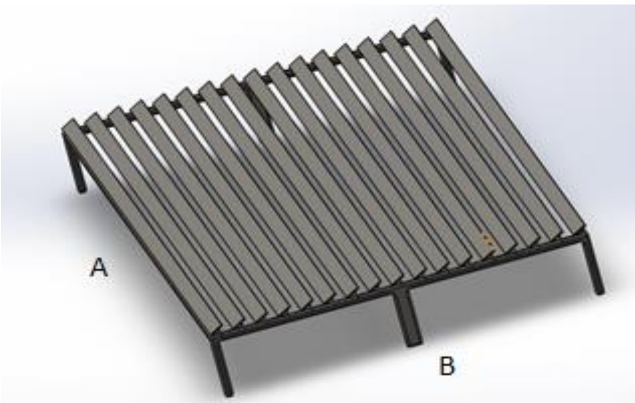
Technologic, Biological and Economic analysis of a dynamic agrivoltaic system in the Dutch agriculture sector



Abstract

Agrivoltaic systems combine agricultural land and the generation of photovoltaic energy. Currently only static agrivoltaic systems are investigated. However, these static systems offer less freedom for farmers to carry out their daily working activities. This research looks at a dynamic agrivoltaic system which moves across the crop plot. The movement of this system is modelled in 3D software on 50x100m field. The 3D-modelling software provides the possibility to simulate the insolation for photosynthesis for 5 different PV-scenarios. The PV-scenarios vary in size from 10% of the plot to 50% which results in an annual average decrease in insolation in the range of 6.81% – 31.1 % respectively. Potato, Sugar Beet and Wheat have been selected because these are widely cultivated in the Netherlands. Additionally, lettuce is added for comparison to static systems because existing agrivoltaic literature primarily included this crop. The accompanied yield of these 4 crops are addressed by the RUE method and qualitatively by incorporating other research which included the combination of shading scenarios and crop yield. In all cases, it seems that the RUE method results in the lowest crop revenues. The more qualitative approach seemed more in line with the actual crop yield and the literature. Lettuce proved to be the most shade tolerant of the crops. However, in nearly all cases the crops are little affected by the PV-scenarios. This ensured that the combination of electricity and crop revenues resulted in a higher Land Equivalent Ratio (1.1 – 1.6) and positive NPVs . Future research should focus on 3D-simulation software which combines movement and insolation. Furthermore, the crop yield under a dynamic system should also be further investigated to increase the reliability data for the Netherlands. Nevertheless, the results suggest that a dynamic agrivoltaic system can enhance land efficiency, increase revenues of both electricity and crops while the farmer can carry out its daily activities. With an increasing pressure on fertile land and relatively high revenues from photovoltaic energy, dynamic agrivoltaics can offer a viable solution.

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Content

1 Introduction

A consensus has emerged that the depletion of fossil fuels must be reduced and the production of renewable energy should be stimulated (Dupraz et al., 2011; Escobar et al., 2009; González, Riba, Puig, & Navarro, 2015). This is a consequence of the nowadays broadly accepted hazards resulting from climate change. These hazards are for a big part the result of the conversion of fossil fuels to energy, which leads to large amounts of greenhouse gas emissions. That is the main reason why the implementation and stimulation of renewable energy has reached one of the top priorities of governments. However, multiple countries among which the Netherlands, face tremendous difficulties to reach the required renewable energy share targets (ECN, 2017; Eurostat, 2014; Szendrei et al., 2016). By 2016 the share of renewable energy was estimated around 6% while the target is currently set at 14% by 2020 (ECN, 2017). Therefore, the Netherlands need to rapidly increase the share of renewable energy by 8% of the total energy consumption (ECN, 2017; Eurostat, 2014). By 2016 around 1.5GWp of solar energy was installed in the Netherlands while the target in the National Solar Power Action Plan is estimated at 4GWp before 2020 (Szendrei et al., 2016). This emphasizes the pressure for the growth of Dutch solar energy capacity.

One of the major difficulties that the Netherlands is facing is that the available land for large-scale solar establishments seems to be scarce (Szendrei et al., 2016). In 2015 around 70% of the solar energy is generated by households in rural areas (Szendrei et al., 2016). However, the possibility to implement photovoltaic panels on land designated for agriculture is often completely neglected. This is in contrast with research on the concept of solar sharing and agrivoltaic systems (Bomers & Russchen, 2016; Dupraz et al., 2011). An agrivoltaic system is the combination of PV-panels placed above agricultural land. These agrivoltaic systems offer the opportunity to grow crops and also generate solar power and thus increasing the amount of land on which photovoltaic (PV) can be implemented (Dinesh & Pearce, 2016). Although it is stated that much of the capacity can be reached by aggressively building PV on rooftops, this is often much more difficult because of the dense urban environment (Dinesh & Pearce, 2016).

According to Dinesh & Pearce (2016), agrivoltaic systems often bring multiple benefits for the growth of crops while also generating solar power. Some examples mentioned by Dinesh & Pearce (2016) are; lower evapotranspiration, (nearly) equal annual crop yield and a higher soil moisture content. The implementation of PV panels on agricultural land results in less solar radiation available for photosynthesis. However, there seems to be a point of discussion about the effects of shading on crop yield. Firstly, Marrou et al. (2013) estimated that the annual lettuce yield under a low-density PV-system can be nearly equal to lettuce that is growing in full sun conditions for these researched species. This is mainly due to the increase in the light harvesting capacity of the lettuce. A different study estimated a decrease in yield in the range of 19% – 41% for a half and full PV panel density respectively (Dinesh & Pearce, 2016). The difference in crop yield can be explained by the different crop species, the amount of shading that is used, the type of configuration and the climatological differences in the two experiments. To be able to assess whether agrivoltaic systems are viable in the Netherlands more in-depth research is necessary.

In 2016 around 54% of the total Dutch land is designated for agricultural purposes[1]. The formation of this large area is highly influenced by the 'inpoldering' concept. This means that the areas are often nearly perfect rectangles. One reason for this is that on both sides a runoff canal is situated which ensures high

[1] https://www.cbs.nl/nl-nl/nieuws/2016/08/minder-landbouw-meer-natuur

ground water levels which benefit crop growth. Moreover, the rectangle shape means the farmers can work in straight lines with machinery which increases the farming efficiency.

Moreover, different studies suggest that the profits from a hectare PV-power is higher than the revenues resulting from crop yield (Spruijt, 2015; [2]; [3]). It seems therefore tempting for farmers to change their core business model from crop cultivation to energy generation. Consequently, farmers find themselves in a difficult position regarding maximizing profits with the production of energy or keeping their core agricultural business. Furthermore, social acceptance of large solar farms is often relatively low as surrounding habitants often agree with the 'Not In My BackYard' principle. One important argument is that they rather have an obstructed view of nature than solar panels. 'LTO Nederland', one of the most important unions for the Dutch agricultural sector, is not happy with the transition from agriculture towards solar power as this leads to a decrease of fertile land ([3]). Both these arguments can be refuted with the implementation of an agrivoltaic system.

Other research merely addresses static systems (Dinesh & Pearce, 2016; Dupraz et al., 2011; Marrou, Wery, Dufour, & Dupraz, 2013). These static systems divide a certain amount of PV-panels above the crops. In this research the necessary amount of sunlight that is needed for photosynthesis is ensured by moving the PV-panels across the land and thus dividing the shade across the crops and field. The size of the PV-area and thus the amount of shade and sunlight is therefore an important parameter. For a larger size there is less direct sunlight available for the crops to carry out photosynthesis. Consequently, there should be an optimum of the number of PV modules and the highest crop yield. This balance differs per crop and this research therefore incorporates an optimization study for different PV-areas and different crops. Moreover, because this system moves across the land, it can provide numerous extra benefits for farmers; data-gathering of the crops, precise fertilization, precise efficient irrigation, less evapotranspiration and of course higher profits resulting from the energy generation while still remain to be a farmer.

The aim of this research is to look into the techno-economic performance of a dynamic agrivoltaic system designs. Agrivoltaic systems are a relatively new topic and further research is necessary to improve efficiencies as current static systems create impracticalities for farmers. This research might reduce this impracticalities by introducing a dynamic agrivoltaic system. By moving the panels across the field, the shade will be equally distributed across the crops and therefore allow enough irradiation to reach the crops for photosynthesis. It is essential to identify certain shade tolerant Dutch crops which are cultivated on large outdoor areas. Because the identified crops are differently tolerant to shade, it is important to find the optimal size of the PV-area. This ensures the highest yield and the maximum electricity generation for each crop. Moreover, because the system is constantly moving and is unique in its kind, it is a complex process to find the precise amount of available photosynthetic radiation. An important aim of this study is to identify this amount. Furthermore, because the use of rails are less interfering for farmers than static poles are across the whole field, it might improve the attractiveness of such a system. However, due to this dynamic system it is likely that there are extra costs and different shading effects present. To see if this solution is viable both from a technological and an economic perspective, multiple research questions have been formulated:

[2] https://www.oneworld.nl/duurzaamheid/oogsten-boeren-binnenkort-de-zon-plaats-van-aardappelen/

[3] https://vroegevogels.bnnvara.nl/nieuws/zonneparken-run-op-landbouwgrond

1. What is the effect of a dynamic agrivoltaic system on annual available insolation for photosynthesis?
   - How do the PV-scenarios influence annual insolation?
   - What are the technological requirements/barriers for such a system?
2. What are the effects on yield due shade, on important shade resistant Dutch crop yield?
   - What are the important Dutch shade resistant crops?
   - What are the yields under different number of shading scenarios per identified crop?
3. How economically attractive is this solution?
   - What are the extra costs of the agrivoltaic system?
   - How much revenue is generated by the crop yield and electricity generation?
   - What are the LCOE & NPV?
   - How attractive is it towards BAU, and maximum PV (LER)?
   - How attractive is it compared to current static systems?

2 Background

2.1 Solar Sharing & Agrivoltaic in general

The literature concerning the concept of Solar sharing dates back to 1982. Goetzberger & Zastrow (1982) are the first who investigated the possibility of the combination of solar energy and crop cultivation. They have calculated the amount of shading and sunlight which is received by both the PV-panels and the crops by mounting these static PV-panels 2 meters above the ground and several meters apart. This ensures that enough sunlight reaches the ground for the crops to carry out photosynthesis (Goetzberger & Zastrow, 1982). Later on, the concept of Solar Sharing is further investigated and it receives the name of an agrivoltaic system. This name addresses more precisely that the solar energy is converted due to PhotoVoltaic panels (PV). Below are two examples given of currently investigated agrivoltaic systems (figure 1 & 2). These systems contain both positive and negative side effects. System 1 has larger PV-panel surface, however the size of agricultural land decreases because farming underneath the panels is not possible. System 2 has a larger area of agricultural land, but the size of the panels are smaller.

Figure 1: Agrivoltaic system in which the PV-panels are mounted on the ground. The space in between the panels ensures the possibility for daily activities of farmers (Dinesh & Pearce, 2016).

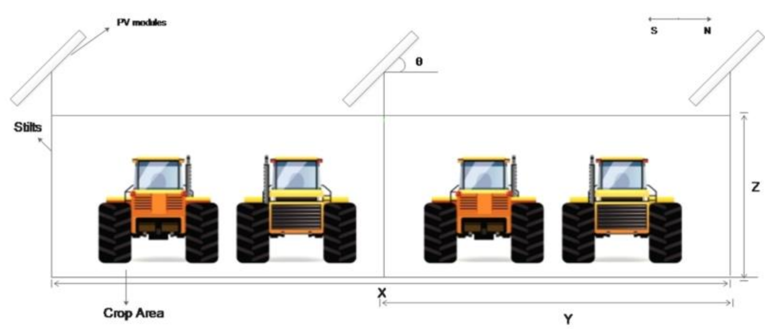


Figure 2: Agrivoltaic system where the PV-panels are mounted 4m above the ground. Daily farming activities can be carried out underneath the panels (Dinesh & Pearce, 2016).

Another important disadvantage of these systems is that numerous vertical poles are mounted on the field. Not only is this expensive, it also reduces the flexibility of the farmers to carry out their daily activities. A rail system as suggested in figure 3 where machinery can move more freely would increase the flexibility and keeps a larger area free for crop cultivation. Next to the disadvantages, different research has found multiple benefits regarding other agrivoltaic systems in; less soil water evaporation, increased leaf area index, increased radiation interception efficiency (RIE), increased land value, increased annual profits (Dinesh & Pearce, 2016; Marrou, Dufour, & Wery, 2013; Marrou, Guilioni, Dufour, Dupraz, & Wery, 2013).

Figure 3: Schematic overview of the agrivoltaic system on a rails. On the bottom of the image are rotary electric engines that move the PV-panels on the rails. Parallel to the small (vertical) trenches are the rails anchored on the ground. The PV-panels are mounted on the rails at a height of 4m (not yet clearly visible). This diminishes the interference with the daily activities of the farmers. (own work)

2.2 Biological current research

Current research regarding agrivoltaics has focused primarily on the cultivation of lettuce. Lettuce is a shade resistant crop and can easily increase the leaf index area to maximize photosynthesis under increased shade conditions. Most recent research showed that land efficiency and profit per square meter, both increased for lettuce in combination with agrivoltaic systems. In the Netherlands, 2120ha is designated for lettuce cultivation, which is more than 7% of the outdoor vegetable horticulture sector (CBS, 2017). In 2013, Marrou et al (2013) carried out a practical experiment with outdoor agrivoltaic systems and different kind of lettuces. In this experiment, three different scenarios have been examined (see figure 4). One reference scenario with full sunny conditions and two conditions with agrivoltaic systems. In both systems the PV-panels are mounted 4m above the ground, separated by 1.6m in the 'full density' (FD) scenario and 3.2m in the 'half density' (HD) scenario. In the first year the results of this study suggests that for the half density scenario, the yield was close to 81% of the control yield. However, the full density scenario clearly shows a large decrease in dry matter yield, 58% of the control yield. However, the next year the yields reductions were decreased. The half density scenario resulted in 99% yield, while the full density scenario showed 79% yield compared to the control yield. Moreover, this showed that the biomass yield reduction is far less than the reduction of available light. This means that this kind of lettuce crops increases its Radiation Use Efficiency (RUE) and can therefore be seen as a shade tolerant crop. Marrou et al (2013) also mentioned that in some cases the biomass even increased in the half density scenario regarding the reference scenario (Marrou, Wery, et al., 2013). Extensive research already has been done regarding the combination of shade and glasshouses (Aroca-Delgado, Pérez-Alonso, Callejón-Ferre, & Velázquez-Martí, 2018). However, because shade of PV-panels on glasshouses are likely to have a different effect on crops than outdoor agrivoltaic systems these results are probably merely indicators regarding this research.

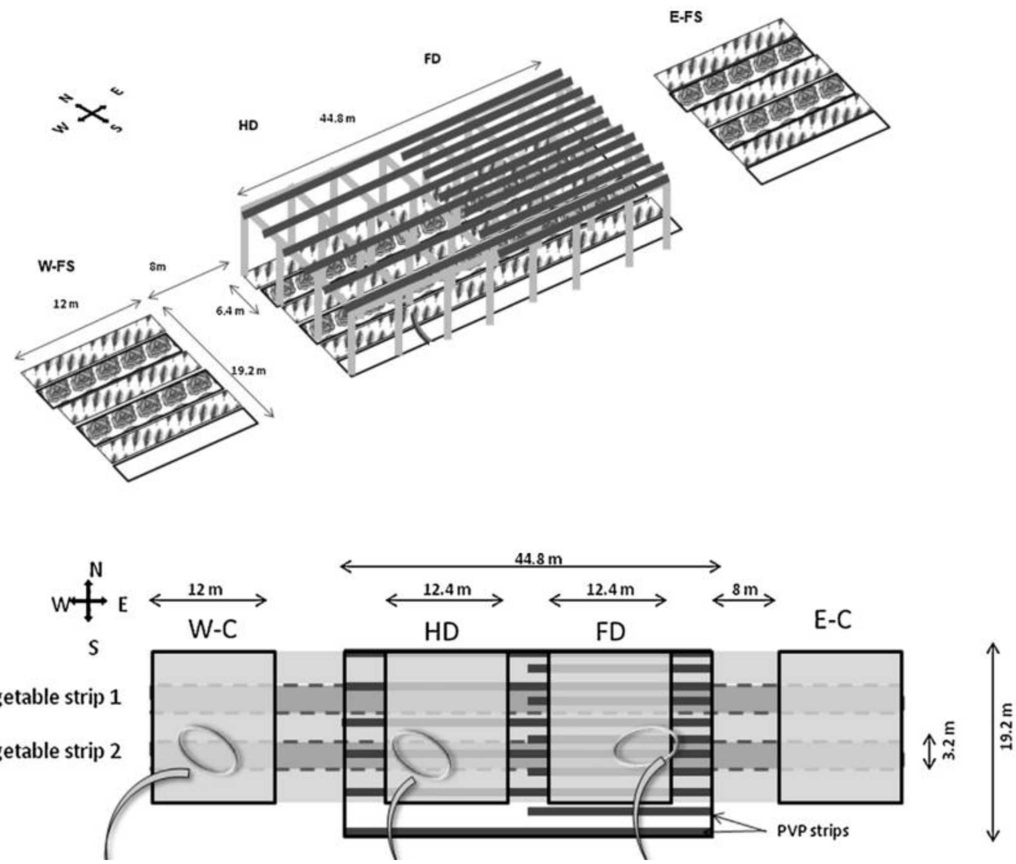


Figure 4: Schematic overview of the PV-panel array and the crop cultivation experiment. The vegetable strips are for cucumber and lettuce. The densities of the PV-panels are indicated by half density (HD) and full density (FD). (Marrou, Guilioni, et al., 2013; Marrou, Wery, et al., 2013)

2.3 Technological current research

Figure 5 depicts another (similar to previous agrivoltaic system mentioned) pilot project which is established near Lake Constanze (Germany). The project is managed by BayWa r.e. As can be seen in the figure numerous vertical poles are needed to support the construction. This decreases the flexibility and thus the efficiency of a farmer because farmers often work with large machines for fertilization, harvesting, seeding and irrigation. This is especially the case for systems with the poles in the centre of the field. If this flexibility could be increased by a rail system which is only implemented at the most outer points of the agricultural land on which the PV-panels are mounted. This could mean that the rail systems can be more attractive than static structures. This research will focus on this lack of knowledge about such a moving system.

Figure 5: An example of the previous mentioned static agrivoltaic system at a height of 5m (The Vallourec Industry Magazine, 2016)

2.4 Economic current research

Dinesh & Pearce (2016) approached the experimental agrivoltaic system of Marrou et al (2013) in a more economical way. This research showed the clear trade-off between the reduction in yield the accompanied loss in profits and the increase in revenue from selling photovoltaic electricity. In the full sun reference scenario, the revenue per hectare is estimated around 209.000$/Ha annually. For the ground mounted scenario (depicted in figure 1) the revenue from crops per hectare was estimated at 133.000$/Ha annually. However, with the generation of electricity the revenue per hectare is in total 207.612$/Ha annually which is close to the reference scenario. For the half density scenario, the crop revenue per hectare is estimated at 182.645$/Ha annually. Adding the annual electricity revenue per hectare which is estimated at 44.071$/Ha, sums up to a total of 226.716$/Ha*yr^{-1}. This is around 15.000$/Ha*yr^{-1} more than the reference scenario. In the full density is becomes visible that the revenues from crops has reduced significantly to: 136.900$/Ha*yr^{-1}. Which is around 50.000$/Ha*yr^{-1} less than the half density scenario. However, the electricity production is estimated at 135.238$/Ha*yr^{-1}. Therefore, the total annual revenues in the full density scenario is estimated at 272.138$/Ha*yr^{-1}. This is nearly 65.000$/Ha*yr^{-1} more than the reference scenario (Dinesh & Pearce, 2016). This shows the important trade-off between the number of crops that can be grown under certain shading conditions and the amount of electricity that can be generated. This research will focus on finding the optimum trade-off point for different crops.

3 Methodology

The research is divided into 3 different parts; *Technological (1), Biological (2) and Economic (3).* Because 4 crops are assessed which can contain different optimal amounts of shade, 4 different case studies are created. For each case study the three different research parts have been carried out. When these three different parts have been answered a complete analysis has been carried out for a new dynamic type of agrivoltaic system in the Netherlands. A complete schematic overview of the methodology is given in Figure 6. Table 1 depicts the characteristics of the three different analyses.

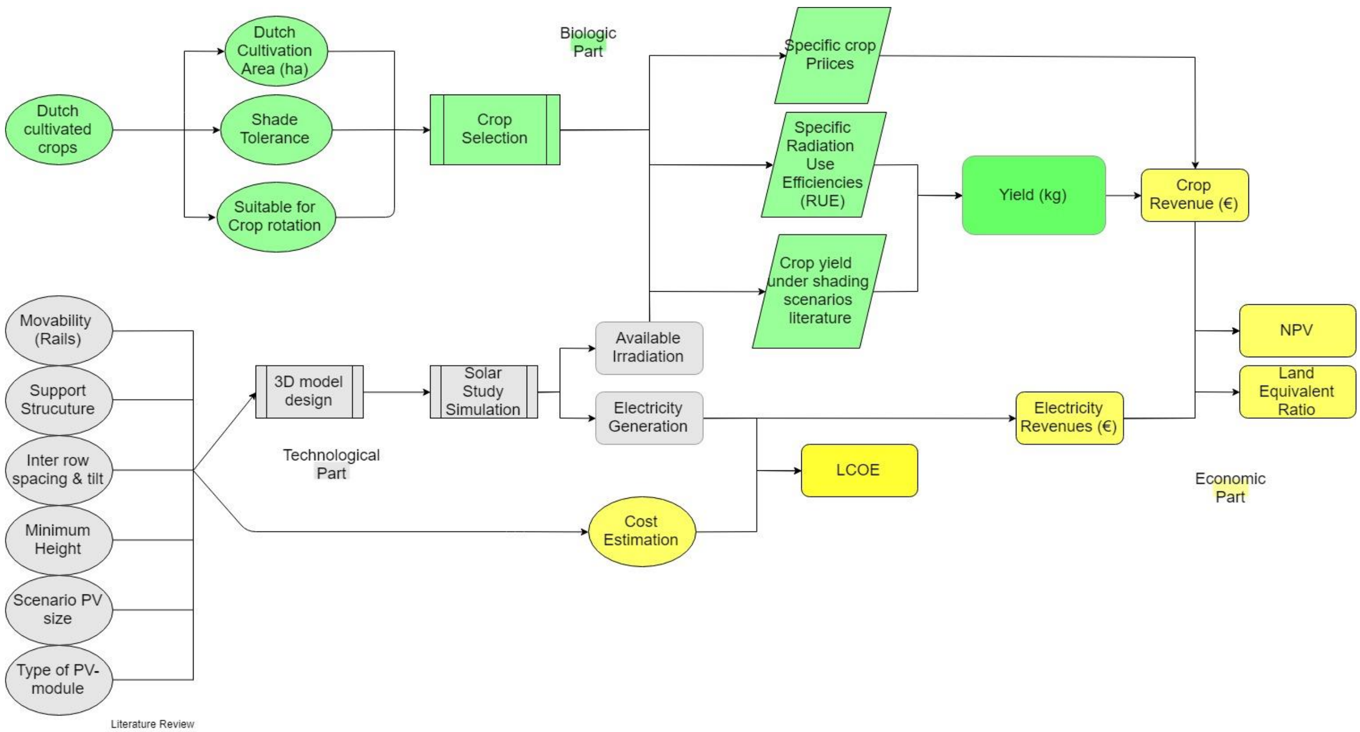


Figure 6: Schematic overview of the methodology. The 3 different analysis are shown in table 1

Technologic Analysis	Biological/Crop Analysis	Economic Analysis
Truss design • Plot dimension • Type of truss • Strength • Size/dimensions • Rails	Identification of important crops • Amount of hectares • Amount of revenues • Shade tolerance	Identification of Costs • Fixed annual farming costs • Trusses • Electrical engines • PV-panels • Maintenance
Photovoltaic panel design • Capacity (Wp) • Transparency • Layout • Angle/tilt • Interspacing	Yield (kg/ha) per crop • Reference case • Static agrivoltaic system	Revenues • Crop revenues from shading scenarios • 'salderen' from PV scenarios • Subsidies
3D model & simulation • Solar Study • Dynamic movement • Irradiation conversion to PAR	Radiation Use Efficiency (kg/Mj_{PAR}) • % of land covered with PV: ○ 0 ○ 10 ○ 20 ○ 30 ○ 40 ○ 50	Analysis: • Net Present Value • Levelized Costs Of Electricity
Electrical Rotating Engines • Power/Capacity	Sowing/Harvesting date	Integration/comparison • LER • Static AV • Between crops • Between PV scenarios

Table 1: Overview of the characteristics of the different research parts. All parts are explained individually below.

3.1 Technological methodology

To be able to answer the research question; *"What is the effect of a dynamic agrivoltaic system on annual available insolation for photosynthesis? ",* multiple aspects need to be addressed. Firstly, a 3D-model needs to be created to simulated insolation. Furthermore, the system design needs to be strong enough to carry the PV-panels while also being light enough to be moved across the land. Therefore, different designs have been explored. Requirements are defined that need to be met in order to see if this dynamic system is viable. These criteria and the approach are described below.

3.1.1 3D model

Firstly the dimensions of the crop plot need to be established in order to be able to design the agrivoltaic system. This is done by creating a fictional plot of 50 x 100m. This plot is used for to simulate the insolation for the 4 different selected crops which will be further explained in the Biological part. The chosen plot is used to simulate the available insolation under the solar panels which is used for the crops to carry out photosynthesis. In order to simulate this a 3D model is created. However, the desired agrivoltaic system is dynamic instead of static. Therefore, some extra steps are carried out to find the most precise amount of light and shade for certain scenarios (0 - 50% PV-panel area). To find these values a model is built in 3D modelling software called Sketchup™ and Autodesk™ Revit™. An example model of a frame with PV-panels on top is given in Figure 7.

The panels are separated and tilted according to the optimum angle specific for the Netherlands to obtain the maximum photovoltaic efficiency ([4]). The orientation of the panels is determined to be West-East so that the panels are facing South with inter row spacing. A different layout is less satisfactory as there would be less light available below the crops for photosynthesis. The length (B) depends on the chosen scenario. The width of the system (A) is defined by the size of a specific crop plot as is explained above. Although this is a static system, it is possible with Autodesk™ Solar Analysis™ to conduct solar irradiation analysis for specific locations based on longitude, latitude, date and time. Moreover, to increase accuracy data from a weather station is incorporated. On the ground level below the PV-panels a grid will be inserted on which the amount of irradiation can be measured accordingly for each grid cell.

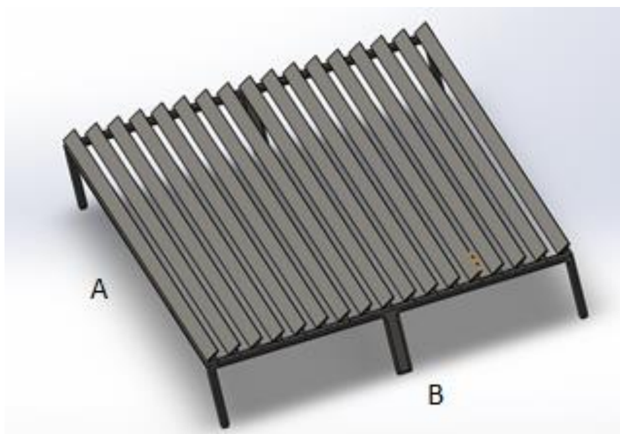


Figure 7: Example model built in Google Sketchup. Length A is defined by the average width of the crop plot. Length B is dependent on the chosen PV scenario. The orientation of the panels is chosen to be east-west with optimal inter-row spacing and tilt angle. (Own work, 2018)

3.1.2 Solar Study

The Solar Analysis™ function from Autodesk Revit™ provides the possibility to simulate the solar irradiance per 15-minutes for a specific day. To simulate the panels moving across the field, it is possible to move the panels by hand every 15 minutes. Finally, the solar irradiance for each 15-minute timestep is summed over a whole day in Microsoft™ Excel™. Because the work needs to be done manually it is almost impossible to simulate every sing day. In order to save time is chosen to simulate the 2 solstices and 2 equinoxes for 2017; March 20, July 21, September 22 and December 21. These dates are the extremes of every season and therefore they show what the influence is of the PV-panels on the amount of shade that is originating below the panels.

When the energy data for the specific dates are known, the whole year can be calculated due to interpolation of the available energy between the solstices/equinoxes. This ensures an accurate estimation of the energy of the whole cultivation period of a certain crop. Furthermore, the solar study from Autodesk™ Revit™ automatically incorporates weather data for the specific date and location. The solar study gathers the data from adjacent weather stations. However, after simulation of these specific

[4] https://www.civicsolar.com/support/installer/articles/determining-module-inter-row-spacing

solstices dates it became clear that the energy values differ significantly from the average insolation measured by the KNMI (2017). Therefore, the simulation used the same dates but in the year 2000. These insolation values are approximately equal to the average measured values (KNMI, n.d.) and are therefore a more accurate representation of insolation than the ones of 2017.

The next figure (Figure 8) shows an example of such a solar study. The yellow rectangle is a field with the dimensions of 50m x 100m. On the field is a grid inserted which measures the incoming insolation density in kWh/m^2. As the field is 5000m^2 the kWh is determined by multiplying the density times the total area. This is done for the 5 PV-panel scenarios which are depicted in Table 2.

Table 2: PV scenarios, PV-panel area and amount of PV for each scenario

PV scenario	Length (m)	Width (m)	PV Area (m^2)	#Panels
1	10	50	318.7	200
2	20	50	557.8	350
3	30	50	796.8	500
4	40	50	1115.5	700
5	50	50	1354.6	850

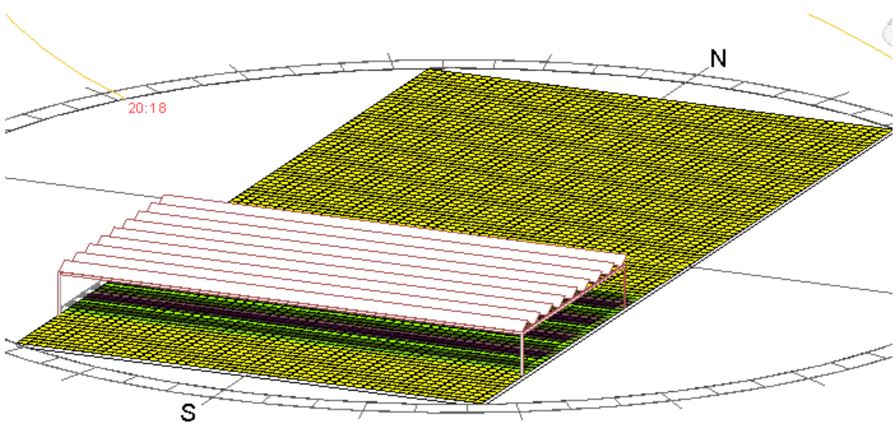


Figure 8: Solar study containing the coordinates of Amsterdam. Beneath the PV-panels is a grid inserted to measure the irradiation more precisely. For example is a random study carried out for which the shadows are simulated beneath the PV-panels. Made in Autodesk™ Revit™ Student version and Google Sketchup™ (Own work, 2018).

3.1.3 PV-panel type

Different types of solar panels can be used in this simulation. Regular solar parks uses poly- or monocrystalline panels. These panels are mostly monofacial instead of bifacial due to the lower manufacturing costs. However, bifacial panels uses both sides of the panel to generate electricity. Both sides of these panels can therefore be covered in glass. When the ground underneath the panels contains a high albedo factor more energy is generated by bifacial panels than monofacial panels. Moreover, because both sides are covered in glass, more light is coming through the panel and thus decreasing the amount of shade. However, the performance of the bifacial panels is highly influenced by the albedo factor below the panels and the installation height. For agricultural practicalities, the panels installed 5m above the ground. This ensures that the bifacial panels are an interesting aspect to take into account. In this research standard monofacial and bifacial 300wp panels are used. As thin film panels are not (yet) a big part of the world market share and due to its lower power capacity, these are not considered.

As bifacial panels are still a relatively new type of PV-panels it is difficult to estimate the bifacial gain without actual site specific measurements. This is due to the fact that the gain is largely dependent on the location specific ground reflectivity (albedo factor) and PV-panel height. In this case the reflectivity is estimated at ±23%, which is the estimated value for grass (SolarWorld, 2015). Figure 5 shows an example of bifacial panels in Konstanz, Germany. Research by Wang et al (2015) simulated the bifacial gain for different heights and albedo factors in Konstanz. This research showed that the bifacial gain for an albedo of 20% and a height of 2m is estimated at 10.4%. Moreover, this research showed that the height saturation point is found around 2.5meters. Meaning that every higher installation height will not lead to a higher amount of additional gain. Combining these factors and making the assumption that the meteorological factors influence bifacial gain leads to an estimated bifacial gain of 11%. As the height in this case is estimated at 5 instead of 2.5 meters and the albedo 23% instead of 20% (Wang et al., 2015).

3.1.4 Support Structure

A simple method of covering a load across a large distance is with the help of trusses. A practical example of a truss are certain bridges. The trusses need to be able to carry the weight of the PV-panels across the width of the field like in Figure 5 except without the centre pole. This way the field is completely open for agricultural purposes. Trusses are chosen because of their strength compared to the low weight. Nevertheless, there are a lot of different types of truss designs. Therefore, different type of trusses have been examined in order to find the most suitable one in an extensive literature study and interviews with truss manufacturers. By gathering the specifications of certain trusses from manufacturers, the desired strength can be found. To find the desired strength it must be noted that wind on the PV-panels can cause extra load on the design. This should be considered when calculating the maximum weight on the truss. See Figure 9 to get an idea of the different types of trusses that are available.

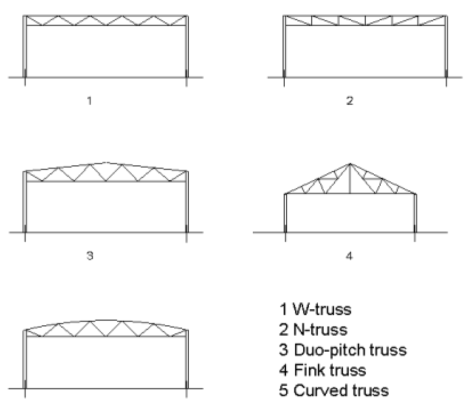


Figure 9: Different type of trusses for carrying weight over a certain distance.([5])

Moreover, the specifications from manufactures specify the maximum load for trusses in different ways. The type of weight distribution over the length of the truss determines the maximum load per meter. In this case the PV panels will be equally distributed across the length of the truss. Therefore, the specific

[5] https://www.steelconstruction.info/Single_storey_industrial_buildings

values for equal weight distribution have been considered to find the maximum load per meter for certain trusses.

This becomes even larger when wind is blowing against a tilted panel as shown in Figure 10. This extra load should therefore be taken into account when calculating the minimum strength of the support. The surface of a solar panel is exposed to two kinds of forces resulting from wind; drag (F_D) and lift (F_L). Drag forces are in parallel to the movement direction of the wind, while lift forces are perpendicular to the drag forces. The drag and lift forces are components of the initial wind force F on the panel. To calculate the force of the wind on the system the following formula has been used (Scaletchi, Visa, & Velicu, 2010):

$$F_{wind} = 0.5 * C_p * A_{ref} * \rho * v^2$$

Where:
Cp = pressure coefficient
A_{ref} = reference area in the direction of the wind
ρ = air density
v = wind velocity

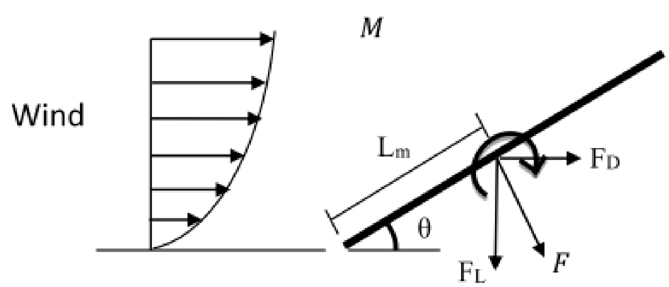


Figure 10: Schematic overview of drag and lift forces resulting from wind on solar panel surface (Samani, 2016).

A_{ref} is the reference area regarding drag or lift force. The v^2 stands for the wind velocity and ρ is the air density which is commonly taken as 1.25 kg/m^3). The surface pressure on an object is expressed with the dimensionless pressure coefficient C_p. The pressure coefficient differs per shape and for solar panels is

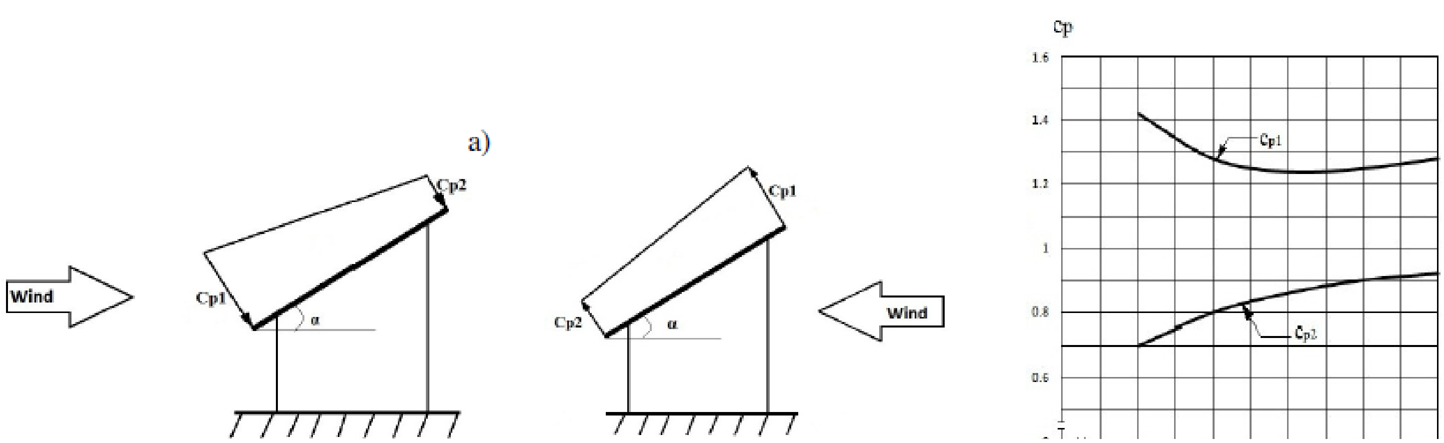


Figure 11: Pressure coefficients for inclined flat surfaces (Scaletchi et al., 2010)

found by other research in multiple wind tests, see Figure 11 (Scaletchi et al., 2010). Assuming the optimal tilt for solar panels in The Netherlands is estimated around 35° ([6]), this would give a C_p around 1.06. Nevertheless, this force is perpendicular to the surface area of the PV-panel. Therefore, the drag and lift forces are components of this coefficients and their respective areas.

3.1.5 Rails

The second requirement for this system is that the panels can be moved across the field to ensure enough sunlight for the crops underneath the panels. When a truss design has been found which is strong enough to carry all the panels and withstand wind forces, the trusses are mounted on vertical poles on a rails. The number of panels and thus the number of poles that are used depends on the scenario. Other research merely looked at a static system for which numerous poles in the centre are needed to carry the weight of the PV-panels. This research looks at the possibilities of a movable system on a heavy duty rails. It is important to note that the PV-panels are mounted 5m from the ground up so that farmers can keep working underneath the panels. It is, therefore, possible that due to windy conditions, the system can experience uplifting forces and thus be detached from the rails. Consequently, one important requirement is that the system cannot be detached from the rails for safety issues.

Therefore, a rail system needs to be designed to ensure safety for the system and its surroundings. An examples of such a rail is given in Figure 12. Data gathering for this specific aspect will be focused on expert interviews with rail manufacturers. Moreover, extensive literature review will be carried out to find similar applications of longitudinal (heavy duty) rails to find more possibilities. Furthermore, because the rail is anchored in the ground, it is very subjective to sand and dirt. It needs to become clear from the expert interviews, how the rails can be easily kept dirt free and therefore durable and sustainable.

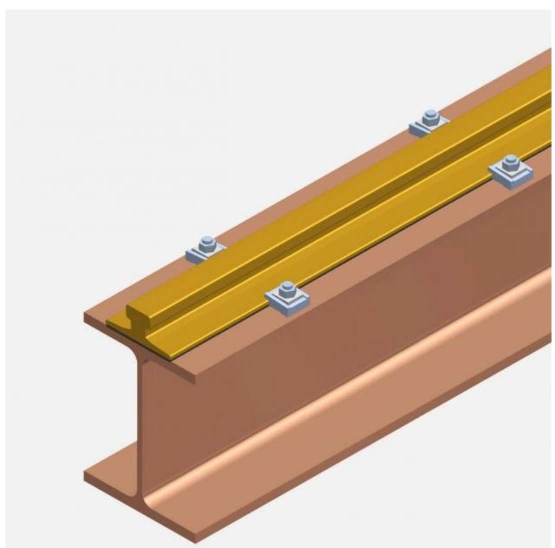


Figure 12: Example of a heavy duty rails. The HEA beam is anchored in the ground to ensure safety for the system. [7]

[6] https://www.zonnepanelen.net/zonnepanelen-plat-dak/

[7] Retrieved from: https://www.bemorail.nl/portfolio-item/staal/

3.1.6 Electrical engines

Furthermore, it needs to be addressed how the panels are going to be moved across the field. As the system is mounted on a chosen rail design, it should be possible to push or pull the system along the rails. This can be done by installing electrical engines at the end of the rails. These engines need to turn, i.e. pulling/pushing via cables attached to the lowest part of the vertical poles right above or next to the rails. Therefore, trucks can still ride over the rails and cables and thus decreasing interference with daily farming activities. Moreover, cable management needs to be further researched in the future to deal with the electrical cables from the PV-panels. This is an important factor as the PV-panels changes the distance to the grid connection hub. Information about the costs and technical requirements about electrical engines will be gathered by interviews with manufacturers. Below you will find a schematic overview of such an engine:

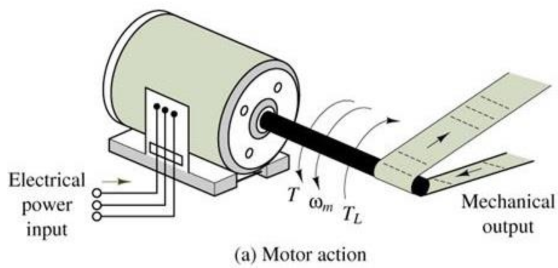


Figure 13: Schematic picture of an electrical engine ([8])

3.2 Biological

Firstly, 4 different crops have been selected: *Lettuce, Sugar Beet, Potato, Wheat.* These crops are then used in case studies with 5 PV-panel area scenarios. Each crop uses light in a certain efficient way. With the Radiation Use Efficiency determined for each crop it is possible to calculate the effects of shade on the yield.

3.2.1 Crop selection

The method concerning the effects of shade on yield. Firstly certain crops have been selected for further analysis. These are crops that are largely cultivated on outdoor soil in the Netherlands. This research does not incorporate crops that are cultivated in glasshouses because. Four crops have been selected for further analysis. The selection of these crops is done through literature review on shade resistant crops as different research has already identified these (Beed, Paveley, & Sylvester-Bradley, 2007; Marrou, Dufour, et al., 2013; Richter, Jaggard, & Mitchell, 2001; Savin & Slafer, 1991). Although this research is not specific for the Netherlands, they incorporate crops which are suitable for agrivoltaic purposes. Several crops are identified, and a selection is made based on the number of hectares of cultivation in the Dutch agricultural sector. This data will be retrieved from the “Centraal Bureau Statistiek”. The selection on the amount of hectares is done to maximize the impact of this new system. It would be illogical to choose a crop that occurs rather rarely with a very low number of cultivated land. By choosing the crops which are widely cultivated, the contribution of renewable energy can be maximized.

There is one exception with regard to the crop selection. Lettuce is included in this research regardless the cultivation size in the Netherlands. This is done because the existing research regarding agrivoltaic systems

[8] https://shannew.files.wordpress.com/2011/04/mot-and-gen.jpg

mostly include the cultivation of lettuce. Therefore, to be able to compare this research with the most important and most recent existing research it is necessary to include the cultivation of lettuce in this research too. The other identified crops are: *sugar beet, winter wheat and potato* (see next chapter: Data). Additionally, one important factor for famers is crop rotation. This ensures a healthy soil and thus increases crop growth. As this research looks at the viability of an agrivoltaic system over several years it is important to see if these identified crops are suitable for crop rotation. Dijk & Geel (2012) shows that a traditional crop rotation system combines wheat, potato and sugar beet (Dijk & Geel, 2012; Interprovinciaal Proefcenttrum voor de Biologische Teelt, 2005). These crops are therefore considered suitable for this agrivoltaic system.

3.2.2 Shade and crop yield

The panels above the field ensure a decrease of available light that is needed for photosynthesis. By moving the panels across the field during the day the light and shade is divided across the whole field. Through thorough literature research it is estimated what the annual yield will be under certain light-stress scenarios (e.g. PV-panel area). Different research determines a parameter called Radiation Use Efficiency (RUE) to theorize the linear link between radiation and biomass accumulation (Bomers & Russchen, 2016; Campillo, Fortes, & Henar Prieto, 2012; Marrou, Guilioni, et al., 2013). This parameter is crop dependent and is calculated as the ratio between dry matter yield (kg/m^2) and the intercepted Photosynthetically Active Radiation (MJ) (Campillo et al., 2012). This parameter is widely applied to express the growth rate efficiencies of different horticultural crops and is usually expressed as g/MJ (Campillo et al., 2012; Monteith & Moss, 1977). The specific RUE values for the chosen crops have been found by extensive literature research.

Furthermore, crops do not use the entire radiation spectrum for photosynthesis but only a small part: 400 – 700nm. This range is called the Photosynthetic Active Radiation (PAR). PAR is measured only rarely by meteorological stations, in contrast to the complete solar irradiation spectrum (Pashiardis, Sa, & Pelengaris, 2017). As the amount of incident solar radiation changes due to the implementation of the PV panels above the field, the PAR value will change accordingly. It is therefore important to calculate the amount of PAR for the different PV-panel area scenarios. There are multiple studies that assess the PAR fraction (*f*PAR) with regard to the broadband solar spectrum in the range of 40% to 50% (Campillo et al., 2012; Ge, Smith, Jacovides, Kramer, & Carruthers, 2011; Pashiardis et al., 2017). With this fraction it is possible to use certain models to estimate the total solar irradiation underneath the panels, as these models only incorporate full solar irradiance values. As mentioned earlier, bifacial modules contain 2 sides covered in glass. This ensures more light coming through the panels.

As the annual energy variation is found in the solar studies for the different PV scenarios, it is possible to calculate the weight according the RUE values. However, when looking at lettuce, for example, it becomes clear that there is not always a linear connection between the decrease in PAR and the decrease in biomass (Dupraz et al., 2011; Marrou, Guilioni, et al., 2013; Talbot et al., 2014). Therefore, the yield will be calculated in 2 ways; Linearly and qualitatively. The first method will look at the average crop specific yields per hectare. Subsequently, the decrease of light is linearly deducted from this average. The latter is by looking at different literature to see what influence a certain amount of shade has on the biomass. For example, Dupraz et al (2011), concluded that a decrease of 59% available PAR only leads to a 19% reduction of wheat yield. These values are used appropriately for the different identified crops.

3.3 Economic analysis

After the identification of the technological requirements in the first part and the shading effects on the selected crops in the second part of this research, an economic analysis will follow. To calculate the costs of this system accurately, online literature is consulted. However, because this is a new specific type of system it is necessary to ask for specific price indications from manufacturers regarding the rails, trusses and PV-panel mounting system. In addition, the extra installation costs and maintenance costs need to be incorporated as well as the costs of the panels.

3.3.1 Levelized Costs Of Electricity (LCOE)

To calculate the costs of this type of renewable energy it is useful to incorporate the formula of the 'levelized costs of electricity (LCOE)'. This formula expresses the costs of electricity in €/kWh over the total lifetime and incorporates all of the above-mentioned aspects. The LCOE will be calculated for the different scenarios mentioned in the previous sections (0 – 50% PV-panel area) and the different crops. By increasing the amount of PV, the costs per installed Wp will drop due to the economies of scale. Consequently, this will result in a lower LCOE in the scenarios with higher percentage of PV. The formula for calculating the LCOE is given below.

$$LCOE_{electricity} = \frac{\sum_0^T \frac{Investment + O\&M}{(1+r)^t}}{\sum_0^T \frac{Electricity\ Generation - Energy\ PV\ movement}{(1+r)^t}}$$

The investment costs will consist of the PV-panels, trusses, rails, engines for moving the system and the installation costs. The O&M costs will consist of cleaning the PV-panels, rail and engine maintenance. The electricity generation is simply the total electricity generated over the complete lifetime (T), and 'r' is the discount rate. Both the costs and electricity generation are discounted back to present values ($€_{2018}$). The average lifetime of PV-panels is estimated at 25 years[9]. The discount rate will be estimated from literature concerning Dutch PV energy (Sark & Schoen, 2017).

3.3.2 Integration of electricity generation and crop yield

As the LCOE merely calculates the costs of electricity generation it is important to integrate both the electricity and crop revenues, therefore, is addition to the LCOE , the 'Net Present Value' (NPV) is also calculated. The NPV will show the present value cash in- and outflow of a project for both electricity and crop. By calculating this for the entire lifetime of a project or investment shows the final profitability calculated back to present value. This way it is easy to see if the project is financially attractive. While the LCOE method merely shows the costs of the electricity generation, the NPV determines if it is attractive to invest in such a project. A positive NPV means that the earnings exceed the costs. It is important to take into account possible subsidies. These will influence the annual cashflows and thus the NPV. The formula for NPV is given below:

$$Net\ Present\ Value = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

Where:

[9] http://www.renewableenergyworld.com/ugc/articles/2010/08/demystifying-lcoe.html

T = the total lifetime

t = a period of one year

C_t = the cash inflow in period t

r = the discount rate

C_0 = total investment.

This research determines the NPV for the different crops and electricity revenues in the different shading scenarios and compares these values to two reference situations. The two reference scenarios are: a scenario without the agrivoltaic system and a scenario in which the field is completely utilized for PV-panels without crops. Additionally, the values of the already researched static agrivoltaic systems will also be incorporated, to see if this solution is more attractive than current static agrivoltaic systems.

In the previous section it is determined if this agrivoltaic system is financially attractive. However, another integration of crop and electricity is necessary because this system influences the designated land for both solar energy and crops. Therefore, is the land equivalent ratio is determined (LER) (Valle et al., 2017). This ratio determines the potential of the system with respect to the full sun conditions and current static agrivoltaic systems as followed:

$$Land\ Equivalant\ Ratio\ (LER) = \frac{Dry\ Mass_{DAV}}{Dry\ Mass_{FS}} + \frac{Electricity\ Production_{DAV}}{Electricity\ Production_{SP}}$$

Where:

$Dry\ Mass_{DAV}$ = Annual Yield (kg/yr) under the dynamic agrivoltaic system

$Dry\ Mass_{FS}$ = Annual yield (kg/yr) in full sun conditions

$Electricity\ Production_{DAV}$ = the annual electricity production (kWh/yr) by the agrivoltaic system

$Electricity\ Production_{SP}$ = the annual electricity production (kWh/yr) by a solar park on an equal area as the plot size.

In which the Dry mass is the annual yield in tonnes for the dynamic agrivoltaic system (DAV) and the full sun condition (FS). The annual electricity production is in kWh and is compared to a hypothetical solar park (SP) with equal dimensions as the plot size in which the design is solely optimized for electricity production. The full sun condition and the solar park are seen as the reference system. The yield and the electricity production are likely to be lower in this agrivoltaic system as compared to the two reference conditions. However, because both activities happen on the same plot it can save required land. This is the case when the LER is above 1. This is an important factor with regard to the Dutch energy targets. As they usually separate designated land for renewable electricity generation and agriculture. This is not accurate if the LER is above 1.

The last step of the economic analysis is to further analyse these economic values. This is done by making a comparison to two reference cases concerning agrivoltaic systems (Dinesh & Pearce, 2016; Dupraz et al., 2011). Because the NPV and LER are estimated, it is possible to tell how much investment is needed and how much land can be designated for other purposes instead of solar parks. This shows the practical potential of this dynamic system for the Dutch agricultural sector.

3.3.3 Sensitivity analysis

A sensitivity analysis is carried out after all values in the previous economic sections are determined. This method determines what input values the LCOE, NPV and LER are relying on. The following items are included in the sensitivity analysis:

Table 3: Overview of the sensitivity analysis for the LCOE and the NPV

LCOE	NPV
• Investment Costs ○ Support structure ○ PV-modules ○ Electrical engines ○ Rails ○ Discount Rate • Electricity generation ○ Bifacial gain ○ Capacity factor	• Discount Rate • Electricity price • Module price • Construction costs

4 Data section

4.1 Technologic Part

4.1.1 PV – panels characteristics

For the PV panels are a bifacial and a monofacial module chosen and explained in section 3.1.3. All input data originates from different sources which are shown under Table 4. The capacity factor is chosen for North Holland 2016 as the meteo-data also comes from this province.

Table 4: Technical input data for the chosen PV modules

Panel	LG300N1T-G4(A)	JAM6k-60-300-PR-B (D)
Mono-/Bifacial	Bi	Single
Mono/poly crystalline	Mono N-type	Mono
Capacity	300Wp	300Wp
Capacity factor(B)	0.97	
Bifacial energy gain	11%	0
Annual Power Degradation (C)	0.4%	
Power Lifetime (yr)	30	

A) (LG NEON, 2016)

B) (SolarCare, 2016)

C) This is the annual power degradation with regard to the rated power (Libal, Berrian, & Kopecek, 2017).

D) (Libra Energy, n.d.)

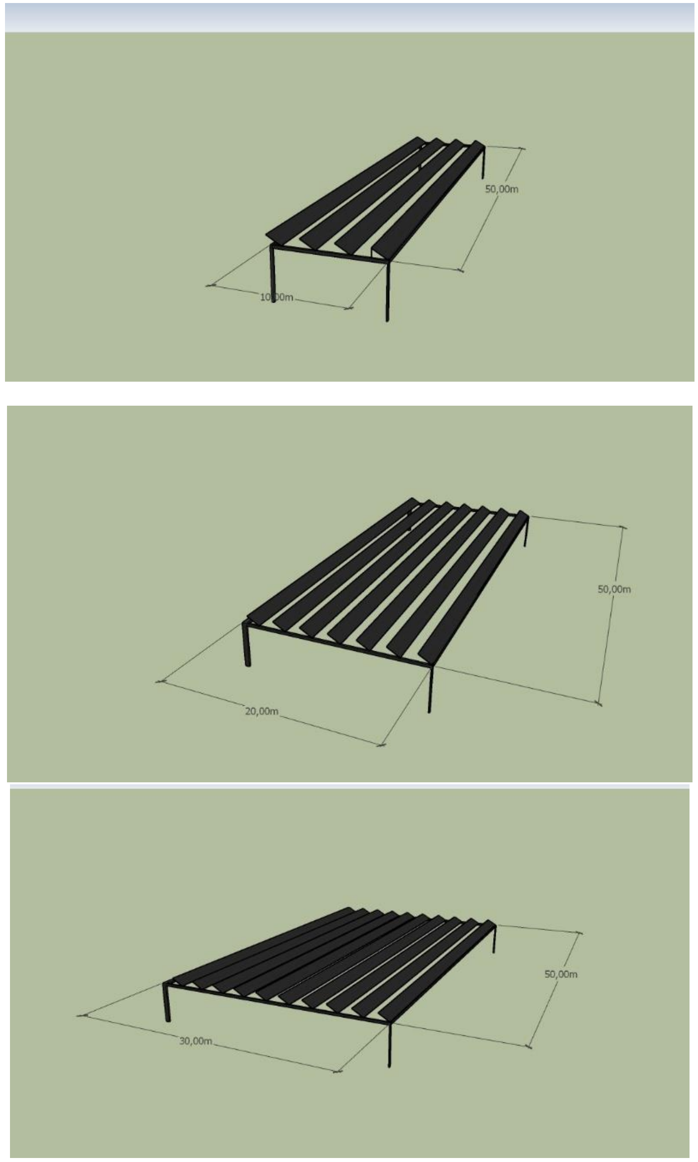
4.1.2 PV scenarios sizes & 3D models

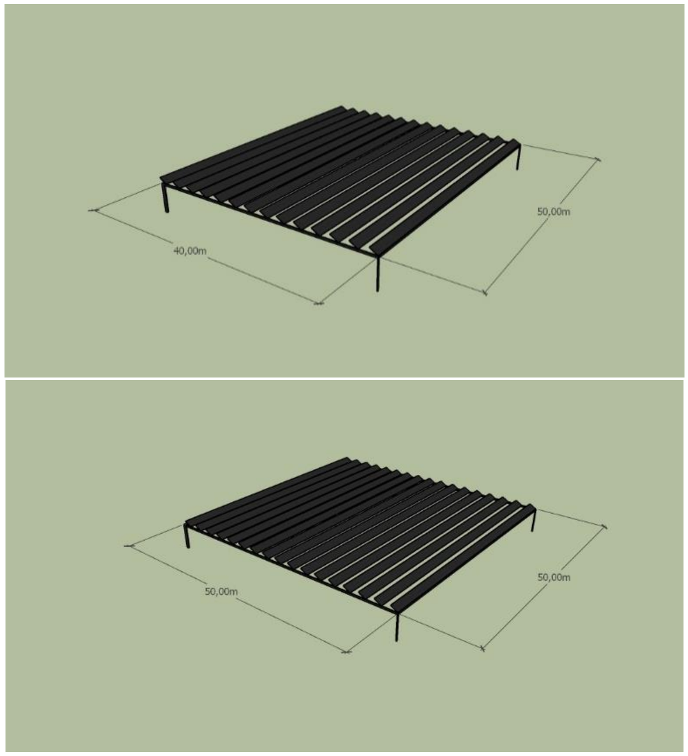
For the insolation simulation in Autodesk™ Revit™ there are 5 different PV-scenarios created. These scenarios are used to simulate the amount of insolation and shade which influence the crop yield underneath the panels. Table 5 depicts the descriptions of these panels scenario and Figure 14 shows how these scenarios look in the 3D modelling software Google™ Sketchup™

Table 5: Descriptions of the 5 different PV-scenarios with the accompanied PV-area on which the panels are places. In the latter column are the amount of panels shown.

PV scenario	Length (m)	Width (m)	PV Area (m^2)	#Panels
10	10	50	318.7	200
20	20	50	557.8	350
30	30	50	796.8	500
40	40	50	1115.5	700
50	50	50	1354.6	850

Figure 14: The 3D models created in Google Sketchup of the 5 different PV-scenarios.





4.1.3 Solstices & Equinoxes

The insolation simulations proved to be extremely time-consuming and therefore is chosen to look at 4 dates. The rest of the annual insolation values can be found due to linear interpolation (for explanation see 3.1.2).

Table 6: Solstices & equinoxes of 2000 which are used to simulate the insolation in Autodesk™ Revit™

Date	Sun up	Sun down	#hours
20 March 2000	07:00	20:00	13
22 June 2000	05:00	22:00	18
21 September 2000	07:00	20:00	13
21 December 2000	10:00	18:00	8

4.1.4 Determination of variable speed

One of the intermediate results of the insolation simulation showed that the amount of insolation in the middle of the field was much lower that on the sides. One of the reasons for this is that the insolation intensity gets higher during the day and is lower in the morning and evening. Therefore is chosen to increase the movement speed when the intensity is higher. The numbers represent the amount of meters the system is moved and between brackets is shown how long the system is moving with that speed. The results showed a very clear linear correlation between the amount of PV and the decrease of insolation. Therefore is chosen for some cases to extrapolate the results to save simulation time. This is also shown in the table.

Table 7: Determining the different specific speeds

Scenario/solstice	Total distance	Spring (March)			Summer (June)		
	Meter	V_{gem}	V_{low}	V_{high}	V_{gem}	V_{low}	V_{high}
10%	90	7.5	3.75 (6)	11.25 (6)	5.29 (17)	1.30 (10)	11 (7)
20%	80	6.67	2.23 (6)	11.15 (6)	4.71 (17)	1 (10)	10 (7)
30%	70	5.83	1.94 (6)	9.71 (6)	4.11 (17)	1 (10)	12 (5)
40%	60	5	1.67	8.34	**Linear extrapolation**		
50%	50	**Linear Extrapolation**					

Scenario/solstice	Total distance	Autumn (September)			Winter (December		
	Meters	V_{gem}	V_{low}	V_{high}	V_{gem}	V_{low}	V_{high}
10%	90	7.5	3.75 (6)	11.25 (6)	12.86	10 (3)	15 (4)
20%	80	6.67	2.23 (6)	11.15 (6)	11.43	6.67 (3)	15 (4)
30%	70	5.83	1.94	9.71	10	6.67 (3)	12.5(4)
40%	60	5	1.67	8.34	**Linear Extrapolation**		
50%	50	**Linear Extrapolation**					

4.1.5 Support Structure & Electrical engine

See 3.1 & 5.3 for further explanation regarding the choice for IPE400 beams and electrical engines.

PV Scenario	Verticale balken	Horizontale balken	Dieptebalk	Totaal (m)	Gewicht 400 (kg)
10	6	4	20	250	16.900
20	6	7	40	420	28.392
30	9	10	60	605	40.898
40	12	14	80	825	55.770
50	15	17	100	1010	68.276

4.2 Economic input data

To calculate the revenues and financial attractiveness of the PV-part of the system the following input parameters have been used. These are based on several sources which are listed below Table 8. In Table 9, the additional remaining costs are depicted which ensure the movement of this dynamic system as well as the supporting structure. Some assumptions are made for the revenue calculation. The supporting structure costs are only based on current steel prices and not on other installation costs. Other costs like welding and placement costs need to be taken into account. Therefore is an extra 5% added to the construction costs of the 10% scenario. For the 20% scenario is 4% added, 30% scenario is 3% added and so on. The decrease in extra costs is done because for larger systems discounts are often given. See 9.1 for an example of a quotation for an aluminum truss (personal communication, 2018). These discounts together with the probability of even further cost reduction due to economies of scale ensure that the percentages mentioned above result in the minimum costs for the construction of this system.

The average module price for April 2018 is estimated at 0.36€/Wp (Beurskens & Lemmens, 2018a). However, bifacial modules tend to be somewhat more expensive; 0.39€/kWh (Libal et al., 2017). The values of Libal et al (2017) are incorporated in this research as they investigated the LCOE of bifacial &

monofacial modules more in depth. Furthermore, the SDE+ subsidy will stop after 15 years. After 15 years the price for electricity drop to 0.048€/kWh (Beurskens & Lemmens, 2018b). The bifacial gain is explained in section 3.1.3. Additionally, all the electricity generation is sold back to the grid. As this price is relatively low in comparison with the price which is paid for electricity from the grid. However, as energy data for farmers are difficult to find, is assumed in this case that all the energy is sold to the grid.

Table 8: Input data for the economic model regarding solar PV

Panel characteristics	Unit	Mono	Bifacial
Module Price [A]	€/Wp	0.31	0.39
Installation (>50kWp)[B]	€/Wp	0.2	
Inverters [C]	€/Wp	0.052	
Performance Ratio [F]	kWh/Wp	0.97	
Capacity Module	Wp	300	
Bifacial Gain [D]		0	11%
yearly power degradation [A]	%/yr	0.40%	
O&M <100kWp [E]	€/Wp	0.009	
O&M >100kWp [E]	€/Wp	0.008	
Price Electricity & SDE+[E]	€/kWh	0.092	
Price Electricity[G]	€/kWh	0.048	
Discount Rate [B]	3%		

A) (Libal et al., 2017) & Table 4
B) (Sark & Schoen, 2017)
C) (Beurskens & Lemmens, 2018a)
D) (See 3.1.3)
E) (Beurskens & Lemmens, 2018a) ; Price electricity = "SDE+Fase bedrag" – "Correctiebedrag" + "Basisprijs Electricity" = 0.108 – 0.038 + 0.022 = 0.092
F) (SolarCare, 2016)
G) (Beurskens & Lemmens, 2018b)

Table 9: Remaining extra cost due to the dynamic capabilities of this system. The support structure, wheels, rails and the electrical motor to move the system

PV-scenario	IPE400	Rails	Wheels [A]	Electrical motor[(B)]
0	0	0	0	0
10	€ 17,367	€ 6,909	€ 760	€1,902
20	€ 29,177	€ 6,909	€ 760	€1,902
30	€ 42,029	€ 6,909	€ 1,139	€1,902
40	€ 58,354	€ 6,909	€ 1,519	€1,902
50	€ 71,206	€ 6,909	€ 1,899	€1,902

A) 200x80 / 90 K45 – Cast Nylon
B) (Powerful Products, 2018)

5 Results

The result section is divided in the three research parts: technological, biological and economic. The first section will show a summary of the results. Consequently the results of the three parts will be addressed in the above mentioned order. The technological results are focussed on the simulations and the solar insolation for each PV scenario. Then the accompanied yield results (biological part) of the different identified crops are explained in detail. Lastly the economic results will follow. Table 10 depicts an overview of the most important results. Starting with the average daily insolation intensity per PV-scenario. Followed by the electricity generated by the two different PV-modules per PV-scenario. The generated electricity is sold back to the grid with and without SDE+ subsidy. Thirdly, the revenues from crop yield is shown per PV scenario. Lastly, the rest of the investment costs are shown per PV-scenario.

Table 10: Result summary overview

Technologic			0 Agri only	10	20	30	40	50
Solar Study	Average Daily Irradiation intensity	$MJ/m2*Day^{-1}$	9.61	8.94	8.41	7.78	7.21	6.62
	MJ $5000m^2$	MJ/yr	48027	44675	42069	38917	36065	33092

Electricity Generation	0	10	20	30	40	50
Monofacial (kWh/yr)	0	54,000	94,500	135,000	189,000	229,500
Bifacial (kWh/yr)	0	59,940	104,895	149,850	209,790	254,745

Revenues Electricity	PV-scenario					
	0	10	20	30	40	50
Monofacial & SDE+ (€/yr)	0	€ 6,318	€ 12,285	€ 17,550	€ 24,570	€ 29,835
Bifacial & SDE+ (€/yr)	0	€ 7,013	€ 12,273	€ 17,532	€ 24,545	€ 29,805
Revenues Without SDE+						
Monofacial (€/yr)	0	€ 2,794	€ 4,889	€ 6,984	€ 9,778	€ 11,873
Bifacial (€/yr)	0	€ 3,101	€ 5,427	€ 7,752	€ 10,853	€ 13,179

Economic			0	10	20	30	40	50
Investment	€	Bifacial Modules	0	€ 23400	€ 40950	€ 58500	€ 81900	€ 99450
		Mono Modules	0	€ 18600	€ 32550	€ 46500	€ 65100	€ 79050
		Support Structure	0	€ 17368	€ 29177	€ 42029	€ 57313	€ 69123
		Inverters	0	€ 3.120	€ 5.460	€ 7.800	€ 10.920	€ 13.260
		Electrical Engines	0	€1,902				
		Rails	0	€6909				
		O&M/yr[1]	0	€ 6674	€ 11680	€ 16685	€ 23360	€ 28365

5.1 Technologic

5.1.1 3D Simulation results

Table 11 shows the result from the solar studies for the different PV-scenarios and for the different solstices/equinoxes. The simulation software gives two different values; the insolation intensity (kWh/m^2) and the total insolation for the chosen field dimension of 50m x 100m (5000m^2). There are 4 dates simulated which are the 2 solstices (June 22 & December 21) and 2 equinoxes (March 21 & September 22). The differences in insolation relative to the current situation (agri only) are depicted in the column Δ kWh. The change in percentage is depicted in the last column.

Looking at the change in the last column (Δ%) it becomes clear that there is a linear connection between the amount of the PV and the decrease in available insolation. However, the amount of linear change is different for each simulated date for instance: ±7% for March & ±5.5% of for June. The largest change is occurring in the December solstice which is nearly 10%. The linearity can be explained by the fact that the amount of PV is linearly increasing and thus the amount of shade is linearly increasing as well. However, it is surprising that the decrease of insolation is lower in every case than the amount of PV installed. This can be explained by the fact that during the morning the sun is so low that sunlight can pass underneath the agrivoltaic system and therefore does not cast any shadows on this field. Another explanation could be that this system is orientated N-S. This means that during the morning and evening hours the sun in not perpendicular to the system and is therefore casting shadows outside this simulated field on a hypothetical neighbouring field. However, it must be noted the solar intensity is low during these morning and evening hours and would therefore impact the surrounding area only slightly.

Furthermore, from Figure 15 becomes clear that in the summer the insolation decreases less than the other seasons (blue line). As march and September have equivalent solar positions the decrease in insolation is also nearly equal (red and yellow lines). The decrease of insolation is the highest in the winter season. This can be explained by the fact that in the summer the sun is higher in the sky and therefore during mid-day only casts the shadow on a small part of the field. While in the winter the sun is less high in the sky and thus casts shadows on the field for longer periods.

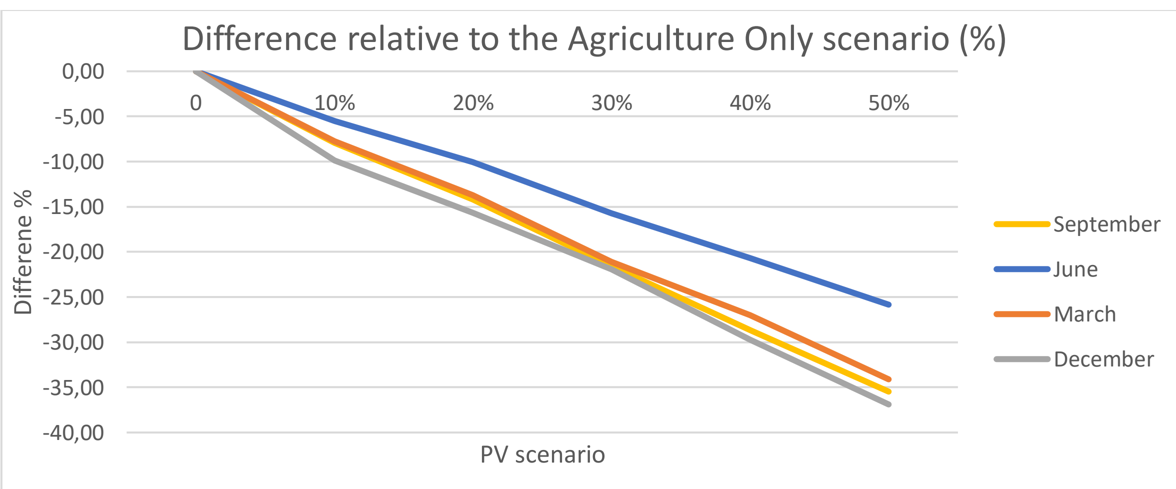


Figure 15: Insolation differences during the 4 seasons. It shows that there is a linear decrease of insolation with the increase of PV-panels.

Table 11: Determination of insolation for different solstices/equinoxes. The values in bold are found by linear extrapolation.

PV-scenario	March Solstice				June Solstice			
	kWh/m2	**kWh**	**Δ kWh**	**Δ%**	**kWh/m2**	**kWh**	**Δ kWh**	**Δ%**
0% Agri only	2.17	10848	0	0	6.30	31489	0	0
10%	2.00	10009	-839	-7.75	5.95	29765	-1724	-5,48
20%	1.87	9362	-1487	-13.70	5.66	28315	-3174	-10,08
30%	1.71	8562	-2287	-21.08	5.31	26543	-4946	-15.75
40%	1.58	7918	-2930	-27.00	**4.99**	**24986**	**-6503**	**-20.71**
50%	**1.43**	**7148**	**-3701**	**-34.11**	**4.67**	**23375**	**-8114**	**-25.84**

PV-scenario	September Solstice				December Solstice			
	kWh/m2	**kWh**	**Δ kWh**	**Δ%**	**kWh/m2**	**kWh**	**Δ kWh**	**Δ%**
0% Agri only	3.14	15707	0	0	0.50	2491	0	0
10%	2.89	14460	-1247	-7.94	0.45	2245	-245.7	-9.87
20%	2.70	13483	-2223	-14.16	0.42	2100	-390.6	-15.68
30%	2.46	12319	-3388	-21.57	0.39	1945	-545.6	-21.90
40%	**2.24**	**11207**	**-4499**	**-28.65**	**0,35**	**1749**	**-740,9**	**-29,74**
50%	**2.02**	**10093**	**-5614**	**-35.47**	**0,31**	**1571**	**-919,1**	**-36,89**

One solar study be in depth explained while the rest of the solar studies excel results can be requested. In Figure 16 can be seen that for the two PV-systems to cross the field different distances need to be covered. For the 10% scenario 90m meters need to be covered in a whole day. While the 20% scenario needs to cover 80m in the same time period. This influences the movement speed of the system to divide the shade equally across the field. Moreover does the amount of sunlight hours differs per date and shall therefor be adjusted accordingly (see 4.1.4). As the first hour 05:00 till 06:00 is simulated as the starting position which is displayed in Figure 16, the remaining 17 hours need to cover the 90m and 80m for each scenario respectively. The following solar irradiation study is done with the following properties:

Date: 15/06/2018; 05:00 – 21:00; 18hrs (after 21:00 there was no significant irradiation)

Meteorological data incorporated: yes

Field size: 50mx100m

PV scenarios: 10% and 20%

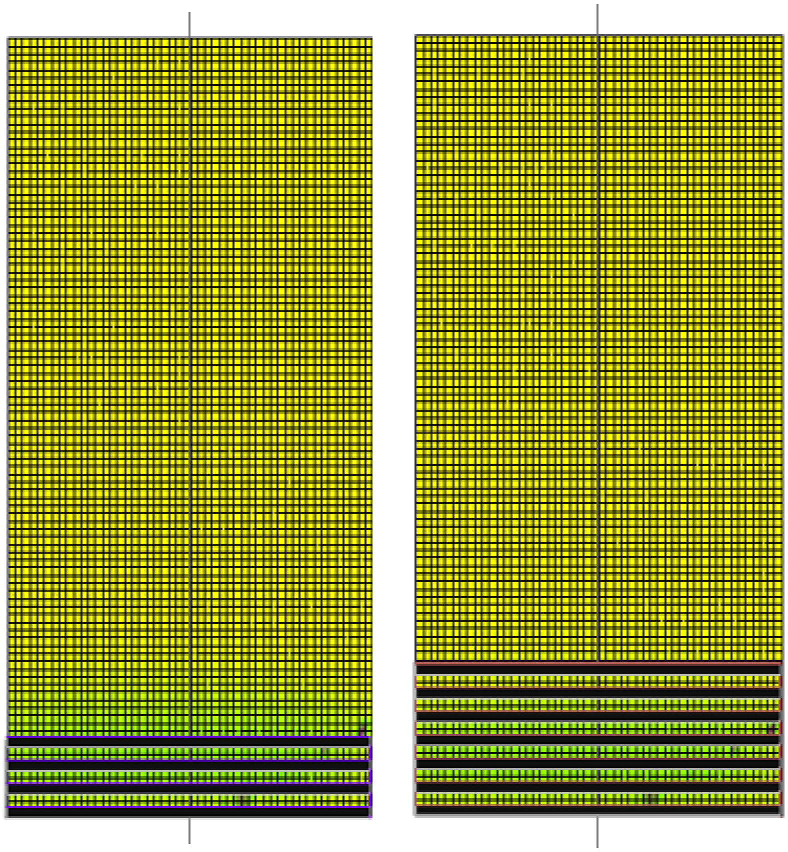


Figure 16: 10% scenario (left) and 20% PV scenario (right) at the starting position at bottom 05:00 – 06:00.

The hourly irradiation data is then exported to excel for further in depth analysis. As the PV system moves across the field, hourly irradiation data is exported which looks as followed:

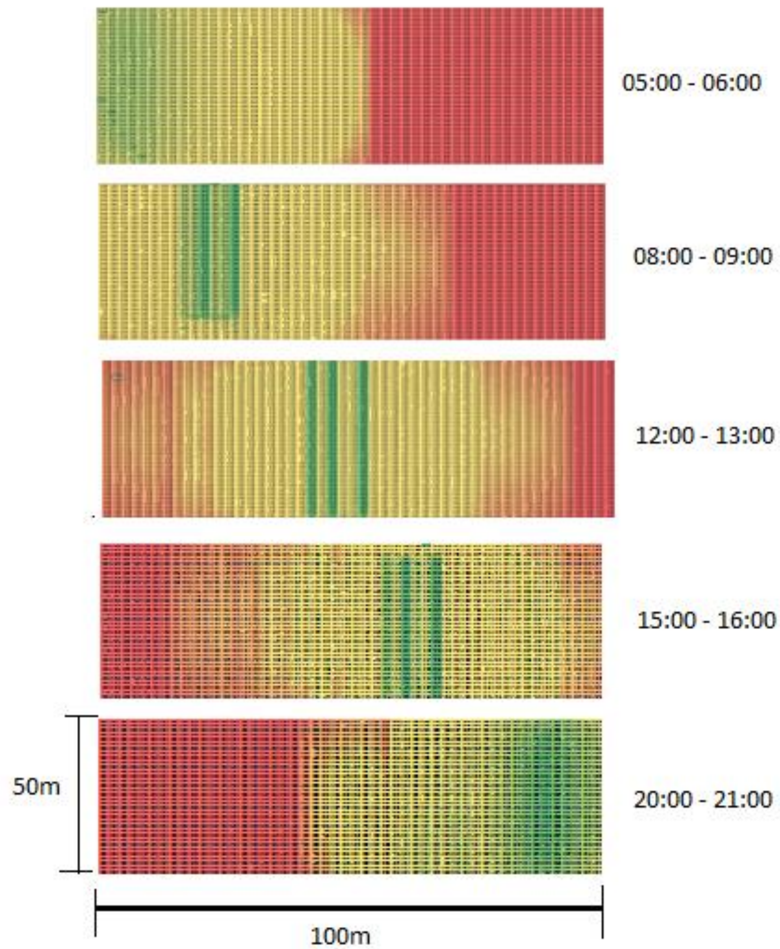


Figure 17: Hourly irradiation values of the 10% PV scenario. Only 5 fragments of the 18 are shown from top to bottom respectively; 05:00-06:00, 08:00 – 09:00, 12:00 – 13:00, 15:00 – 16:00, 20:00 – 21:00.

When all simulated hours are summed up the total daily irradiation values have been found for that specific date. The following pictures represents the total irradiation with in red the highest irradiation and in green the lowest:

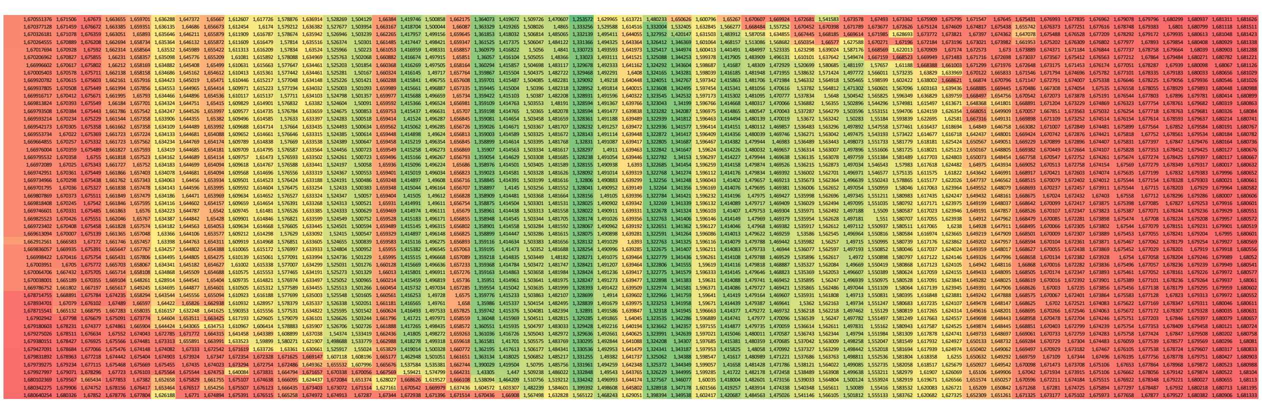


Figure 18: total solar irradiation for the 10% PV scenario for the date: 15/06/18

When the columns are further analysed it becomes clear that there are large differences present between the daily irradiation values in the middle of the field and the edges (see Figure 19). The blue line shows the level of daily irradiation (from Figure 19). This is due to the higher insolation values (intensity) during the middle of the day when the sun is at the highest point. This can be more evenly spread across the field when the movement speed of the systems is higher during the peak insolation and lower during the morning and evening hours.

Another simulation which incorporates different speeds during low intensity and high intensity hours shows that the shade can be more equally divided. The yellow line is the distribution when the speed is doubled during peak hours and halved during morning and evening hours. It shows that the shade is already more spread instead of concentrated between 30m -70m. This division of the shade can be even more optimized when the movement speeds are more closely related to the insolation intensities. This can be achieved when simulation software provides the possibility to simultaneously measure the insolation and move the system.

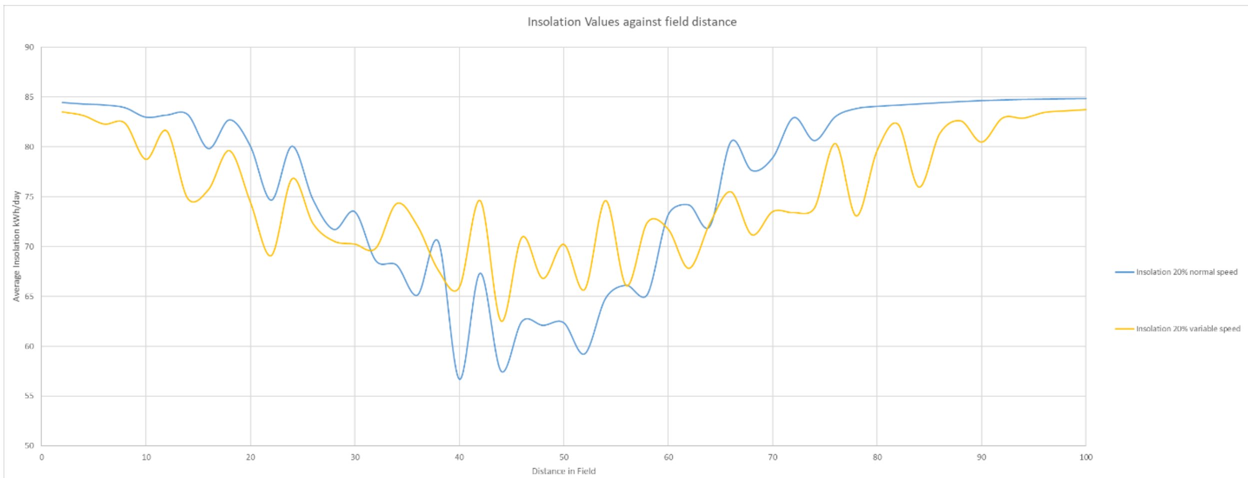


Figure 19: Distribution of insolation values across the field. Horizontally is distance in the field displayed. The insolation values drop at 50m. The blue line depicts the insolation values for the system with a constant movement speed. The yellow line depicts the insolation when the speeds is higher during mid-day and lower during morning/evening hours.

5.1.2 Interpolation

The average yearly insolation values are found in an extensive report of the KNMI. As the insolation values are simulated for each PV-scenario (see Table 11) on the according solstices the differences in insolation are only found for these 4 days. Due to interpolation in Excel the insolation differences for the whole year can be found. These differences are calculated by using the average values of the KNMI and decrease these values by the simulated change (ΔkWh) of Table 11. Figure 20 shows the insolation values for each PV-scenario and in blue the values found by the KNMI (KNMI, n.d.). As mentioned before, there is a linear connection between the decrease of insolation and the size of the PV-scenarios. This is also visible in Figure 20.

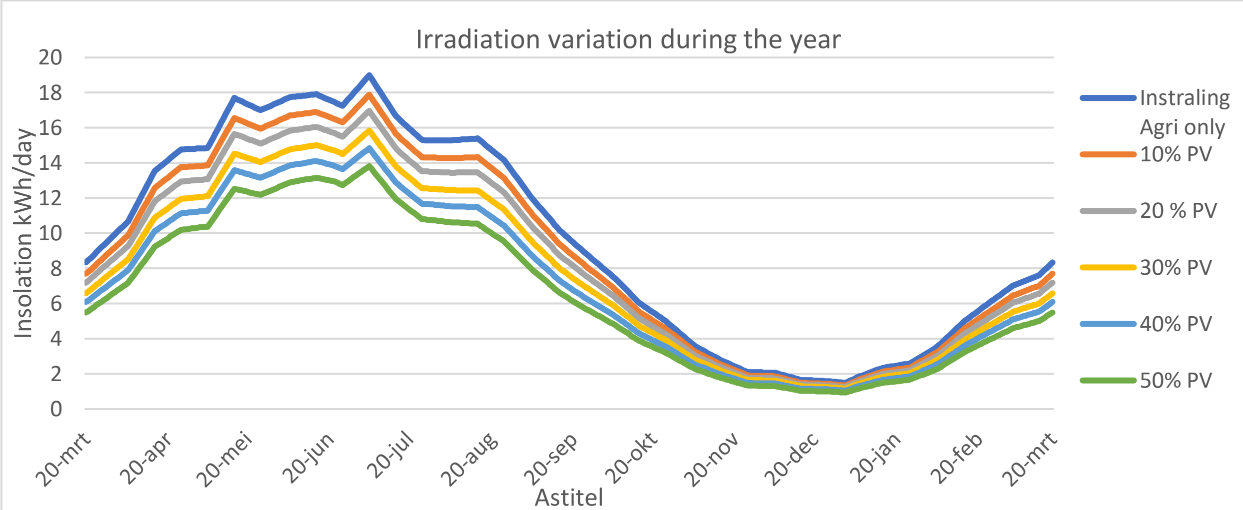


Figure 20: Interpolation values of the yearly insolation. The blue graph depicts the insolation values found by the KNMI. The other graphs depicts the simulated insolation values for each PV-scenario.

Firstly, only the differences in insolation for the 4 specific dates have been found. However, due to the linear interpolation (Figure 20) is ensured that the average insolation differences for the complete year have been found. These values are presented in the following table:

Table 12: Due to linear interpolation between the solstices/equinoxes the annual change in insolation averages have been found.

PV scenario	MJ/m^2*day^{-1}	Δ%	$kWh_{totalfield}$
0	9,60	**0%**	48027
10	8,94	**-6,98%**	44675
20	8,41	**-12,4%**	42069
30	7,78	**-19,0%**	38917
40	7,21	**-24,9%**	36065
50	6,62	**-31,1%**	33092

These values are necessary to calculate the accompanied differences in yield for the different identified crops which will be further explained in the next section.

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5.2 Biological

As mentioned in the methodology the crop yields are approached in two different ways; quantitatively and qualitatively. The first method is by looking at the decrease of solar irradiation and using that same percentage to calculate the decrease in yield. However, as different research already mentions that crop yield under shading conditions varies. Therefore will the identified crops be approached in a more qualitative way by looking at research and the crop yield under other shading conditions.

5.2.1 Lettuce

Lettuce can be grown throughout the year in glasshouses. However, to grow lettuce outside conditions are only preferable in summer (warmer) periods. Therefore will this research only look at lettuce that is grown in summer periods. The annual changes in insolation are now simulated for each PV-scenario. When looking at the RUE method to calculate the yield, the change in available insolation will linearly affect the annual yield. This is shown in the last column of Table 13. The other columns are different lettuce varieties used in other literature. Dinesh & Pearce (2016) used the same PV configuration as Marrou et al (2013) which consists of two PV densities; Half density (HD) and Full density (FD). These densities ensured a decrease of 28% and 48% of available insolation. The accompanied yields for these densities are shown in Figure 22. The spring variety is used by Dinesh & Pearce (2016) the other two are used by Marrou et al (2013). As the PV scenario's in this research only showed a maximum decrease of ±31% insolation (for the 50% PV scenario). The accompanied revenues and yields for this configuration are shown in Table 13 and Figure 21. The revenues for lettuce are estimated at 12,645€/ha (Hendriks-goossens, 2009). However is stated that specialized lettuce farmers can do three rounds of lettuce per year (Hendriks-goossens, 2009). Therefore for this research is estimated that the annual revenues will be 13,392€/year for a half hectare land.

Table 13: Revenues from lettuce yield. Varieties and prices are explained in the section above.

Revenues Lettuce	Varieties			Linear (RUE)
	Spring	**B-**	**FC+**	
Agri only	€ 13,392	€ 13,392	€ 13,392	€ 13,392
10	€ 13,958	€ 14,595	€ 13,759	€ 12,457
20	€ 14,257	€ 15,133	€ 13,861	€ 11,731
30	€ 14,453	€ 15,320	€ 13,769	€ 10,852
40	€ 14,475	€ 15,050	€ 13,483	€ 10,056
50	€ 14,339	€ 14,326	€ 12,980	€ 9,228

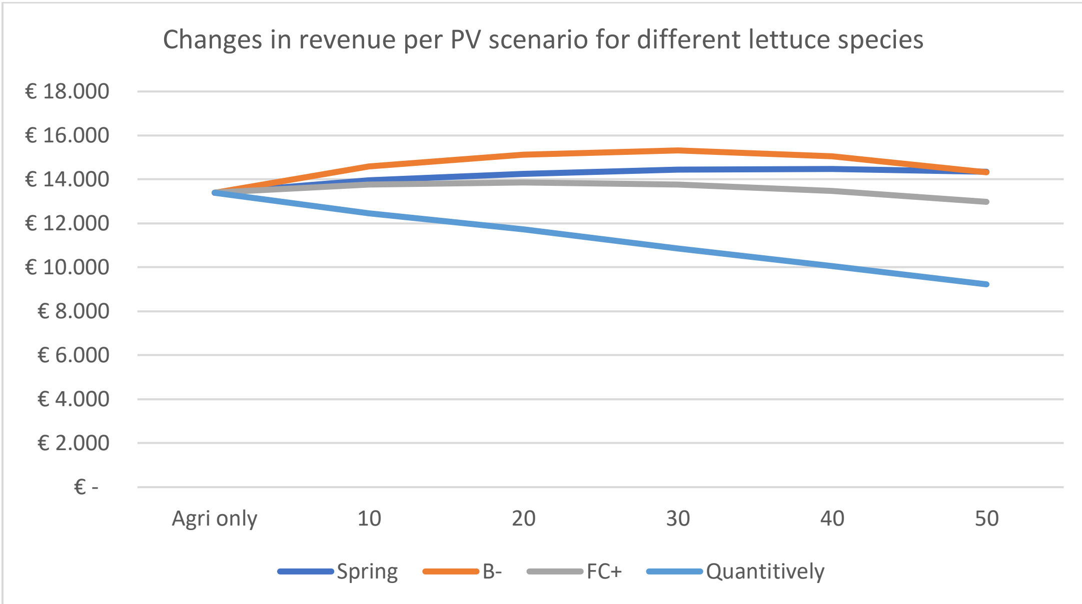


Figure 21: Lettuce yield for different varieties and the accompanied PV-scenarios for this research.

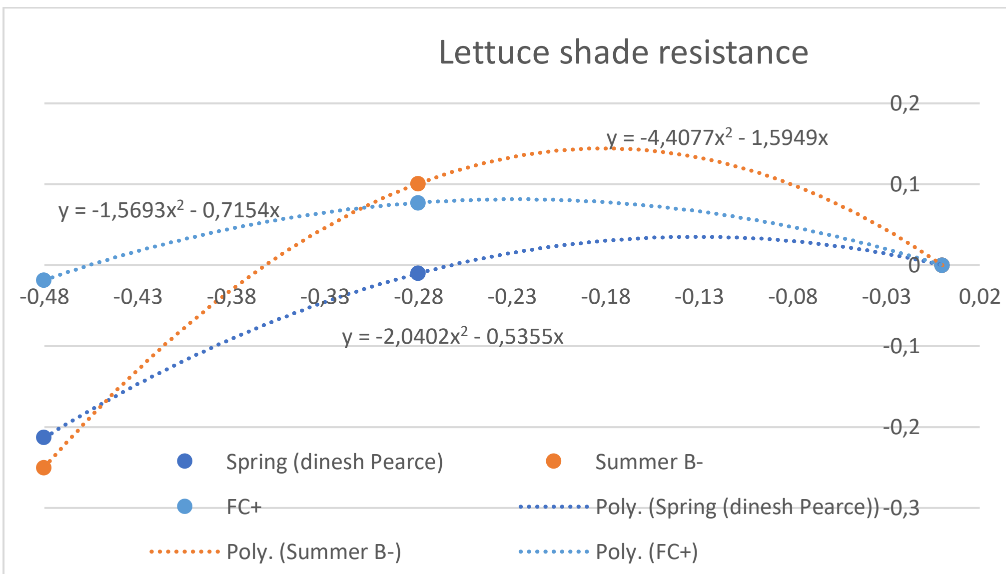


Figure 22: Graph of lettuce yield under different shading scenarios from different research. The formulas are used to calculate the yield for the shade specific conditions for this research. Because the FD scenario of research results in a maximum decrease of 48% insolation the graph only goes to -48%. The spring variety retrieved from Dinesh & Pearce (2016). The other 2 varieties are retrieved from Marrou et al (2013).

5.2.2 Sugar beet

Sugar beet is seen as profitable spring crop and 50% of the global production is produced in Europe (Artru, Lassois, Vancutsem, Reubens, & Garré, 2018). According to the literature does sugar beet contain a relatively high tolerance to shade. This can be seen in Figure 23 where for 2016 the yield is reduced by 14% while the insolation is reduced by 24%. However, when there is too much shade the yield drops more significantly. The estimated revenues of wheat are retrieved from the Wageningen University[10] and is estimated at 3320€/ha. An important factor for high revenues is the sugar content in sugar beet. However, the incorporated study of Artru et al (2018) showed that the sugar content dropped only 1,4% for the largest shading scenario (Artru et al., 2018). Therefore is assumed that the shading scenarios do not further affect revenues by the change of the sugar content.

Table 14 & Figure 23 depicts the changes in revenues according to the PV-scenarios of this research. Surprisingly does the yield decreases with such magnitude for the 2 varieties, that in the end the linear approximation proves to be the most attractive for the 50% scenario. However, for the 0 – 20% percent scenarios the revenues increase. Therefore, can be assumed that the shade tolerance of sugar beet only enough till around 25%. This can also be seen in Figure 23. Both the blue and orange line are rapidly decreasing after 25% of shade. Moreover, the 2015 case was even less shade tolerant. The reason for this is that both cases divided the shade somewhat different. The 2015 case had two shading scenarios; partial and constant. While the 2016 case divided the shade between PM and AM time frames. However, previous mentioned literature claimed that sugar beet can cope very well with stressful conditions (Richter et al., 2001)

Table 14: Changes in revenue according to the PV-scenarios of this research. Based on the shading scenarios of Artru et al (2018)

Revenues Sugar Beet	**Varieties**		**Linear (RUE)**
PV-scenario	2016	2015	
0	€ 1,660.00	€ 1,660.00	€ 1,660.00
10	€ 1,703.92	€ 1,565.76	€ 1,544.14
20	€ 1,673.37	€ 1,465.82	€ 1,454.08
30	€ 1,560.75	€ 1,313.69	€ 1,345.12
40	€ 1,387.50	€ 1,146.63	€ 1,246.55
50	€ 1,134.74	€ 942.73	€ 1,143.79

10 https://www.agrimatie.nl/Binternet.aspx?ID=14&Bedrijfstype=11&SelectedJaren=2017%402016%402015%402014

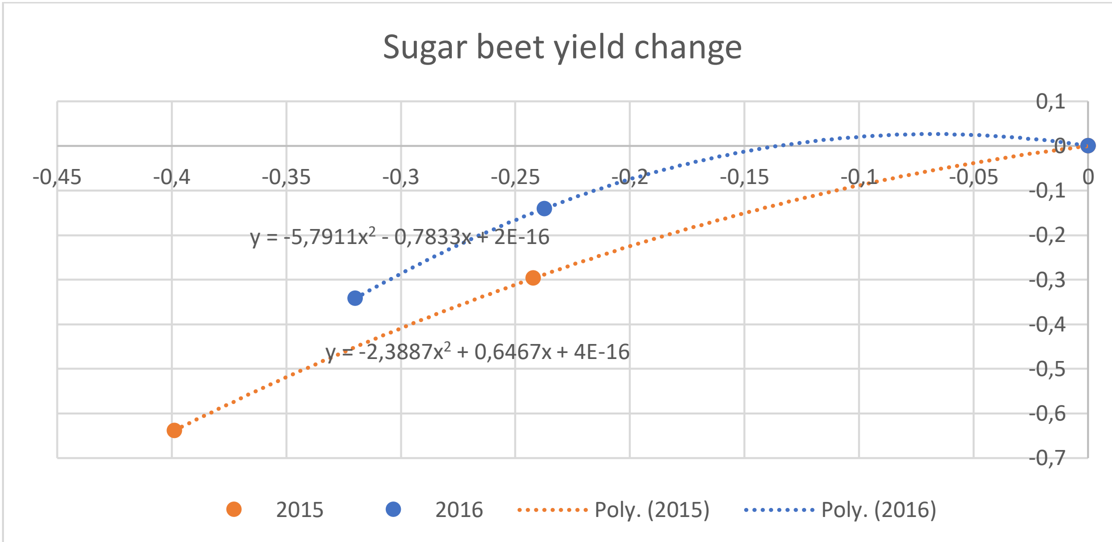


Figure 23: Sugar Beet yield change for 2 different shading scenarios for 2015 and 2016.

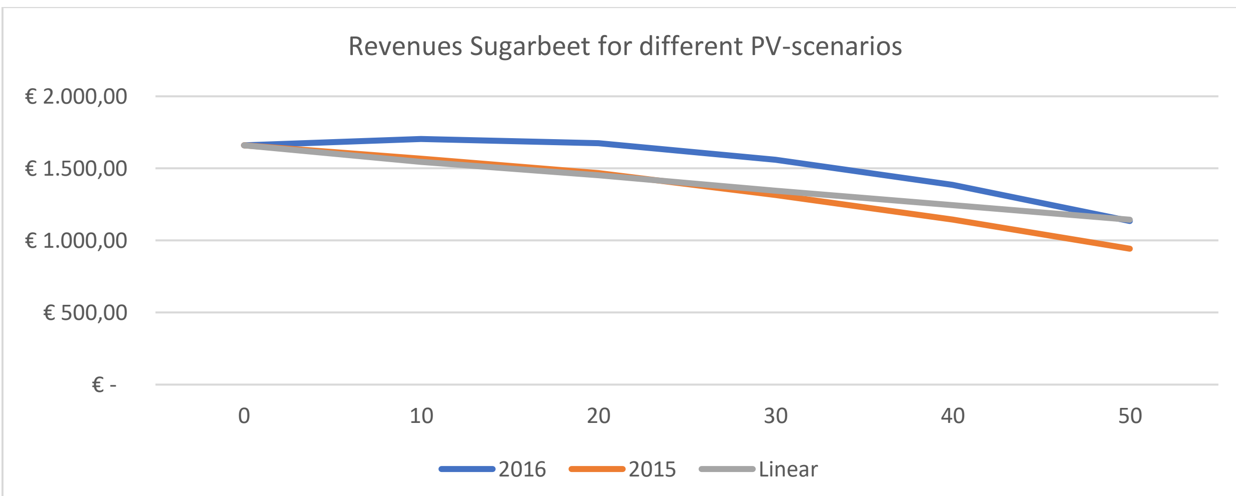


Figure 24: Revenue changes for two different years according to the literature (Artru et al., 2018). *In grey are the linear changes in revenues depicted.*

5.2.3 Wheat

Wheat is an important crop for feeding the world as it provides 20% of the calories and proteins consumed by humans (Reynolds et al., 2012). This research only incorporates winter wheat. Two different literature studies researched the behaviour of winter wheat under shading conditions (Dupraz et al., 2011; Lakshmanakumar, 2018). The changes in yield as a result of shading conditions are depicted in Figure 25. The dark orange line is the result from the report of Dupraz et al (2011) which only mentioned durum wheat but not a specific variety. The other 2 lines depict the changes in yield for two varieties PDW233 & UP2113 (Lakshmanakumar, 2018). There are 3 more varieties included in the original report however these are not as shade tolerant as these two varieties.

In Figure 26 are the accompanied changes in revenue depicted. Table 15 depicts the changes in revenues for the PV-scenarios of this research. One important results of Dupraz et al (2011) was that sugar beet increases its light efficiency in shading scenarios. Therefore is this crop seen as a suitable crop for cultivation under PV modules (Dupraz et al., 2011). However, in contrast to lettuce the literature does not show an increase in yield under minor shading conditions. Lettuce enlarges its leaves in its competition for sunlight which therefore increases the yield. However, wheat can relatively sustain its yield under shading conditions but does not increases its biomass.

Figure 26 & Table 15 show that the linear approximation of wheat revenues is less attractive than the approximation with shade tolerant research. When looking at the research of Dupraz et al (2011) the revenues for the 50% scenario will only drop 8.71%. This clearly shows the attractiveness of the combination of PV and durum wheat.

Table 15: Revenues of wheat for the different PV-scenarios of this research. Values are estimated based on two different researches which incorporated wheat growth under shading scenarios

Revenues Winter Wheat	Linear (RUE)	Varieties		
PV-Scenario		Durum Wheat	UP 2113 (2011)	PDW 233 (2012)
0	€ 741.50	€ 741.50	€ 741.50	€ 741.50
10	€ 689.75	€ 729.56	€ 731.59	€ 690.72
20	€ 649.52	€ 719.26	€ 718.66	€ 652.77
30	€ 600.85	€ 705.60	€ 696.90	€ 608.63
40	€ 556.82	€ 692.11	€ 671.45	€ 570.37
50	€ 510.92	€ 676.90	€ 639.08	€ 532.20

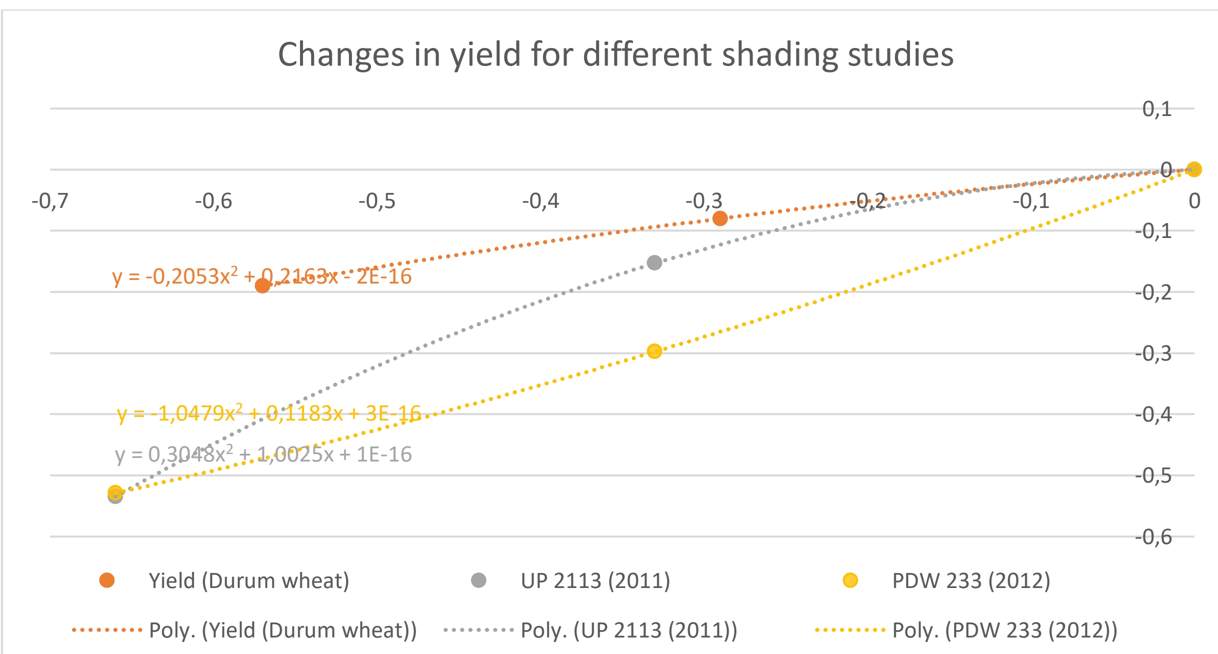


Figure 25: Changes in yield as a result of different shading conditions in two different reports (Dupraz et al., 2011; Lakshmanakumar, 2018).

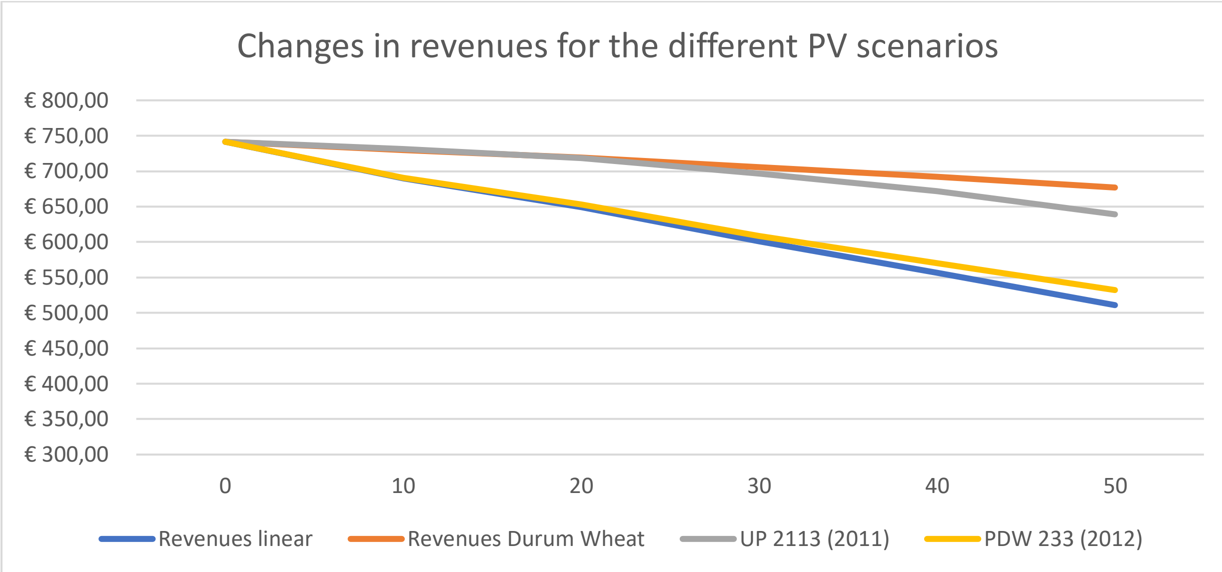


Figure 26: Change in revenues according to the yield changes which are depicted in Figure 25. Wageningen University estimated the revenues of wheat at 1483€/m^2 for 2018.

5.2.4 Potato

Around 1992, the potato was one of the Dutch most important crop as it took up around a quarter of the arable land. Moreover, the revenues from potatoes made up around half of the total value of production from arable lands (Zaag, 1992). Nowadays the percentage of arable land which cultivates potato lies around 28% (Centraal Bureau voor de Statistiek, 2018). The cultivation of potato has been improved over the years and the Dutch farmers are seen as the world leaders. There is little research available concerning potato growth under shading scenarios. The research which is incorporated here is done by Ghosh et al (2002). The research investigated the influence of two shading densities during different growth stages for two different potato varieties. This research took the average yield decrease for the two varieties which is shown in Figure 27 & Table 16. Although is mentioned that potato is a rather shade tolerant crop it is not clear from existing literature that the crop will increase biomass under low shading scenarios. The orange trendline of the Dejima variety in Figure 27 shows an increase for shading scenarios between 0% - 35%. Because the largest shading scenario in this research shows a decrease of 31% this would mean that in all scenarios the potato yield would increase. As this result is not supported by existing literature it the values of the May Queen variety are used for further analysis.

Table 16:Potato revenues according to yield changes.

Revenues Potato	Linear (RUE)	Varieties	
PV-senario	Linear	Dejima	May Queen
0	€ 4,539.00	€ 4,539.00	€ 4,539.00
10	€ 4,222.20	€ 4,593.01	€ 4,528.38
20	€ 3,975.95	€ 4,616.90	€ 4,511.92
30	€ 3,678.01	€ 4,624.66	€ 4,482.42
40	€ 3,408.48	€ 4,611.72	€ 4,446.69
50	€ 3,127.52	€ 4,578.06	€ 4,400.30

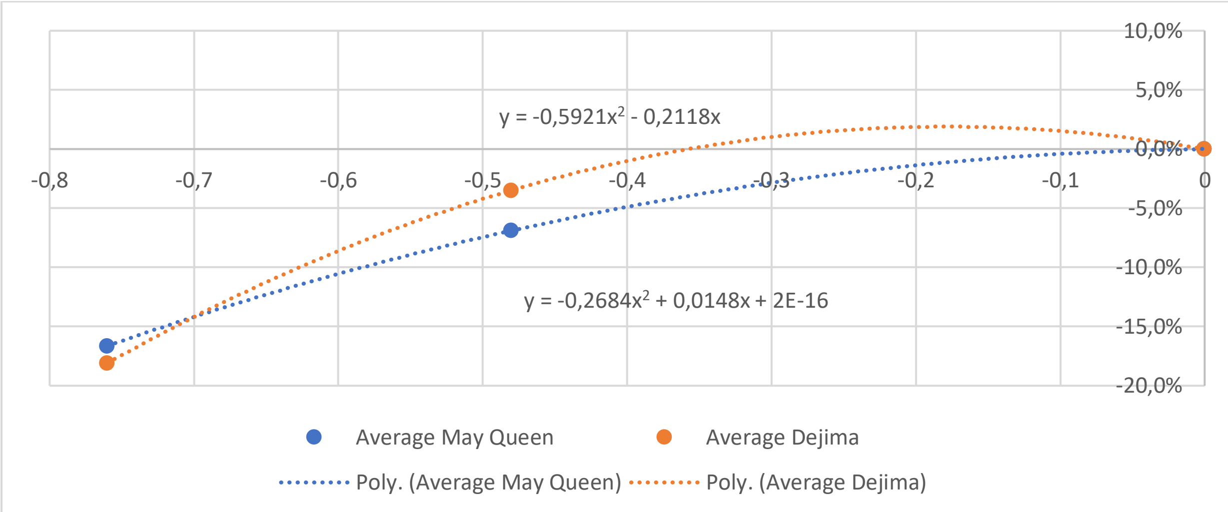


Figure 27: Yield decrease for two different potato varieties under 2 different shading scenarios (Ghosh, Asanuma, Kusutani, & Toyota, 2002).

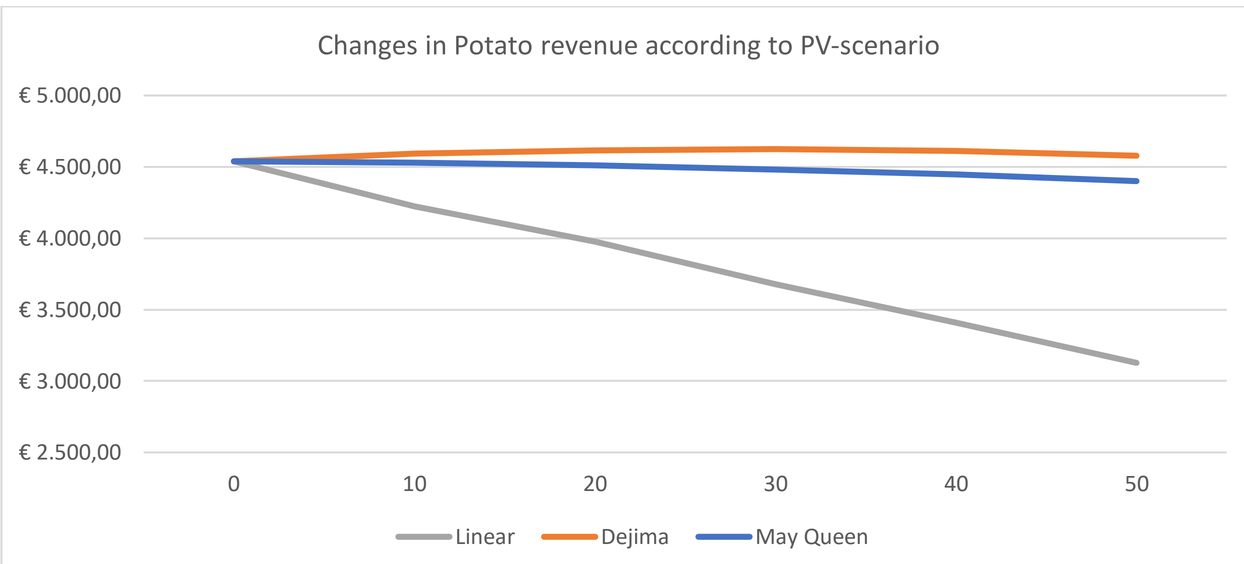


Figure 28: Change in revenuea ccording to literature and the RUE method.

5.3 Economic analysis

The economic result section will further analyse the crop and electricity yields from the previous section (5.1 & 5.2). There had to be some assumptions made to calculate the costs of this newly designed system. The supporting construction consists of IPA400 construction beams. These beams can carry weights across relatively long distances. Firstly was assumed that aluminium trusses were capable of carrying the weight over 25m. However due to several interviews with manufacturers it became clear that due to wind loads and other variables this was practically impossible. IPA400 construction beams can carry more weight and in the end seem to be cheaper than a large aluminium truss. For the rails is also chosen to use a IPA200 beam. As these are H-shaped on which the construction will move across the field. The economic input data is given in 4.1.5.

5.3.1 NPV

This research has incorporated all the identified crops in a crop rotation plan as seen in . It seems that there is an increase in crop revenues when there are more PV-modules installed. This is mostly due to the fact that lettuce generates the most revenues and according to the literature even increases its biomass under minder shading conditions. Furthermore, the yield of other crops is not very affected by the PV-scenarios of this research either. However one important aspect should be taken into account is that the costs for crop revenue are not considered in this research. Nevertheless, in all cases is the NPV positive over a lifetime of 30 years. The full annual values are included in section 0. The revenues of the 10% & 20% scenario increases the most by 20%. The other PV scenarios increase less because the crop revenues increases less than the 10% and 20% scenario.

Table 17: Discounted revenues over a 30yr lifetime of both crops and electricity. See for full annual values appendix 0.

Total Revenues	PV-scenario					
	0	**10**	**20**	**30**	**40**	**50**
Crop revenues	€ 97.500	€ 103.518	€ 105.918	€ 106.159	€ 103.863	€ 98.930
Electricity revenues	€ -	€ 12.997	€ 33.549	€ 51.708	€ 77.076	€ 96.496
Total	**€ 97.500**	**€ 116.515**	**€ 139.468**	**€ 157.867**	**€ 180.939**	**€ 195.426**
Difference to previous scenario	**0**	20%	20%	13%	15%	8%

5.3.2 LCOE & PBP

The LCOEs are calculated as is explained in section 3.3.1. There are multiple interesting facts seen in the results of the LCOE in Figure 29 & Figure 30. Firstly the LCOE of the monofacial PV-scenarios is higher than the LCOE of the bifacial PV-scenarios. One explanation for this is that the bifacial gain ensures more kWh than that the costs total costs increase. Secondly the costs of the rails as well as the costs of the electrical engines are equal for all PV scenarios. Furthermore is there a decrease of LCOE visible with an increase of PV-scenario. This is due to the fact that the costs of the rails and elecrtical engines are equal for all scenarios but the electricity generation increase which leads to a lower LCOE. Additionally the lower LCOE is ensured by the fact that some economies of scale take place as is explained in section 4.2.

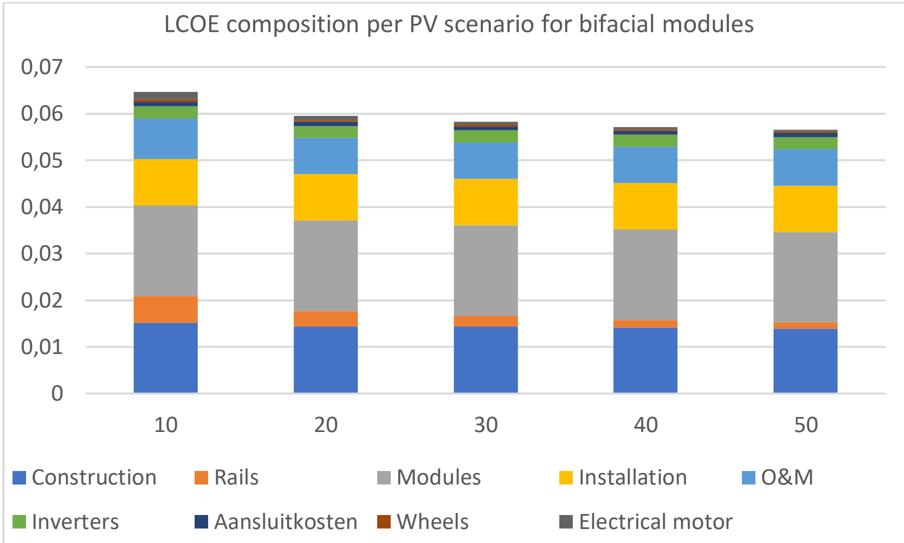


Figure 29: LCOE composition of bifacial PV-modules.

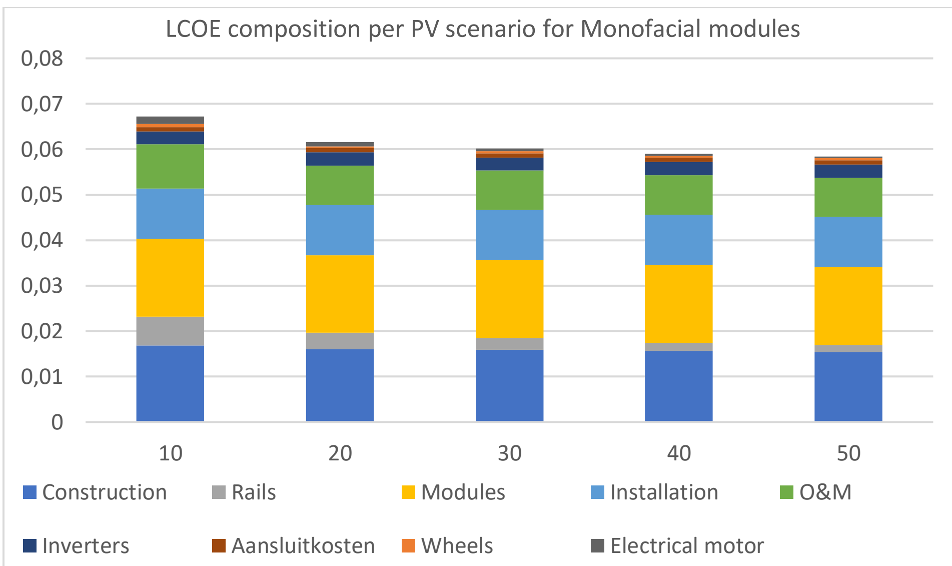


Figure 30: LCOE composition of monofacial modules.

In Figure 31 is the annual cash flow analysis depicted. For this analysis is assumed that the investment costs for the construction, electrical motors, modules, rails, wheels and installation have been done in year 0. The annual revenues from electricity are starting in year 1 as are the operating and maintenance costs. Achter 15 years the SDE+ subsidy is stopped and the annual revenues from electricity drop. The payback periods for the 20 -50% PV-scenarios are shorter, around year 14. The 10% scenario has the longest payback period of 19 years. This is due to the fact that the wheels and rail infrastructure are roughly equal for all scenarios. This means that the relative costs of this infrastructure is larger for the 10% scenario which is also visible in the LCOE in Figure 29 & Figure 30.

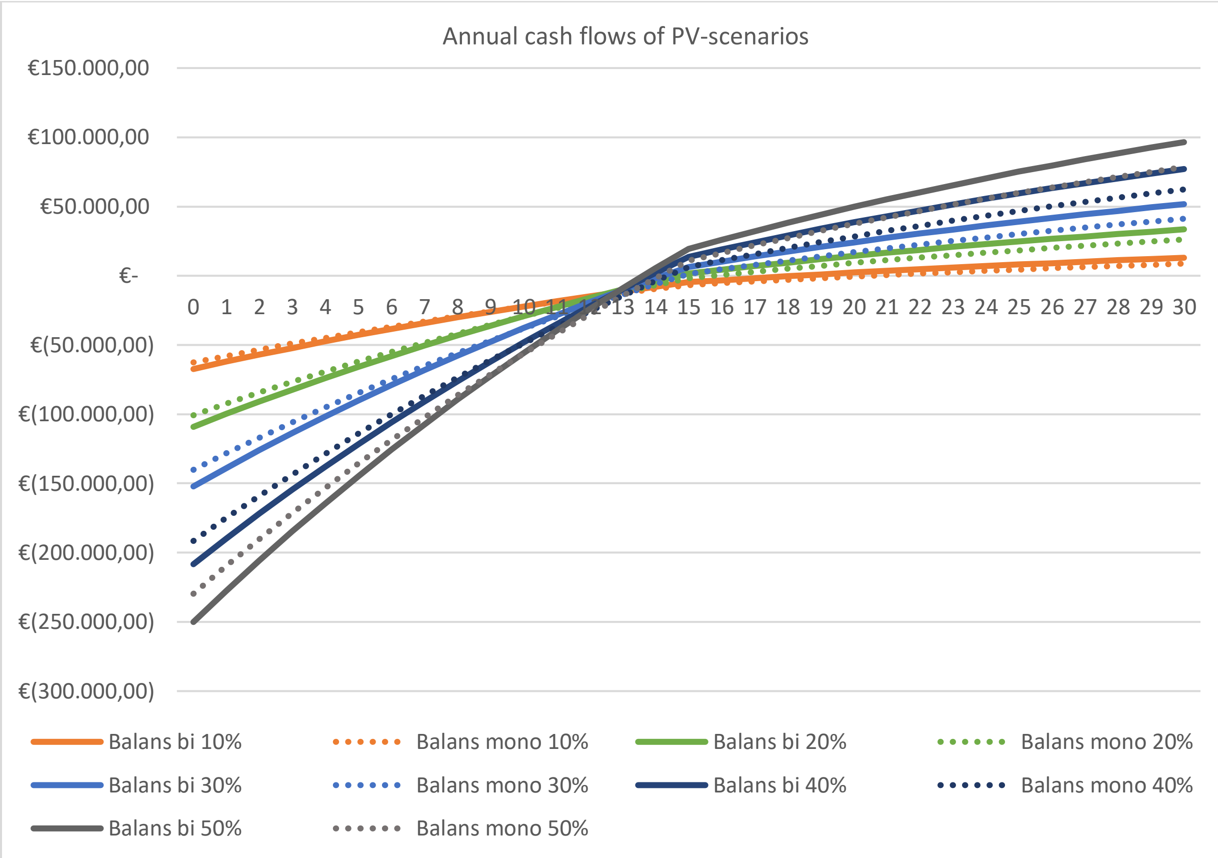
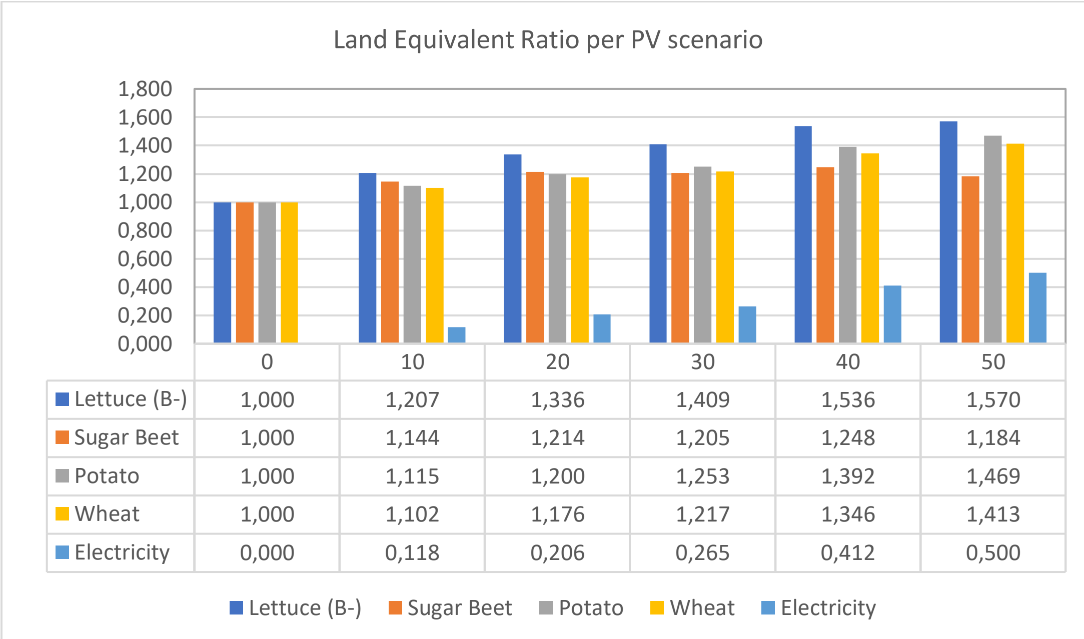


Figure 31: Cashflows during the 30 years. The graph is explained in the paragraph above.

5.3.3 Land Equivalent ratio

The LER method combines the revenues of both the crops and the electricity generation. It compares every crop scenario to the agriculture only scenario. For the electricity generation the PV-scenarios are compared to a full solar park. The LER is composed of these two factors. Therefore should Figure 32 be read as followed: The total LER is divided per crop and PV scenario. For the 10% scenario the total LER for lettuce is estimated at 1.207. Subtract the electricity part (0.118) to find the LER solely of the crop: 1.089 (1.207-0.118). This is in line with previous results as crop increased its biomass in this PV-scenario.



	0	10	20	30	40	50
Lettuce (B-)	1,000	1,207	1,336	1,409	1,536	1,570
Sugar Beet	1,000	1,144	1,214	1,205	1,248	1,184
Potato	1,000	1,115	1,200	1,253	1,392	1,469
Wheat	1,000	1,102	1,176	1,217	1,346	1,413
Electricity	0,000	0,118	0,206	0,265	0,412	0,500

Figure 32: Different LER per PV-scenario. All scenarios are above 1, which implies that in all cases land can be saved by combining crops and PV-modules (Agrivoltaic). The graph should be read is explained above the figure.

The largest LER is in the 50% PV-scenario. This means that the gain by the electricity generation is larger than the decrease of crop yield. This implies that the combination of crops and photovoltaic energy is more land efficient than separating the two. For lettuce is the LER the largest because lettuce has the highest shade tolerance and even increases biomass. Therefore will the combination be extra effective which can also be seen in Figure 32 when looking at the blue bar. However, all LER are above one so these results suggest that the implementation of a dynamic agrivoltaic system would be land efficient.

5.4 Sensitivity Analysis

For the sensitivity analysis are the LCOE (see Figure 33) and je NPV included (Figure 34& Figure 35). The LCOE does not include the energy price as this only incorporates the costs of electricity generation. A second sensitivity analysis regarding the NPV is also included to see how large the influence is of the electricity price. However, each crop is addressed individually according to different literature extensively in section 5.2. Therefore, is the sensitivity regarding crop revenues are not further incorporated in the NPV sensitivity analysis. The range for the electricity price has been set from -25 – 25%. This is done because there is still an ongoing debate about the SDE+ subsidy and the basic electricity price. The first differs each year and per requesting time slot (fase bedrag) while the latter differs per energy company. However the 10% scenario is the least affected by the electricity (see Figure 34). The NPV is more affected with an increase in PV-scenario. Furthermore, all scenarios will result in a negative NPV if the electricity price decreases over 20% (see Figure 34). The change due to electricity price is larger than the changes due to the installation costs (Figure 35). From the LCOE sensitivity analysis has become clear that the discount rate and modules price are largest influencers of the LCOE. The construction costs are also largely influential for the LCOE.

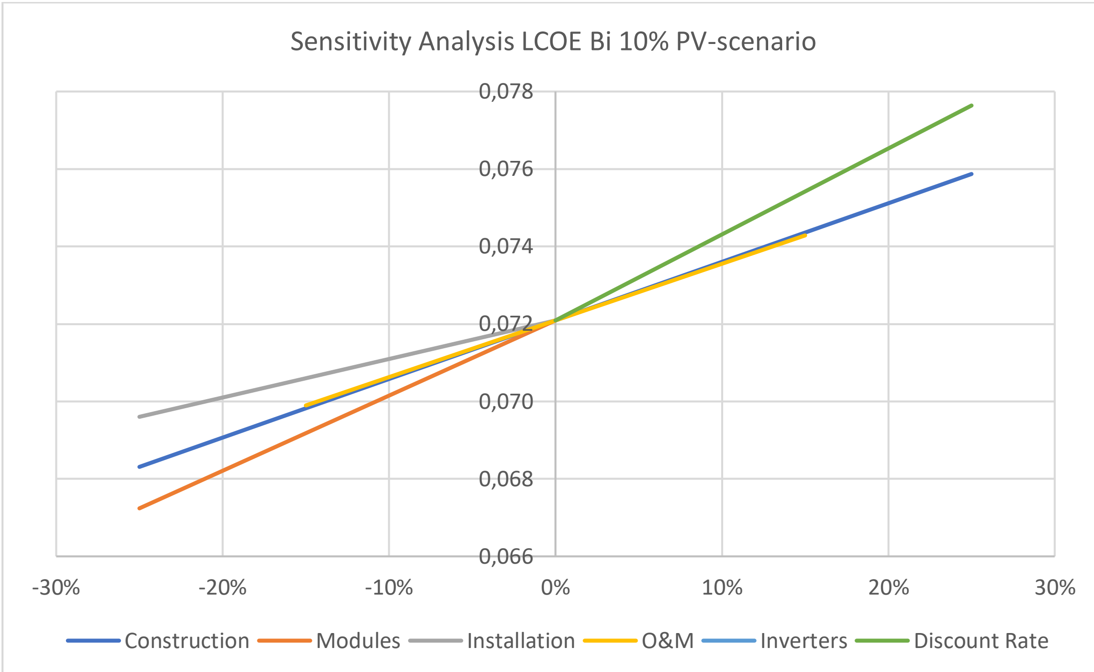


Figure 33: Sensitivity analysis of the LCOE of bifacial module. As the only difference between the monofacial and bifacial scenarios is the cost price of the modules, the graphs would almost equal. The ranges of the different factors are established as followed: Due to technological learning and economies of scale will the costs only drop for; module, inverter and installation. Construction costs can both increase and decrease as this values are relatively uncertain. Therefore is chosen to see the sensitivity when these costs drop or increase to a maximum of 25%. However the discount rate was established from literature which used 3%. However other literature incorporated discount rates in the range of 3% – 7%. However this would mean that the increase in percentages would be over 200% and will result in a unreadable graph. Therefore is chosen to show the discount rate change only to 25% in this graph to show the effect in regard to the other aspects. However, a discount rate of 7% results in a LCOE of over 0,1025€/kWh.

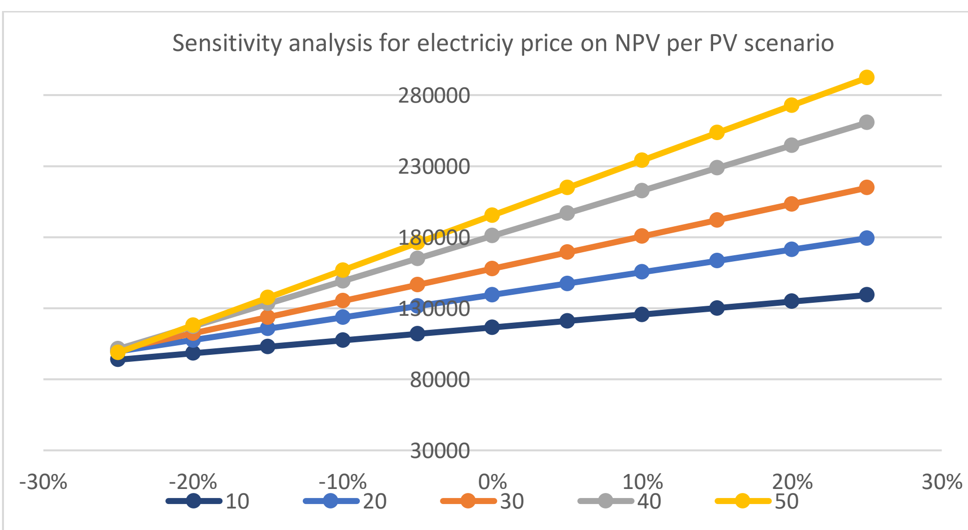


Figure 34: Sensitivity analysis for electricity price on the total NPV per crop. Other crop revenues are not taken into account as the results of section 5.2. The sensitivity of the other costs are equal to the results of the LCOE analysis.

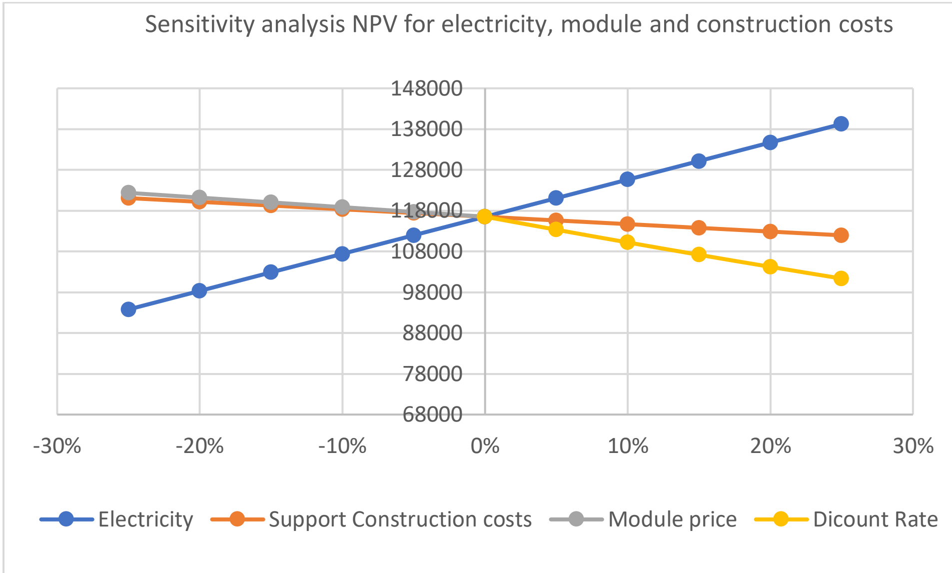


Figure 35: Sensitivity analysis of NPV of the 10% bifacial scenario. The blue line depicts the NPV of the electricity generation. Electricity prices can fluctuate up and down and is therefore varied of the whole range. The discount rate can only go up as this is currently set at 3% and the module price is estimated to decrease due to technological learning. The change due to the electricity price variation is larger than the construction module costs and discount rate.

6 Discussion

As this research is constantly divided into three aspects, the discussion will address these aspects accordingly. Firstly, the technological aspects will be discussed followed by the crop yield and the economic part. At the end of this chapter suggestion for future research and possibilities are given with an overall integration of the mentioned discussion points.

6.1 Technologic

One of the most important aspects worth mentioning regarding this research is the fact that the software that is used to simulate the daily insolation is not specifically designed for this purpose. Although the 3D model can be precisely designed it proved difficult to accurately design other variables like transparency and reflection of incoming solar radiation. Nevertheless, the insolation values which are presented in Table 12 give a good idea of the decrease of daily average insolation per PV-scenario. However, because this simulation proved to be time consuming only 4 dates have been simulated. The linear interpolation between the 4 solstices/equinoxes (Figure 20) decreased the required simulation time. However, simulating a whole year would definitely increase the accuracy of the insolation results.

Therefore, an important suggestion would be to further develop a dynamic 3D model which simulates insolation values while also moving the structure across the field. The Autodesk™ Revit™ software does not combine these two aspects which leads to less accurate results. Further developing simulation software can also optimize the variable speed which is necessary to distribute the shade more equally across the field. The simulation software should incorporate the factor that the insolation intensity directly increases the movement speed of the panels. This ensures that the lines in Figure 19 are even more straight and thus ensures that the whole field receives an even amount of insolation.

Another interesting part for future research is that the Photosynthetically Active Radiation spectrum and the Photovoltaic spectrum operate the most efficiently in two different regions, 400-700nm and 800-1200nm respectively. If future technologies are able to accumulate only the most efficient part of the spectrum and let the PAR spectrum pass through for the crops it might even be possible to gain even higher efficiencies. One solution could be the implementation of transparent modules which are nowadays installed in offices or houses instead of regular glass. The development of transparent panels is already happening. However, industrial purposes are not yet feasible, to my knowledge. Nevertheless, with the increasing pressure on fertile land to feed the world, it might be worthwhile to further investigate and develop this technology.

A point of discussion is the bifacial gain which is included in the analysis. Current literature does not have a standard method of calculating this gain. This gain is often given by manufacturers for these modules, but it decreases the reliability when this gain is not tested by an independent third party. The bifacial gain that is incorporated in this research is estimated on both manufacturers' values and other research. The gain is dependent on different aspects as ground albedo and installation height. However, the current literature does not contain any examples which installs the modules at a height of the desired 5m. Therefore, future research should establish the bifacial gain for higher placed modules. Additionally, the albedo factor of agriculture should be established with higher accuracy to further increase the reliability of the results.

The supporting structure is another important aspect which should be further investigated, as different assumptions have been made regarding the construction material and installation costs. Primarily it was thought that aluminium trusses would be sufficiently strong to carry the weight of the modules across large distances. However, from personal communications (email communication and quotations may be requested) it became clear that this was practically impossible or extremely expensive. Therefore, the steel beams have been chosen and an extra rails was put in the middle so that the carrying distance is only 25m instead of 50m. This research incorporates some simplified (static) calculation regarding wind loads and rolling friction while this can also be modelled/estimated with higher precision. Some research did this by means of computational fluid design (CFD) methods. However, this specific construction system is not incorporated and should be done with the help of a structural engineer to prove even more that the IPE400 beams are indeed strong enough to carry the total loads on the construction. Additionally, this research created a hypothetical field with the North-South orientation. Future research should incorporate different orientations because the panels need to be mounted differently to efficiently generate electricity.

In this research the movement of the system is done by installing electrical rotating motors. In order to do this can the electricity be drawn directly from the PV-panels. However, the necessary power to move the system at the desired variable speeds is addressed simply by calculating the drag forces on the first row of panels. While drag forces from wind should also be calculated in a more precise manner by CFD. The drag forces as well as the rolling friction need to be overcome by these electrical rotating motors. As the movement speeds are relatively low (as can be seen in Table 7) these electrical motors do not have to be powerful and a 5kW will be more than sufficient. This aspect however should be further integrated in future research as well as an efficient cable management system.

6.2 Biological

The specific crop yields of this research is based on different shading scenarios of other research (Dinesh & Pearce, 2016; Dupraz et al., 2011; Marrou, Wery, et al., 2013). The difference between the existing literature and this research is the amount of shading that is resulting from the chosen shading scenarios (0 -50%). Existing literature often incorporates only 2 shading scenarios (FD & HD) while this research did 5 in total. Accompanied by the two shading scenarios is a certain crop yield. This research used the yield and shading scenarios by creating a polynomial trendline. This trendline resulted in multiple cases in a positive (increase) in yield. However, literature research often shows that it is possible that some crops can increase their biomass in shading conditions because it means increasing the leaf area and thus increasing photosynthesis with less sunlight.

Addressing each crop individually has certainly increased the reliability of the crop yield results in the shading scenarios of this research. However, it is still suggested that this should be proven by actual field trials. Moreover, because the system is moving across the field, the intermittency of insolation can influence crops differently which should also be investigated further. Nevertheless, with regard to the RUE method, it seems that the qualitative approach does seem useful when it comes to modelling crop yield under shading scenarios. This is argument is even supported by the fact that most crop growth models, among which the LINTUL-model, use the RUE method which according to this research would give substantially different answers with lettuce being the most extreme example (see Figure 21). In most cases the yield and thus the revenues are, according the RUE method, the lowest with regard to the qualitative approach. This would suggest that findings from incorporated literature would not be in line with crop growth models which should also be further investigated in future research.

Future research should incorporate more crops to see if agrivoltaic systems are more applicable in the Netherlands. For example, union cultivation in the Netherlands is relatively large but not taken into account due to the scope of this research. Nevertheless, more data about more different crops can support the choice of agrivoltaics because it also increases the flexibility for possible crop rotation. Furthermore, the included crops in this research should be analysed more in-depth, as the dynamic part of this agrivoltaic system ensures a certain intermittency in insolation. This could influence crop growth in a different way than is measured by the included literature regarding crop yield and shading scenarios of section 5.2. Furthermore, other limiting factors nutrients, fertilizers and irrigation are not taken into account in this research due to the time and scope. Future research should incorporate these factors in combination with agrivoltaics to further increase the available data. A suggestion would be to combine crop models with better simulation software where these factors can be incorporated more easily.

6.3 Economic

For the economic analysis some assumption had to be made. One being that the farmer only cultivates one crop each year. The economic input values for all crops except lettuce originate from the Wageningen University which depicts the revenues per hectare. However, farmers do implement crop rotation in different ways. Which means that these revenues do not fully depict the annual revenues of a crop plot. Furthermore, farmers tend to rent out land or use land in the combination with livestock. Which leads to extra annual revenues that are not taken into account in this research. Additionally, these revenues should be addressed with caution as these do not incorporate other costs like labour, machinery or energy, for instance. Future analysis should further incorporate more accurate revenue and costs data from farmers to further increase reliability about the agrivoltaic financial attractivity.

Nevertheless, the NPV of all scenarios seemed to be positive for all PV-scenarios. The payback periods where relatively long, while normal PV modules contain a payback period between 10 a 14 years according to Spruijt, J (2015). However, in this case is assumed that all the electricity is sold back to the grid. The prices which consumers pay for electricity are higher. Therefore can the financial attractivity be even larger when the electricity which is consumed by the farmer be generated by the agrivoltaic system. This might even further reduce the payback period. However, due to the scope of this research is chosen not to take this into account and future research should definitely incorporate this factor.

Another important result from the sensitivity analysis was that the module price influences the LCOE severely (see Figure 33). The module price of bifacial panels is retrieved from Libal et al. (2017). However, this module price differs from the estimated module price from Beurskens & Lemmers (2017). This means that the input data for the PV-modules with regard to the overall financial attractivity of this system is important. Future research should combine the research with more accurate quotations of different distributors to increase the reliability of the results. Additionally, getting accurate quotations for the construction and rails should also be more in-depth analyzed as the construction costs are a large part of the costs. The reduction of installation costs (see 4.2) for the construction due to economies of scale need to be further supported by incorporating quotations of multiple manufacturers.

The LER for the identified crops and the accompanied PV-scenarios were all above 1. Which means that all scenarios have a positive effect on land efficiency. When looking at existing literature, agrivoltaics showed a LER of around 1.73 for the Full density scenario (Dupraz et al., 2011). The largest scenario of this research showed a LER of around 1.5. The differences can be explained by the fact that the relative PV size in the literature is larger. The decrease of crop LER is also larger in the literature. This means that the increase of the total LER is due to the larger increase of the PV-part. This is line with the results of this research. The LER is more affected by the increase of the PV part than by the decrease of the crop part (see 5.3.3)Figure 32.

7 Conclusion

7.1 Technological conclusions

Agrivoltaic systems already exists but influence the farmers freedom to execute their work in practice. This research looks at how a dynamic system which gives the farmer more freedom, influences the amount of solar insolation. The used 3D modelling software was not designed for this purpose but still showed accurate insolation values.

The distribution of shade needs to be done equally by increasing the movement speed of the system during the time the sun is at its highest point and thus insolation intensity is the highest. The first results with constant movement speed showed that insolation values in the middle of the field are much lower than at the edges of the field.

Simulation time is efficiently decreased by simulating only 4 dates and finding the rest of the insolation values by linear interpolation. The largest PV-scenario (50%) resulted in an annual average insolation decrease of **31.1%**, while the smallest PV-scenario (10%) showed a decrease in insolation of **6,98%**. These decreases in insolation have been used to simulate crop yields and revenues. Moreover, there is a linear correlation between the increase of PV-modules (up to 50%) and the decrease of insolation Figure 15.

7.2 Biological conclusions

To maximize the potential of this dynamic system 3 crops have been identified which are cultivated at a relatively large scale in the Netherlands; Potato, Wheat and Sugar Beet. Lettuce is also included because existing literature regarding agrivoltaics have incorporated this crop. The inclusion of this crop creates the possibility to compare this dynamic system to the existing agrivoltaic literature.

Several literature studies have been incorporated to investigate how the identified crops behave under shading conditions. However, these studies often contained 2 shading scenarios. By plotting polynomial trendlines for the 4 crop, the accompanied yields for the 5 shading scenarios of this research have been found. This resulted in the fact that under small shading scenarios the identified crops were minimally affected or sometimes even increased their biomass. It can therefore be concluded that the RUE (linear) method is **not** reliable enough to be solely used to estimate crop revenues/yield. However, to which extent the crops are affected need to be more accurately proven in further field trial experiments under dynamic shading conditions.

7.3 Economical Conclusions

The agrivoltaic system increases the initial installation costs which resulted in a relatively large payback period of around 14 - 19 years. Nevertheless, when looking at the LER for this agrivoltaic system it shows that there is an increase in land efficiency for all crops under all PV-scenarios. The largest increase in LER is seen at the 50% PV-scenario with the combination of lettuce (see Figure 32). The lowest increase in LER is found for sugar beet, which can sustain a normal yield under a low number of shading conditions. However, with the 50% shading scenario the yield drops significantly and the LER results at 1.184. This value is relatively low in comparison with the other crops which are all above 1.4 in the largest shading scenario.

Furthermore, the total NPV was positive for all PV-scenarios which is also stimulated by the fact that crop revenues were relatively little affected by the PV-scenarios and thus contained relatively high crop revenues. However, the larger agrivoltaic construction costs ensures a payback period of around 15years but annual revenues increase significantly. The NPV of the technological part became negative with a decrease of around 20 of the electricity price.

7.4 Future research & possibilities

The goal of this research was to identify the potential of a dynamic agrivoltaic system. Despite of the mentioned discussion points, the results showed that this system seems relatively attractive. With regard to the overall insolation, results show that on large parts of a plot PV-modules can be installed with enough insolation available for crops to grow. Even while this insolation data should be gathered with higher precision. The assumptions regarding the supporting structure need to be further addressed in future research. Nevertheless, does this research provide an idea of the magnitude of the additional costs that need to be taken into account. The crop yields are estimated with the help of numerous literature studies and showed a higher reliability than the RUE method. However for future research is suggested to build the system on a small scale with different crops to find the accompanied crop yields and installation costs.

Next to the mentioned barriers of the system there are also multiple other possibilities. When there are no crops cultivated on the land, farmers can easily increase the number of PV-modules installed as most of the infrastructure is already installed. Which can lead to even more electricity revenues. Future models should incorporate these possibilities with the combination of detailed crop rotation. However, this research did not include personal interviews with farmers which is also a suggestion for future research. The dynamic aspect of this system can be even further expanded with possible crop monitoring equipment, precise irrigation & fertilization and even manual control of the precise shade and insolation for different parts of the crop plot. These factors offer the possibility to further reduce costs and enhance crop yield and thus revenues. With an increasing pressure on fertile land and relatively higher revenues from electricity production, the implementation of agrivoltaics could offer a viable solution. Moreover, the possible implementation in the Netherlands should be further investigated. Eventually, the agrivoltaic system can contribute to the renewable energy targets and also save land which is solely designated for PV or agriculture. The extent of this needs to be further addressed.

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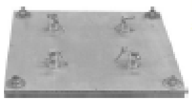
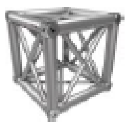
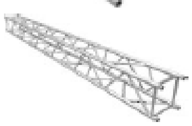
9 Appendix

9.1 Price indication for truss solution 20% PV

Pos.	Artikel-Bild	Bezeichnung	Menge	ME	Einzelpreis EUR	Gesamtpreis EUR
001		Naxpro-Truss - FD-HD 44 - Bodenpaltte 520 x 520 x 20 mm	8,00	Stück	439,00 EUR	3.512,00 EUR
002		Naxpro-Truss HD 44 Boxcorner mit 8 Halbverbinder	8,00	Stück	459,00 EUR	3.672,00 EUR
003		Naxpro-Truss Halb-Konusverbinder M12 für Boxcorner	48,00	Stück	9,00 EUR	432,00 EUR
004		Naxpro-Truss HD 44 Strecke 150 cm	6,00	Stück	259,00 EUR	1.554,00 EUR
005		Naxpro-Truss HD 44 Strecke 500 cm	42,00	Stück	609,00 EUR	25.578,00 EUR
		Static calculation All Naxpro-Truss trusses are statically calculated as single-span trusses. If a truss is used as a multi-span truss or outdoor, an additional individual construction static for the systems static is necessary. The operator can order this at a static engineering office of its choice.				
					Zwischensumme :	34.748,00 EUR

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Herr
Naut Loots
Looiersgracht, 30 30
1016 AMSTERDAM
NIEDERLANDE

Freibleibendes Angebot

Datum	: 28.08.2018
Angebot Nr.	: **AG2018064468 ***
Kunden-Nr.	: 462207 *
Kommission	: E-Mail
Seite	: 2 von 2

*** Bitte stets mit angeben!**

Pos.	Artikel-Bild	Bezeichnung	Menge	ME	Einzelpreis EUR	Gesamtpreis EUR
					Übertrag:	34.748,00 EUR

Zahlungsbedingungen	: Vorkasse, ohne Abzug	**Zwischensumme**	34.748,00 EUR
Zahlungsart	: Überweisung	15,00 % Rabatt	4.380,00 EUR
Lieferbedingungen	: EXW - ab Lager Bocholt	Gesamt brutto	29.535,80 EUR
Lieferart	: Abholung	inkl. 19 % MwSt	4.715,80 EUR
		Endsumme	**29.535,80 EUR**

Es gelten ausschließlich unsere beigefügten AGB. (www.LTT-Group.de/UAGB)
Dieses Angebot ist freibleibend. Ein Kaufvertrag soll erst dann zustande kommen, nachdem Sie uns eine dem Angebot entsprechende Bestellung übermittelt haben und wir Ihre Bestellung mit einer Auftragsbestätigung angenommen haben.

Delivery time: to be clarified

9.2 NPV

9.2.1 Annual Crop Revenues

Annual crop revenues	PV-scenario						
Year	**0**	**10**	**20**	**30**	**40**	**50**	**Crop**
0							
1	€ 1.611,65	€ 1.654,29	€ 1.624,63	€ 1.515,29	€ 1.347,09	€ 1.101,69	Sugarbeet
2	€ 4.278,44	€ 4.329,35	€ 4.351,87	€ 4.359,18	€ 4.346,99	€ 4.315,26	Potato
3	€ 12.255,58	€ 13.356,68	€ 13.849,02	€ 14.019,62	€ 13.772,90	€ 13.110,20	Lettuce
4	€ 658,81	€ 648,21	€ 639,06	€ 626,92	€ 614,93	€ 601,42	Winterwheat
5	€ 1.431,93	€ 1.469,82	€ 1.443,46	€ 1.346,32	€ 1.196,87	€ 978,83	Sugarbeet
6	€ 3.801,34	€ 3.846,57	€ 3.866,58	€ 3.873,08	€ 3.862,24	€ 3.834,06	Potato
7	€ 10.888,92	€ 11.867,23	€ 12.304,68	€ 12.456,25	€ 12.237,05	€ 11.648,25	Lettuce
8	€ 585,35	€ 575,92	€ 567,79	€ 557,01	€ 546,36	€ 534,35	Winterwheat
9	€ 1.272,25	€ 1.305,92	€ 1.282,50	€ 1.196,19	€ 1.063,40	€ 869,68	Sugarbeet
10	€ 3.377,44	€ 3.417,63	€ 3.435,41	€ 3.441,18	€ 3.431,55	€ 3.406,51	Potato
11	€ 9.674,67	€ 10.543,88	€ 10.932,55	€ 11.067,21	€ 10.872,46	€ 10.349,32	Lettuce
12	€ 520,07	€ 511,70	€ 504,48	€ 494,89	€ 485,43	€ 474,77	Winterwheat
13	€ 1.130,38	€ 1.160,29	€ 1.139,48	€ 1.062,80	€ 944,82	€ 772,70	Sugarbeet
14	€ 3.000,81	€ 3.036,52	€ 3.052,31	€ 3.057,44	€ 3.048,89	€ 3.026,64	Potato
15	€ 8.595,82	€ 9.368,10	€ 9.713,43	€ 9.833,08	€ 9.660,04	€ 9.195,23	Lettuce
16	€ 462,08	€ 454,64	€ 448,22	€ 439,71	€ 431,30	€ 421,82	Winterwheat
17	€ 1.004,33	€ 1.030,90	€ 1.012,42	€ 944,28	€ 839,46	€ 686,53	Sugarbeet
18	€ 2.666,18	€ 2.697,91	€ 2.711,94	€ 2.716,50	€ 2.708,90	€ 2.689,13	Potato
19	€ 7.637,27	€ 8.323,44	€ 8.630,25	€ 8.736,56	€ 8.582,82	€ 8.169,85	Lettuce
20	€ 410,55	€ 403,94	€ 398,24	€ 390,67	€ 383,20	€ 374,79	Winterwheat
21	€ 892,33	€ 915,94	€ 899,52	€ 838,98	€ 745,85	€ 609,98	Sugarbeet
22	€ 2.368,87	€ 2.397,06	€ 2.409,52	€ 2.413,57	€ 2.406,82	€ 2.389,26	Potato
23	€ 6.785,62	€ 7.395,27	€ 7.667,87	€ 7.762,32	€ 7.625,72	€ 7.258,80	Lettuce
24	€ 364,77	€ 358,90	€ 353,83	€ 347,11	€ 340,47	€ 332,99	Winterwheat
25	€ 792,83	€ 813,80	€ 799,21	€ 745,42	€ 662,68	€ 541,96	Sugarbeet
26	€ 2.104,71	€ 2.129,75	€ 2.140,83	€ 2.144,43	€ 2.138,43	€ 2.122,82	Potato
27	€ 6.028,93	€ 6.570,60	€ 6.812,80	€ 6.896,72	€ 6.775,36	€ 6.449,35	Lettuce
28	€ 324,09	€ 318,88	€ 314,37	€ 308,40	€ 302,50	€ 295,86	Winterwheat
29	€ 704,41	€ 723,05	€ 710,09	€ 662,30	€ 588,78	€ 481,52	Sugarbeet
30	€ 1.870,01	€ 1.892,26	€ 1.902,10	€ 1.905,30	€ 1.899,97	€ 1.886,10	Potato
Totaal	**€ 97.500,44**	**€ 103.518,45**	**€ 105.918,47**	**€ 106.158,73**	**€ 103.863,29**	**€ 98.929,68**	**30**

9.2.2 Annual electricity revenues

Electricity Revenues	PV-scenario				
Year	**10**	**20**	**30**	**40**	**50**
0	€ -67.376,48	€ -109.162,60	€ -152.165,63	€ -208.347,10	€ -250.089,25
1	€ 5.246,00	€ 9.282,45	€ 13.260,64	€ 18.564,90	€ 22.543,09
2	€ 5.070,80	€ 8.972,87	€ 12.818,39	€ 17.945,74	€ 21.791,26
3	€ 4.901,44	€ 8.673,60	€ 12.390,86	€ 17.347,21	€ 21.064,47
4	€ 4.737,72	€ 8.384,31	€ 11.977,58	€ 16.768,61	€ 20.361,88
5	€ 4.579,47	€ 8.104,64	€ 11.578,06	€ 16.209,29	€ 19.682,71
6	€ 4.426,49	€ 7.834,30	€ 11.191,85	€ 15.668,60	€ 19.026,15
7	€ 4.278,62	€ 7.572,96	€ 10.818,51	€ 15.145,92	€ 18.391,47
8	€ 4.135,68	€ 7.320,32	€ 10.457,61	€ 14.640,65	€ 17.777,93
9	€ 3.997,50	€ 7.076,11	€ 10.108,72	€ 14.152,21	€ 17.184,83
10	€ 3.863,94	€ 6.840,03	€ 9.771,47	€ 13.680,05	€ 16.611,49
11	€ 3.734,83	€ 6.611,81	€ 9.445,45	€ 13.223,62	€ 16.057,26
12	€ 3.610,03	€ 6.391,20	€ 9.130,29	€ 12.782,40	€ 15.521,49
13	€ 3.489,40	€ 6.177,94	€ 8.825,63	€ 12.355,88	€ 15.003,57
14	€ 3.372,78	€ 5.971,79	€ 8.531,13	€ 11.943,58	€ 14.502,91
15	€ 3.260,06	€ 5.772,50	€ 8.246,44	€ 11.545,01	€ 14.018,94
16	€ 1.483,11	€ 2.660,88	€ 3.801,26	€ 5.321,76	€ 6.462,14
17	€ 1.432,85	€ 2.571,01	€ 3.672,88	€ 5.142,03	€ 6.243,89
18	€ 1.384,28	€ 2.484,17	€ 3.548,82	€ 4.968,34	€ 6.032,99
19	€ 1.337,36	€ 2.400,25	€ 3.428,93	€ 4.800,51	€ 5.829,19
20	€ 1.292,01	€ 2.319,16	€ 3.313,09	€ 4.638,32	€ 5.632,25
21	€ 1.248,20	€ 2.240,80	€ 3.201,14	€ 4.481,60	€ 5.441,95
22	€ 1.205,87	€ 2.165,08	€ 3.092,97	€ 4.330,16	€ 5.258,05
23	€ 1.164,97	€ 2.091,91	€ 2.988,44	€ 4.183,82	€ 5.080,35
24	€ 1.125,46	€ 2.021,20	€ 2.887,43	€ 4.042,40	€ 4.908,63
25	€ 1.087,27	€ 1.952,88	€ 2.789,83	€ 3.905,76	€ 4.742,70
26	€ 1.050,38	€ 1.886,86	€ 2.695,51	€ 3.773,71	€ 4.582,36
27	€ 1.014,74	€ 1.823,06	€ 2.604,37	€ 3.646,12	€ 4.427,43
28	€ 980,30	€ 1.761,41	€ 2.516,30	€ 3.522,82	€ 4.277,71
29	€ 947,02	€ 1.701,84	€ 2.431,20	€ 3.403,68	€ 4.133,05
30	€ 914,87	€ 1.644,28	€ 2.348,97	€ 3.288,56	€ 3.993,25
Totaal	**€ 12.997,01**	**€ 33.549,04**	**€ 51.708,14**	**€ 77.076,18**	**€ 96.496,15**

9.2.3 Annual total revenues

Total revenues	PV-scenario					
Year	**0**	**10**	**20**	**30**	**40**	**50**
0	€ -	€ -67.376,48	€ -109.162,60	€ -152.165,63	€ -208.347,10	€ -250.089,25
1	€ 1.611,65	€ 6.900,30	€ 10.907,08	€ 14.775,93	€ 19.911,98	€ 23.644,78
2	€ 4.278,44	€ 9.400,15	€ 13.324,74	€ 17.177,57	€ 22.292,73	€ 26.106,52
3	€ 12.255,58	€ 18.258,11	€ 22.522,63	€ 26.410,48	€ 31.120,11	€ 34.174,67
4	€ 658,81	€ 5.385,93	€ 9.023,36	€ 12.604,50	€ 17.383,54	€ 20.963,30
5	€ 1.431,93	€ 6.049,29	€ 9.548,11	€ 12.924,38	€ 17.406,16	€ 20.661,54
6	€ 3.801,34	€ 8.273,06	€ 11.700,88	€ 15.064,93	€ 19.530,84	€ 22.860,21
7	€ 10.888,92	€ 16.145,85	€ 19.877,64	€ 23.274,76	€ 27.382,96	€ 30.039,72
8	€ 585,35	€ 4.711,60	€ 7.888,12	€ 11.014,61	€ 15.187,01	€ 18.312,28
9	€ 1.272,25	€ 5.303,42	€ 8.358,61	€ 11.304,91	€ 15.215,62	€ 18.054,51
10	€ 3.377,44	€ 7.281,57	€ 10.275,43	€ 13.212,65	€ 17.111,61	€ 20.018,00
11	€ 9.674,67	€ 14.278,72	€ 17.544,36	€ 20.512,66	€ 24.096,08	€ 26.406,57
12	€ 520,07	€ 4.121,73	€ 6.895,68	€ 9.625,18	€ 13.267,83	€ 15.996,26
13	€ 1.130,38	€ 4.649,68	€ 7.317,43	€ 9.888,43	€ 13.300,70	€ 15.776,27
14	€ 3.000,81	€ 6.409,30	€ 9.024,10	€ 11.588,57	€ 14.992,47	€ 17.529,55
15	€ 8.595,82	€ 12.628,17	€ 15.485,93	€ 18.079,51	€ 21.205,05	€ 23.214,17
16	€ 462,08	€ 1.937,75	€ 3.109,10	€ 4.240,97	€ 5.753,06	€ 6.883,97
17	€ 1.004,33	€ 2.463,75	€ 3.583,43	€ 4.617,16	€ 5.981,49	€ 6.930,43
18	€ 2.666,18	€ 4.082,19	€ 5.196,11	€ 6.265,32	€ 7.677,25	€ 8.722,12
19	€ 7.637,27	€ 9.660,80	€ 11.030,51	€ 12.165,50	€ 13.383,33	€ 13.999,03
20	€ 410,55	€ 1.695,96	€ 2.717,40	€ 3.703,76	€ 5.021,53	€ 6.007,04
21	€ 892,33	€ 2.164,15	€ 3.140,32	€ 4.040,13	€ 5.227,45	€ 6.051,92
22	€ 2.368,87	€ 3.602,93	€ 4.574,60	€ 5.506,54	€ 6.736,98	€ 7.647,31
23	€ 6.785,62	€ 8.560,24	€ 9.759,78	€ 10.750,76	€ 11.809,54	€ 12.339,15
24	€ 364,77	€ 1.484,35	€ 2.375,03	€ 3.234,54	€ 4.382,88	€ 5.241,63
25	€ 792,83	€ 1.901,08	€ 2.752,09	€ 3.535,25	€ 4.568,43	€ 5.284,66
26	€ 2.104,71	€ 3.180,13	€ 4.027,69	€ 4.839,94	€ 5.912,14	€ 6.705,19
27	€ 6.028,93	€ 7.585,34	€ 8.635,86	€ 9.501,09	€ 10.421,47	€ 10.876,78
28	€ 324,09	€ 1.299,17	€ 2.075,78	€ 2.824,70	€ 3.825,33	€ 4.573,57
29	€ 704,41	€ 1.670,07	€ 2.411,93	€ 3.093,50	€ 3.992,46	€ 4.614,57
30	€ 1.870,01	€ 2.807,13	€ 3.546,38	€ 4.254,27	€ 5.188,53	€ 5.879,35
Totaal	**€ 97.500,44**	**€ 116.515,46**	**€ 139.467,51**	**€ 157.866,87**	**€ 180.939,47**	**€ 195.425,83**