

**ENERGY PRODUCTION COMPARISON OF BIFACIAL SOLAR PANELS
FOR AGRIVOLTAIC APPLICATIONS IN VERTICAL FIXED AND
HORIZONTAL AXIS TRACKING CONFIGURATIONS**

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ABSTRACT

Master's Thesis

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Solar energy is one of the fastest growing renewable energy sources in the world. Increasing concern of greenhouse gas emissions and climate change has led to a higher demand for clean energy. This has led to innovative solutions from engineers such as the use of bifacial photovoltaic systems in combination with agriculture, commonly referred to as agrivoltaic farming. In this study, the performance of fixed vertical agri-photovoltaic (APV) and horizontal tracking APV systems was studied by simulating a 132 kWp bifacial system on PVsyst and PVSOL. The annual output power of the two systems, performance ratio (PR) and bifacial performance ratio were obtained. The degree of shading on the crops as a result of APV was also studied. The beam horizontal irradiance under shading conditions, and diffuse horizontal irradiance under shading conditions were calculated for 21 April, 21 June, 23 September, and 23 December for both APV systems. The global horizontal irradiation under shading conditions at 9:00, 12:00 and 16:00 o' clock was calculated using the shading factor for beam f_b , and shading factor for diffuse f_d , values obtained from the shading factor table. Finally, the bifacial and monofacial output power of a bifacial panel was measured hourly from 09:00 to 18:00, to determine the bifacial gain (BG).

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Key Words: Agriphotovoltaic systems (APV), Performance ratio (PR), Bifacial Gain (BG), Beam horizontal irradiance under shading conditions, Diffuse horizontal irradiance under shading conditions, Global horizontal irradiation under shading conditions

ÖZET

Yüksek Lisans Tezi

DİKEY SABİT VE YATAY EKSEN GÜNEŞ TAKİP SİSTEMİ ÜZERİNDEKİ ÇİFT YÜZLÜ GÜNEŞ PANELLERİNİN AGRI-VOLTAİK UYGULAMALAR İÇİN ENERJİ ÜRETİMİ KARŞILAŞTIRMASI

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Güneş enerjisi, dünyanın en hızlı büyüyen yenilenebilir enerji kaynaklarından biridir. Sera gazı emisyonları ve iklim değişikliği konusundaki artan endişe, temiz enerjiye olan talebin artmasına yol açmıştır. Bu, mühendislerin tarımla birlikte çift taraflı fotovoltaik sistemlerin kullanımı gibi yenilikçi çözümlere yol açmıştır; buna yaygın olarak agrivoltaik çiftçilik denir. Bu çalışmada; sabit dikey ve yatay izlemeli çift yüzeyli tarımsal fotovoltaik (APV) sistemlerin performansı, PVsyst ve PVSOL üzerinde 132 kWp'lik bir sistem simüle edilerek incelenmiştir. İki sistemin yıllık çıkış gücü, performans oranı (PR) ve çift taraflı performans oranı elde edildi. APV'nin bir sonucu olarak mahsullerdeki gölgelenme derecesi de araştırıldı. Gölgelediği direkt yatay ışınım ve gölgelediği dağınık yatay ışınım, her iki APV sistemi için 21 Nisan, 21 Haziran, 23 Eylül ve 23 Aralık tarihlerinde hesaplandı. Sabah 9:00, öğlen 12:00 ve 16:00'daki gölgelediği küresel yatay ışınım, gölgeleme faktörü tablosundan elde edilen ışınım gölgeleme faktörü f_b ve yaygın gölgeleme faktörü f_d değerleri kullanılarak hesaplandı. Son olarak, iki yüzeyli bir panelin iki yüzeyli ve tek yüzeyli çıktı gücü, iki yüzeyli kazancı (BG) belirlemek için saat 09.00'dan 18.00'e kadar saatlik olarak ölçüldü.

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Anahtar Kelimeler: Tarımsal fotovoltaik sistemler (APV), Performans oranı (PV), İki Yüzlü Kazanç (BG), Gölgelediği yatay ışınım, Gölgelediği dağınık yatay ışınım, Gölgelediği küresel yatay ışınım

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SYMBOLS AND ABBREVIATIONS

G	Irradiation
G^{Front}	Front side irradiation
G^{Rear}	Rear side irradiation
h	Module elevation from ground
P_{BPV}	Bifacial Output Power
η	Efficiency
α	Ground albedo
β	Module's tilt angle
θ_z	Solar zenith angle
AgriPV	Agriphotovoltaic System
APV	Agrivoltaic System
BG	Bifacial Gain
BPV	Bifacial Photovoltaic
DHI	Diffuse horizontal irradiation
DNI	Direct Normal Irradiation
EArray	Effective energy at the output of the array
EdF	Électricité de France
FF	Fill factor
GCR	Ground Coverage Ratio
GHI	Global Horizontal Irradiation
GlobEff	Effective global coefficient for IAM and shadings
GlobInc	Global incident irradiation

I_{SC}	Short-circuit current
LAOR	Land area occupation ratio
LER	Land Equivalent Ratio
LCOE	Levelized Cost of Electricity
MPV	Monofacial Photovoltaic
P	Power
PAR	Photosynthetically Active Radiation
POA	Plane of array
P_{MPP}	Power output at maximum power point
PR	Performance ratio
PV	Photovoltaic
STC	Standard Test Conditions
T_{NOCT}	Nominal operating cell temperature
V_{OC}	Open-circuit voltage
V_{MPP}	Voltage at Maximum Power Point
$V_{abs\ max}$	Maximum Absolute DC voltage

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1. INTRODUCTION

Solar energy is one of the fastest growing renewable energy sources in the world. Up till now, the common method of solar power harvesting is the use of photovoltaic (PV) solar cells. However, since PV module efficiencies are quite low, huge portions of land are required to generate electricity (Katsikogiannis, 2022). Often, land use is preferred for agriculture in place of electricity generation. This has led to innovative solutions from engineers, such as the use of bifacial photovoltaic systems in combination with agriculture, commonly referred to as agrivoltaic farming. While monofacial modules are still the most widely used PV solar cells, bifacial modules will soon substitute monofacial cells. Bifacial solar modules produce more energy than monofacial modules because they can capture irradiation from the front and back sides of a solar panel. Vertical bifacial PV systems are installed with the modules not tilted, and they can therefore be used in variable applications such as solar fences or novel agro-PV systems (Varbov, 2023). When compared to conventional PV installations, which are commonly installed at a tilted angle, vertical bifacial systems require less land and are therefore advantageous. Furthermore, vertically mounted modules accumulate less snow and dust compared to tilted modules. In most scenarios, the power generated on the back side of a bifacial module is expressed in terms of ‘bifacial gain’, which refers to the fraction of energy produced from the back side in comparison to that produced from the front side. Research has shown that there is an increase of between 3-30 % in total power output due to the extra rear side power (Dullweber & Schmidt, 2016). The output energy of a bifacial module can vary due to parameters such as the albedo, module elevation and orientation, the ground coverage ratio (GCR), and the azimuth angle (Muehleisen et al., 2021). These parameters must be considered in a detailed manner during the design and installation of the system to ensure optimum energy production.

On the other hand, energy generation activities can be unfavorable when combined with crop production activities. This is because plants require sunlight to grow, and installing PV modules on a farm, casts a shadow on the plants and this negatively impacts their growth. Photosynthetically active radiation (PAR) refers to the light spectrum portion that is necessary for plant photosynthesis and therefore growth. When plants do not receive

the right quantity and quality of light, their growth is stunted, and crop yield is negatively impacted. When PV arrays are integrated with farming, engineers must be careful not to sacrifice plant yield in pursuit of energy production. The right balance that ensures maximum energy and minimum PAR deficit must be established.

This thesis study aims to compare the performance of fixed vertical and horizontal tracking bifacial agri PV systems. The objectives of the study are:

- To obtain the annual output power from a fixed vertical and horizontal tracking bifacial agriPV by simulation using PVsyst and PVSOL software.
- To obtain the shaded beam and shaded diffuse horizontal irradiance in the systems above in order to understand the effect of PV installation on agricultural land.
- To illustrate bifacial gain (BG) in a solar module by measuring hourly output power in a monofacial and bifacial solar panel.

2. LITERATURE REVIEW

2.1 Bifacial Photovoltaic Technology

Bifacial solar technology was first explored in the 1960s, but bifacial solar cells were developed in later years (Hiroshi, 1961). Interest in bifacial photovoltaic technology peaked in the 2010s as the world shifted toward renewable energy and researchers focused on photovoltaics. A bifacial solar cell works the same way a monofacial cell does. Both cells convert solar radiation to electric energy through photoelectric effect. The sun's rays fall upon a photovoltaic material causing the electrons to move from the non-conducting band to the conducting band. This results in electron-hole pairs (Gu et al., 2019). The negative electrons move towards the n-type silicon semiconductor and the positively charged holes move towards the p-type silicon semiconductor. An electromotive force is then generated between the solar cell's contacts. Connecting two sides of a photovoltaic cell causes the electrons to move through the external charge. However, unlike the monofacial PV cells whose back side is coated in aluminium, in a bifacial solar cell there are silicon cells in on front and rear side which convert diffuse and reflected radiation to electricity. An anti-reflective layer maximizes collection of received irradiations. Figure 2.1 below shows the internal structure of solar cells.

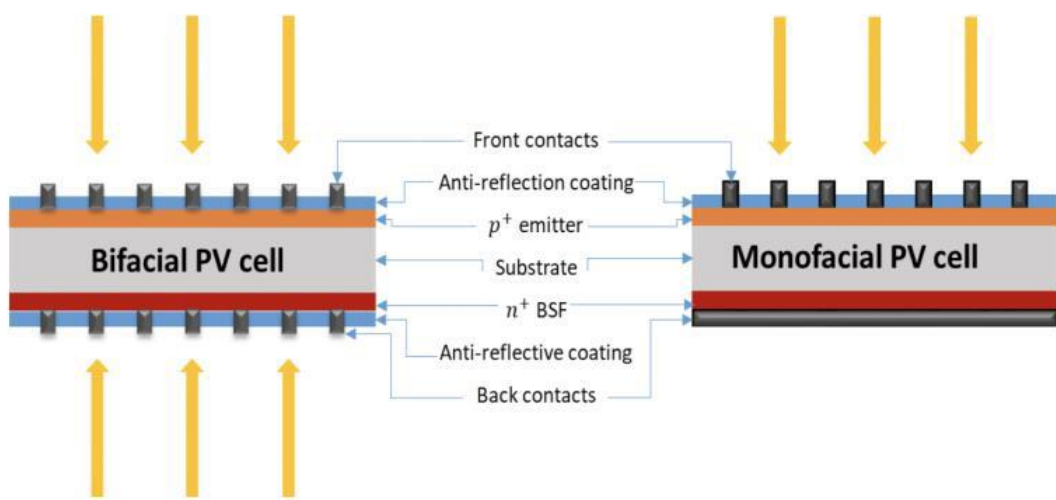


Figure 2.1 Internal structure of solar cells (Wang & Xuan, 2018)

There are several applications that are suitable for bifacial PV panels. The most commonly explored include agrivoltaic (APV) systems, floating photovoltaic systems, aquavoltaic systems, and building-integrated PV systems. A plot of land is used for agricultural activities and solar energy production in APV systems. Vertical bifacial and elevated horizontal are the most common types of APV systems. Floating photovoltaics involves energy generation from PV modules on waterbodies such as seas, lakes, ponds, dams and reservoirs. These systems are advantageous because they require no land. Aquavoltaic systems utilize water bodies simultaneously for fish farming and solar energy production (Pringle, 2017). For aquavoltaic systems, there is fish farming involved while for floating photovoltaic systems, fish farming is not practiced. Aquaculture is a high energy input activity which requires an external supply of oxygen, since cultured fish consume less fish feed when the oxygen levels are low. This results in low fish output. Energy from aquavoltaic systems can be used in water pumping to ensure sufficient oxygen mixing in the different oxygenation zones in water bodies. This results in greater fish production and less energy input.

2.2 Performance Parameters of Bifacial Photovoltaic Technology

The energy gained at the back side of a bifacial cell is referred to as bifacial gain (BG). It is the ratio of back side to front side energy in kWh under the same installation configurations and conditions. Albedo and pitch, which can also be referred to as the spacing between the solar panels, values determine BG. Higher albedo results in more BG. Low pitch results in low BG (Stein et al., 2021).

$$Bifacial\ Gain\ (BG) = \frac{Energy(Rear)}{Energy(Front)} \quad (1)$$

The bifacial gain can also be expressed as:

$$Bifacial\ Gain\ (\%) = \frac{E_{bifacial} - E_{monofacial}}{E_{monofacial}} \times 100 \quad (2)$$

Where $E_{bifacial}$ is the bifacial photovoltaic (BPV) system's output power, and $E_{monofacial}$ is the monofacial photovoltaic (MPV) system's output power, when measured under the same conditions, that is, same site, same installation parameters and same time frame.

Another important term is the bifaciality factor/ bifaciality coefficient (ϕ) which refers to rear-to-front power ratio at standard test conditions (STC). This coefficient demonstrates the additional power generated from rear side irradiation. PV manufacturers specify this factor which typically ranges from 70-80% based on the technology used and the production year (Daniels, 2022). Electrical properties of BPV cells, such as, output power, efficiency, short circuit current (I_{SC}) and open circuit voltage (V_{OC}), can also be used to calculate BG. (Mouhib, 2022).

$$\phi_{I_{SC}} = \frac{I_{scr}}{I_{scf}} \quad (3)$$

$$\phi_{V_{OC}} = \frac{V_{ocr}}{V_{ocf}} \quad (4)$$

$$\phi_{P_{max}} = \frac{P_{max,r}}{P_{max,f}} \quad (5)$$

$$\phi_{\eta} = \frac{\eta_r}{\eta_f} \quad (6)$$

The term ‘albedo’ is another important and commonly used term in bifacial photovoltaic technology. It describes the proportion of light reflected from different surfaces to incident radiation. Values lie between 0 and 1, and are referred to as the albedo coefficient. Different surface types have got different albedo coefficient values. The albedo of fresh snow is between 0.80 and 0.90 (Anderson, 2011). Green grass has an albedo of 0.20-0.25. Agricultural crops have an albedo of 0.18-0.25, and fresh asphalt has an albedo of 0.03-0.04. The darker the surface type the lower the albedo value. The albedo coefficient is important in BPV technology which relies on rear side irradiation for maximum energy. Higher albedo leads to more rear side irradiation and consequently, more power output.

2.3 Optimum Mounting of Bifacial Solar Modules

Bifacial modules allow more flexibility in their mounting options since they capture the sun’s rays from both sides. Several studies have been conducted under a variety of tilt and installation options, to determine the optimal and optimum mounting configurations. Elevating the mounting structure above the ground and increasing the pitch, increases

diffuse light on the module's back side leading to higher BG (Solarworld). This is very effective in building integrated systems, especially in flat-roof-buildings. The classical fixed tilt installation of bifacial PV modules has been proved to be advantageous in cloudy areas where there is more diffuse light compared to direct light (Singh, 2012). BG of approximately 20% can be achieved in the fixed tilt configuration without any special conditions. In optimal conditions, where the edge of the module is more than 50 cm from the ground, minimal shading on the back side, pitch distance is greater than 2m and the albedo is very high, such as in fresh snow, BG of 30% can be achieved (Sciara, 2012). Non tracking horizontal installations are applicable in carports. Researchers from Électricité de France (EdF) found that, when compared to standard monofacial panels, bifacial panels in a horizontal fixed tilt position have a bifacial gain of 5–15%, and 3–11% in a horizontal tracking system, for albedos between 0.2 and 0.5 (Lindsay, 2016). According to research, regions with high DNI produce high energy and low levelized cost of electricity (LCOE) for horizontal bifacial single axis tracking system. EdF's analysis therefore proves that bifacial modules are advantageous compared to monofacial modules in locations with high albedos and low land costs.

The other interesting bifacial configuration is the vertical bifacial modules system. These systems have previously been effectively used as sound and light barriers on highways. Studies have shown that vertical BPV systems produce more power than MPV systems anywhere in the world, for albedo values 0.05-0.3 (Guo, 2013). Vertically mounted bifacial systems generally take up less space compared to horizontal or tilted bifacial systems. As a result, due to their low ground coverage ratio (GCR), these systems are commonly used in agriPV. Figure 2.2 below shows the different installation configurations and applications of bifacial PV systems (Kopecek, 2021).



Figure 2.2 Various bifacial PV systems installation configurations and applications (Kopecek, 2021)

Two orientations can be applied in vertical bifacial systems, north- south orientation and east-west orientation. Half of the panels face east to generate peak power in the morning and the other half faces west to generate peak power in the late afternoon when the angle of incidence is optimal, in east – west (E-W) configurations. Generally, electricity demand is highest at these times. Therefore, this double peak energy profile ensures that the demand and supply needs match each other. In north-south (N-S) bifacial panel orientations, the front side receives direct and diffuse irradiation, and the rear side receives only diffuse irradiation throughout the day. When using north-south bifacial panels, the front side is exposed to both direct and diffuse light during the day, while the back side is only exposed to diffuse light. E-W orientation results in both sides receiving direct and diffuse irradiation throughout the day, resulting in higher energy output compared to the north-south orientation. Vertical bifacial panels have reduced dust and snow accumulation resulting in lower maintenance efforts. Figure 2.3 below shows the annual output power vs time curve for different mounting configurations of monofacial and bifacial panels (Gamma Solar via NREL).

Yearly average of daily power distribution (365 days)

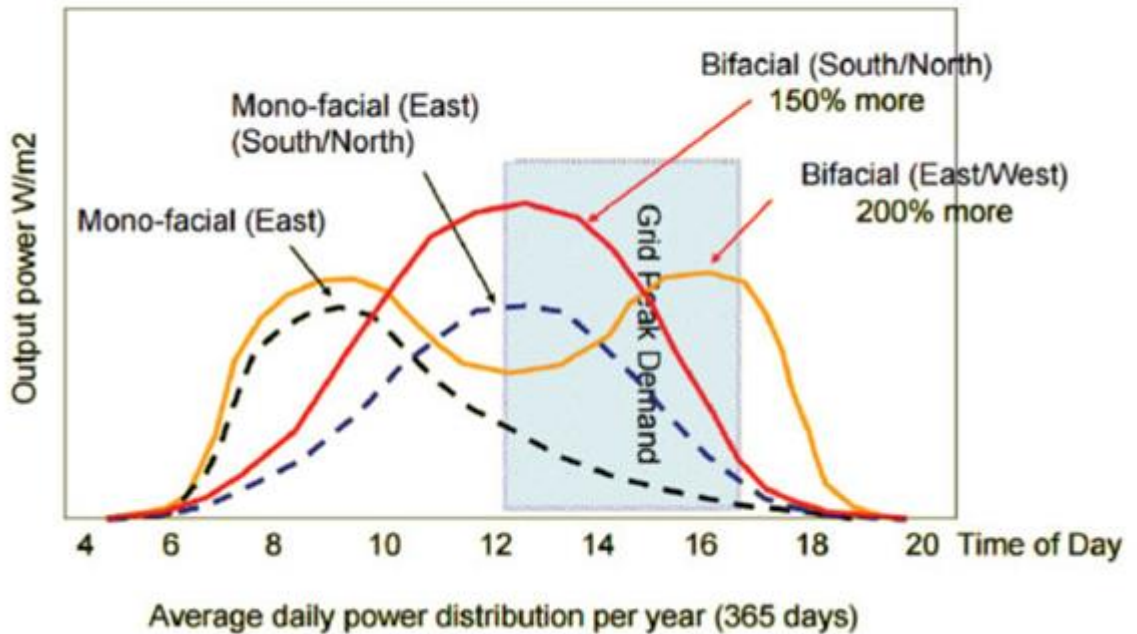


Figure 2.3 The annual output power vs time curve for different mounting configurations of monofacial and bifacial panels (Gamma Solar via NREL)]

2.4 Vertical Bifacial Configuration

The vertical bifacial system refers to an installation configuration in which BPV modules are installed at 90° tilt angle for maximum electricity production at peak hours, that is, in the mornings and afternoons (Campana, 2021). This system is ideal for solar fence applications and agrivoltaics. In solar fences, vertical bifacial modules are used to generate electricity in residential and industrial areas and can be installed in place of a traditional protective fence. Vertical BPV systems are preferred in agrivoltaics because they have lower effects on crop photosynthetic activities. Additionally, this configuration offers interdependent advantages to both the crops and the solar modules. Panel shading on crops can promote water retention resulting in minimal water loss from the plants through transpiration while transpiration from the crops results in module cooling which promotes energy production especially at midday. Furthermore, the panels prevent wind erosion from the land by acting as a barrier, slowing down wind speed (Schindele S. T., 2020). These advantageous factors result in a lower LCOE, making an agrivoltaic system

a cost-effective solution to both food and energy production activities. Figure 2.4 below shows the first vertical bifacial agrivoltaic system installed in Sweden (Campana, 2021). Figure 2.5 below shows a solar fence manufactured by Next2Sun (Next2Sun, 2024).



Figure 2.4 Vertical bifacial agrivoltaic system in Sweden (Campana, 2021)



Figure 2.5 Solar Fence manufactured and installed by Next2Sun (Next2Sun, 2024)

3. AGRIVOLTAICS

3.1 Background

Installing PV panels has negative effects on the environment including excessive land use, climate change and competition for land. Consequently, engineers have come up with solutions such as APV systems. (Weselek, 2019). Energy generation and agricultural production can be antagonistic activities when carried out together since PV panels could reduce the favorable agricultural conditions that are required by shading the plants. Thus, in order to achieve the same energy output as ground-mounted PV systems without obstructing agricultural operations and ensuring that there is minimum photosynthetically active radiation deficit, geometric configurations for the APV system must be determined. Vertical bifacial PV systems offer a unique perspective to achieve this.

Vertical BPV systems lead to one major challenge, namely co-optimization. Maximizing energy yields from the PV system leads to shading which affects photosynthetic efficiency negatively, and the PV structures interfere with the use of agricultural machines like tractors. Co-optimization presents difficulties with regard to where to put the PV modules, how high to put the modules and support systems above ground, and whether to use different PV technologies than those found in conventional solar systems (Dinesh, 2016).

However, an APV system is agronomic and energetic (Scognamiglio, 2016). Coactive advantages of APV farming include decreased plant evapotranspiration because of the PV panels' ability to shade the plants (Elamri, 2018). This is especially advantageous for plants that need a lot of irrigation. Other APV farming benefits include landscape preservation due to reduced soil erosion and enhanced farmers' socioeconomic well-being (Schindele & Trommsdorff, 2020), enhanced agricultural production (Majumdar, 2018), biodiversity, and ecology (Barron-Gafford, 2019). Additionally, especially in arid and semi-arid regions of the world, APV systems can help increase the agricultural sector's resistance to heat waves and dry spells (Trommsdorff, 2021).

There are three main types of APV systems:

- Elevated systems- PV panels are placed directly above the vegetation. These kinds of systems have PV panels placed horizontally at elevations of up to 2m high. An example of elevated systems is the stilt-mounted system, shown in figure 3.1 below, which was developed in 2004 (Nagashima, 2005). The system is built with pipes and rows of PV panels that are positioned above ground. It is planned so that the crops can receive enough sunlight for photosynthesis at predetermined intervals. Furthermore, the structure does not have a solid ground foundation, and it can therefore be easily dismantled. In certain cases, the PV panels are typically located on top of greenhouses. These systems provide protection to the plants against extreme weather such as heavy rains and drought. However, they also reduce sun exposure which can be detrimental to the plants as this can ultimately reduce the crop yield. For this reason, the crops planted underneath are usually shade tolerant such as lettuce, berries, grapes, and apples.
- Ground-mounted inter row systems- These systems are designed to have plants grown between rows of solar panels instead of underneath them. Ground mounted systems can be installed horizontally or vertically. Generally, these systems do not protect the plants against extreme weather to the same extent as elevated systems. Luckily, in these systems, plants usually have additional access to sunlight when compared to elevated systems. Furthermore, the pitch, is often designed such that tractors and other mechanical equipment needed to cultivate the crops can easily fit in the spacing. Some of the plants that can be grown in these systems include grasses, grains, and hardy vegetables like kale and broccoli.
- Combined elevated and inter-row systems- These systems are made to be installed on the same plot of land with both elevated and interrow PV panel configurations. Advantages of these configurations are that they favor activities such as beekeeping and livestock farming. These systems also encourage habitat restoration.

Other types of agrivoltaic systems include solar fences. Solar fences are bifacial PV panels that are installed in place of traditional fences and are used to collect solar energy

especially in the mornings and evenings when peak power is available. Solar fence systems are often used together with chicken farming and livestock grazing activities.

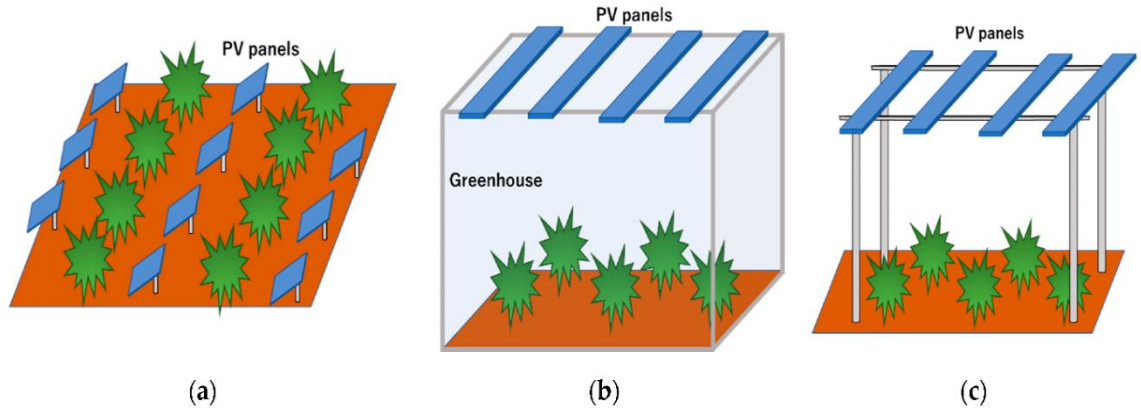


Figure 3.1 Types of agrivoltaic systems installed on a crop farm (Nagashima, 2005) (a) Ground mounted inter-row systems, (b) Elevated systems installed on the roof top of a greenhouse, (c) Stilt-mounted systems installed on a crop farm (Nagashima, 2005)

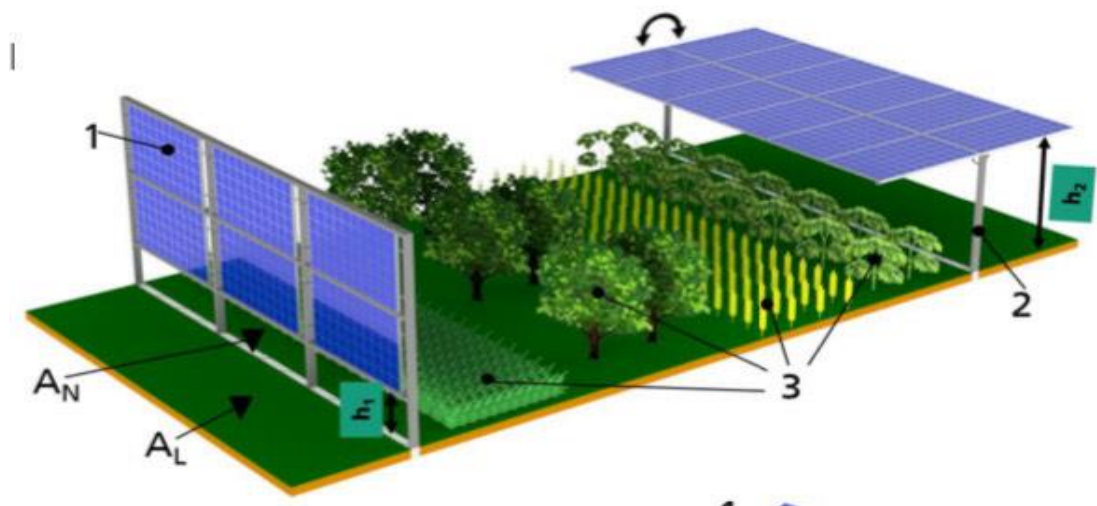


Figure 3.2 Types of agrivoltaic systems: Combined elevated and inter-row systems (Nagashima, 2005)

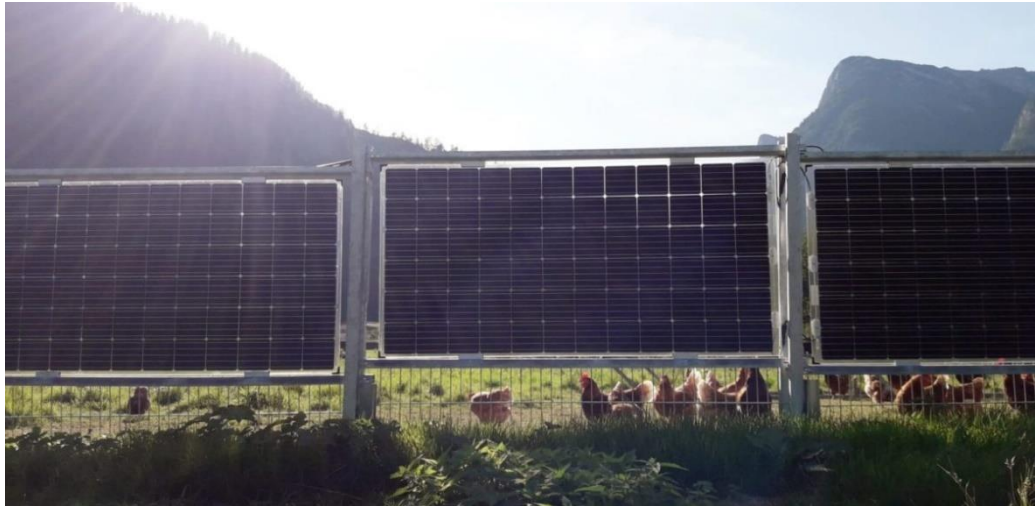


Figure 3.3 Solar fence installed on a chicken farm (Nagashima, 2005)

3.2 Impact on Crop Yield and Livestock Farming

Plants require light for photosynthesis and optimal growth and development. The required light can be classified into three aspects: light quality, light quantity, and light duration. These aspects impact greatly on the growth and health of the plants. Another important term used to define the light required by plants is the photosynthetically active radiation (PAR). PAR refers to the portion of the light spectrum that is utilized by plants for photosynthesis, and this light is of wavelengths 400-700 nm. At these wavelengths, plants convert sunlight to energy. Chlorophyll in plant cells absorbs sunlight and produces glucose, in a process that releases oxygen simultaneously. PAR quality contributes to better plant growth, and influences their leaf size, and both flower and fruit production, which consequently increases crop yield. For healthy growth, different plants need varying amounts of PAR (Lopez, 2022).

Plants reach the ultimate threshold for maximum photosynthesis rate at a specific light intensity referred to as the light saturation point. Every plant has a light saturation point, after which additional sunshine has no effect on the PAR, does not increase photosynthesis, nor does it promote growth. Finding this point helps us understand how shade-tolerant a crop is. Beyond the light saturation point, additional sunlight increases the water requirements of plants, leading to excessive transpiration (Marrou, 2013). On

the other hand, PV panels perform ideally at STC conditions, which is at 25°C. Under these conditions, maximum electricity production is expected. The efficiency of solar panels decreases with temperature, which lowers the amount of electricity produced. However, by utilizing evaporative cooling to lower the temperature of the PV arrays we can boost electricity production. Integration of crops beneath PV arrays can help mitigate temperature related efficiency loss.

Many experimental studies that have been carried out on APV systems with stilt-mount configurations in France (Marrou, 2013) and Japan. These studies have shown that incorporating PV panels and thereby planting shade-tolerant crops beneath the PV panels does not lower the productivity of land. Consequently, using APV systems does not require too many changes in plant production practices. The first known experiment with APV systems took place in Montpellier, France in 2013 (Marrou, 2013). A system of 0.8 m wide stilt-mounted PV arrays positioned at a height of 4 m and a tilt angle of 25° was used to plant lettuce. Electricity and food were successfully produced from the same parcel of land. The experiment's findings demonstrated that the shading caused by the PV panels had no negative impact on the amount of lettuce produced. On the contrary, there was a 30% increase in the lettuce yield when cultivated under the PV panels as compared to traditional agricultural systems with the absence of PV panels. This experiment results demonstrated that elevated APV systems are particularly beneficial for shade-tolerant crops.

Dupraz et al. carried out an experiment in Montpellier, France, to examine the advantages of setting up an APV system compared to traditional systems (PV and farming separately) on the same plot of land. In order to evaluate if the combined contributions of crop yield and energy yield are greater, equal, or lower than those obtained from individual use of the land, they introduced the land equivalent ratio (LER). They compared conventional options (where electricity production and farming are carried out separately) with two APV systems with half and full panel densities. PV panels covered half of the agricultural land area at half panel density, and at full panel density, the entire agricultural land was covered with PV panels. Wheat was planted underneath the PV arrays. The results showed that APV systems raised land productivity by 35-72% (Dupraz et al., 2011).

Wolf et al. carried out an experiment and observed that while full shading of crops by PV panels caused a crop production loss of up to 50% when compared to crops planted without any shade, there were some exceptions among several plants. Lettuce had a 36% yield increase due to shading, whereas the yields of Chinese and head cabbage increased by 21% and 23%, respectively (Wolff, 1990). Another experiment was carried out in Spain by Martinez et al. to examine how bean plant growth is affected by PV panel shading. The results obtained showed that no change in height or appearance was observed when beans were grown in full sunlight and when grown under partial shading (Martínez, 2022).

Livestock farming activities can also be practiced together with PV systems. An analysis by Maia et al. carried out in Oregon focused on lamb growth and pasture production beneath PV panels. The results demonstrated a 200% increase in land productivity. Additionally, the system created better animal welfare compared to conventional farming. The animals were able to utilize the shade from the PV, with results showing that when the irradiance was higher than 800 W/m^2 , animals spent more than 70% of their time in the shade provided by the PV panels (Maia, 2020).

3.3 Guidelines on Agricultural PV Plants

APV systems are considered to be fairly new technology, and just as it is with other emerging technologies, many governments have not yet developed guidelines on agricultural PV plants. Currently, Turkey launched its first APV research project, which features a solar tracking system with a single axis, based in Ayaş, Ankara. The project consists of 14 rows of PV arrays in an East-West orientation and tracking at $+55^\circ$ and -55° . 122 kWp of electricity can be generated from the system. Tomatoes, peppers, cucumbers, carrots, spinach, and red cabbage were planted for the trial's first year, and it will run for the following four years (Meza, 2024). Agricultural activities in a different area whose surface area is the same as that of the experimental area are being monitored concurrently. Aside from energy production, researchers are also monitoring other environmental parameters such as irrigation, soil moisture and temperature.

Since APV technology is still recently new in Turkey, the minimal qualities and specifications that a PV plant must meet in order to be classified as an APV plant are currently not specified in any established guidelines.

Recently, the Italian government published, “Guidelines on Agricultural PV Plants”, which defines the requirements that an APV plant needs to meet (Green Dealflow, 2024).

These include:

- An APV plant must have a land area occupation ratio (LAOR) of less than 40 %. The ratio of the area of land used for agriculture to the area occupied by the modules is known as LAOR.
- The specific electricity produced by an APV (Y_{APV}) plant annually should be greater than 60% of the specific electricity produced by a standard PV (Y_{PV}) plant installed in the same area of land. Both values are expressed in GWh ha/ year.

$$Y_{APV} \geq 0.6Y_{PV}$$

- APV systems should be integrated with innovative solutions such as PV modules raised off the ground to ensure installations don't affect the area's degree of connection. This means that passage of animals underneath the panels and activities related to animal husbandry must be carried out without any negative implications to or from the PV arrays.
- Installing APV systems requires a minimum height of 1.3 meters, in the case of livestock farming and 2.1 m, in case of plant cultivation. This is done to ensure passage of livestock and necessary machinery for farming.
- Lastly, it is advised to assess how installing the APV system will affect the environment. This can be done in a variety of ways, including maintaining water conservation, assessing the effects on crops and livestock productivity, ensuring the restoration of soil fertility, microclimate, and the system's resistance to climate change.

4. METHODOLOGY

4.1 PVsyst Software

PVsyst is a web-based software used for designing, simulating and analyzing PV systems. This software was conceptualized and founded by A. Mermoud and M. Villoz, and is often used by researchers, engineers, students and architects for simulation. PVsyst can be used to simulate grid-connected, stand-alone and pumping solar systems (Akcan, 2020). Results obtained from PVsyst have been proven to be consistent with literature and real data obtained from solar power plants.

PVsyst is famous among engineers due to its features that include system design and sizing, and wide range of weather databases such as Meteonorm 8.1, NASA, PVGIS, etc. It is also possible to simulate the shading scene with its 3D drawing feature, and it also allows for economic analysis, from which CAPEX (installation costs) and OPEX (operating costs) can be obtained (Bolat, 2020; S., 2021). PVsyst also offers data on system ageing. Additionally, PVsyst can simulate the latest solar technologies including bifacial systems.

PVsyst has a HELP menu, where users can easily obtain information and guidance on the step-by-step process of developing a project. Furthermore, video tutorials that offer visual guidance in various languages are available for the PVsyst.

Once the user is done creating their simulation, a report with graphs and tables in PDF format is generated containing the obtained results. The results include annual energy production, specific energy yield, based on the irradiation and location, and PR (%), which describes the quality of the PV system. The monthly diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI) values, as well as the shading factor for diffuse and albedo can be obtained from the shading factor table. The results can be exported in PDF and Excel form.

The input details in the design process of a project include system specification, location (latitude and longitude), angle of tilt, pitch, azimuth angle and module elevation. These values are used to generate the results in the simulation.

4.1.1 132-KW Vertical Bifacial System Design on PVsyst

A 132-KW vertical bifacial system was designed on 668 m² panel area and the simulation was carried out on PVsyst version 7.4. The simulation was set up as a grid connected system. The size of the simulated system is selected to approximately match with the system previously established agrivoltaics project in Ayaş by ODTÜ-GÜNAM. The first step in the design was obtaining the geographical site parameters for the simulation. This is necessary for obtaining meteorological data. The system was designed for Ayaş, Ankara province in Turkey. The project's geographic co-ordinates and monthly meteorological data were taken from Meteonorm 8.1 database. Ayaş's location coordinates are 40.0248° N (latitude), 32.3409° E (longitude), and 1043 meters above sea level. Ayaş was selected for this simulation because the location is perfect for agrivoltaic activities, as proven by the installation of the first agrivoltaic project in Turkey in Ayaş, Ankara. The main parameters that serve as system input are orientation, system, horizon and near shading details.

4.1.2 Design and Shading Scene Construction

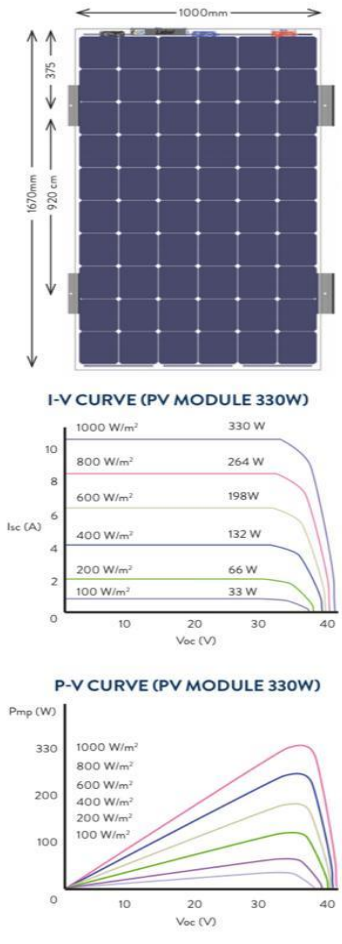
After selecting the orientation, the next step was to define the field type. There are several options available including unlimited sheds, tracking horizontal axis N-S, tracking horizontal axis E-W, fixed tilted planes and unlimited trackers. Since PVsyst (at this moment) can only simulate bifacial systems with tracking using unlimited sheds and unlimited trackers with 2D shading scenes, a fixed tilted plane was selected as the field type. This field type allows for a 3D shading construction scene under but does not allow for a tracking simulation.

Under the field parameters, the plane tilt was set as 90^0 since it's a vertical system and the azimuth was set as -90^0 as the collectors are facing East. This field azimuth angle was chosen as it offers the best conditions for maximum energy production. According to the energy generation curve of bifacial panels, maximum energy production occurs in the morning and evening hours, unlike monofacial panels whose maximum energy production occurs at midday. It is therefore important for the bifacial panels to face East-West to capture maximum sunlight at sunrise and sunset.

The system parameters were then defined. Using the pre-sizing tool, the pre-planned power was set as 132kW_p, and the available area of the modules was set as 668 m². The next step was to select the PV module. Several PV modules are available on the PVsyst database. For this simulation, GTC Solar Turkey, GG1H-330 Mono PERC bifi 60 PV modules were selected since they are locally available in Turkey. The panel has got 60 cells in series and a nominal power output of 330W at STC. The cells are made from monocrystalline silicon and the front cover consists of low iron tempered solar glass. The bifaciality factor of the module is 0.7. The length of the module is 1.67m, the width is 1.0m and the weight is 20.10 kg. Figure 4.1 below shows the performance characteristics of the module at STC as provided by the manufacturer. The I_{sc} is 10.67 A, and the V_{oc} is 38.0 V.



**BIFACIAL
DUAL GLASS MODULE**
ULTRA POWER 330W MONO
PERC+ BIFI GG1H-60



ELECTRICAL PERFORMANCE

Max. Power P _{max} (W)	315	320	325	330
Max. Power Voltage V _{MPP} (V)	33.34	33.65	33.97	34.20
Max. Power Current I _{MPP} (A)	9.45	9.51	9.57	9.66
Open-Circuit Voltage V _{oc} (V)	39.62	39.91	40.15	40.52
Short-Circuit Current I _{sc} (A)	10.32	10.41	10.50	10.59
Performance η _m (%)	18.86	19.16	19.46	19.76

Standard Test Conditions (STC); 1000 W/m², AM1.5, 25 °C, Power Tolerance (W) +/- 3%

BOOST FROM THE BACKSIDE

Power (W)	337	342	348	353
Performance (%)	20.18	20.50	20.82	21.14
Power (W)	362	368	374	380
Performance (%)	21.69	22.04	22.38	22.72

Bifaciality depends on Albedo

ELECTRICAL PARAMETERS AT NOMINAL OPERATING CELL TEMPERATURE (NOCT)

Power Output P _{MAX} (W)	282	286	290	294
Max. Power Voltage V _{MPP} (V)	30.91	31.21	31.48	31.72
Max. Power Current I _{MPP} (A)	7.60	7.64	7.69	7.76
Open-Circuit Voltage V _{oc} (V)	36.75	37.02	37.24	37.58
Short-Circuit Current I _{sc} (A)	8.29	8.36	8.44	8.51

NOCT: open-circuit module operation temperature at 800W/m² irradiance, 20°C ambient temperature, 1m/s wind speed

OPERATING CONDITIONS

Operating Temperature	-40°C/+85°C
Max. System Voltage	1500V
Max. Series Fuse Rating	20A
Wind Load	2400 Pa
Snow Load	5400 Pa

TEMP. CHARACTERISTICS

Temp. coefficient P _{MAX}	-0.38%/K
Temp. coefficient V _{oc}	-0.29%/K
Temp. coefficient I _{sc}	0.04%/K
Nominal Operating Temperature (NOCT)	46°C

MATERIAL SPECIFICATION

Front Cover	2mm ARC Low Iron Tempered Solar Glass
Cell Type	Bifacial Mono PERC
Cell Matrix	60 Cells (6 x 10)
Lamination material	EVA
Back Glass	2 mm ARC Low Iron Tempered Solar Glass
Junction Box	IP67 rated, 1500V Compatible, 3 Diodes
Cables and connectors	DC Cable 4 mm ² MC4 compatible, 1500 V Cable length 15cm male - 40cm female
Frame	Portable Frame
Module Dimensions	1670 mm x 1000 mm x 5 mm (without J-box)
Module Weight	20.1 kg
Module Per Box	30
Box per Truck	30

ENGINEERED AND MADE IN TURKEY

Figure 4.1 The solar module’s performance parameters as provided by GTC Solar Turkey

The next step was to define the bifacial system characteristics of the designed system. Here, the unlimited sheds 2D model was selected since the simulation was conducted without trackers and therefore the unlimited trackers 2D model was not applicable. The pitch for the plane field was set as 10.0m. Since the design has got two panels, one stacked above the other in the vertical direction, the shed total width was set as 2.02m. Each module’s width is 1m and there is a 0.02m gap width between the two modules. This sets the total width to 2.02m. The module’s height above ground was set as 1.5 m and the

ground albedo was set as 0.2. Figure 4.2 below shows the bifacial system characteristics of the designed system.

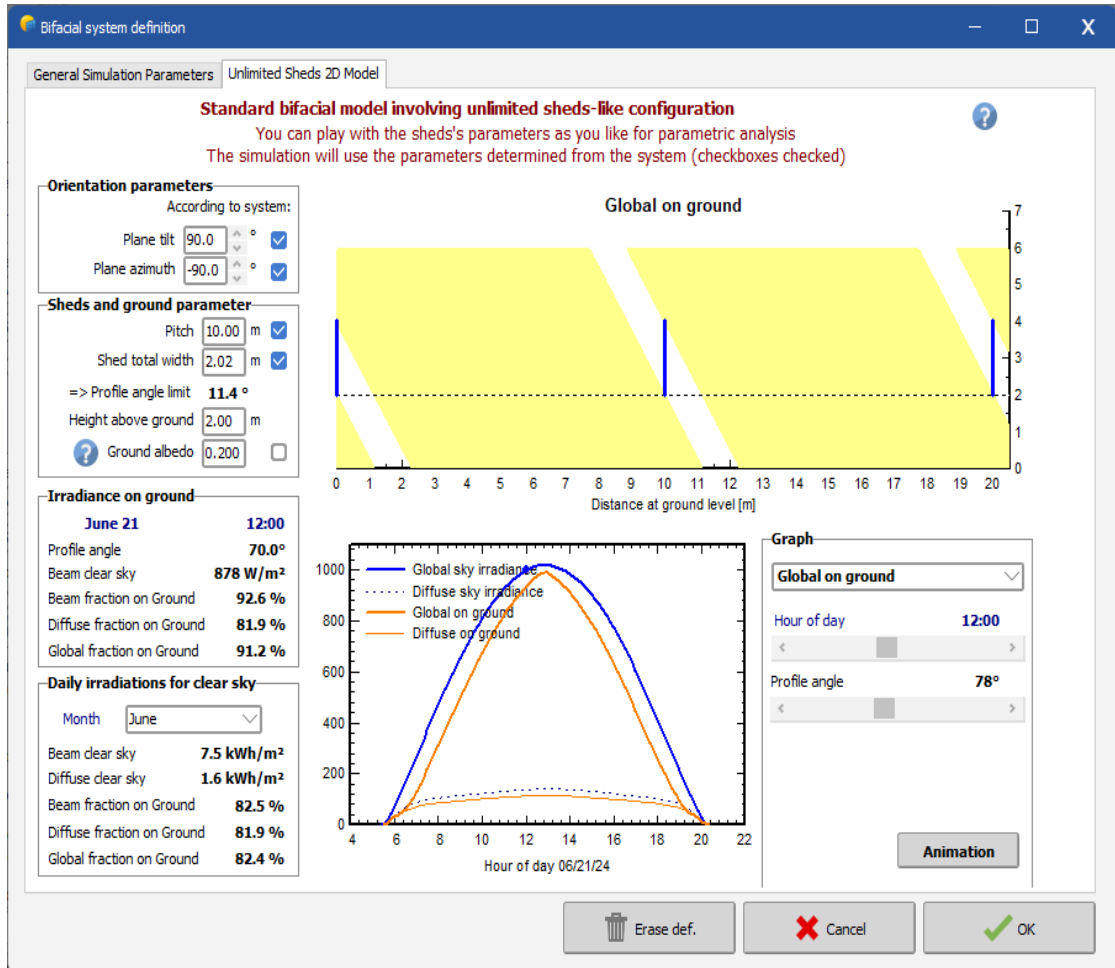


Figure 4.2 Bifacial system characteristics of the designed system

After this, the inverter was selected. When selecting the inverter, it is important to ensure that the voltage at maximum power point (V_{MPP}) values of the module, when the module is operating at cell temperature $T=20^{\circ}\text{C}$ (which signify winter conditions), and cell temperature $T= 60^{\circ}\text{C}$ (which signify summer conditions), lies between the $V_{MPP\ min}$ and $V_{MPP\ max}$ values. This ensures that the designed system does not have over or under voltage losses due to the inverter. It is mandatory for the open circuit voltage at -10°C ($V_{OC} - 10^{\circ}\text{C}$) to not exceed the maximum absolute DC voltage ($V_{abs\ max}$) to prevent damage to the inverter. Another important value that should be taken into consideration is the P_{nom} ratio value. The installed PV power (nominal at STC) divided by the inverter's P_{nom} (AC)

is referred to as the P_{nom} ratio. It is recommended that the P_{nom} ratio lies between 1.0 and 1.1 to cause negligible overload loss.

Based on the important points mentioned above, the Growatt New Energy 25 kW 200-1000V 50/60 Hz (Growatt MID 25 KTL 3-X1) was selected for this design. The inverter's operating voltage is between 200 V and 1000 V. The inverter's maximum input voltage is 1100 V. In this design, the MPPT feature was disabled to ensure power sharing within this inverter. 5 inverters were used for a total output power of 125 kW_{ac}. The P_{nom} ratio for this design is 1.06. The array was then defined. The number of modules in series and the number of strings was determined. Based on the inverter sizing characteristics, PVsyst will suggest the range of series modules and strings that is suitable for the design. For this simulation, 20 modules in series and 20 strings were chosen to result in a total of 400 modules in a 668 m² panel area.

Once the system characteristics were defined, the next step was to define the horizon characteristics. The horizon or far shadings in PVsyst allows the user to define large far away structures that can shade a PV field. This refers to shading that is due to objects that are significantly far from the project design area. These objects act globally on the PV field and determine sun's visibility on the field at a specific moment. Generally, the shading objects should be more than ten times as far away as the PV field and the objects should be higher than 2 degrees from the horizon. Objects that are responsible for far shadings include mountains, hills and large buildings. Horizon shadings blocks the entire PV system from direct sunlight as opposed to near shadings that only blocks a fraction of the sunlight available to the PV system. According to PVsyst user guide, the horizon is a broken line superimposed on the sun path diagram, which can hold any number of height/azimuth points. PVsyst ignores horizon/ far shadings if the horizon line of the designed system doesn't exceed a height of two degrees above the horizontal. For this simulation, the horizon profile for Ayaş, Ankara was imported from Meteonorm web service.

The near shading properties of the project are next. Here, a 3D shading scene was constructed as defined in the orientation/system details of the project. In the construction

zone, 20 tables and 20 zones with a total table height of 2.02 m and total table length of 16.88 m were created. The zone's pitch was set as 10m and the height above ground was set as 1.5m. A ground object was also constructed to represent the portion of land that is used for farming. Figure 4.3 below shows the 3D shading scene and the zone properties for the PV field.

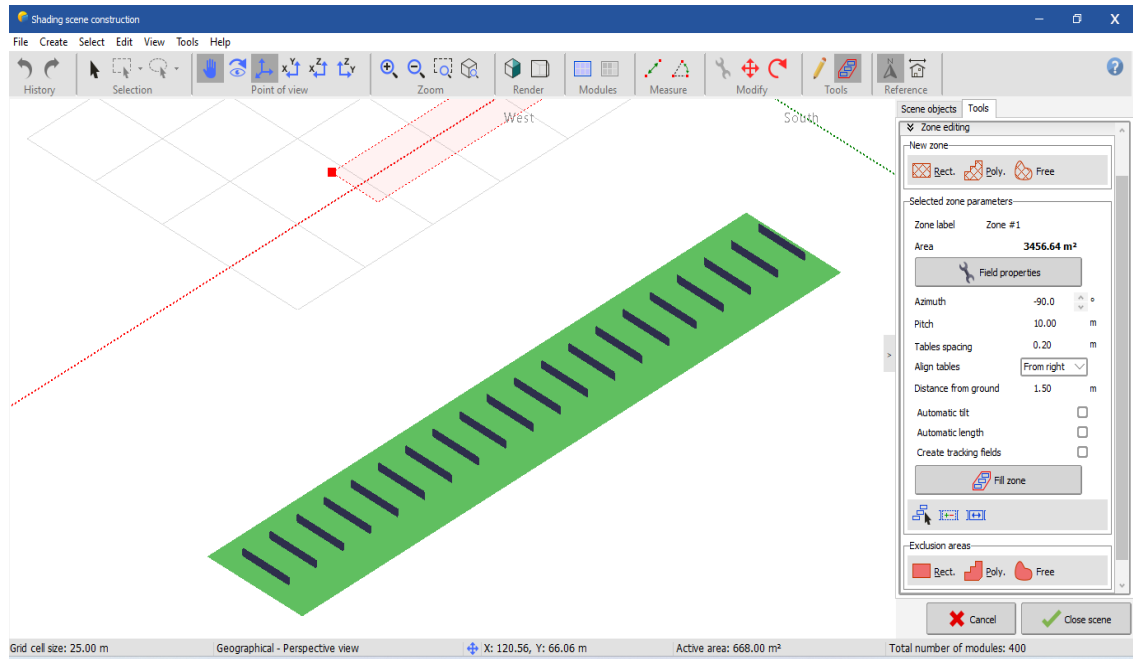


Figure 4.3 3D shading scene and the zone properties for the designed PV field

PVsyst uses linear shadings to compute the shading factor table or graph. The next step after computing the shading factor was to run the simulation.

4.1.3 132-KW Tracking Horizontal Bifacial System Design on PVsyst

A 132-kW horizontal bifacial tracking system on a 668 m² panel area in Ayaş, Ankara was designed. The geographic co-ordinates and monthly meteorological data were taken from Meteonorm 8.1 database.

4.1.4 Design and Shading Scene Construction

The field type was set as tracking horizontal N-S. The axis tilt and the axis azimuth were set as 0° . The phi min angle was set to -55.0° and the phi max angle was set to 55.0° . The values -55.0° and 55.0° were selected because they are the tracking angles in the agriPV setup in Ayaş. The phi angles define the angle of rotation of the trackers. In this case, the trackers can rotate to a maximum of 55° towards west and 55° towards East. Unlimited trackers 2D model was selected. The axis azimuth, phi min and phi max were set according to the orientation parameters defined earlier in the design process. The pitch was set to 10 m and the shed total width was set to 2.0m. The height above ground was set to 3.5 m and the ground albedo was set to 0.2, which is the average albedo for grass or vegetation. Figure 4.4 below shows the bifacial system characteristics of the tracking horizontal designed system.

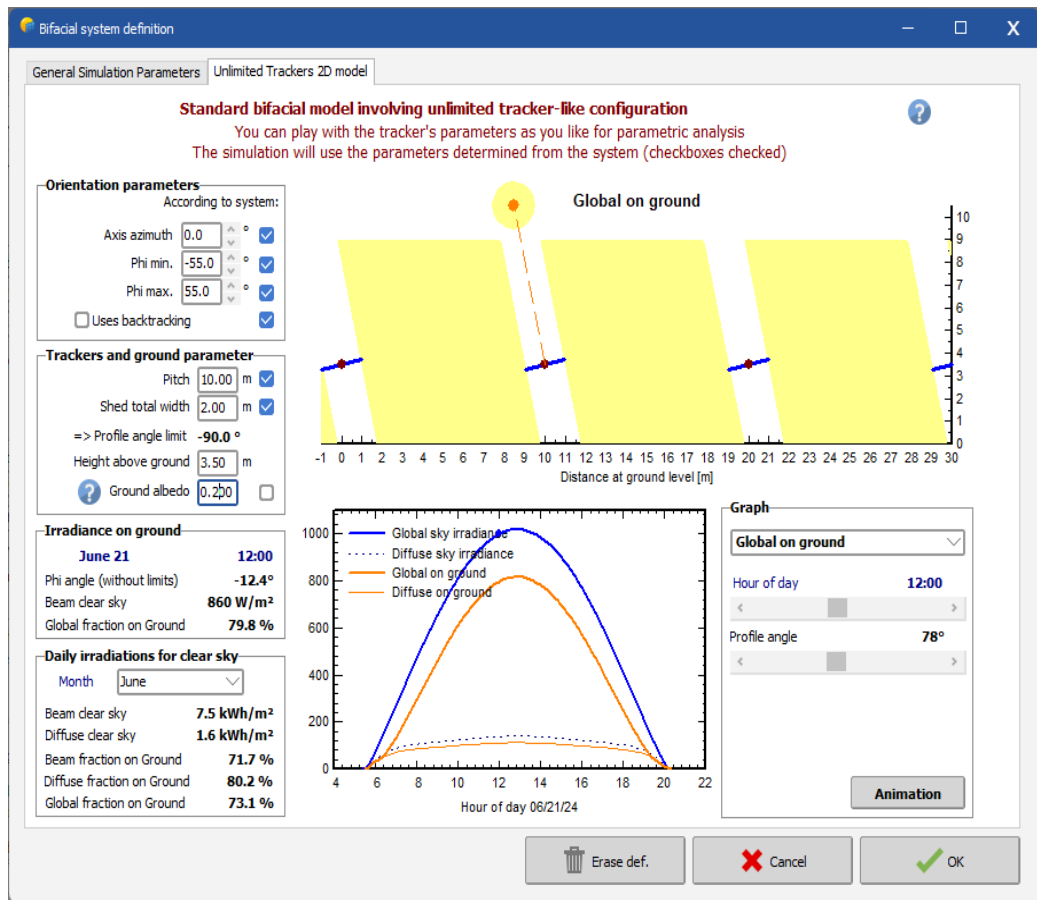


Figure 4.4 Bifacial system characteristics of the tracking horizontal designed system

5 Growatt New Energy 25 kW 200-1000V 50/60 Hz (Growatt MID 25 KTL 3-X1) inverters and 400 GTC Solar Turkey modules were used, just like in the vertical system. The computed overload loss was 0.0% and the P_{nom} ratio was 1.056. The horizon profile for Ayaş was then defined.

The near shading scene was then constructed, the shading factor computed, and simulation was carried out. Figures 4.5 below show the 3D shading construction scene.

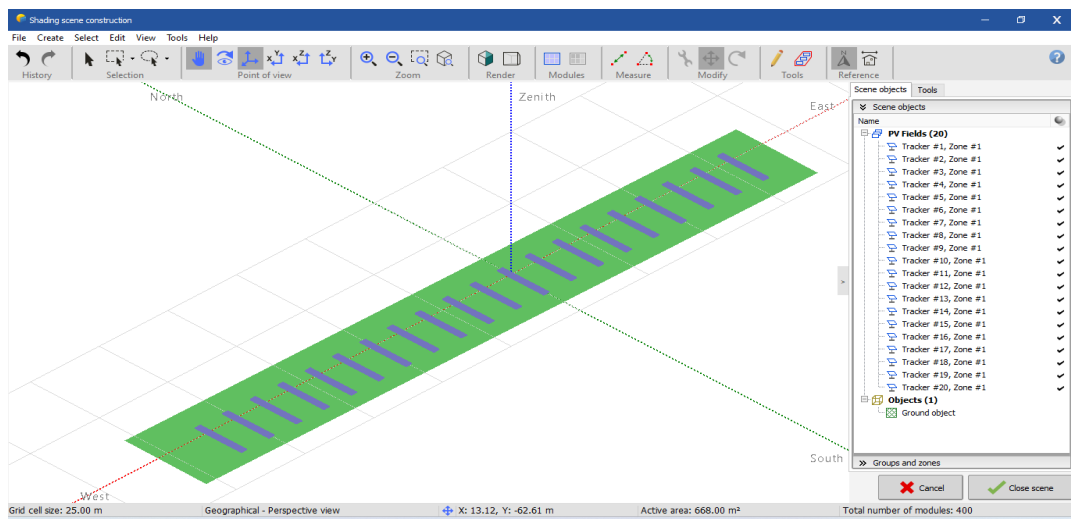


Figure 4.5 The 3D shading scene for the tracking horizontal designed system

4.2 PVSOL Premium Software

PVSOL premium is a software designed by Valentin Software and used for the design and simulation of photovoltaic systems. It was created in Germany. PVSOL can simulate grid, off-grid and EV systems. It is also used to design systems with battery storage, rooftop and ground mounted installations. PVSOL'S shading analysis using its 3D visualization tool, is the most detailed shading configuration among solar design software. PVSOL obtains meteorological data from the German Meteorological Service and Meteonorm. PVSOL is also very efficient at computing the financial analysis for designed projects.

4.2.1 132-KW Tracking Horizontal Bifacial System Design on PVSOL Premium

A 132- kW tracking horizontal bifacial system was designed on PVSOL Premium 2021. In this design 3D shading construction was disabled since PVSOL Premium can only simulate tracking systems in 2D. 400 GTC Solar Turkey modules and 5 Growatt New Energy inverters were used in the design.

The installation type was set as Mounted- Open Space and Tracking was set as Single North-South Axis. The rotation incline was set to 0^0 and the rotational angle of opening was set as 110^0 . Backtracking was not enabled and the surface usage factor was set as 0.0. Surface usage factor determines the modules' distances apart from each other. 1 means the pitch is equal to module's length or width, and 0 means the pitch is too much and rows are far apart. Pitch was set as 10 m, the mount height was set as 3.5m, the number of vertical modules was set as 2, and the shading by the assembly system was set as 1 %. Since the surface usage factor was 0, the mutual shading of the module rows was ignored.

The horizon line figures were defined. The cable loss was set as a total loss of 1.5%. The simulation was run, and the report obtained.

4.2.2 132-KW Vertical Bifacial System Design on PVSOL Premium

A 132-kW vertical bifacial system was designed on PVSOL premium 2021 to fulfill the objectives of this project. This design was carried out to compare the annual power obtained from PVsyst and PVSOL software. The System type, Climate and Grid, were selected to match the design on PVsyst. Under the type of design, the Use 3D design click box was checked. The time step of the simulation was set as 1 hour, to save on time as this was the faster option. The AC mains parameters were set as default values as these are the standard parameters in Europe.

The next step was the 3D design. Here, Open Areas was selected under the coverable object. Then the width of the open area was set as 18.0 m and the length of the area was set as 200 m. The orientation was set to 90^0 to face the East direction. Modules can be added to PVSOL Premium in two ways, by clicking the module coverage or the module mounting options. In this project, modules were added using the module mounting option. Under the edit assembly system page, PVSOL Facade Tilt was selected for the vertical bifacial simulation. Under the active module no, a new module was input into the system. PVSOL does not include the modules from GTC Solar Turkey under the manufacturer's page. However, PVSOL allows for manual input of PV manufacturers and PV modules and all the performance characteristics. Therefore, using the performance characteristics of the GG1H-330 Mono PERC bifi 60 PV modules provided by the manufacturer and available on the PVsyst software, the modules details were input manually on the PVSOL software. Under the module mounting section of the edit assembly page, the number of vertical modules was set as 2, the module spacing for both horizontal and vertical was set as 0.02 m, and the mount angle was set as 89.90^0 . This is the maximum value of the mount angle that can be applied on the software and is suitable for vertically mounted systems. The depth of row value was computed by the software to be 0.004 m. The depth of row value refers to the difference between the pitch between the row and the mounting support clearance of the PV module installation. The mounting support clearance was then set as 9.996 m so that the row spacing, which refers to the pitch distance, could be computed by the software as 10 m. The area utilization ration was computed as 0.02 by the software. Figure 4.6 below shows the assembly system details of the vertical bifacial system designed on PVSOL Premium. The next step was to fill the entire open area with modules. This resulted in 20 rows each with 20 modules, making a total of 400 modules.

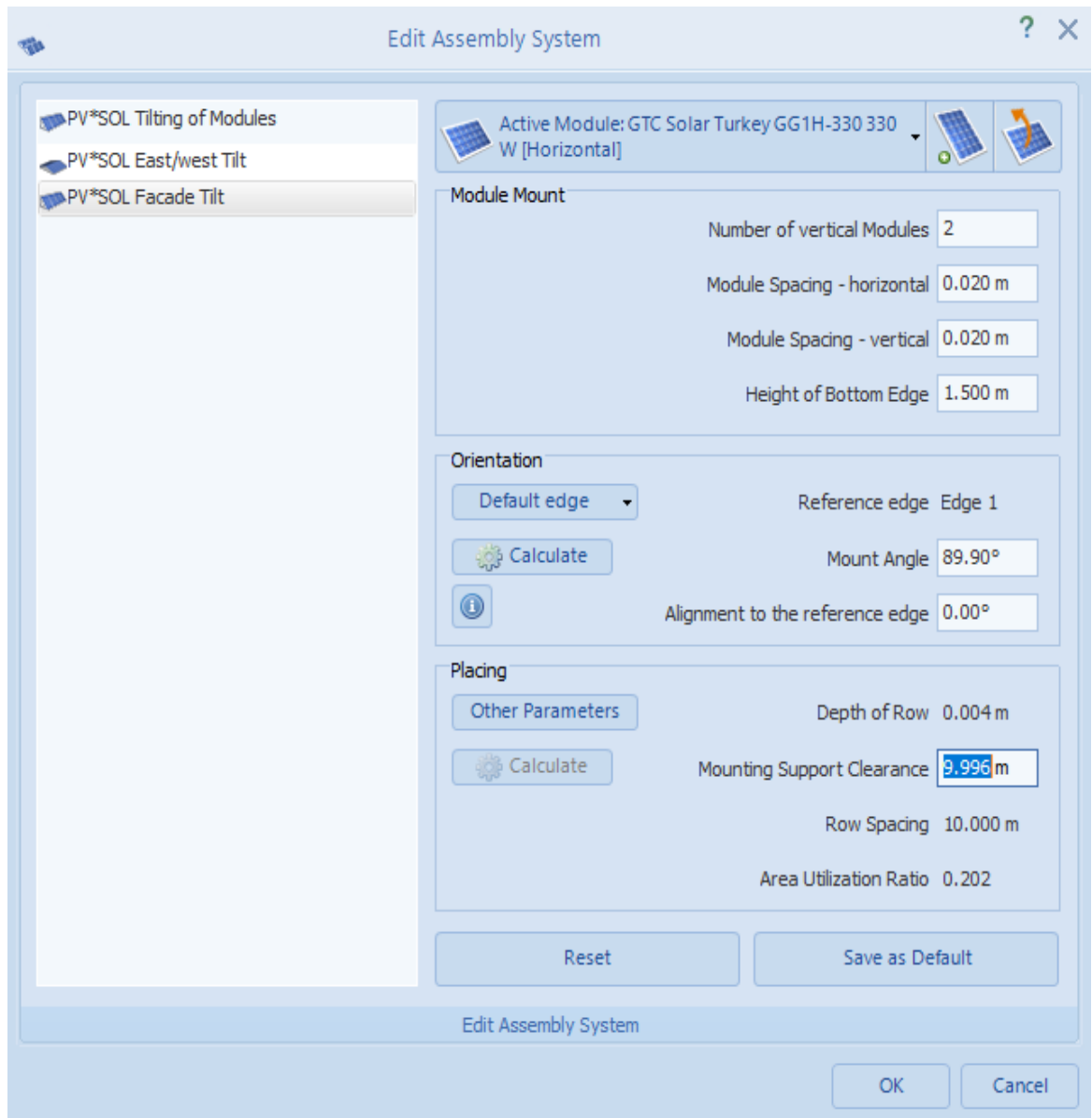


Figure 4.6 Assembly System Details of the designed vertical bifacial system

After the addition of the PV modules, the horizon was then defined in the design. 5 Growatt New Energy 25 kW 200-1000V 50/60 Hz (Growatt MID 25 KTL 3-X1) inverters was then selected to match the selection on PVsyst, and the shading simulation was carried out. 1.5% cable losses at STC was input. The financial analysis was calculated and the simulation was run.

4.3 Shading Analysis on PVsyst software

Shading in agrivoltaics occurs due to the dual use of land for agriculture and energy generation activities. Shading analysis is important for determining the correct balance between agriculture and energy production activities, to avoid compromising one activity for the other. Shading analysis was done to analyze the effect of the solar panels on the plants growing underneath. This guides the farmers on deciding which plants to grow on land used for agrivoltaic activities, and depending on the shading effect, how much produce loss is expected due to the loss of sunlight and therefore reduced photosynthetic activities from the plants.

4.3.1 Shading analysis for a fixed vertical bifacial system on PVsyst

Shading analysis for a fixed vertical bifacial system was carried out on a 518m² panel area on PVsyst version 7.4. For this simulation, the solar panels were placed flat on the ground, to represent the plants, and the vertical bifacial solar panels were modelled as shading objects in order to obtain the shading factor, and therefore the percentage of shading impacted on the plants. The system was designed as described in Chapter 4.1.1, however, bifacial system characteristics were not taken into consideration for this simulation.

In the Near Shadings section of the project, 4 rows of shading objects were modelled as building objects and placed 10 m apart from each other and at 90⁰ vertically. The building object consisted of a parallelepiped shape and a handrail with two crossbars. The parallelepiped shape had a length of 16.88m and width of 2.02m, to represent the total length and height of the solar panels from the previous simulations. The handrail with two crossbars represented the mounting support. The lower crossbar was placed at an elevation height of 1.5m and the top crossbar at a height of 3.52m from the ground. The crossbar was modelled with 20 rungs, where each rung represents a mounting support for the 20 panels in each row. A ground object was also included to represent the area of land. 5 zones were created and a total of 31 rows of panels were placed in the zones. Each row consisted of 10 panels with a module spacing of 0.02m apart. The azimuth was set as –

90°, so that the panels face East, and the tilt was set to 0°. In order to avoid overlapping of modules, the pitch was set as 1.20m, which was the minimum pitch value possible without module overlap in this simulation. The table spacing was set as 1m, and the distance from the ground was set as 20cm. The near shading construction was then complete, and the shading factor table was computed. Figure 4.7 below shows the 3D near shading construction scene for the shading analysis of a fixed vertical bifacial system on PVsyst.

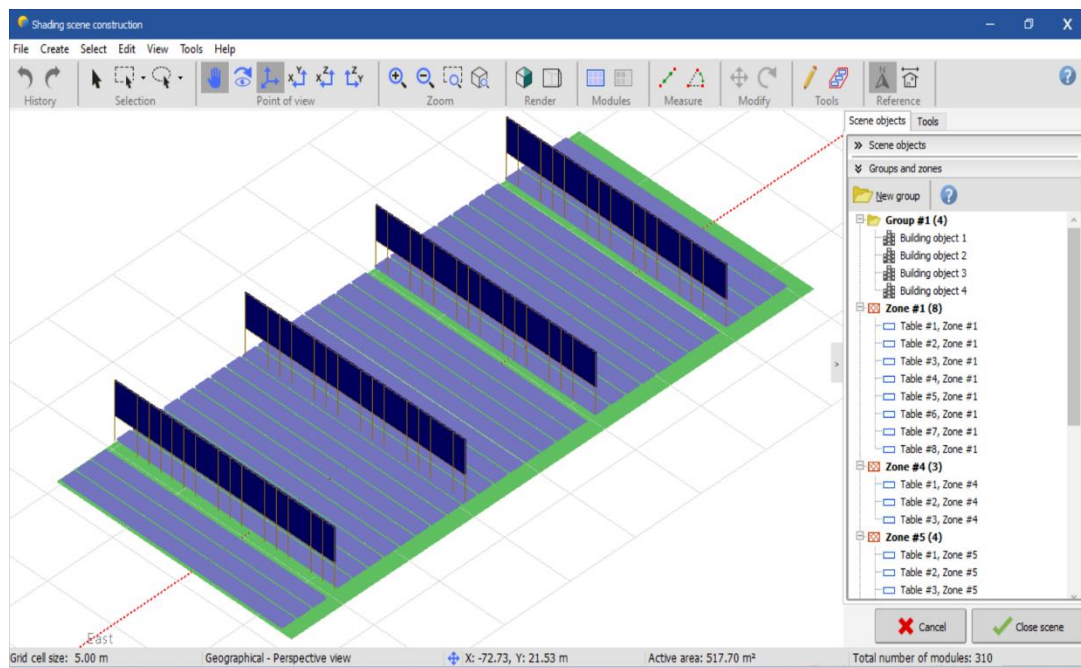


Figure 4.7 Shading analysis simulation for a fixed vertical bifacial system

4.3.2 Shading analysis for a horizontal tracking bifacial system on PVsyst

Shading analysis for a horizontal tracking bifacial system was carried out on a 518m² panel area on PVsyst version 7.4. For this simulation, again the solar panels were placed flat on the ground, to represent the plants, and the horizontal tracking solar panels were modelled as shading objects. However, it is difficult to model the tracking PV panels as stationary shading objects. Therefore, for this simulation, the PV panels (shading objects) were modelled as fixed objects, just like in the previous section, but at 0°, +30°, -42°, +53°, and -55°. These values were not chosen randomly. +55° and -55° were selected

since they are the maximum angles that can be achieved by the trackers. $+53^\circ$ and -42° were selected because these were the optimum tilt angle values achieved by the trackers on 21 December. After computing the shading factors from the different simulations at different angles, the DHIs and DNIs values were then computed. Figures 4.8 and 4.9 below show the 3D near shading construction scene for the shading analysis of a horizontal tracking bifacial system at 0° and $+55^\circ$ on PVsystem.

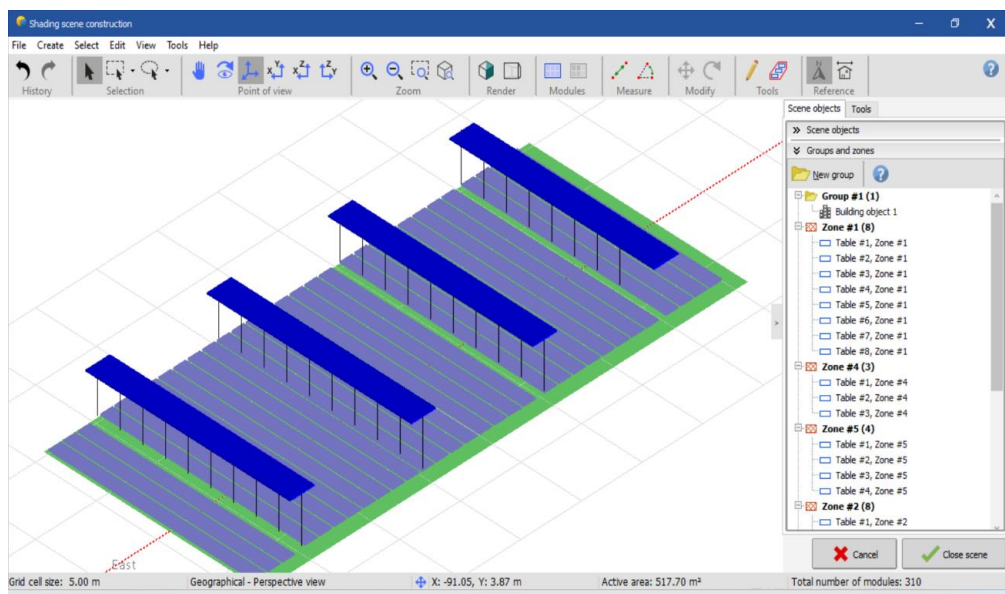


Figure 4.8 Shading analysis simulation for a horizontal tracking bifacial system, (0°)

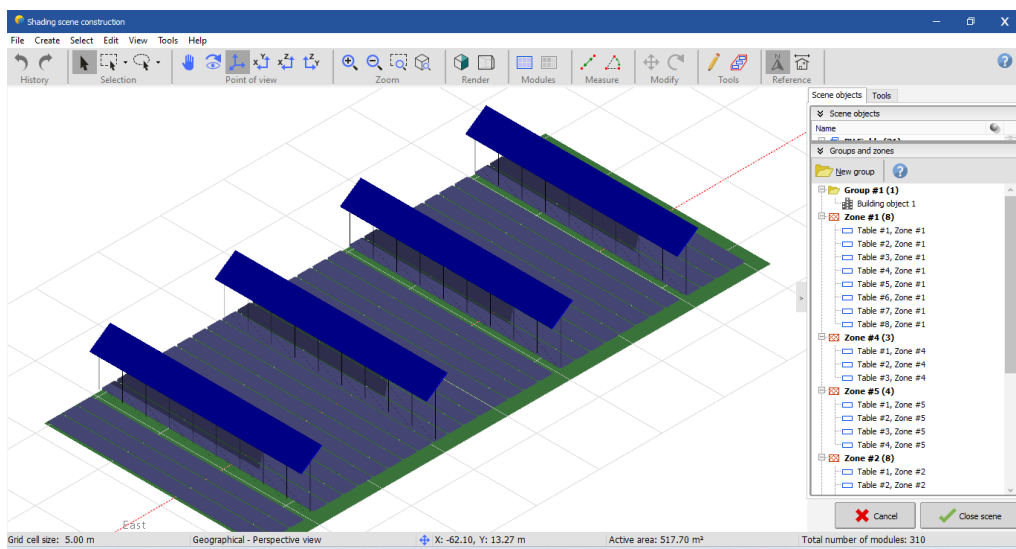


Figure 4.9 Shading analysis simulation for a horizontal tracking bifacial system, ($+55^\circ$)

4.4 Outdoor Measurements of a Bifacial Solar Panel

To get insight about bifaciality of a solar panel, the electrical characteristics of the solar panel was measured using a DC voltmeter and a DC ammeter. The objective was to determine how much current is produced by single and dual face of the bifacial solar panel as it is strongly correlated with output power.

One bifacial solar panel was used to obtain electrical measurements for both bifacial and monofacial scenarios. The panel's width was 0.78m and the length was 0.98m. The solar panel was set up vertically, at a 90° tilt angle, and N-S orientation. Initially, it was intended for the orientation to be E-W but the windy conditions posed a risk of toppling and cracking the glass on the panel's surface.

For the monofacial measurements, cardboard was used to cover the rear side of the panel therefore preventing sunlight from reaching the solar cells. The open circuit voltage and short circuit current were then measured. For the bifacial measurements, current and voltage values were obtained when the solar panel was producing energy from both the front and the rear side, that is, without the cardboard cover. Using the current and voltage values, the BG was illustrated from the values obtained in the two scenarios. The data was collected on the 4th of June 2024, in Ankara, from 0900 hrs. to 1800 hrs. The local temperature was 33⁰C. The results are discussed in Chapter 5 of this thesis study.

5. RESULTS AND DISCUSSION

5.1 Vertical Bifacial System Design on PVsyst

The results obtained from designing a 132- kW vertical bifacial system on PVsyst software is presented below. The average annual ambient temperature was 11.8⁰C. The annual produced energy was 187.093 MWh, and the performance ratio (PR) was 133.72 %. The specific production was 1417 kWh/kWp/year. The graph of normalized energy productions shows that the system produces the most energy in July and the least energy in December. In July, 23689 kWh of energy was added to the grid, and in December, 7235 kWh of energy was added to the grid. Figure 5.1 below shows the monthly normalized productions per installed kWp and figure 5.2 below shows the monthly performance ratio. The monthly performance ratio is not constant through the year. PR is higher in December and January, and lower in May and July as shown in figure 5.3 below.

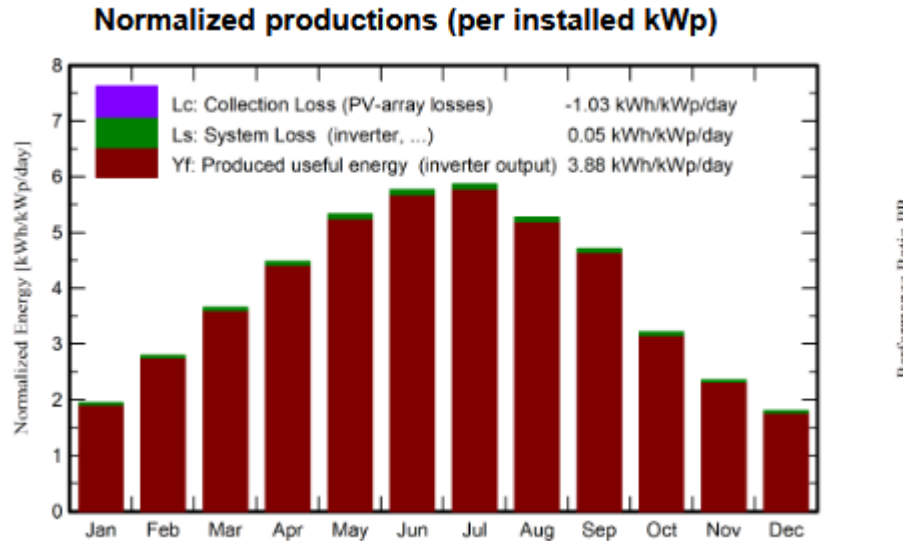


Figure 5.1 The monthly specific production for a fixed vertical bifacial system

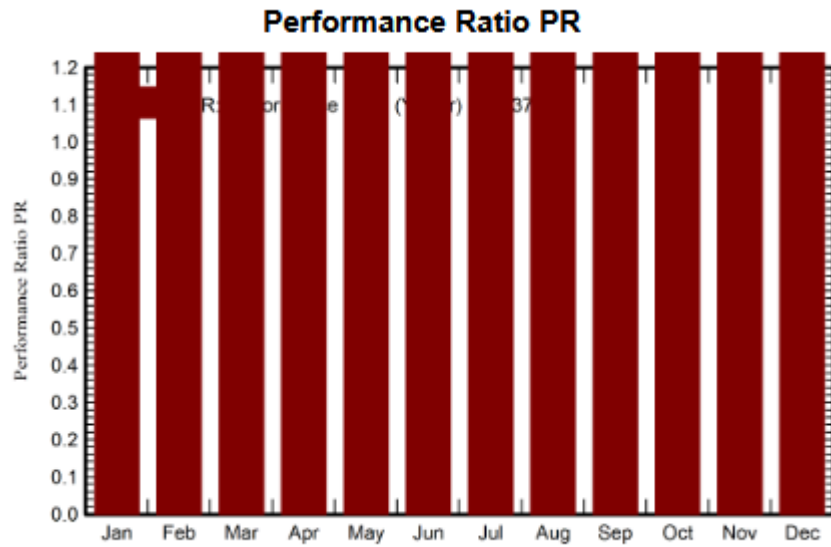


Figure 5.2 The monthly performance ratio for a fixed vertical bifacial system

The performance ratio (PR) is a value that compares the energy produced by a system to that which would be produced if the system worked non-stop at nominal STC efficiency (PVsyst User Guide Manual, 2024). For vertical bifacial systems with a 90° tilt angle and East- West orientation, the PR value can be greater than 100 %, since the system interprets the rear side contribution as gain when compared to energy produced by monofacial PV panels at nominal STC efficiency. For this simulation, the PR value is 133.72 % and this is a normal value for such a system. However, the PR value should not be confused with the bifacial performance ratio value. The bifacial performance ratio value should be less than 1. The bifacial performance ratio value obtained from this simulation is 0.731, as shown in figure 5.3 below.

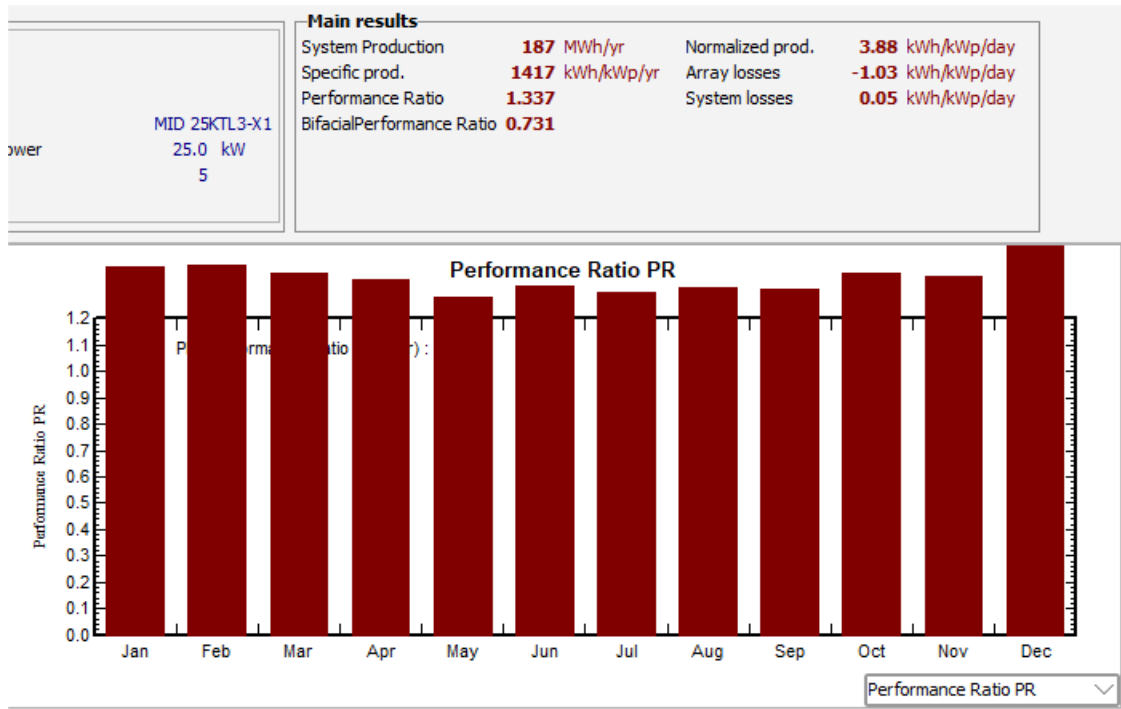


Figure 5.3 The bifacial performance ratio and main results for a fixed vertical bifacial system

The other section of the main results shows the monthly values of GHI, DHI, and GlobInc on the collector plane. The additional sum of the direct normal and horizontal diffuse irradiation components received on a surface with a specific tilt and angle of incidence, is known as GlobInc or POA irradiation. These values are important in the calculation of the PR as illustrated below. Values of the EArray as well as the energy injected into the grid are also included in this section of the results. The annual GHI for this system is 1680 kWh/m², and the annual DHI is 572.04 kWh/m². The annual GlobInc on the collector plane is 1060 kWh/m². The effective global irradiance after accounting for losses due to shading and array incidence losses (IAM losses) is 992 kWh/m². Array incidence losses occur due to reflection and transmission of the rays of the sun on the collector plane. The annual EArray is 189726 kWh. Figure 5.4 below shows the irradiation components and energy output results for a fixed vertical bifacial system.

Balances and main results								
	GlobHor kWh/m ²	DiffHor kWh/m ²	T_Amb °C	GlobInc kWh/m ²	GlobEff kWh/m ²	EArray kWh	E_Grid kWh	PR ratio
January	62.5	27.69	-0.17	42.4	38.7	7944	7815	1.396
February	83.3	34.39	1.76	55.1	49.9	10343	10194	1.401
March	126.0	45.76	6.19	81.5	75.6	14962	14747	1.372
April	160.1	61.78	10.75	98.3	92.6	17749	17508	1.349
May	200.0	73.07	15.82	127.3	120.3	21808	21510	1.280
June	214.7	69.40	19.97	128.7	123.6	22830	22529	1.326
July	223.9	63.27	23.99	138.1	131.4	24007	23689	1.299
August	205.6	58.49	24.13	122.4	115.7	21573	21284	1.317
September	162.0	47.25	18.80	106.3	99.4	18661	18413	1.312
October	111.7	37.14	12.65	71.5	65.7	13158	12969	1.375
November	73.7	28.60	6.31	51.2	45.7	9339	9201	1.360
December	56.5	25.19	1.40	37.1	33.5	7353	7235	1.477
Year	1680.0	572.04	11.86	1060.0	992.0	189726	187093	1.337

Legends			
GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

Figure 5.4 The irradiation components and energy output results for a fixed vertical bifacial system

The loss diagram is another important section of the main results obtained in the fixed vertical bifacial system simulation. The loss diagram is a Sankey diagram that visualizes the energy at different stages in the simulation. The top of the diagram starts with the input energy, which is global horizontal irradiation. The bottom of the diagram finishes with the output energy, which is the electrical energy that is added to the grid. The width of the loss diagram represents the energy flow. The first part of the diagram represents only irradiation, and the energy in this part is referred to as luminous energy. Bifacial/back side irradiation is considered in the dashed box. The second part of the diagram represents the electrical losses in the system. The energy in this part of the diagram is referred to as electrical energy. The loss diagram values are required for the calculation of the bifacial PR value. The loss diagram values can be expressed in MS excel or in the form of a Sankey diagram that shows the losses experienced throughout the whole year. Figures 5.5 below shows the loss diagram values as a Sankey diagram.

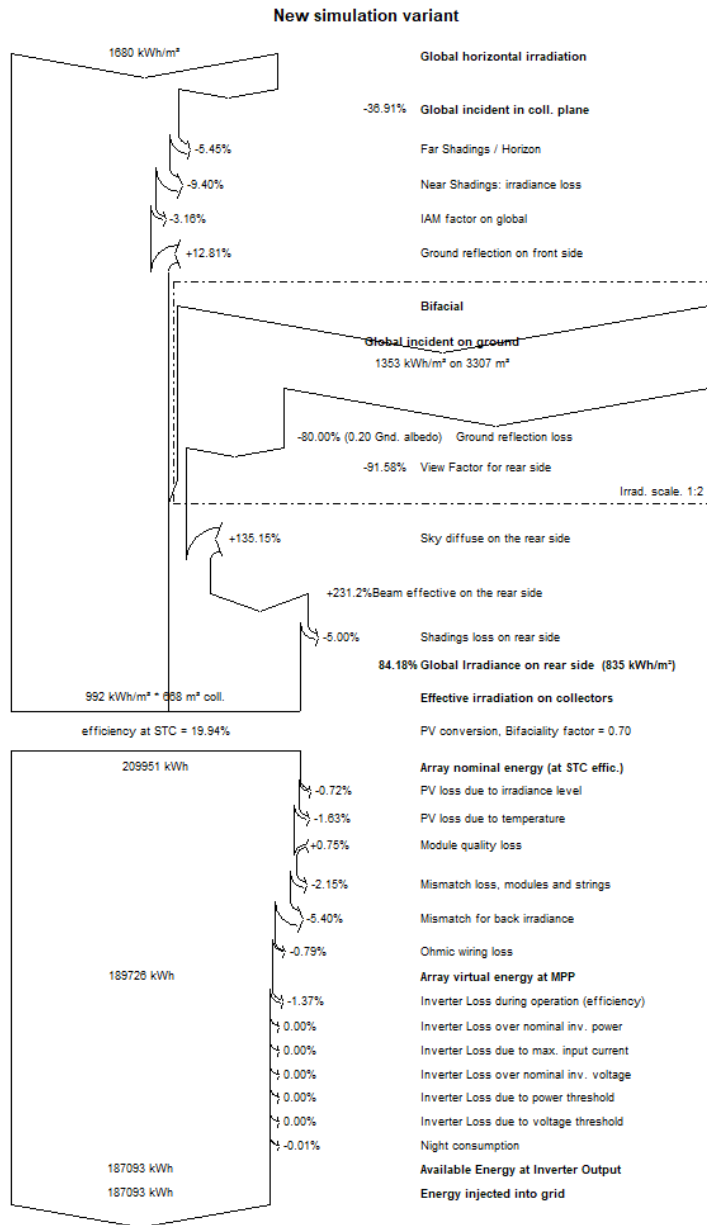


Figure 5.5 The loss diagram values for a fixed vertical bifacial system expressed as a Sankey diagram

The formula for obtaining the performance ratio can be summarized as follows:

$$PR = \frac{AC\ Yield\ (kWh) * 1(kWm2)}{DC\ installed\ capacity\ (kWh) * POA\ irradiation\ (kWh/m2)} \times 100 \quad (38)$$

$$PR = \frac{187093 * 1}{132 * 1060} \times 100 = 133.71\% \quad (39)$$

The formula for obtaining the bifacial performance ratio can be summarized as follows:

$$PR_{bifi} = \frac{PR}{1 + \frac{(GlobBak + BackShd)}{GlobInc}} \quad (40)$$

Where the term GlobBaK describes the global or effective irradiance on the PV modules' back side. This value can be obtained from the loss diagram as 835 kWh/m². In bifacial model definitions, BackShd are the losses due to the "Structure shading factor". The BackShd value can be obtained from the loss diagram as "5 % - shading loss on the rear side". Back side irradiance is 835 kWh/m² and therefore the shading loss is 5 % of 835 kWh/m², which equates to 41.75 kWh/m². GlobInc refers to the global incident irradiance on the collector plane and this value can be obtained from figure 5.4 as 1060 kWh/m². Therefore, the bifacial PR can then be calculated as:

$$PR_{bifi} = \frac{1.3372}{1 + \frac{(835 + 41.75)}{1060}} = 0.73186 \quad (41)$$

The first loss on the diagram is the irradiation loss on the global incident collector plane. This loss accounts for 36.91 % of the total loss and is due to the vertical tilt of this system. Due to the 90° tilt as a result of the system orientation, the irradiation that is available on the collector plane is less than the global horizontal irradiation. The loss diagram also indicates the shading losses in the system. Far shadings/ horizon losses account for 5.45 % of the losses, near shading losses account for 9.4 % of the losses, while rear shading losses account for 5 % of the losses. Reflection and transmission of irradiation on the collector plate accounts for 3.16 % of the losses. This loss is referred to as "IAM factor on global", on the loss diagram. The IAM factor is directly proportional to the sun's position, that is, the higher the angle of incidence, the greater the loss. Loss of energy due to low irradiance level is 0.72 %. This is the loss brought about by changes in weather. In cloudy weather, this loss is greater. Temperature- related PV loss is 1.63 %. The modules and strings mismatch loss are 2.15 %. The loss due to mismatch for back irradiance is

5.40 %. The ohmic wiring loss is 0.79 %. The inverter loss due to its efficiency is 1.37 % and the inverter loss due to night consumption is 0.01 %.

5.2 Vertical Bifacial System Design on PVSOL

The results obtained from designing a 132- kW vertical bifacial system on PVSOL software is presented below. The annual average temperature obtained by PVSOL was 11.3°C. The ground albedo was 20 % and the bifaciality factor was 70 %. The annual produced energy was obtained as 192.843 MWh, and the performance ratio of the system was obtained as 0.708. The specific annual energy yield was obtained as 1460.65 kWh/kWp. The graph of the monthly energy production forecast shows that the greatest amount of energy is produced in July and the least amount of energy is produced in January. The energy produced in July is 25,422.4 kWh and in January 7,356.2 kWh of energy was produced. Figure 5.6 below shows the graph of monthly energy production forecast and a summary of the results obtained.

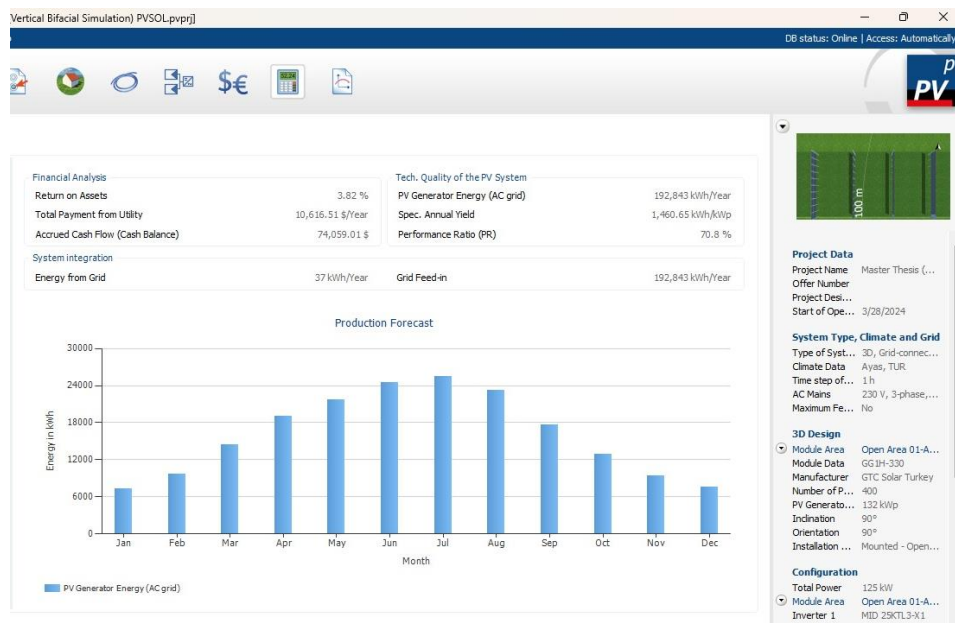


Figure 5.6 The monthly energy production forecast for a fixed vertical bifacial system on PVSOL

The next section of the results are the results per module area and PV system energy balance. From the simulation, PVSOL determines the global horizontal radiation as

1466.67 kWh/m². Because the PV panels are bifacial, there is a 20 % or 293.33 kWh/m² increase in the radiation at the module because of ground albedo. The orientation and inclination of the module surface leads to 39.83 % or 700.97 kWh/m² loss of radiation at the module. Module- independent shading leads to 3.10 % or 32.79 kWh/m² loss of radiation reaching the module. Reflection on the module interface leads to 5.75 % or 58.98 kWh/m² loss of radiation reaching the modules. The back side irradiance leads to an additional 1034.60 kWh/m². After summing up all gains and losses, the global radiation at the module is 2001.86 kWh/m². The global radiation on the module without reflection is 2060.85 kWh/m². Since the module area is 668m², the total luminous energy reaches to the PV modules is 1,337,245.42 kWh. However, bifaciality (70 % of the back side irradiance) leads to 15.50 % loss and STC conversion (Rated efficiency of module 19.78 %) leads to 80.22 % loss. The available electrical energy before the electrical losses is obtained as 200,038.12 kWh.

Further electrical losses in the system include:

- Module-specific partial shading loss- 2.22 % or 4,972.94 kWh.
- Low-light performance loss- 4.12 % or 9,008.24 kWh.
- Deviation from nominal module temperature loss- 2.02 % or 4,231.38 kWh.
- Diodes loss- 0.09 % or 182.18 kWh.
- Mismatch loss according to manufacturer information- 2.10 % or 4,307.84 kWh.
- Mismatch loss due to configuration/ shading – 0.39 % or 789.05 kWh.
- PV energy (DC) loss due to inverter down regulation- 451.92 kWh.
- Input voltage loss due to deviation from rated voltage- 0.31% or 612.91 kWh.
- DC/ AC conversion loss- 1.61 % or 3, 193.57 kWh.
- Inverter loss due to standby conversion- 0.02 % or 36.66 kWh.
- Total cable losses- 1.5 % or 2,936.70 kWh.

Figures 5.7, 5.8 and 5.9 below show the results per module area and PV system energy balance.

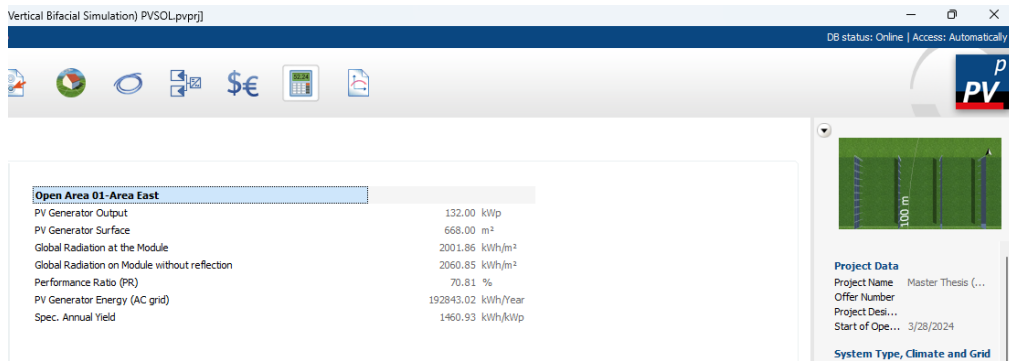


Figure 5.7 The results per module area for a fixed vertical bifacial system on PVSOL

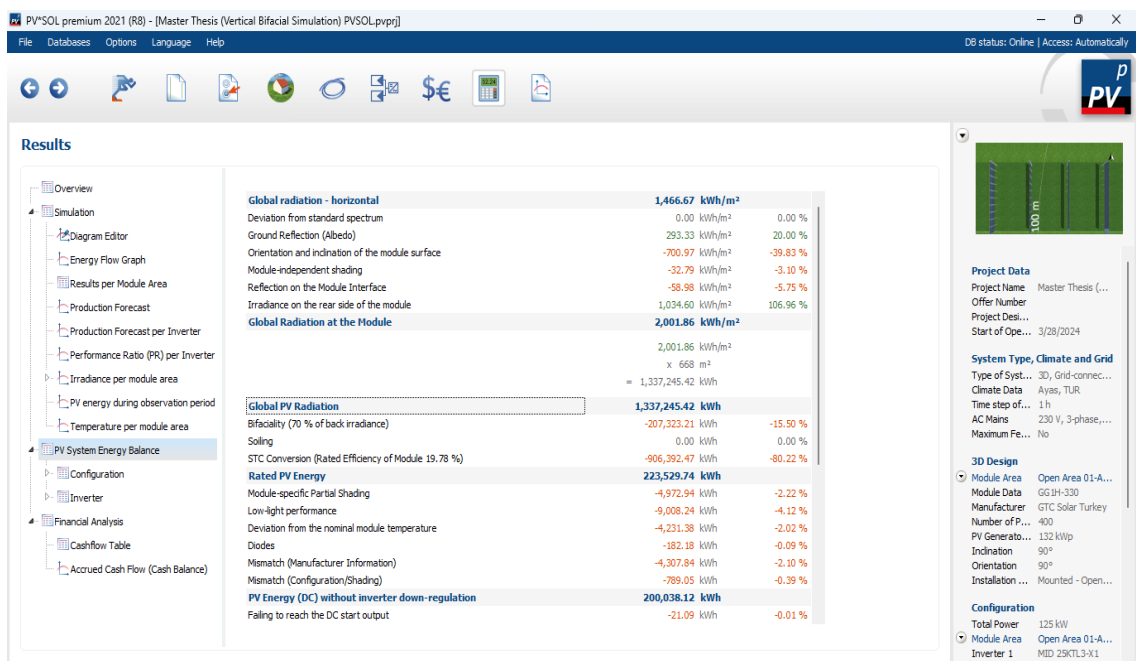


Figure 5.8 The PV system energy balance for a fixed vertical bifacial system on PVSOL

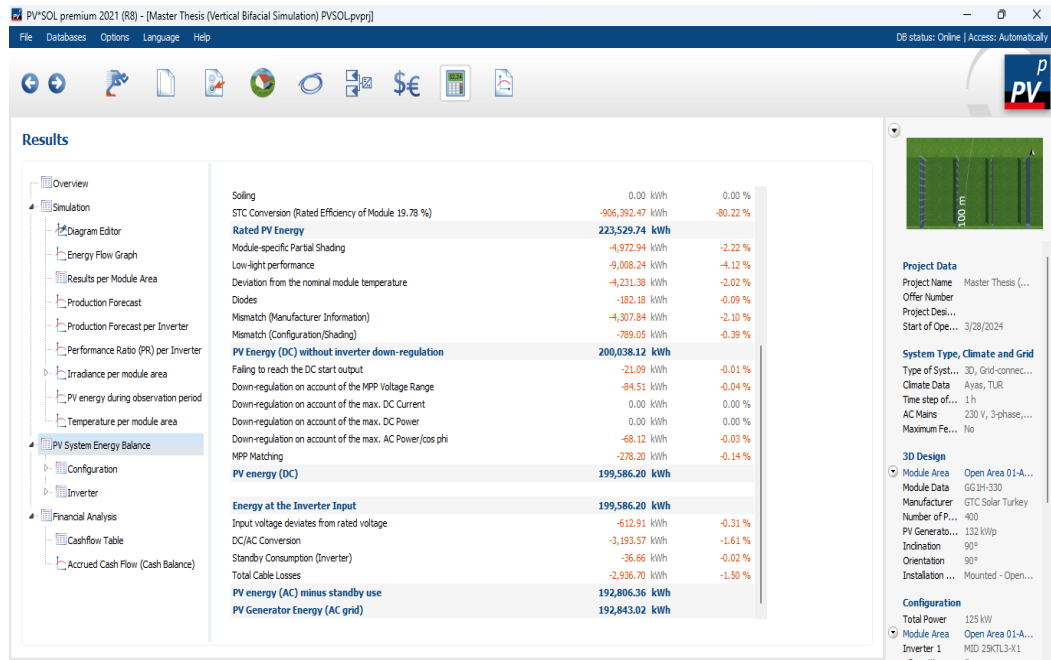


Figure 5.9 The PV system energy balance for a fixed vertical bifacial system on PVSOL (continuation)

The last section of the results describes the financial analysis of the system. Here, the price of electricity is 0.048 \$/kWh to residential buildings and 0.128 \$/kWh for commercial purposes. The average price of electricity is 0.088 \$/kWh. The inflation rate for feed-in for electricity is 2.67% per annum. The interest on capital is 1% over an assessment period of 20 years. The installation costs are determined to be 198,000 \$. The accrued cash flow within the system is negative for the first eight years. On the 20th year, the accrued cash flow within the system is 172,203.00 \$.

5.3 Horizontal Tracking Bifacial System Design on PVsyst

The results obtained from designing a 132- kW horizontal tracking bifacial system on PVsyst software are presented below. The average annual ambient temperature was 11.8^oC. The P_{nom} ratio of the inverters was obtained as 1.056. The annual produced energy was 287.390 MWh, and the performance ratio (PR) was 91.57 %. The specific production was 2177 kWh/kWp/year. The graph of normalized energy productions shows that the system produces the most energy in July and the least energy in December. In July, 36,

285 kWh of energy was added to the grid, and in December, it was 11, 126 kWh. The bifacial performance ratio was obtained as 0.837. Figures 5.10 and 5.11 below show the monthly normalized production per kWp, monthly performance ratio, and the bifacial performance ratio for the designed system.

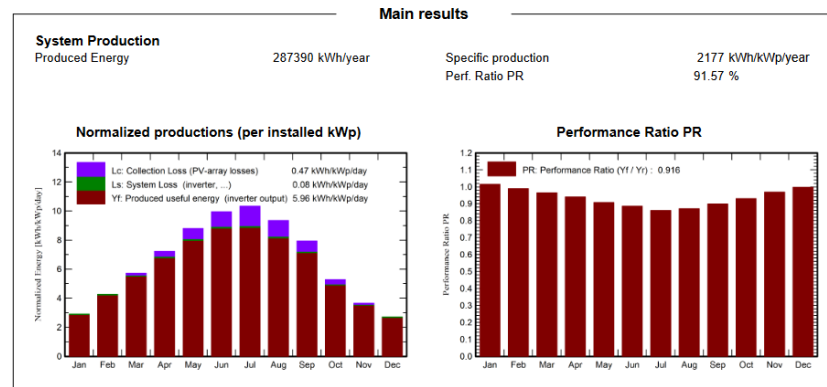


Figure 5.10 The monthly normalized productions and performance PR ratio for a horizontal tracking bifacial system

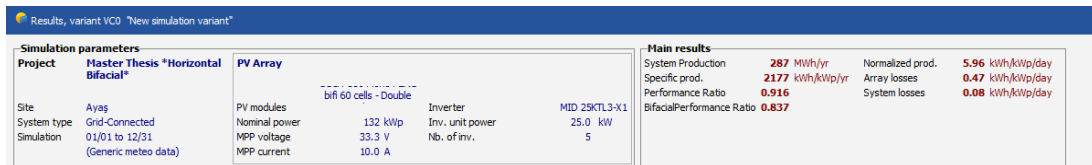


Figure 5.11 The bifacial performance ratio for a horizontal tracking bifacial system

The next section of the main results shows the monthly GHI, DHI and GlobInc values. These values are important in the calculation of the PR as illustrated below. Values of EArray as well as the energy added to the grid are also included in this section of the results. The annual GHI is 1680 kWh/m², and the annual DHI is 572.04 kWh/m². The annual GlobInc is 2377.6 kWh/m². The GlobEff after accounting for losses due to shading and array incidence losses (IAM losses) is 2318.1 kWh/m². The annual EArray is 291,375 kWh, and the energy added to the grid after losses is 287,290 kWh. Figure 5.12 below shows the irradiation components and energy output results for a horizontal tracking bifacial system.

Balances and main results								
	GlobHor kWh/m ²	DiffHor kWh/m ²	T_Amb °C	GlobInc kWh/m ²	GlobEff kWh/m ²	EArray kWh	E_Grid kWh	PR ratio
January	62.5	27.69	-0.17	88.0	85.0	11954	11784	1.014
February	83.3	34.39	1.76	119.2	115.0	15777	15562	0.989
March	126.0	45.76	6.19	177.4	173.1	22888	22569	0.964
April	160.1	61.78	10.75	216.7	212.6	27270	26894	0.940
May	200.0	73.07	15.82	272.8	267.0	33116	32660	0.907
June	214.7	69.40	19.97	298.7	293.1	35419	34937	0.886
July	223.9	63.27	23.99	320.1	312.2	36825	36325	0.860
August	205.6	58.49	24.13	290.0	285.2	33821	33358	0.871
September	162.0	47.25	18.80	238.3	232.7	28631	28249	0.898
October	111.7	37.14	12.65	163.6	157.9	20370	20092	0.930
November	73.7	28.60	6.31	109.5	104.5	14179	13991	0.968
December	56.5	25.19	1.40	83.3	79.6	11126	10969	0.997
Year	1680.0	572.04	11.86	2377.6	2318.1	291375	287390	0.916

Legends			
GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

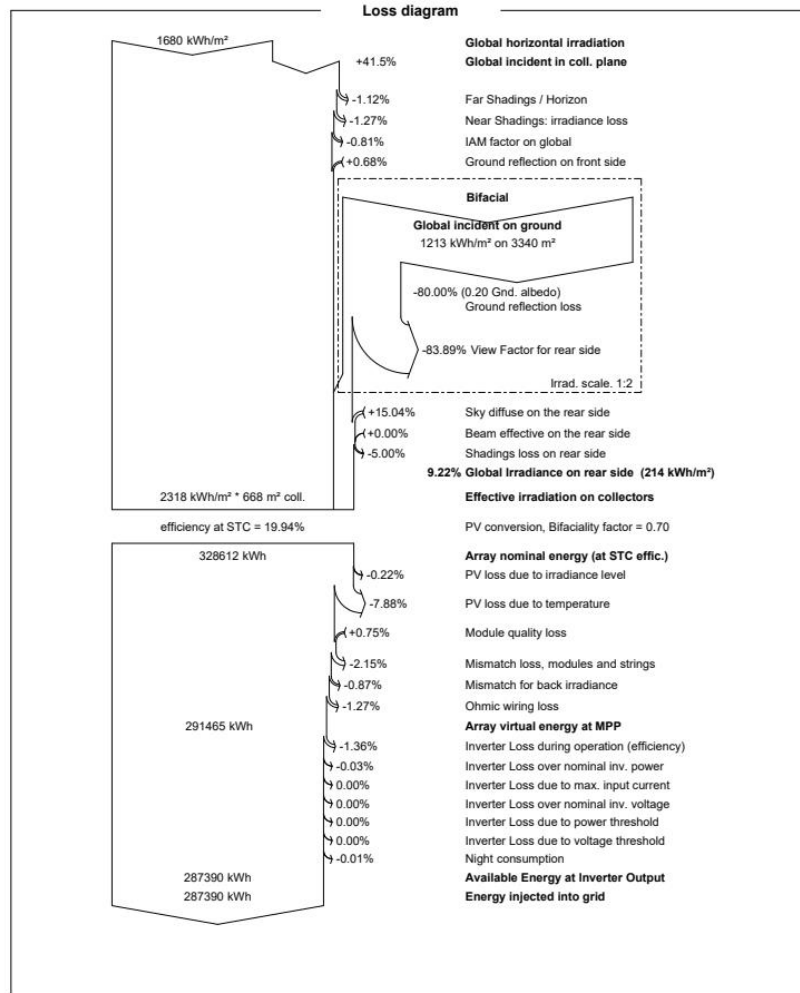
Figure 5.12 The irradiation components and energy output results for a horizontal tracking bifacial system

The loss diagram is the next important section of the main results obtained in the horizontal tracking bifacial system simulation. Figure 5.13 below show the loss diagram values as a Sankey diagram.



PVsyst V7.4.0
 VCO, Simulation date:
 07/10/24 13:03
 with v7.4.0

Project: Master Thesis *Horizontal Bifacial*
 Variant: New simulation variant



07/10/24

PVsyst Licensed to

Page 8/10

Figure 5.13 The loss diagram values for a horizontal tracking bifacial system expressed as a Sankey diagram

Using equation 38 expressed above, the performance ratio can be obtained as:

$$PR = \frac{287390 * 1}{132 * 2377.6} \times 100 = 91.57\% \quad (42)$$

Using equation 40 expressed above, the bifacial performance ratio can be obtained as:

$$PR_{bifi} = \frac{PR}{1 + \frac{(GlobBak + BackShd)}{GlobInc}} \quad (40)$$

where GlobBaK value can be obtained from the loss diagram as 214 kWh/m². The BackShd value is “5 % - shading loss on the rear side”. The rear side irradiance is 214 kWh/m² and therefore the BackShd value is 5 % of 214 kWh/m², which equates to 10.7 kWh/m². GlobInc is 2377.6 kWh/m². Therefore, the bifacial PR can then be calculated as:

$$PR_{bifi} = \frac{0.9157}{1 + \frac{(214+10.7)}{2377.6}} = 0.8366 \quad (43)$$

In this loss diagram, there is a +41.5 % gain in the GlobInc compared to the GHI. In the fixed vertical bifacial system, this was obtained as a loss in the irradiation available on the collector plane. However, in the tracking horizontal bifacial system, this gain is obtained due to the ability of the modules to optimize the tilt angle and collect more energy than the horizontal. The loss diagram also indicates the shading losses in the system. Far shadings/ horizon losses account for 1.12 % of the losses, near shading losses account for 1.27 % of the losses, while rear shading losses account for 5 % of the losses. Reflection and transmission of irradiation on the collector plate accounts for 0.81 % of the losses. The energy loss due to the low irradiance levels is 0.22 %. Temperature-related loss is 7.88 %. The modules and strings mismatch loss are 2.15 %. The loss due to mismatch for back irradiance is 0.87 %. The ohmic wiring loss is 1.27 %. The inverter loss due to its efficiency is 1.36 %. The inverter loss over nominal inverter power is 0.03 % and the inverter loss due to night consumption is 0.01 %.

5.4 Horizontal Tracking Bifacial System Design on PVSOL

The results obtained from designing a 132- kW vertical bifacial system on PVSOL software are presented below. The annual average temperature obtained by PVSOL was 14.7°C. The annual produced energy was obtained as 263.062 MWh, and the performance ratio of the system was obtained as 0.842. The specific annual energy yield was obtained

as 1,992.62 kWh/kWp. The graph of the monthly energy production forecast shows that the highest amount of energy is produced in July- 34,582.3 kWh and the least amount of energy is produced in December- 8,919.2 kWh. Figure 5.14 below shows the graph of monthly energy production forecast and a summary of the results obtained.

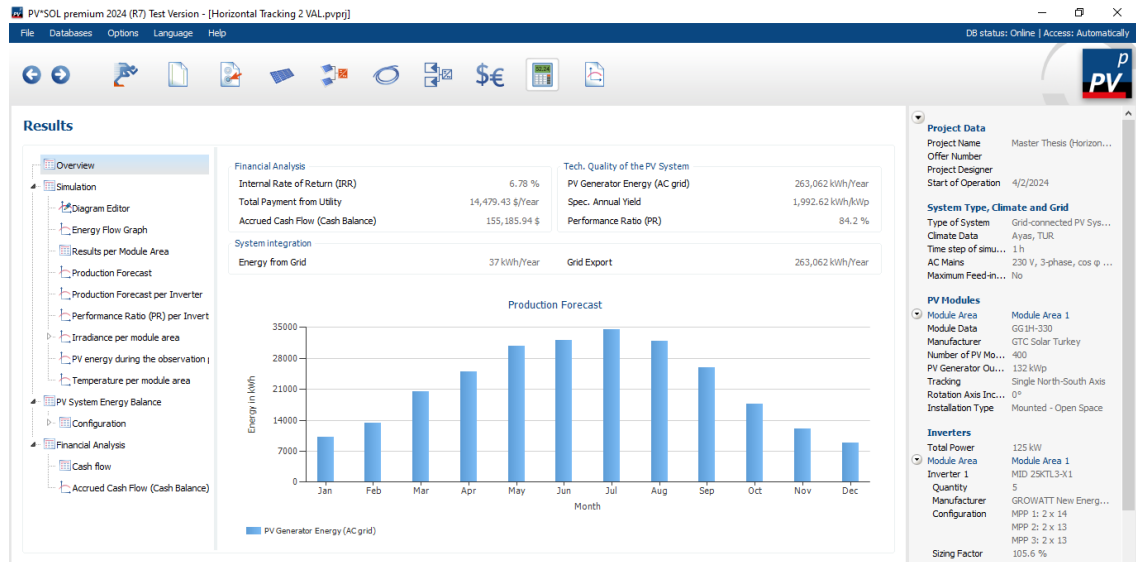


Figure 5.14 The monthly energy production forecast for a horizontal tracking bifacial system on PVSOL

The next section of the results are the results per module area and PV system energy balance. From the simulation, PVSOL determines the global horizontal radiation as 1466.67 kWh/m². There is a 4.06 % or 67.76 kWh/m² increase in the radiation at the module because of ground albedo. The orientation and inclination of the module surface leads to 29.90 % or 519.46 kWh/m² increase in radiation at the module. Shading leads to 0.18 % or 4.14 kWh/m² loss of radiation reaching the module. Reflection on the module interface leads to 2.81 % or 63.36 kWh/m² loss of radiation reaching the modules. Rear side irradiance leads to an additional 111.83 kWh/m². After summing up all gains and losses, the global radiation at the module is 2301.11 kWh/m². The global radiation on the module without reflection is 2364.47 kWh/m². Since the module area is 668m², the total luminous energy reaches to the PV modules is 1,537,140.95 kWh. However, bifaciality (70 % of the back side irradiance) leads to 1.46 % loss and STC conversion (Rated efficiency of module 19.78 %) leads to 80.22 % loss. The available electrical energy before the electrical losses is obtained as 272,905.95 kWh.

Further electrical losses in the system include:

- Low-light performance loss- 2.91 % or 8,730.67 kWh.
- Deviation from nominal module temperature loss- 4.18 % or 12,164.93 kWh.
- Mismatch loss according to manufacturer information- 2.10 % or 5,853.96 kWh.
- PV energy (DC) loss due to failure to reach the DC start output- 0.01 % or 17.84 kWh.
- Down regulation due to the highest AC power/ cos phi- 4.27 kWh.
- MPP matching loss- 0.12 % or 315.88 kWh.

Figures 5.15, 5.16 and 5.17 below show the results per module area and PV system energy balance.

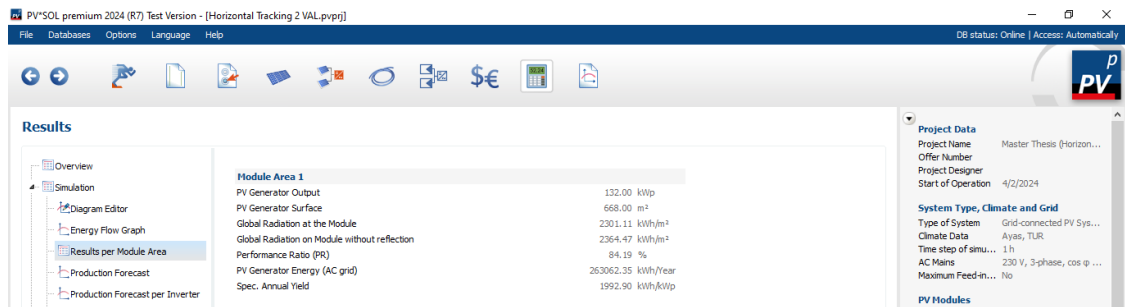


Figure 5.15 The results per module area for a horizontal tracking bifacial system on PVSOL

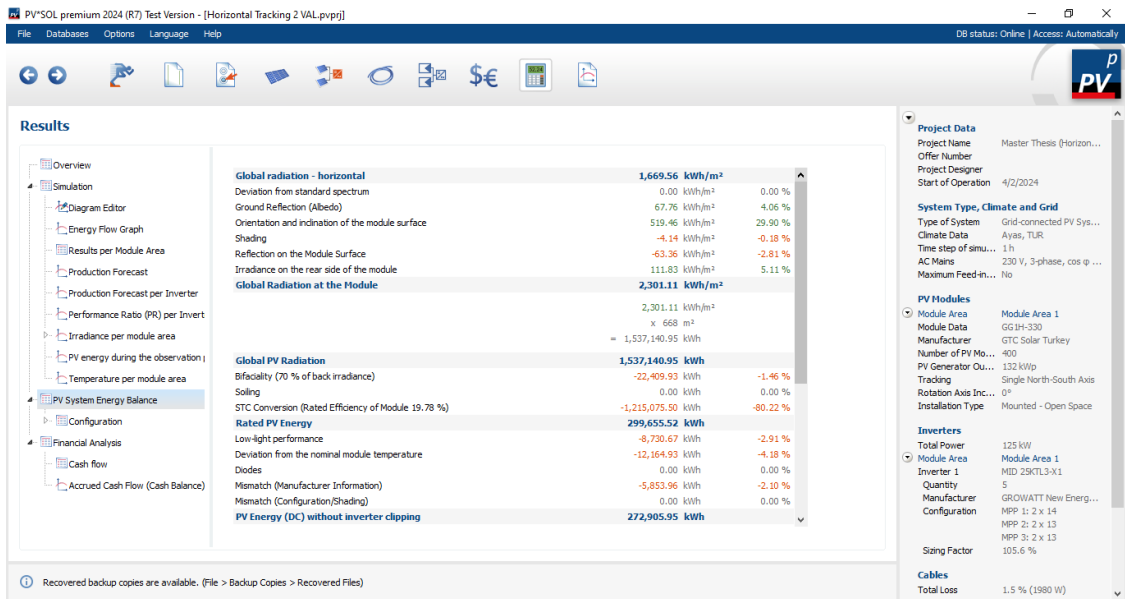


Figure 5.16 The PV system energy balance for a horizontal tracking bifacial system on PVSOL

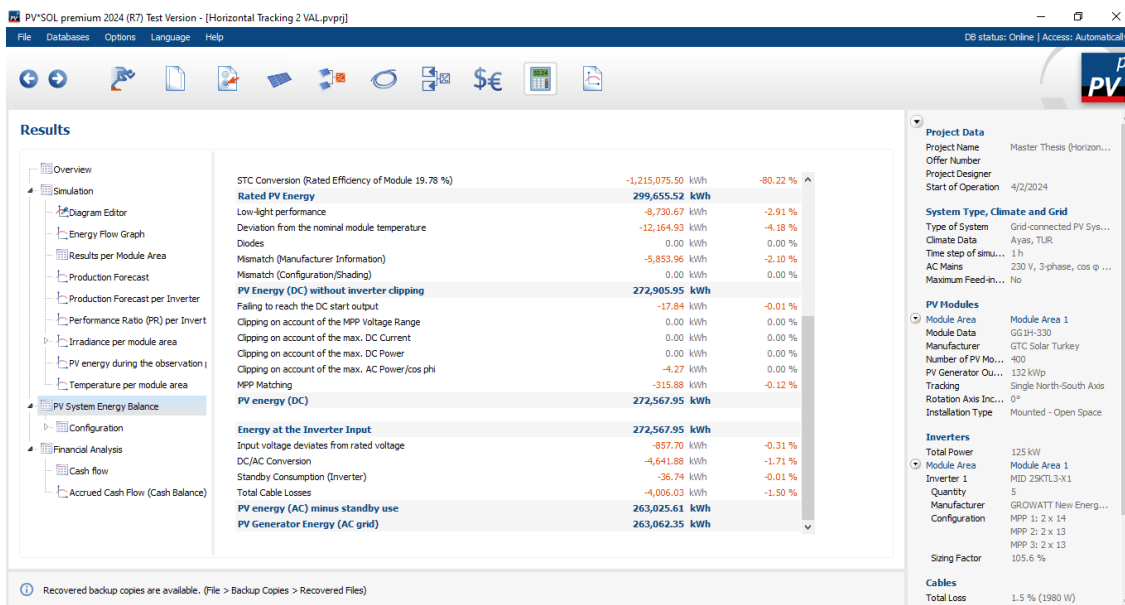


Figure 5.17 The PV system energy balance for a horizontal tracking bifacial system on PVSOL (continuation)

The last section of the results describes the financial analysis of the system. Here, the price of electricity is 0.048 \$/kWh to residential buildings and 0.128 \$/kWh for commercial purposes. The average price of electricity is 0.088 \$/kWh. The inflation rate for feed-in for electricity is 2.67 % per annum. The interest on capital is 1% over an

assessment period of 20 years. The installation costs are determined to be 198,000 \$. The accrued cash flow within the system is negative for the first four years. On the 20th year, the accrued cash flow within the system is 1,615,608.74 \$. Although the financial analysis from the software determined the installation costs for both the fixed vertical and horizontal tracking systems is the same, the values cannot be the same. Tracking systems cost more to install compared to fixed systems. As a result of this assumption, the value of the accrued cash flow on the 20th year for the horizontal tracking system was too high.

Comparison of the power output of a horizontal tracking bifacial agri-PV system simulated on PVsyst and PVSOL, shows that there is a significant difference between the two software results. This difference in power can be accounted for with the following reasons:

1. Layout of the modules in the software- In PVsyst, using the 3D near construction scene, the panels can be laid side by side, with one panel next to another. However, in PVSOL, due to the 2D nature of the tracking systems, one cannot choose the design or layout of the panels. By default, the panels are laid on top of each other, resulting in a difference in the rear side irradiance values.
2. Module unavailability in database- In PVsyst the module used in the simulation was available (provided by the manufacturer) in the software database. However, in PVSOL, the module was not available in the database resulting in the manual input of module data. The software calculated the low-light behavior of the module. The values obtained are generally worse than if measured values from the manufacturer are used.

5.5 Shading Analysis for a Fixed Vertical Bifacial System Design

In order to determine how the PV panels in an agriPV system affect the plants growing beneath them, it is important to evaluate how much sunlight gets to the plants. The beam horizontal irradiance under shading conditions, BHI_s , and the diffuse horizontal irradiance under shading conditions, DHI_s , values describe the irradiance received by the crops after shading by PV panels. These values help in the calculation of what percentage of shading

is experienced by the crops. The shading factor table obtained from the 3D shading construction scene can be used to calculate the amount of sunlight that reaches the plants. The ratio of the shaded area to the field's entire sensitive area is commonly referred to as the shading factor. PV modules' shading effect consists of both direct and diffuse shading factors. The geometry of the module, objects shaded by it, and the position of the sun, affect the direct component (Zainali, 2023). The geometry of the module and the shading objects affect the diffuse component. The reflected component is reduced by the shading objects, and results in reduced albedo (Silva M, 2021). However, since we are investigating the effect on the plants and not the panels, the reflected component shall not be included in the calculations below. The BHI_s and DHI_s , can be calculated as follows:

$$BHI_s = BHI (1 - f_b) \quad (44)$$

$$DHI_s = DHI (1 - f_d) \quad (45)$$

Where f_b is the shading factor for beam, f_d is the shading factor for diffuse, BHI_s is the beam horizontal irradiance under shading conditions, and DHI_s is the diffuse horizontal irradiance under shading conditions. The shading factor for diffuse value is constant and can be directly obtained from the shading factor table. However, the shading factor for beam value changes depending on the sun height and the solar azimuth angle. f_b value can also be obtained for a given day and time using the shadows drawing feature in the 3D shading construction scene in PVsyst. For this study, f_b for 21 March 2023, 21 June 2023, 23 September 2023, and 21 December 2023 at 12:00 noon will be used for the calculations, since photosynthesis rate is highest at noon time. Figure 5.18 below shows the shading factor table for shading analysis of a fixed vertical bifacial system.

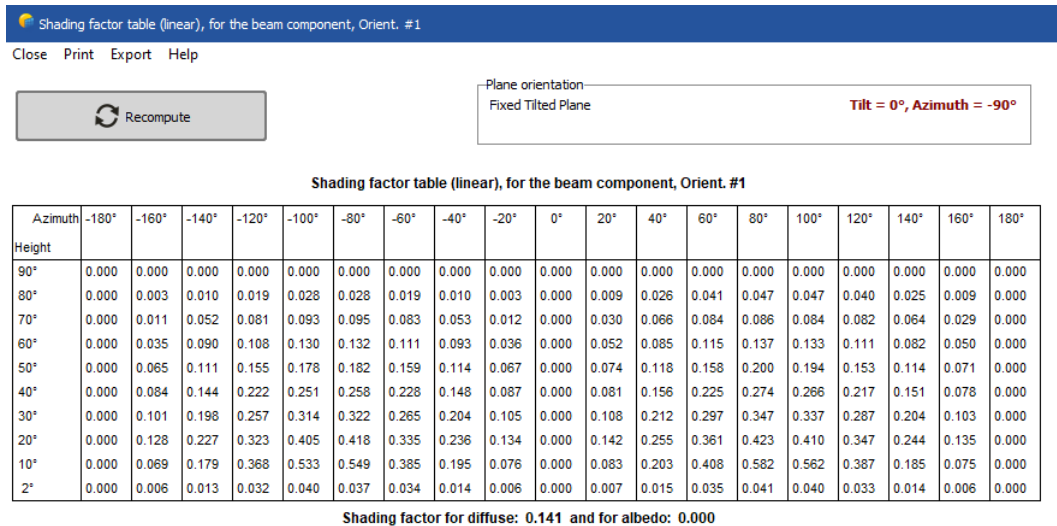


Figure 5.18 Shading factor table obtained for the shading analysis for a fixed vertical bifacial system on PVsyst

From the table above, it can be observed that the shading factor for diffuse, f_d , is 0.141. The shading factor for beam can be obtained using the shadings animation feature in the near shading construction scene. It was determined that the beam linear loss through the day on 21 April 2023 was 14.8 %, with maximum beam loss at 8.00 am and 6.00 pm, and minimum beam loss at 1.00 pm. On 21 June 2023, the beam linear loss was 14%, with maximum beam loss at approximately 7.00 am and 7.00 pm, and minimum beam loss at 1.00 pm. On 23 September 2023, the beam linear loss was 14.2 %, with maximum loss at 8.00 am and 6.00 pm, and minimum loss at 1.00 pm. On 21 December 2023, the beam linear loss was 9.6%, with maximum loss at 9.30 am and 4.30 pm, and minimum loss at 1.00 pm. Figure 5.19 below shows the shadows drawing and the shading animation scene for a fixed vertical bifacial system on 21 April 2023 at 12:00 noon. The shadows are illustrated in dark brown.

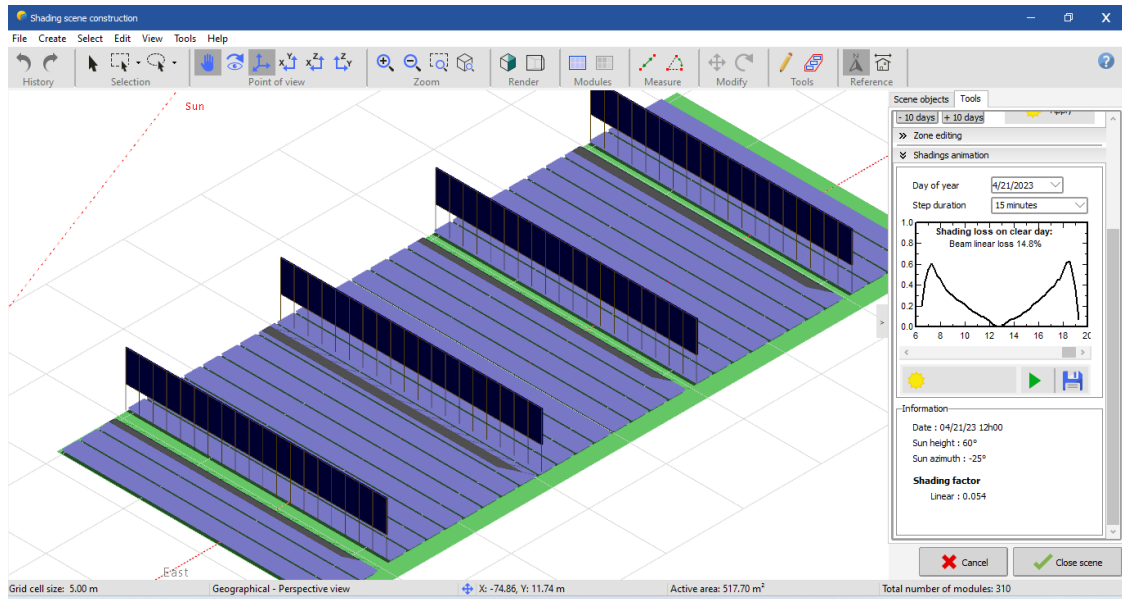


Figure 5.19 The shadows drawing and shading animation scene for a fixed vertical bifacial system on 21 April 2023 at 12:00 noon

The shading factor for beam, f_b , is then obtained as follows:

- 21 April 2023 at 12:00 noon (sun height- 60° , solar azimuth angle- -25°)- 0.054.
- 21 June 2023 at 12:00 noon (sun height- 70° , solar azimuth angle - -37°)- 0.047.
- 23 September 2023 at 12:00 noon (sun height- 49° , solar azimuth angle - -16°) - 0.054.
- 21 December 2023 at 12:00 noon (sun height- 26° , solar azimuth angle - -12°) - 0.073.

After running the simulation, the results obtained showed that DHI is 572.04 kWh/m^2 , and the global horizontal irradiation is 1680 kWh/m^2 . BHI can be obtained as the difference between GHI and DHI, and the value is 1107.96 kWh/m^2 . The GHI_s is also obtained as the sum of BHI_s and DHI_s . Additionally, the percentage difference between GHI and GHI_s is also obtained from calculations. BHI_s and DHI_s , are obtained as shown in the Table 5.1 below:

Table 5.1 Irradiance parameters for 21/04/2023, 21/06/2023, 23/09/2023, and 21/12/2023 at 12:00 noon

Day of the Year At (12:00)	Beam shading factor (f_b)	BHI _s (kWh/m ²)	DHI _s (kWh/m ²)	GHI _s (kWh/m ²)	$\frac{GHI_s}{GHI} \times 100$ (%)
21 April 2023	0.054	1048.13	491.382	1539.512	91.638
21 June 2023	0.047	1055.886	491.382	1547.268	92.099
23 September 2023	0.054	1048.13	491.382	1539.512	91.638
21 December 2023	0.073	1027.079	491.382	1518.461	90.385

The above procedure was used to obtain BHI_s and DHI_s values at 9:00 am and 4:00 pm. Tables 5.2 and 5.3 below show the values obtained.

Table 5.2 Irradiance parameters for 21/04/2023, 21/06/2023, 23/09/2023, and 21/12/2023 at 9:00 am

Day of the Year At (9:00 am)	Beam shading factor (f_b)	BHI _s (kWh/m ²)	DHI _s (kWh/m ²)	GHI _s (kWh/m ²)	$\frac{GHI_s}{GHI} \times 100$ (%)
21 April 2023	0.295	781.11	491.382	1272.492	75.74
21 June 2023	0.270	808.81	491.382	1300.192	77.39
23 September 2023	0.319	754.52	491.382	1245.902	74.16
21 December 2023	0.209	876.40	491.382	1367.782	81.42

Table 5.3 Irradiance parameters for 21/04/2023, 21/06/2023, 23/09/2023, and 21/12/2023 at 4:00 pm

Day of the Year At (4:00 pm)	Beam shading factor (f_b)	BHI _s (kWh/m ²)	DHI _s (kWh/m ²)	GHI _s (kWh/m ²)	$\frac{GHI_s}{GHI} \times 100$ (%)
21 April 2023	0.255	825.43	491.382	1316.812	78.38
21 June 2023	0.226	857.56	491.382	1348.942	80.29
23 September 2023	0.302	773.36	491.382	1264.742	75.28
21 December 2023	0.271	807.70	491.382	1299.082	77.33

From the results above it can be observed that there is an 8- 10% shading loss at 12:00 noon, 18-25% at 9:00 am and 20-25% shading loss at 4:00 pm. Additionally, the loss diagram indicates that there is a 16.23% near shadings irradiance loss throughout the year. Figure 5.20 below shows the shadows drawing and the shading animation scene for a fixed vertical bifacial system on 21 April 2023 at 9: 00 am.

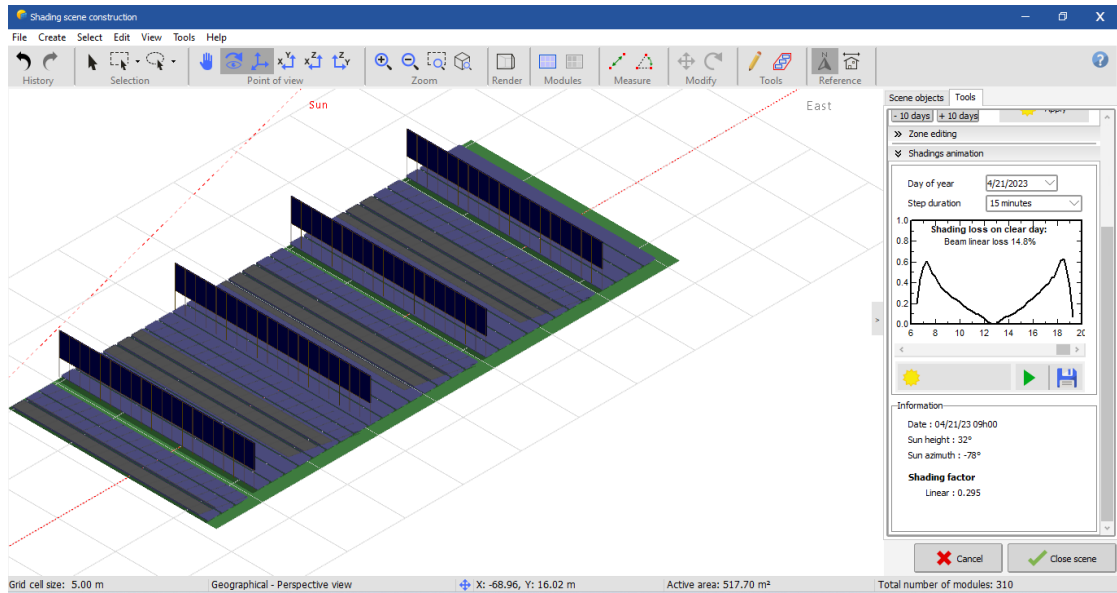


Figure 5.20 The shadows drawing and shading animation scene for a fixed vertical bifacial system on 21 April 2023 at 9:00 am

5.6 Shading Analysis for a Horizontal Tracking Bifacial System

Determining the shading factor for a tracking system is different from that of a fixed vertical system because tracking systems ensure maximum absorption of sun and therefore optimize energy output. In order to accurately determine the PV panel's tilt angle at a specific time, it is important to obtain the maximum energy output at that time. The optimal tilt angle value yields the highest energy output, and its value changes with seasons. For this study, the optimal tilt angle at 9:00 in the morning 12:00 noon and 4:00 in the afternoon will be obtained for 21 April, 21 June, 23 September and 21 December. Ayaş is located at a latitude of 40.0248 N and a longitude of 32.3409 E. The declination angle, δ , is given by:

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365} \right) \quad (48)$$

Where n is 111 for 21 April, 172 for 21 June, 266 for 23 September and 355 for 21 December. Therefore, $\delta = 11.58^\circ$ on 21 April, 23.45° on 21 June, -1.01° on 23 September, and -23.45° on 21 December. The hour angle, ω , can be obtained as: $\omega = -45^\circ$ at 9:00 am, $\omega = 0^\circ$ at 12:00 noon, and $\omega = 60^\circ$ at 4:00 pm. The solar altitude angle, α_s , can be calculated as follows:

$$\sin \alpha_s = \cos \varphi \times \cos \delta \times \cos \omega + \sin \varphi \times \sin \delta \quad (49)$$

Where φ is the latitude of the location of the PV system. The solar altitude angle, α_s is 41.27° at 9:00 am on 21 April, 61.56° at 12:00 noon, and 30.28° at 4:00 pm. On 21 June, the solar altitude angle, α_s is 48.82° at 9:00 am, 73.43° at 12:00 noon, and 37.39° at 4:00 pm. On 23 September, the solar altitude angle, α_s is 32° at 9:00 am, 48.97° at 12:00 noon, and 21.81° at 4:00 pm. On 21 December, the solar altitude angle, α_s is 13.94° at 9:00 am, 26.53° at 12:00 noon, and 5.47° at 4:00 pm. Now we can calculate the solar azimuth angle, γ , which determines the optimum tilt angle for maximum energy output. The solar azimuth angle, γ , is calculated as follows:

$$\gamma = \text{sign}(\omega) \cos^{-1} \left(\frac{\cos(90 - \alpha_s) \sin \varphi - \sin \delta}{\sin(90 - \alpha_s) \cos \varphi} \right) \quad (50)$$

Where sign is +1 for positive ω and -1 for negative ω . The optimal tilt angle, and solar azimuth angle, γ , in this case is -67.15° for 9:00 am on 21 April, 0° for 12:00 noon on 21 April, and 79.23° for 4:00 pm on 21 April. The solar azimuth angle, γ , is -80.17° for 9:00 am on 21 June, 0° for 12:00 noon on 21 June, and 90.7° for 4:00 pm on 21 June. The solar azimuth angle, γ , is -56.5° for 9:00 am on 23 September, 0° for 12:00 noon on 23 September, and 68.85° for 4:00 pm on 23 September. The solar azimuth angle, γ , is -41.93° for 9:00 am on 21 December, 0° for 12:00 noon on 21 December, and 52.95° for 4:00 pm on 21 December. Table 5.4 below shows the summary of the results from the calculations.

Table 5.4 Summary of the results for shading analysis for a horizontal tracking bifacial system

Day of the year	Time of the day	Declination angle (δ)	Hour angle (ω)	Latitude (\square)	Solar altitude angle (α_s)	Solar azimuth angle (γ)	Optimum system design tilt angle ($^\circ$)
21 April	9:00 am	11.58°	-45°	40.0248° N	41.27°	-67.15°	-55°
	12:00	11.58°	0°	40.0248° N	61.56°	0°	0°
	4:00 pm	11.58°	60°	40.0248° N	30.28°	79.23°	55°
21 June	9:00 am	23.45°	-45°	40.0248° N	48.82°	-80.17°	-55°
	12:00	23.45°	0°	40.0248° N	73.43°	0°	0°
	4:00 pm	23.45°	60°	40.0248° N	37.39°	90.7°	55°
23 September	9:00 am	-1.01°	-45°	40.0248° N	32°	-56.5°	-55°
	12:00	-1.01°	0°	40.0248° N	48.97°	0°	0°
	4:00 pm	-1.01°	60°	40.0248° N	21.81°	68.85°	55°
21 December	9:00 am	-23.45°	-45°	40.0248° N	13.94°	-41.93°	-42°
	12:00	-23.45°	0°	40.0248° N	26.53°	0°	0°
	4:00 pm	-23.45°	60°	40.0248° N	5.47°	52.95°	53°

After determining the optimum tilt angle, BHI_s and DHI_s , can be calculated as follows:

$$BHI_s = BHI (1 - f_b) \quad (51)$$

$$DHI_s = DHI (1 - f_d) \quad (52)$$

BHI_s and DHI_s , values are obtained for 9:00 am, 12:00 noon and 4:00 pm on 21 April 2023, 21 June 2023, 23 September 2023, and 21 December 2023. These values are summarized in the table 5.5 below.

Table 5.5 Summary of the irradiance values obtained on 21 April, 21 June, 23 September, and 21 December 2023.

Day of the Year	Time of the day	Beam shading factor (f_b)	Diffuse shading factor (f_d)	BHI_s (kWh/m ²)	DHI_s (kWh/m ²)	GHI_s (kWh/m ²)	$\frac{GHI_s}{GHI} \times 100$ (%)
21 April 2023	9:00 am	0.277	0.144	801.06	489.67	1290.73	76.83
	12:00	0.154	0.164	937.33	478.23	1415.56	84.26
	4:00 pm	0.288	0.145	788.87	489.09	1277.96	76.07
21 June 2023	9:00 am	0.287	0.144	789.98	489.67	1279.65	76.17
	12:00	0.156	0.164	935.12	478.23	1413.35	84.13
	4:00 pm	0.288	0.145	788.87	489.09	1277.96	76.07
23 September 2023	9:00 am	0.283	0.144	794.41	489.67	1284.08	76.43
	12:00	0.145	0.164	947.31	478.23	1425.54	84.85
	4:00 pm	0.259	0.145	821	489.09	1310.09	77.98
21 December 2023	9:00 am	0.026	0.133	1079.15	495.96	1575.11	93.76
	12:00	0.132	0.164	961.71	478.23	1439.94	85.71
	4:00 pm	0.133	0.144	960.60	489.67	1450.27	86.33

Graphs showing GHI_s versus time of the day for fixed vertical and horizontal tracking systems are illustrated below.

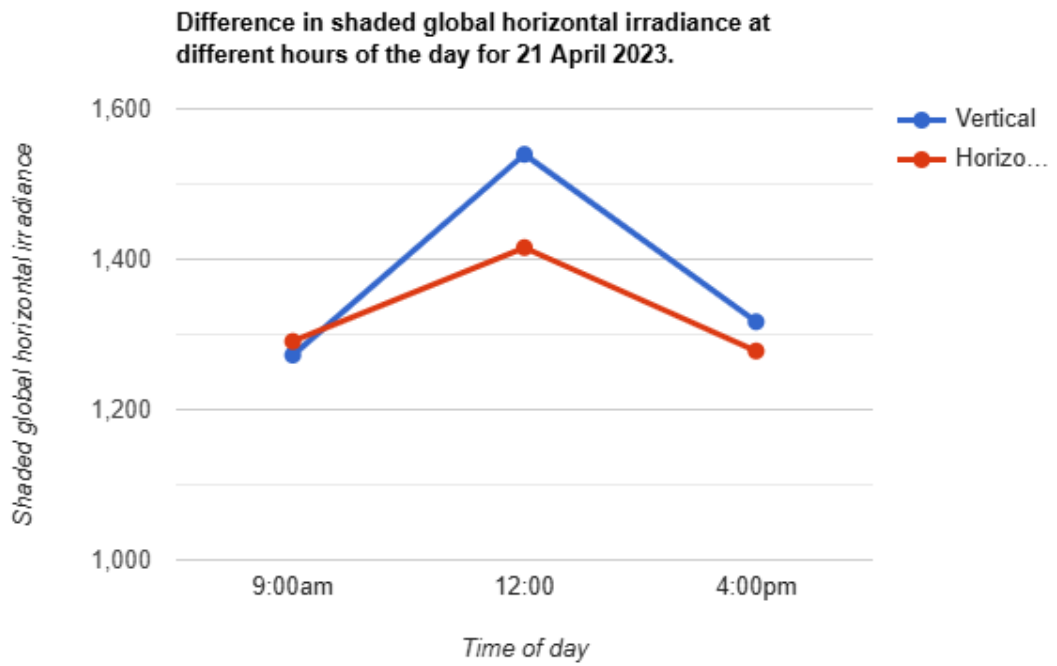


Figure 5.21 Difference in shaded global horizontal irradiance at different hours of the day for 21 April 2023

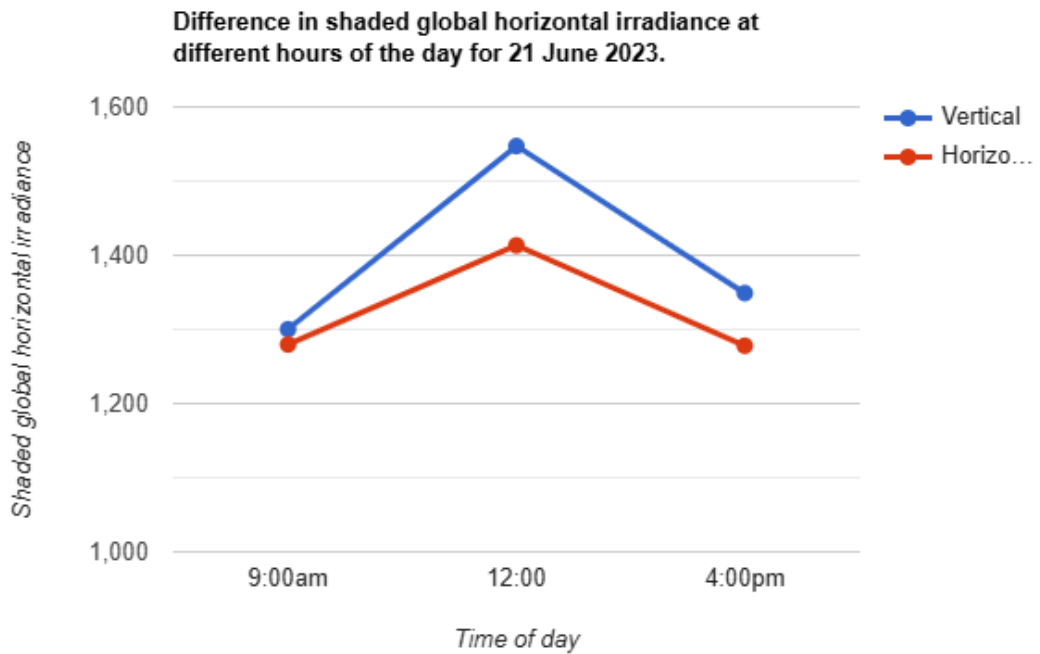


Figure 5.22 Difference in shaded global horizontal irradiance at different hours of the day for 21 June 2023

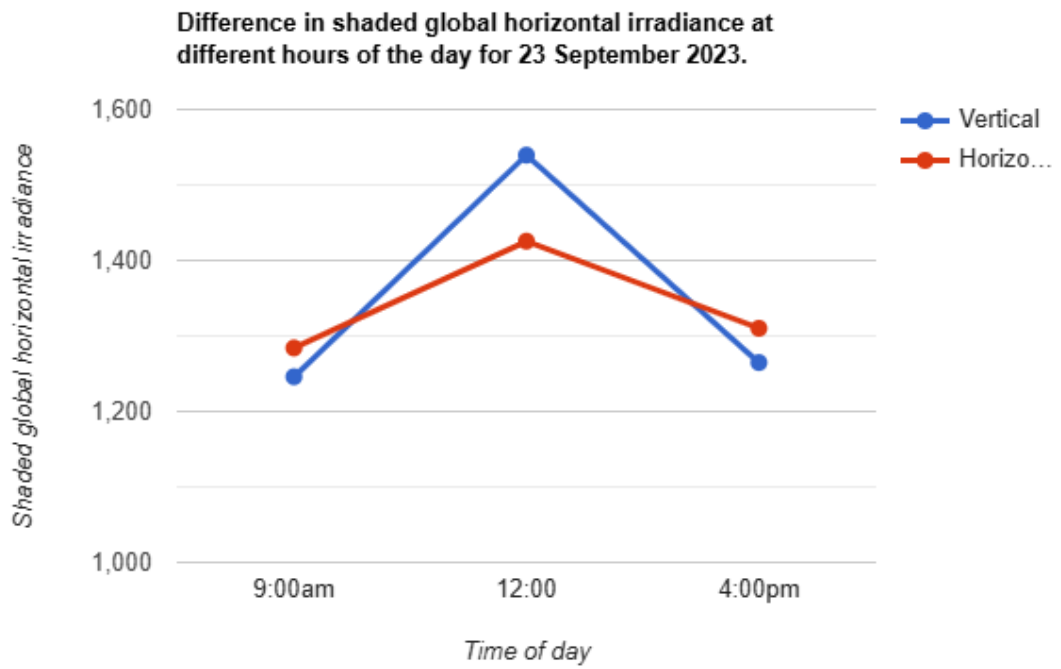


Figure 5.23 Difference in shaded global horizontal irradiance at different hours of the day for 23 September 2023

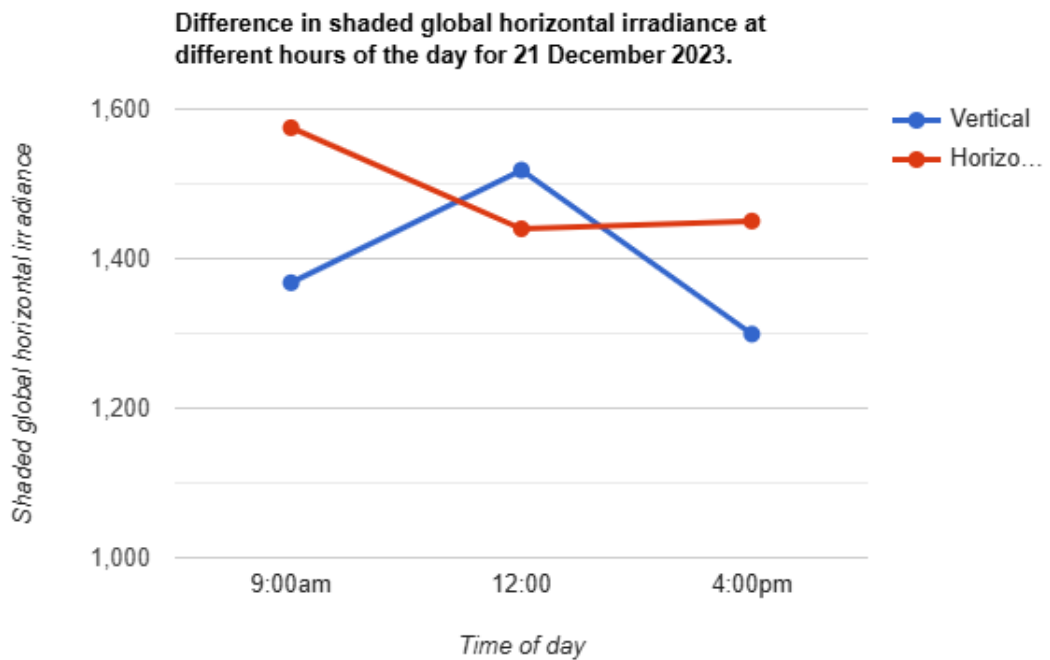


Figure 5.24 Difference in shaded global horizontal irradiance at different hours of the day for 21 December 2023.

5.7 Summary of Comparison Between Fixed Vertical and Tracking Horizontal Bifacial AgriPV Systems

The summary of results obtained in the performance and comparison of fixed vertical and horizontal tracking bifacial agriPV system is shown in table 5.6 below. $\frac{GHIs}{GHI} * 100$ at noon refers to the percentage of irradiance available to the crops after shading at noon when photosynthesis rate is highest.

Table 5.6 Summary of comparison results between fixed vertical and horizontal tracking bifacial agriPV systems

	Fixed Vertical	Horizontal Tracking
Annual Output Power- PVsyst	187.093 MWh	287.390 MWh
Annual Output Power-PVSOL	192.843 MWh	263.062 MWh
P.R- PVsyst	133.72 %	91.57 %
P.R- PVSOL	70.8%	84.2%
P.R _{bifi} - PVsyst	73.1%	83.7%
Investment costs	198,000 \$	198,000 \$
Accrued cash flow on the 21 st year	1,136,435.96 \$	1,385, 239.31 \$
$\frac{GHIs}{GHI} * 100$ on 21/04/2023 at noon	91.638 %	84.26 %
$\frac{GHIs}{GHI} * 100$ on 21/06/2023 at noon	92.099 %	84.13 %
$\frac{GHIs}{GHI} * 100$ on 23/09/2023 at noon	91.638 %	84.85 %
$\frac{GHIs}{GHI} * 100$ on 21/12/2023 at noon	90.385%	85.71%

5.8 Results of Outdoor Measurements of a Solar Panel

The table below shows the data measured from a solar panel using a DC Voltmeter and a DC Ammeter. The monofacial column refers to values measured when the solar panel was producing energy from only the front side of the bifacial panel. The bifacial column refers to values measured when the solar panel was producing energy from both the front

and the rear side. The values were measured on the 4th of June 2024, in Ankara. The data was collected from 0900 hrs to 1800 hrs. The local temperature was 33⁰C. Since there is an increase in the bifacial current values compared to the monofacial current values, we can infer that there is an increase in power when a bifacial solar panel panel is used. This increase due to rear side solar cells, is the BG. Table 5.7 below shows the data obtained.

Table 5.7 Voltage and current values measured from a bifacial solar panel using a DC voltmeter and DC ammeter

Time	MONOFACIAL (Mono)		BIFACIAL (Bifi)	
	Volts (V)	Amps (A)	Volts (V)	Amps (A)
9.00	26	0.78	25	0.92
10.00	25	1.03	26	1.5
11.00	25	1.03	26	1.5
12.00	25	1.85	25	2.24
13.00	26	3.79	26	4.18
14.00	25	4.08	26	4.42
15.00	26	4.08	26	4.52
16.00	25	4.12	25	4.24
17.00	25	4.02	26	4.16
18.00	25	3.84	26	4.09

6. CONCLUSION AND RECOMMENDATIONS

Bifacial solar panel technology can improve agrivoltaic applications which is one of the solutions for meeting food and energy demands in a common area. Additionally, the advantages that are offered by PV systems to agriculture, and those offered by plants to PV systems, make agrivoltaic systems highly efficient. Furthermore, the dual use of land contributes to low LCOE when compared to traditional PV systems.

In this thesis study, comparison of fixed vertical bifacial and horizontal tracking bifacial agriPV systems, modelled in Ayaş, Ankara, was done. PVSyst and PVSOL software were used to simulate the output power. The results from both software showed that horizontal tracking bifacial agriPV systems produce more energy than the fixed vertical bifacial agriPV system. Additionally, the degree of shading on the crops as a result of the PV modules in agriPV systems was determined by using shading factors to determine the shaded and unshaded beam, diffuse and global horizontal irradiation received on the ground on the summer and winter solstices, and the equinox dates in 2023. Results showed that horizontal tracking systems in agriPV applications lead to more shading compared to fixed vertical systems on 21 April and 23 September. On 21 June, fixed vertical systems result in more shading in the morning, but after 11:00 am, the shading is minimal. Horizontal tracking systems result in more shading compared to fixed vertical systems after 11:00 am on 21 June.

Shading is the biggest problem for the crops. However, this problem can easily be avoided by using intelligent tracking systems. When more sunlight is needed, tracking systems can be configured at a parallel orientation to the beam radiation. Therefore, agriculture can be promoted. As the crops are only active for a few months, tracking systems give opportunity to control the shading.

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