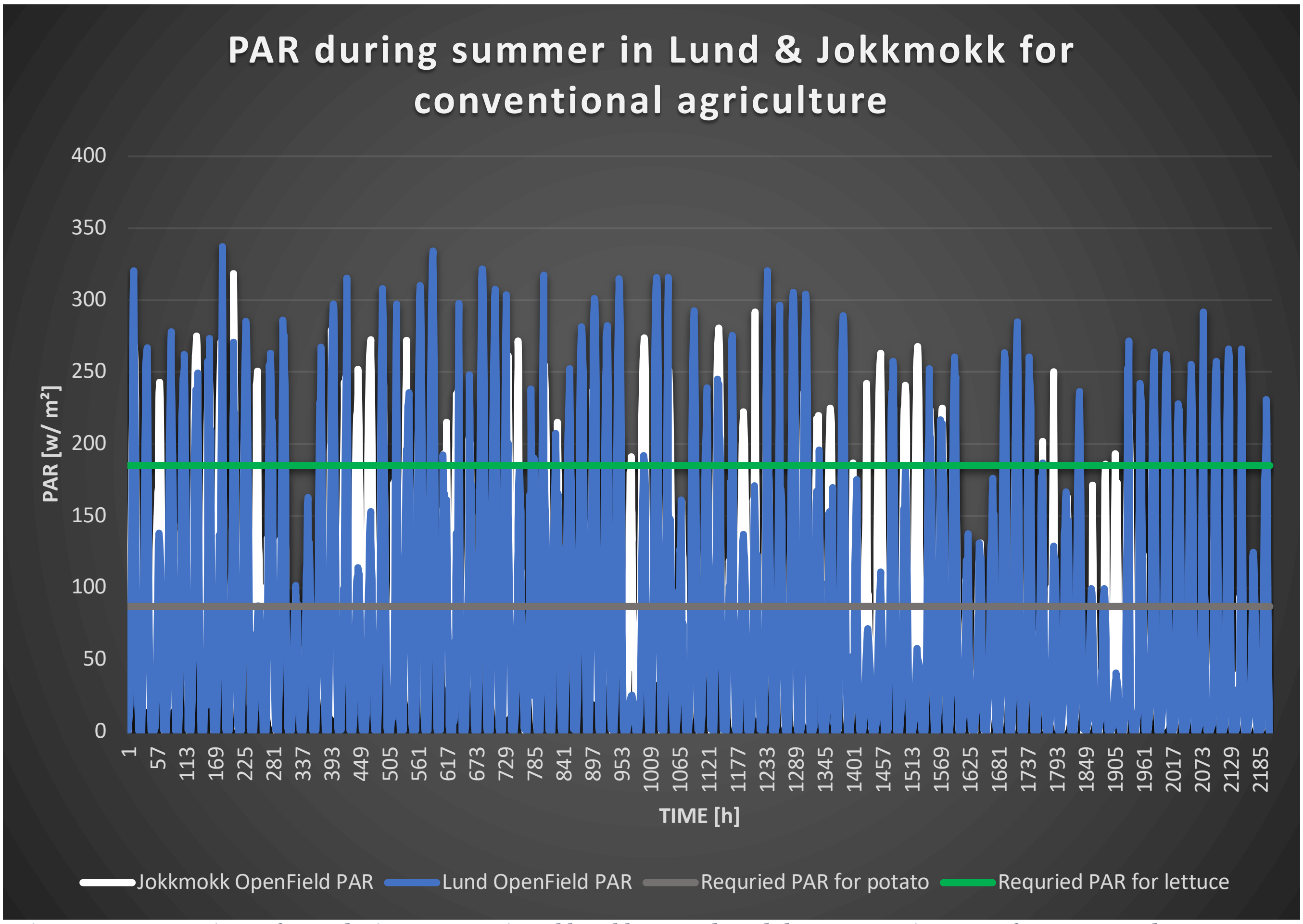

Figure 13: Comparison of PAR during summer in Jokkmokk & Lund, and the PAR requirements for potato and lettuce.

5.1 Scenario 1. Exploring Latitude Variation

In this scenario, the fixed variables consisted of an azimuth angle set at 90°, a slope of 10°, and a row spacing of 5 meters. The following tables presents the outcomes observed in Lund and Jokkmokk for both crops, accompanied by diagrams illustrating the hourly PAR results during the summer, with AV and conventional agriculture.

5.1.1 AV system in Lund

The table below presenting the results for lettuce and potato crops. The first row represents the total number of approved hours for the crops during the summer, while the second row indicates the corresponding percentage of approved hours. Additionally, the table provides information on the number of approved hours per day and the average PAR value for each month.

The diagram x-axis represents the time in hours, ranging from the first of June to the 31st of August. Meanwhile, the y-axis represents the PAR measured in [W/m2]. The graph includes two fixed lines that indicate the required PAR value for lettuce, displayed in green (186 PAR), and the required PAR value for potato, displayed in light brown (87 PAR).

Table 6: Result for average PAR and approved hours for scenario 1 in Lund.

	Lettuce	Potato	Unit
Approved hours during summer period	184	888	h
Percentage of approved hours	**15**	**70**	%
Approved hours per day	**2.1**	**9.76**	h
Average PAR in June	114.2	114.2	W/m^2
Average PAR in July	107.4	107.4	W/m^2
Average PAR in August	92.0	92.0	W/m^2

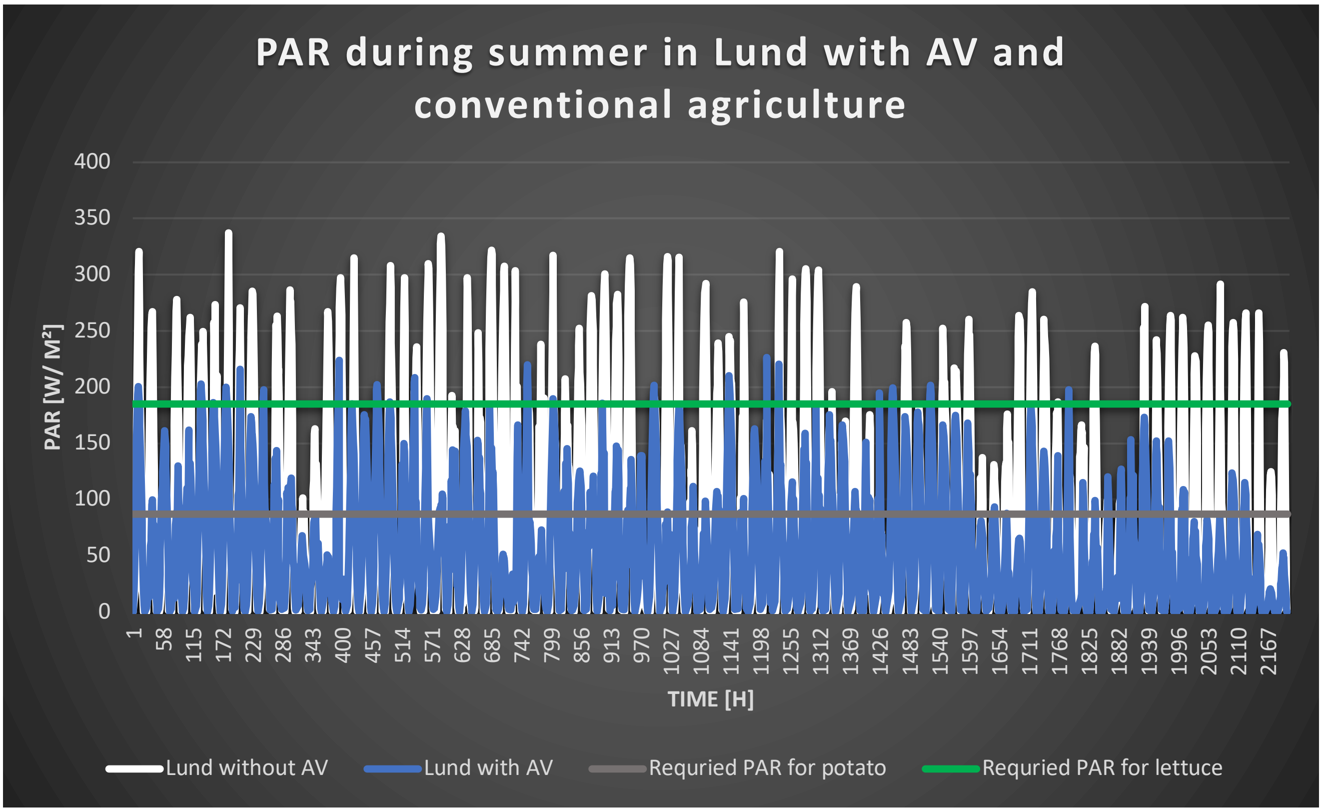

Figure 14: Comparison of PAR during summer in Lund with an agrivoltaic system and conventional agriculture, and the PAR requirements for potato and lettuce.

5.1.2 AV system in Jokkmokk

The table below presents the results for lettuce and potato crops, including the total number of approved hours for the crops during the summer in the first row and the corresponding percentage of approved hours in the second row. Additionally, the table provides data on the number of approved hours per day and the average PAR value for each month.
The accompanying diagram illustrates the time in hours on the x-axis, spanning from the first of June to the 31st of August. The y-axis represents the PAR measured in units of [W/m2]. The graph features two fixed lines: a green line representing the required PAR value for lettuce (186 PAR) and a light brown line representing the required PAR value for potato (87 PAR).

Tablel 7: Result for average PAR and approved hours for scenario 1 in Jokkmokk.

	Lettuce	Potato	Unit
Approved hours during summer period	141	882	h
Percentage of approved hours	**11**	**70**	%
Approved hours per day	**1.56**	**9.8**	h
Average PAR in June	104.7	104.7	w/m^2
Average PAR in July	98.2	98.2	w/m^2
Average PAR in August	76.9	76.9	w/m^2

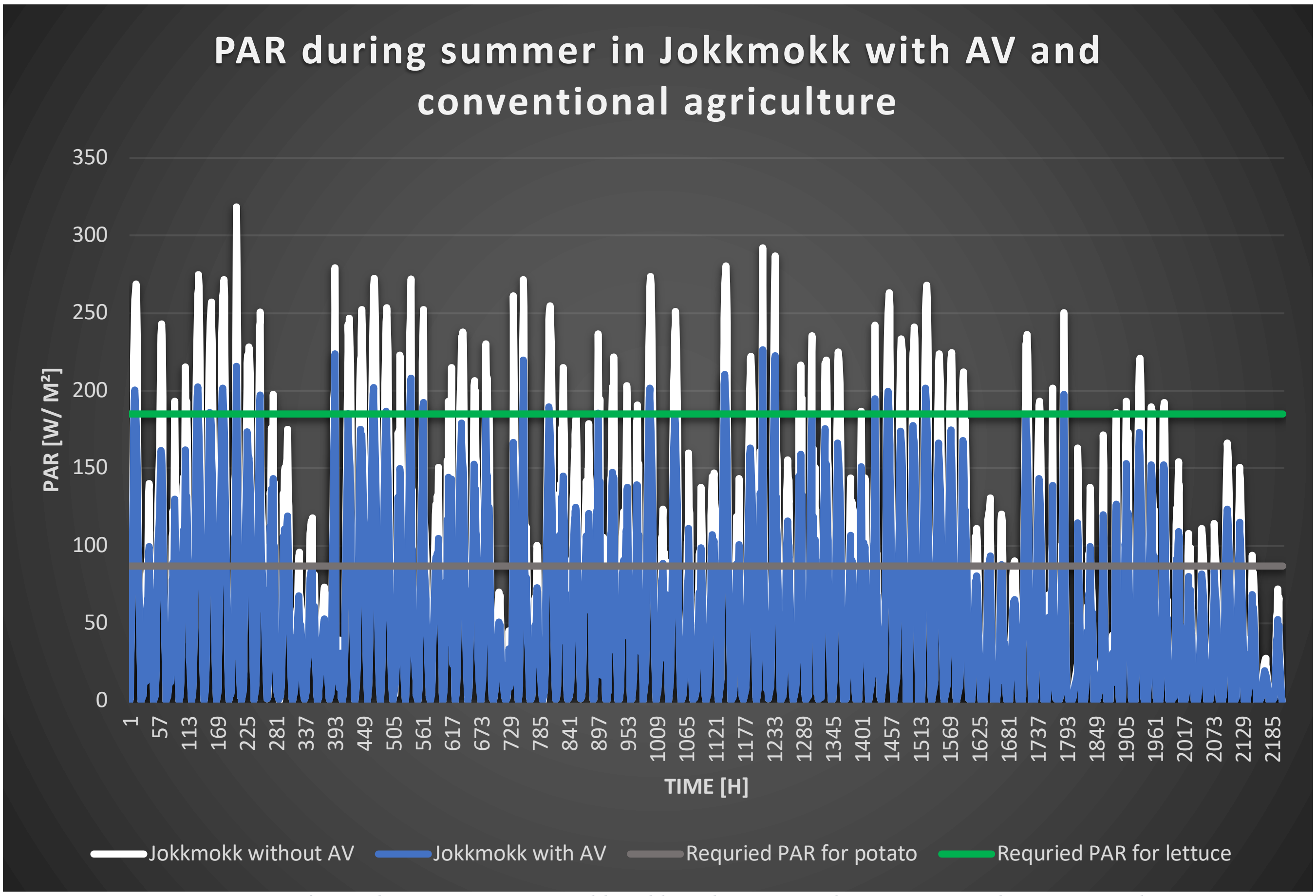

Figure 15: Comparison of PAR during summer in Jokkmokk with an agrivoltaic system and conventional agriculture, and the PAR requirements for potato and lettuce.

5.2 Exploring Azimuth Variation

In this scenario, the fixed variables consisted of the latitude, a slope of 10°, and a row spacing of 5 meters. The following tables presents the outcomes observed in Lund for both crops, accompanied by diagrams illustrating the hourly PAR results during the summer, with AV and conventional agriculture.

5.2.1 AV system using a 0° azimuth

In the table below shows the results for lettuce and potato crops. The first row displays the total number of approved hours for these crops during the summer, while the second row indicates the corresponding percentage of approved hours. Additionally, the table provides details on the number of approved hours per day and the average PAR value for each month. Regarding the accompanying diagram, the x-axis represents the hours of the day, covering the period from the first of June to the 31st of August. On the other hand, the y-axis represents the PAR measured in units of [W/m2]. The graph features two fixed lines: a green line indicating the required PAR value for lettuce (186 PAR) and a light brown line representing the required PAR value for potato (87 PAR).

Table 8: Result for average PAR and approved hours for scenario 2 with azimuth 0°.

	Lettuce	Potato	Unit
Approved hours during summer period	169	892	h
Percentage of approved hours	**13**	**71**	%
Approved hours per day	**1,9**	**9,9**	h
Average PAR in June	107.3	107.3	w/m^2
Average PAR in July	100.9	100.9	w/m^2
Average PAR in August	86:0	86:0	w/m^2

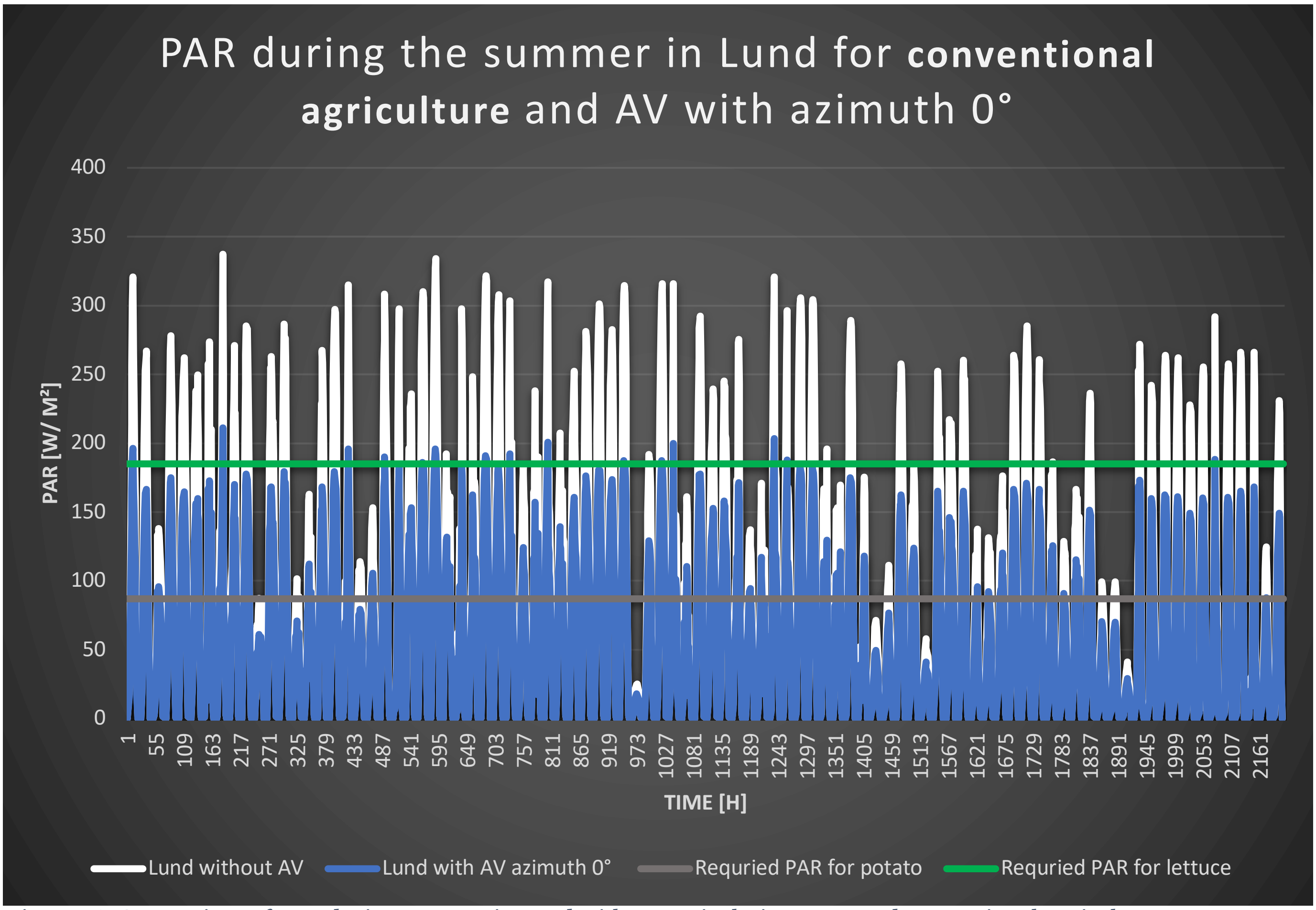

Figure 16: Comparison of PAR during summer in Lund with an agrivoltaic system and conventional agriculture for the 0° azimuth, and the PAR requirements for potato and lettuce.

5.2.2 AV system using a 90° azimuth

The below table presenting the results for lettuce and potato crops. The first row provides the total number of approved hours during the summer, while the second row shows the corresponding percentage of approved hours. Additionally, the table includes information about the number of approved hours per day and the average PAR) value for each month. Furthermore, there is a diagram where the x-axis represents the time in hours from the first of June to the 31st of August. The y-axis represents the PAR measured in [W/m2]. The diagram includes two fixed lines: a green line indicating the required PAR value for lettuce (186 PAR) and a light brown line indicating the required PAR value for potato (87 PAR).

Table 9: Result for average PAR and approved hours for scenario 2 with azimuth 90°.

	Lettuce	Potato	Unit
Approved hours during summer period	184	888	h
Percentage of approved hours	**15**	**70**	%
Approved hours per day	**2.1**	**9,9**	h
Average PAR in June	114.2	114.2	w/m^2
Average PAR in July	107.4	107.4	w/m^2
Average PAR in August	92:0	92:0	w/m^2

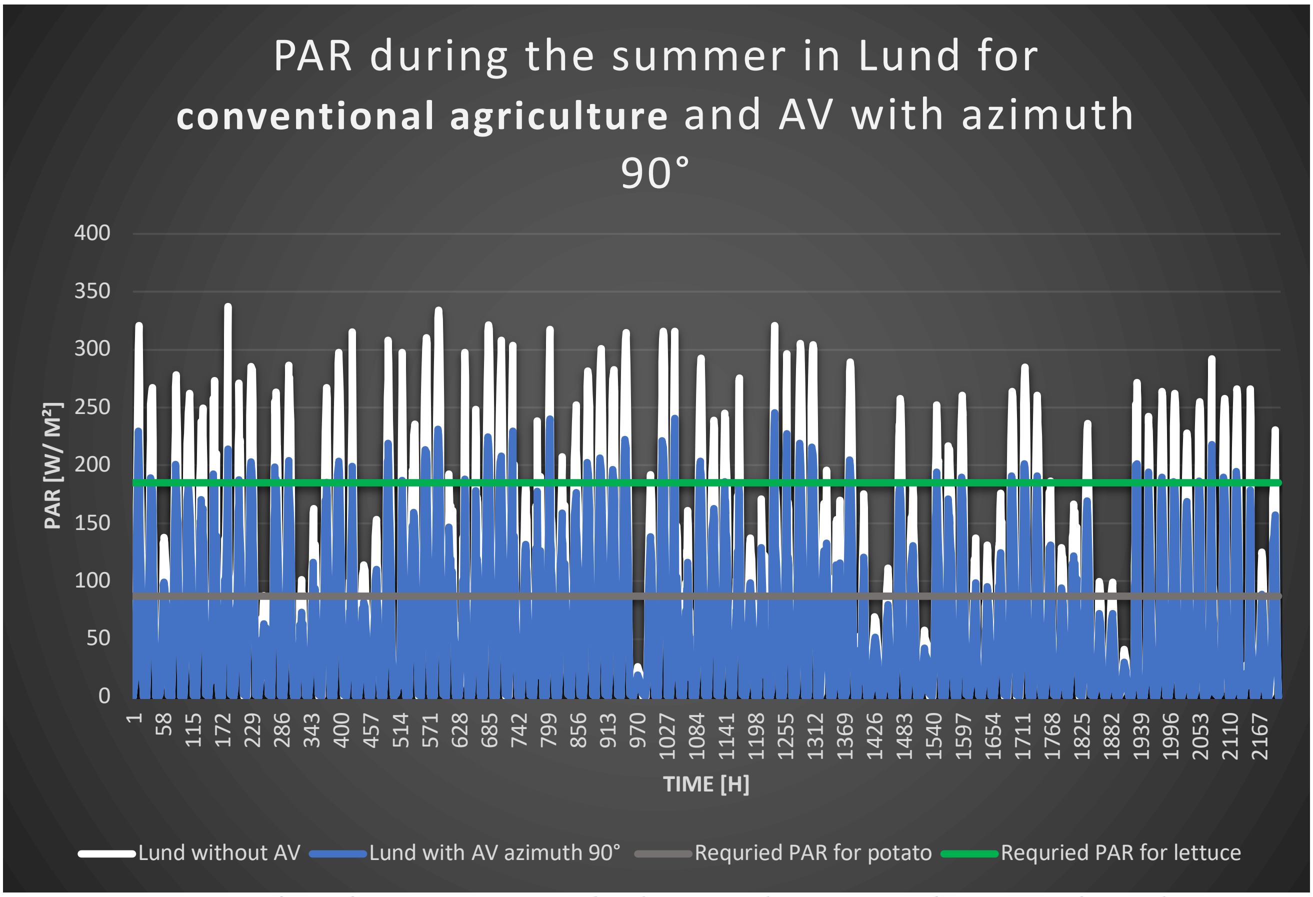

Figure 17: Comparison of PAR during summer in Lund with an agrivoltaic system and conventional agriculture for the 90° azimuth, and the PAR requirements for potato and lettuce.

5.3 Exploring Distance Variation

In this scenario, the fixed variables consisted of the latitude, a slope of 10° and the azimuth of 0°. The following tables presents the outcomes observed in Lund for both crops, accompanied by diagrams illustrating the hourly PAR results during the summer, with AV and conventional agriculture.

5.3.1 AV system using 2 m row distance

The results for lettuce and potato crops are presented in the table below. The first row shows the total number of approved hours for these crops during the summer, while the second row displays the corresponding percentage of approved hours. Additionally, the table provides details on the number of approved hours per day and the average PAR value for each month. In the accompanying diagram, the x-axis represents the time in hours, spanning from the first of June to the 31st of August. On the other hand, the y-axis represents the PAR measured in [W/m2]. Within the diagram, you will notice two fixed lines: a green line indicating the required PAR value for lettuce (186 PAR) and a light brown line representing the required PAR value for potato (87 PAR).

Tablel 10: Result for average PAR and approved hours for scenario 3 with 2 m distance between the rows.

	Lettuce	Potato	Unit
Approved hours during summer period	0	715	h
Percentage of approved hours	**0**	**57**	%
Approved hours per day	**0**	**7.94**	h
Average PAR in June	63.51	63.51	w/m^2
Average PAR in July	60.14	60.14	w/m^2
Average PAR in August	52.32	52.32	w/m^2

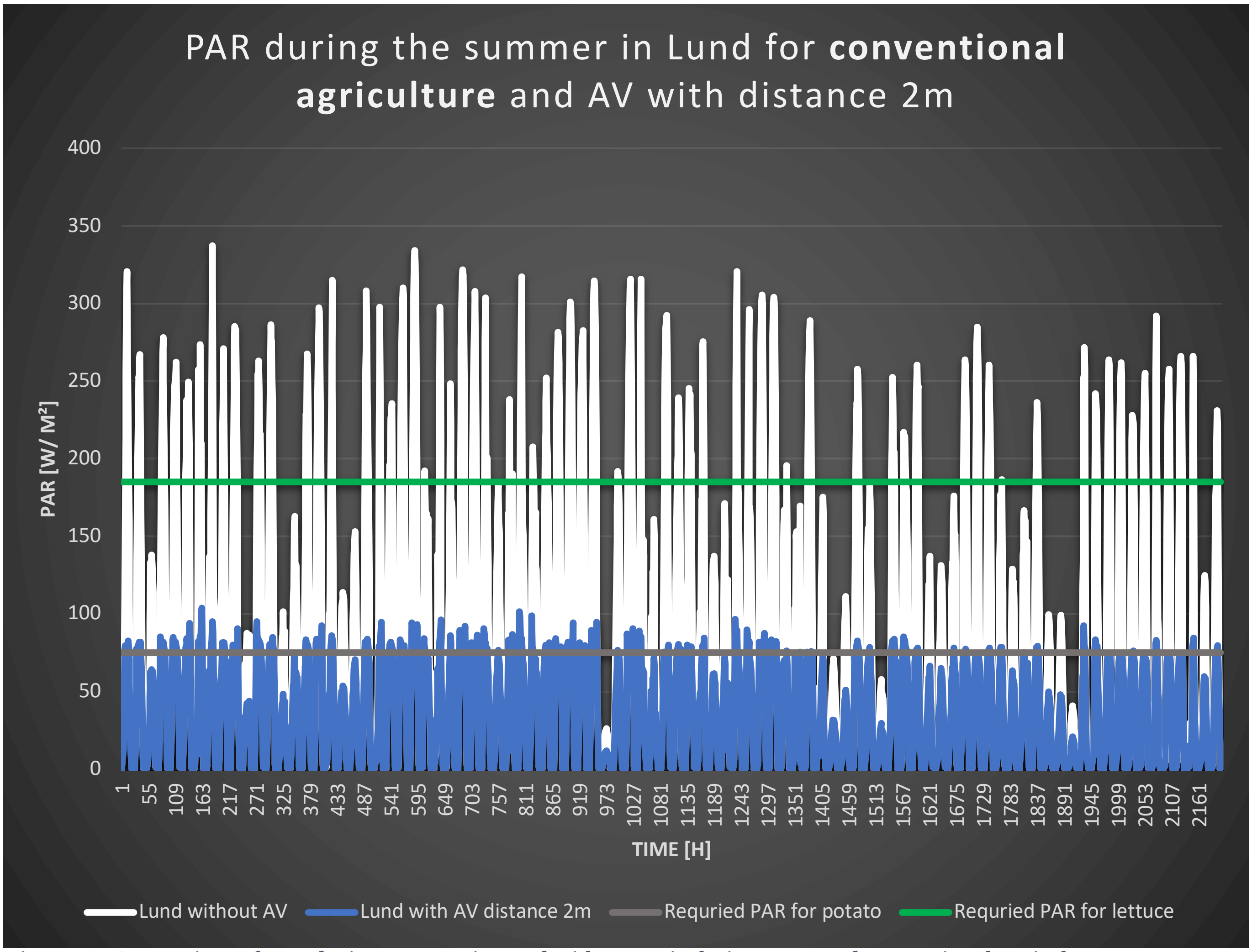

Figure 18: Comparison of PAR during summer in Lund with an agrivoltaic system and conventional agriculture for the 2 m distance between the rows, and the PAR requirements for potato and lettuce.

5.3.2 AV system using 7 m row distance

The table below presents the results for lettuce and potato crops, including the total number of approved hours for the crops during the summer in the first row and the corresponding percentage of approved hours in the second row. Additionally, the table provides data on the number of approved hours per day and the average PAR value for each month.
The accompanying diagram illustrates the time in hours on the x-axis, spanning from the first of June to the 31st of August. The y-axis represents the PAR measured in units of [W/m2]. The graph features two fixed lines: a green line representing the required PAR value for lettuce (186 PAR) and a light brown line representing the required PAR value for potato (87 PAR).

Table 11: Result for average PAR and approved hours for scenario 3 with 7 m distance between the rows.

	Lettuce	**Potato**	**Unit**
Approved hours during summer period	316	957	h
Percentage of approved hours	**25**	**76**	%
Approved hours per day	**3,5**	**10.6**	h
Average PAR in June	126.40	126.40	w/m^2
Average PAR in July	118.13	118.13	w/m^2
Average PAR in August	97.60	97.60	w/m^2

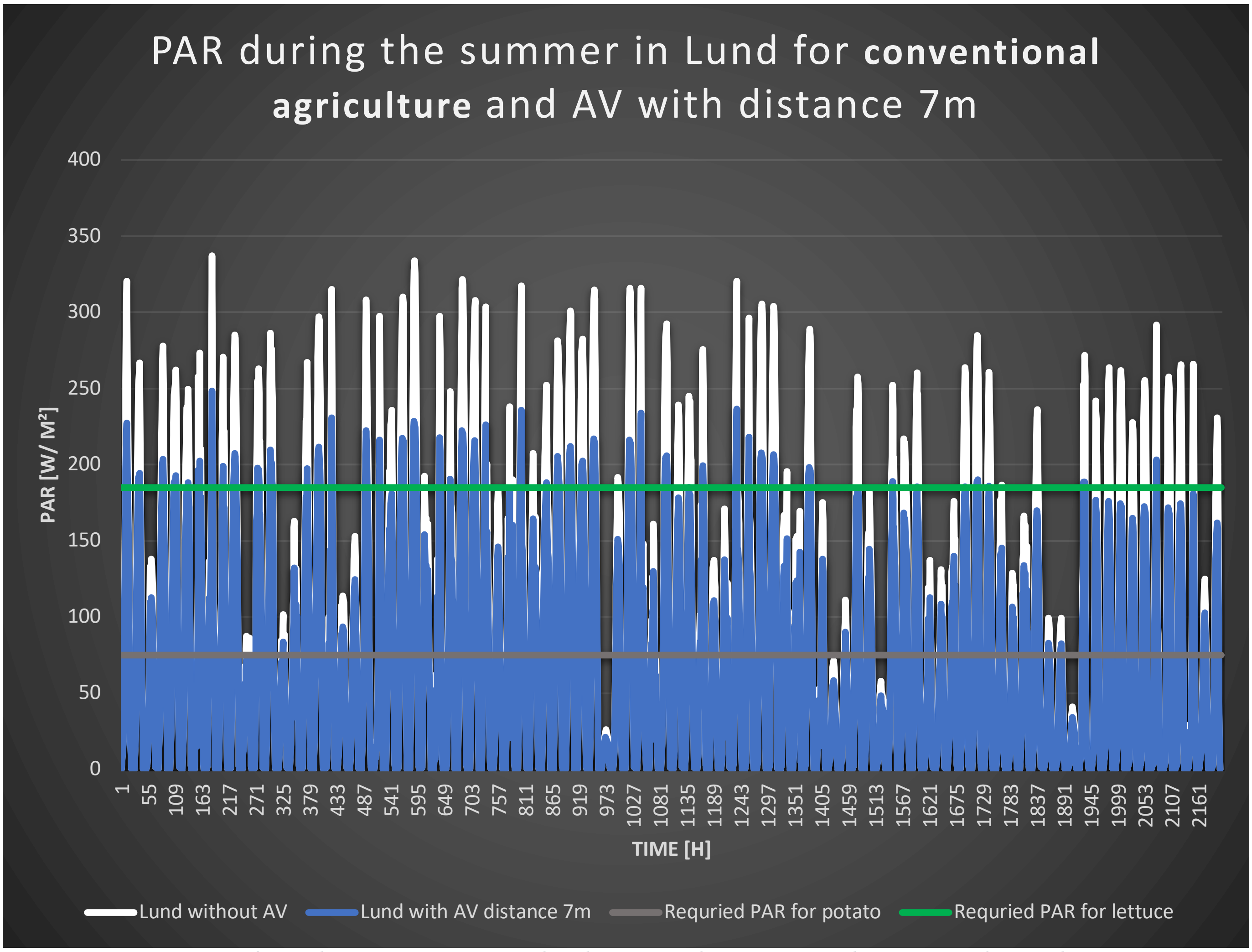

Figure 19: Comparison of PAR during summer in Lund with an agrivoltaic system and conventional agriculture for the 7 m distance between the rows, and the PAR requirements for potato and lettuce.

5.4 Exploring Slope Variation

In this scenario, the fixed variables consisted of the latitude, row distance of 5 m and the azimuth of 0°. The following tables presents the outcomes observed in Lund for both crops, accompanied by diagrams illustrating the hourly PAR results during the summer, with AV and conventional agriculture.

5.4.1 AV system using a 10° slope

The table below presents the results for lettuce and potato crops, including the total number of approved hours for the crops during the summer in the first row and the corresponding percentage of approved hours in the second row. Additionally, the table provides data on the number of approved hours per day and the average PAR value for each month.
The accompanying diagram illustrates the time in hours on the x-axis, spanning from the first of June to the 31st of August. The y-axis represents the PAR measured in units of [W/m2]. The graph features two fixed lines: a green line representing the required PAR value for

lettuce (186 PAR) and a light brown line representing the required PAR value for potato (87 PAR).

Table 12: Result for average PAR and approved hours for scenario 4 with 10° slope.

	Lettuce	Potato	Unit
Approved hours during summer period	184	888	h
Percentage of approved hours	**15**	**70**	%
Approved hours per day	**2.1**	**9.86**	h
Average PAR in June	114.2	114.2	w/m^2
Average PAR in July	107.4	107.4	w/m^2
Average PAR in August	92.0	92.0	w/m^2

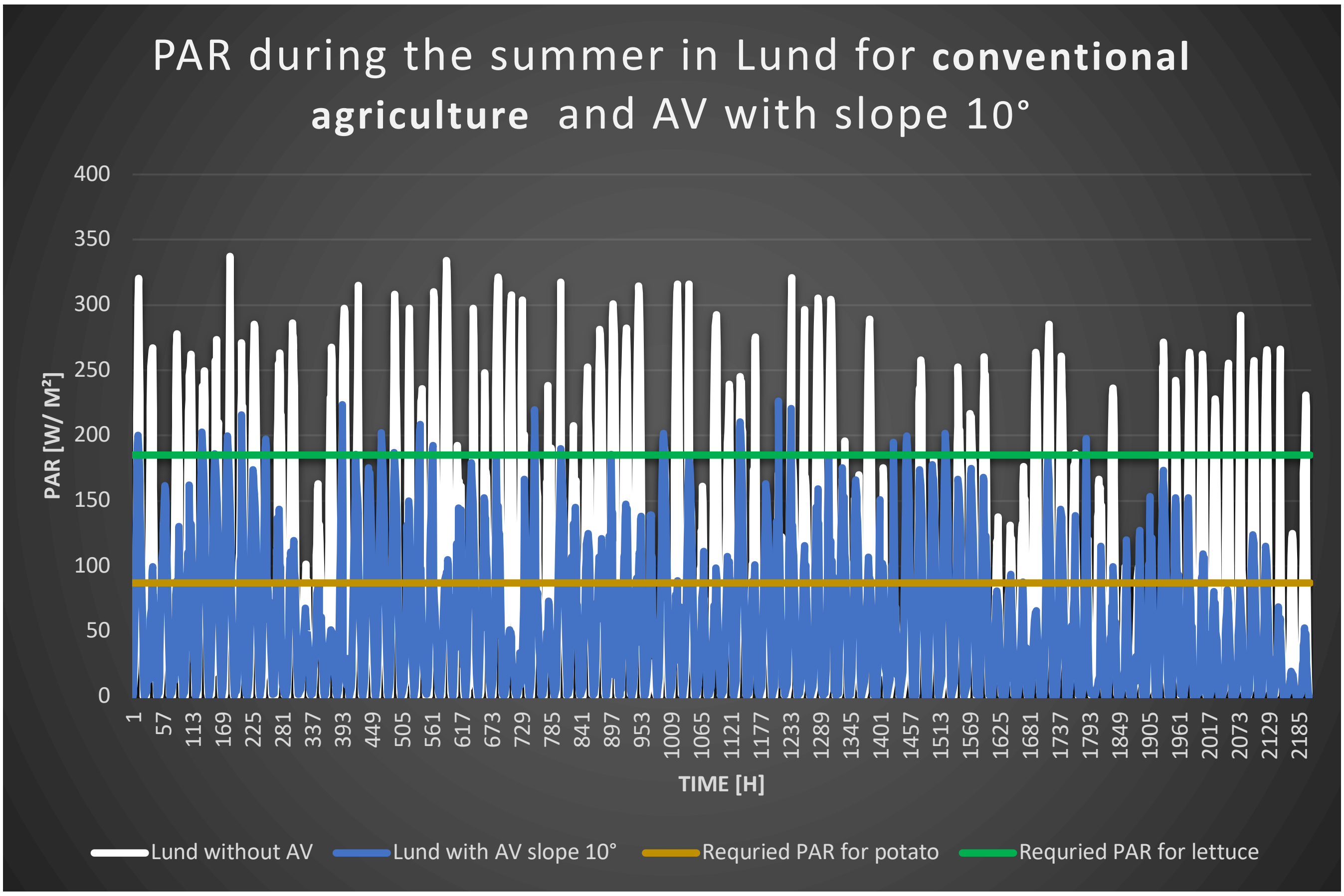

Figure 20: Comparison of PAR during summer in Lund with an agrivoltaic system and conventional agriculture for the 10° slope, and the PAR requirements for potato and lettuce.

5.4.2 AV system using a 45° slope

The below table presenting the results for lettuce and potato crops. The first row provides the total number of approved hours during the summer, while the second row shows the corresponding percentage of approved hours. Additionally, the table includes information about the number of approved hours per day and the average PAR) value for each month.

Furthermore, there is a diagram where the x-axis represents the time in hours from the first of June to the 31st of August. The y-axis represents the PAR measured in [W/m2]. The diagram includes two fixed lines: a green line indicating the required PAR value for lettuce (186 PAR) and a light brown line indicating the required PAR value for potato (87 PAR).

Tablel 13: Result for average PAR and approved hours for scenario 4 with 45° slope.

	Lettuce	Potatis	Unit
Approved hours during summer period	270	896	h
Percentage of approved hours	**21**	**71**	%
Approved hours per day	**3**	**9,95**	h
Average PAR in June	122.6	122.6	w/m^2
Average PAR in July	117.8	117.8	w/m^2
Average PAR in August	99.7	99.7	w/m^2

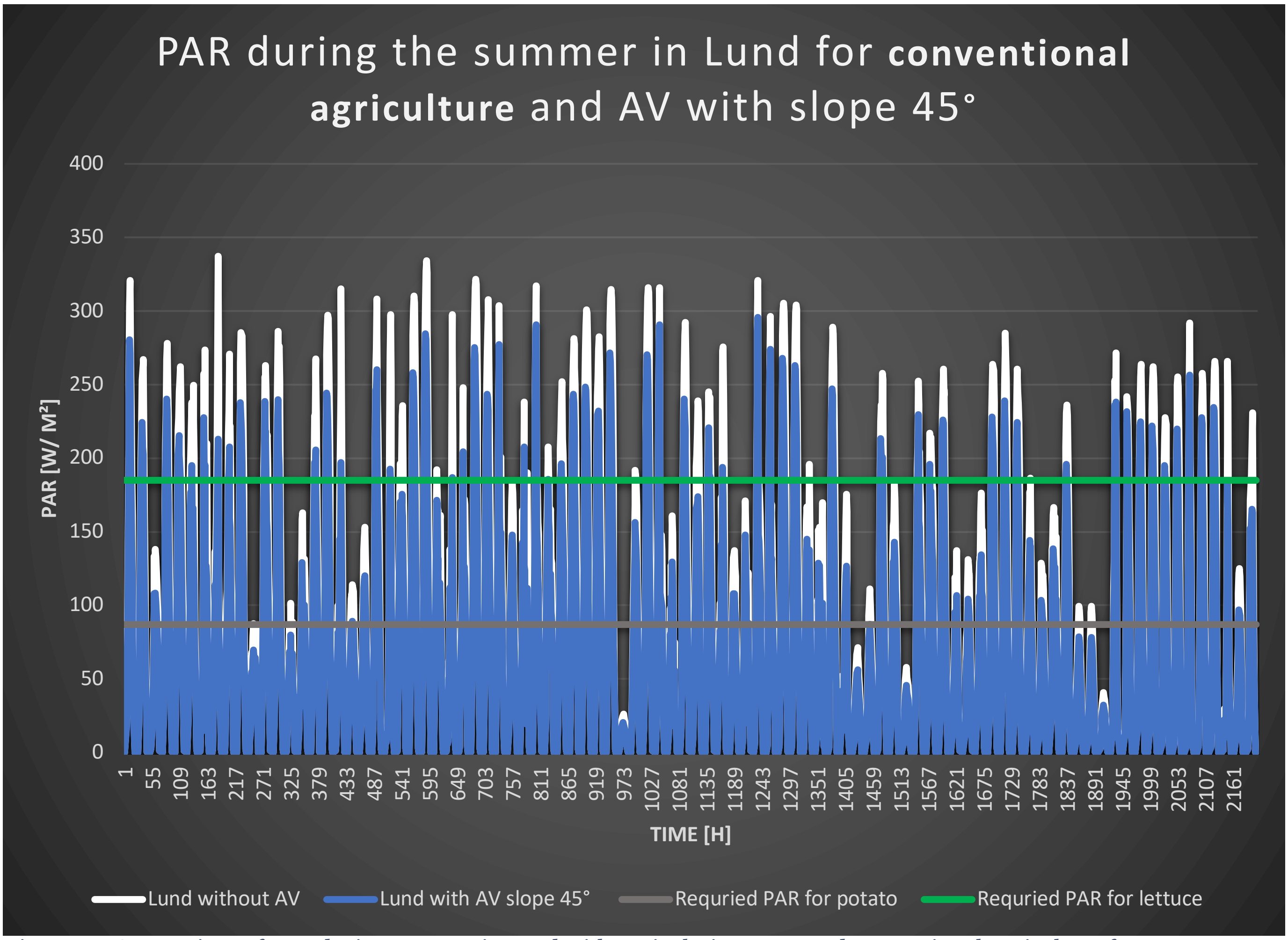

Figure 21: Comparison of PAR during summer in Lund with agrivoltaic system and conventional agriculture for the 45° slope, and the PAR requirements for potato and lettuce.

6 DISCUSSION

The result obtained from conventional agriculture showed that Lund has higher solar intensity which corresponds 5.2 approved hours per day which is sufficient for lettuce to grow, due to the lettuce high required PAR value, which is around 186 PAR. Even though Jokkmokk has a bit lower solar intensity compared to Lund, but in the other hand Jokkmokk has more solar hours per day during the summer, which is good enough for potato that has low required PAR value, approximately 87 PAR.

In the first scenario, the result for number of approved hours for Lettuce were 2.1 h in Lund and 1.56 h in Jokkmokk, the reason behind this result is that lettuce requires more solar intensity, which is higher in Lund compared to Jokkmokk. While the number of approved hours for potato were 9.76 h in Lund and 9,8 h in Jokkmokk. Jokkmokk had the preference of the potato growing because of the potato's lower need for solar intensity. As it's mentioned above that Jokkmokk has high solar hours per day, those factors led to increased approved hours per day for potato in Jokkmokk. However, the potato can also be grown in Lund, because the city also has a high number of solar hours but with higher solar intensity more than what is required and that can lead to stress the potato growing and increases the need for irrigation. When comparing AV with conventional agriculture for both selected crops, the result showed that both cities had a huge reduction of approved hours when it came to lettuce, the reduction was around 61% for both cities. In the case of potato, the reduction was not significant. The value for Jokkmokk and Lund were 12.5% and 7.1% respectively. Even though the results from both cities were quite similar, but according to the result, the lettuce growing in both cities is quite impossible with AV. Although the AV in both cities had the following constant parameters like AV system, azimuth, latitude, and row distance between modules, but the latitude variation was the reason for these differences in results between the cities.

In the second scenario, the constant parameters in this case were the latitude (Lund), a row distance of 5 meters, and a slope of 10 degrees. However, azimuth angles of 0° and 90° were chosen. The results revealed that lettuce received a total of 169 approved PAR hours during the summer in the case of 0° azimuth. When the azimuth was adjusted to 90°, the value increased to 184 hours. This increase can be attributed to the installation of solar modules facing westward at the 90° azimuth, whereas Sweden predominantly receives solar radiation from the south. Consequently, the solar panels do not cast as much shade on the agricultural field compared to a 0° azimuth. On the other hand, for potatoes, there was no significant difference in the approved PAR hours between the two azimuth angles.

In the third scenario, the simulation was done for two different distances between the solar module rows. The distances were 2 m and 7 m. In the case of 2 meters there was room for 10 rows of solar modules with 20 modules in each row, which was a total of 200 modules. The result showed that the average value of PAR for June and July was 63 and 60 respectively, and an average value of 52 in August. This result showed no approved hours of the required PAR for lettuce. However, according to figure 18 the required PAR for potatoes is sufficient and do not exceed as much, because potato needs around 87 PAR to grow normally. In this case, the result for approved hours is about 8 hours per day during the selected period, which is enough for potatoes. This result proved to be a good alternative for AV with potatoes as the selected crop because it also provides good electricity production due to more installed solar modules.
When a row spacing of 7 meters was implemented, the findings revealed a substantial 33% reduction in the approved hours of required PAR for lettuce in comparison to conventional agriculture condition. Consequently, this led to a daily allocation of 3.5 hours of approved PAR.

However, it is important to note that lettuce necessitates a minimum of 5 to 8 hours of desired PAR per day to attain satisfactory quality and yield. Regarding potatoes, the reduction in the approved hours of required PAR did not demonstrate a significant difference when compared to the conventional agriculture conditions. Furthermore, in comparison to a 2-meter row distance, a notable disadvantage in this scenario was the decrease in the number of solar modules, which declined from 200 panels to 60 panels.

In the last scenario, the primary parameter that was varied was the slope, while other parameters such as azimuth (90°), latitude (Lund), and row distance between the modules (5 m) remained constant. The slopes selected for this scenario were 10° and 45°. For the 10° slope, the approved hours of PAR were 184 hours for lettuce, whereas for the 45° slope, this value increased to 270 hours. The reason behind the lower PAR values for the 10° slope is that the solar modules are implemented like a roof over the agricultural field, limiting the amount of solar radiation reaching the field. Conversely, the 45° slope allows for sufficient space for solar radiation to reach the field. However, changes were also observed for potatoes in both cases, the differences in results for potatoes were not as significant. However, the result for approved hours showed 9.86 for 10° slope and 9.95 for 45°, these values are higher than the required approved hours which is maximum of 8. Consequently, it leads to a little stress for potato and increasing the need of irrigation.

7 CONCLUSIONS

This study examines the coexistence of solar panel installation and agriculture, specifically focusing on the impact of shading on lettuce and potato crops.

The results of this study demonstrate that potatoes can be successfully cultivated under all scenarios of solar panel installation on farmland. The optimal conditions for potato growth are found in scenario 3, where the row distance between PV modules is 2 meters. This finding highlights the potential for coexistence between solar energy production and potato cultivation, providing an opportunity for sustainable agriculture and renewable energy generation. However, in terms of lettuce cultivation, the study reveals that the only viable option is conventional agriculture in Lund, without the presence of solar panels. Lettuce, being a high-intensity solar crop, requires ample sun hours with high solar intensity, making it less adaptable to shading conditions caused by solar panels.

These findings emphasize the need to consider crop-specific requirements when implementing solar panel systems on farmland. By recognizing the varying tolerances of different crops to shading. This study contributes valuable insights that can guide future initiatives in sustainable agriculture and renewable energy integration.

8 SUGGESTIONS FOR FURTHER WORK

Based on the findings, which indicated the high potential for potato growth under PV modules while highlighting challenges affecting lettuce growth, there are several suggestions for future studies in this field.

Explore crops with high shading tolerance: Conduct further research using crops known for their resilience to shading, such as onions. Investigate their growth performance and productivity when cultivated under PV modules. This will provide valuable insights into the viability of other shade-tolerant crops for AV systems.

Assess electricity production profitability: In addition to examining crop growth, it is recommended to calculate the electricity production potential for all scenarios investigated in this study. This analysis will enable an evaluation of the economic feasibility and profitability of the PV installation. Understanding the financial aspects of AV systems can help inform decision-making processes for farmers and potential investors.

By pursuing these directions, future studies can enhance our understanding of crop suitability under PV modules and shed light on the economic viability of AV installations.

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