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Agrophotovoltaic Technology for Smart Farming

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ABSTRACT

Agrophotovoltaic (APV) systems offer an innovative approach to maximizing land use by simultaneously supporting agricultural activities and solar energy generation. This study focuses on the development and testing of a smart APV prototype to assess its impact on crop growth, environmental conditions, and energy output in a tropical farming setting. The system was built using polycrystalline solar panels. It was installed at a fixed tilt angle, with sensors for monitoring temperature, light intensity, and soil moisture. Real-time data collection was performed using an IoT platform integrated with an ESP32 microcontroller and visualized through the Blynk dashboard. Experimental results showed that the average daily solar energy output from the panels was 0.25 kWh, sufficient to power low-energy devices such as pumps or sensors. Temperature readings beneath the panels were consistently 2–3°C lower than in open field areas, indicating improved microclimate conditions. The soil under the APV structure retained more moisture, reducing evaporation and potentially lowering irrigation needs. Crop growth performance remained consistent, demonstrating that partial shading from the panels did not negatively affect the yield of leafy vegetables. These findings validate the effectiveness of APV systems for tropical environments. By enabling efficient resource use and real-time environmental monitoring, the APV setup supports sustainable farming practices without compromising agricultural productivity.

Keywords: Agrophotovoltaic, Solar energy, IoT platform, Soil moisture, Crop growth.

1. INTRODUCTION

With the growing demand for sustainable agricultural and renewable energy solutions, agrophotovoltaic (APV) systems offer a strategic approach by combining crop cultivation with photovoltaic (PV) energy production. These systems enable dual land use, reducing the pressure on available agricultural land while contributing to environmental conservation and energy independence. When enhanced with smart farming technologies, APV systems allow for data-driven decision making, resource optimization, and adaptive responses to microclimate variability [1-2]. Based on the research that has been conducted, solar energy technology has emerged as one of the most promising and sustainable options for electricity generation, especially in regions that receive high levels of solar irradiance throughout the year [3]. As the world transitions toward greener energy sources, solar photovoltaic systems offer a clean, renewable, and environmentally friendly solution that reduces reliance on fossil fuels and minimizes greenhouse gas emissions.

The PV panel functions by converting absorbed solar radiation directly into electricity through the photovoltaic effect [4-5]. This electricity can then be used to power a wide range of applications, from household appliances to large-scale industrial operations, including those in

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the agricultural sector. With advancements in PV materials, efficiency improvements, and declining production costs, solar power has become increasingly accessible and cost-effective. In the context of agriculture, there is a growing interdependence between energy and food production, often referred to as the “energy-food nexus.” Modern agricultural practices now require significant energy input for irrigation systems, greenhouse operation, mechanized farming equipment, temperature control, lighting, water pumping, and post-harvest processing [6]. Therefore, to increase food production sustainably, particularly in rural or off-grid areas, there must be a corresponding increase in energy availability, and solar energy can fulfill this role efficiently.

Moreover, the integration of solar-powered systems in agriculture, such as solar water pumps, solar-powered greenhouses, and solar-driven hydroponic or aquaponic systems, can significantly reduce operational costs, improve productivity, and ensure energy security. Therefore, the APV system is used to consider both sectors. APV is one of the implementations of solar panels in the agricultural area at the same time on the same land to capture solar energy [7]. APV is involved in co-developing land for both solar PV power and agriculture [8]. Solar panels and crops coexisting indicate that light is shared between the two types of production. The system’s concept combines the production of electrical energy with the production of agricultural products in the same region. In other words, this creates a positive relationship, or symbiosis, between these two productions in the same location [9]

Additionally, the application of the APV system has many advantages, such as improving the efficiency of land use, water efficiency, and PV panel efficiency. Based on the project of APV that has been done in some countries, the APV system is helping to mitigate land-use conflicts [10] and it opens a new source of income for the farmers. Based on the research that has been done, the APV system helps to increase the efficiency of land use by around 60% to before [9]. Besides, in this modern technology, the APV system is one such smart technology. Like other sectors, the agriculture sector is also involved in smart technology, such as smart farming [11]. It is one technology that focuses on the purpose of boosting productivity and improving the product’s quality while reducing the cost of production [12]. This system will also help farmers increase production in agriculture, which is one of the needs in the 21st century. Agriculture’s long-term viability is key to ensuring food security and hunger eradication for the world’s ever-growing population [13]. So, to ensure that the agriculture sector is preserved and developed with advanced technology, sufficient energy is required to supply the system and ensure that the system operates smoothly. There are many sustainable and renewable energy sources in our country, such as wind, solar, thermal, and bioenergy sources [14] that can be used to get a better supply of energy.

As a typical green energy source, solar power generation has been encouraged and implemented in comparison to other power technologies due to lower photovoltaic panel manufacturing costs and improved photoelectric conversion efficiency. With regard to the important impact on agriculture, this project aims to evaluate the energy generation and agricultural performance of an APV system under tropical climate conditions. Furthermore, we aimed to analyze the effects of partial shading from PV panels on soil temperature, moisture retention, and crop yield for shade-tolerant vegetables. The impact of smart farming technologies will enhance land efficiency, reduce energy costs, and support sustainable food and energy production.

2. METHODOLOGY

The prototype was developed using two 50W polycrystalline solar panels mounted on a 25° tilted metallic structure. Leafy vegetables were planted beneath the panels to assess the impact of shading. Environmental sensors, including LDR for light intensity, DHT11 for temperature and humidity, and soil moisture sensors were connected to an ESP32 microcontroller. Data was transmitted every 10 seconds via Wi-Fi to a Blynk IoT dashboard. Monitoring was conducted over four weeks to observe energy generation, microclimate effects, and crop growth.

2.1 Database of the project

In order to start the simulation for both software, the related parameters need to be set to obtain the exact result of the simulation output with the real site project. Both software that has been used was related to each other. So, the parameter of the first software, which is PVsyst software, will be used to link to the second software, which is Agrivoltaic simulation software. So, all the important and needed data are listed in this section.

2.1.1 Location of The Project

Table 1 shows all data for the project address, which is Kampung Pering, that has been measured and taken from Google Maps and Google Earth. Google Maps is used to find the exact coordinates, such as latitude and longitude of the project site, while Google Earth can help to get the altitude data and to measure the areas of that project. The value of the data listed is based on the real-time project site. This project has been run in the form of a quarter that represents all the months in a year.

Table 1: The Meteonorm data for the project site.

Data	Value
Coordinate of the project (Latitude, Longitude)	6.374^{o}N, 100.3402^{o}E
Address	Kampung Pering, Padang Sera, Kodiang Kedah.
Altitude	11m
Time zone	+8
Temperature	30^{o}C
Air pressure	100110 Pa
Simulation time	7.30 am to 7.30 pm

2.1.2 Orientation Parameters

Table 2 shows the value of the tilt angle and the orientation of the solar panel. Tilt angle is one of the important parameters that make the system operate at the optimal condition, which is to maximize the absorption of the solar radiation by the PV panel. The tilt angle has been measured based on the rule of thumb. The rule of thumb states that the tilt angle is equal to the project's latitude. It has been measured using the solar panel tilt angle calculator that has been released by Footprint Hero. Next, the project's location, which is Kampung Pering, is located in the northern hemisphere. So, the optimum orientation of the solar panel is set to face South. This orientation of the solar panel will help the panel to absorb optimum light intensity at all times throughout the year.

Table 2: The Orientation data of PV Panel.

Data	Value
Tilt angle	8.5°
Orientation	South

2.2 Solar Radiation on an Inclined Surface

To achieve the main objective of this project, the total solar radiation of the APV system for this project needs to be identified. This is the first part of the simulation. The aim of this simulation is to obtain the data on the total solar radiation, which is global solar radiation on the inclined surface. In addition, the monthly solar radiation, also known as monthly solar irradiances such as global horizontal irradiance (GHI), diffuse horizontal irradiance (DNI), and direct horizontal irradiance (DNI), also needs to be identified, which will be used as an input parameter in the second part of the simulation. In addition, all of these values are also important parameters to determine the value of solar radiation on the ground, Ig. The database of the real project location is used in this simulation to make sure that the simulation of the output is also based on the real conditions. There is a flowchart of the PVsyst software that will be used to generate the output data.

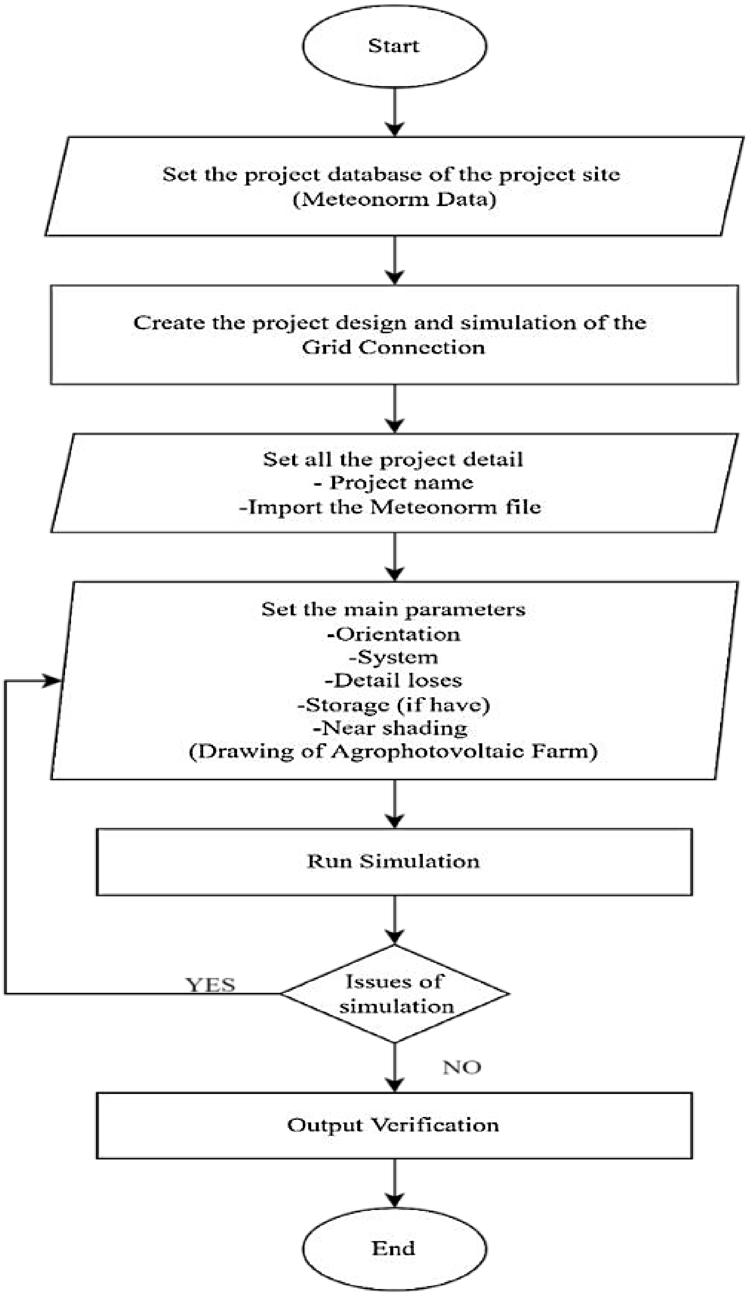

Figure 1: The Flowchart of the PVsyst Software.

Figure 1 shows the flowchart of the second simulation, which is the Agrivoltaic simulation software. All the data that has been simulated in the first part will be used in this part. The first simulation is related to the second simulation in terms of parameters and the arrangement of the PV array in the APV farm. This second Agrivoltaic simulation will help to generate the energy map of the project based on the data that has been input. The global ground radiation, also known as global horizontal radiation on the ground, is the main value that needs to be generated before suggesting a suitable crop for that APV system.

3. RESULTS AND DISCUSSION

3.1 Agrophotovoltaic (APV) Farm

This is the first result of the simulation in the Pvsyst software. The APV farm that has been created is a system of PV panels that have been implemented in the agricultural areas. The project was simulated based on the real project site situation. All the important parameters related to the APV farm have been considered and used as the parameters in the Pvsyst software. Figure 2 shows the 3D view of the APV farm that was simulated at one agricultural area, which is located at Kampung Pering, Kedah.

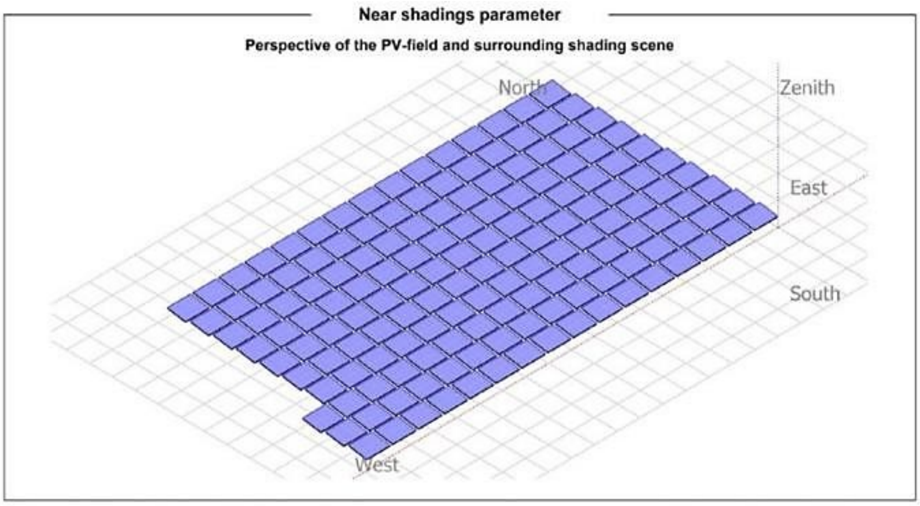

Figure 2: Agrophovoltaic farm at Kampung Pering.

Table 3: Details of the APV farm.

Detail	Value
Area of the project	3143.32 m^2
Total number of PV modules	1560 unit
Height of solar panel array (from ground)	2m
Distance between rows	1m
Distance between columns	0.5m
Length of the PV module	5.09m
Height of PV module	4.04m
Module width	1.002

Table 3 shows all the parameters that need to be considered for the construction of the APV farm. Based on the stated parameters, the total area of the project site was around 3143 m^2. After running some simulations on the Pvsyst software, the total number of PV modules that can be installed in those places was around 1560 units. All the PV module was connected properly and linked to each other to produce a perfect solar array. The PV modules can be electrically connected in a few ways, which as in series, parallel, or a combination of series and parallel. Based on this project, the PV module was connected in a combination way, which is in 15 panels in series and 104 panels in parallel. The PV modules that are connected in series will help to produce more output voltage, while the parallel connection will help to produce more output current to the system. So, a high voltage and current output in the solar array will produce more power output from that solar farm.

3.2 Simulation result for solar radiation using Pvsyst software

When a PV system is combined with the agriculture sector, the solar radiation that is emitted by the sun needs to be shared by both sectors. The solar radiation that is absorbed by PV modules is not equal to the solar radiation that is absorbed by the plant in the agricultural area. Therefore, this project has been run to measure the value of the solar radiation on both media, which were on inclined surfaces such as PV modules and, on the ground, or in other words, on the earth's surface. So, for this part, the solar radiation on the PV module has been simulated and measured using the Pvsyst software. All the parameters that were used in this software were based on the real database of the project.

All the databases, such as GHI, DNI and DHI, were generated by the Meteonorm 8.0. Total solar radiation on PV modules, also known as GHI on PV module, was the summation of direct beam solar radiation (IbPV), diffuse horizontal radiation (IdPV), and reflected radiation (IrPV). This simulation was the result of solar radiation for the inclined PV module with an 8.5-degree tilt angle. The angle of the solar panel was determined based on the latitude of the project site.

3.3 Simulation result for solar radiation using Agrivoltaic Simulation

This was the second part of the simulation; it was run based on the parameters obtained in the first simulation, which was the Pvsyst software. As stated in the methodology, the second part of the simulation has been done by the Agrivoltaic simulation, which was created by nanoHUB. This Agrivoltaic simulation tool calculates the data based on the solar panel parameters, geometries, patterns, and tracking system to provide the output of a contour energy map, raw data output, and the irradiance model of the project. The solar radiation on the ground was simulated based on the reference date of each quarter. The result was simulated for each quarter. In this part, the average value of Ig was calculated based on the irradiance model that has been generated in the Agrivoltaic simulation.

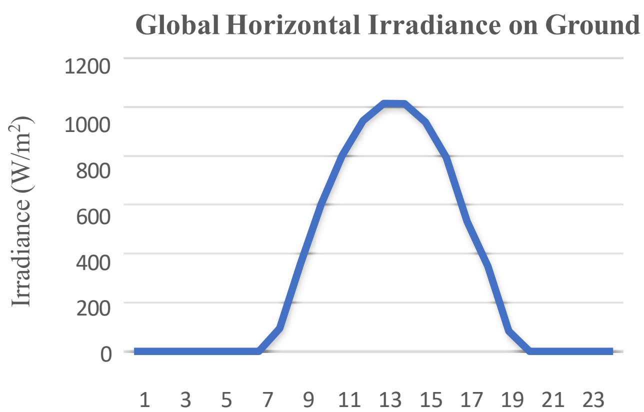

Figure 3: Global horizontal irradiance on the ground for quarter 1.

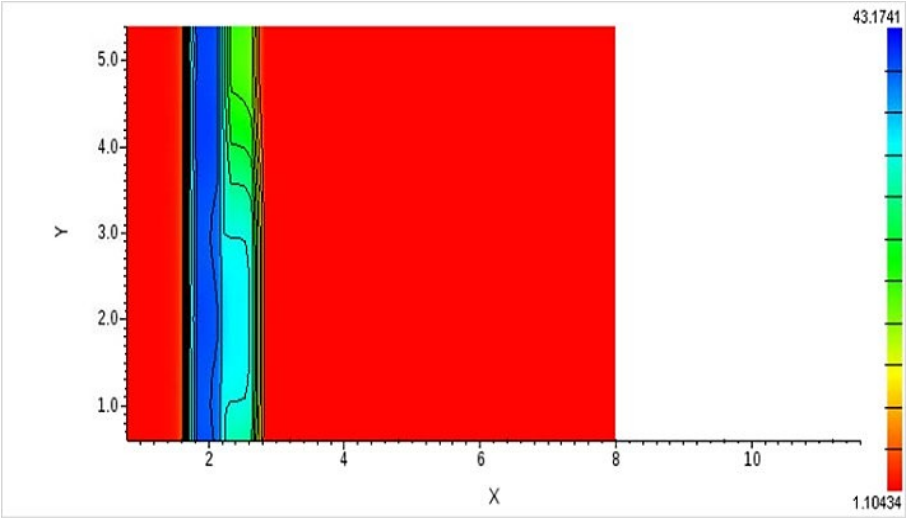

Figure 4: The energy map of the PV module for quarter 1.

Figure 3 shows the graph of global horizontal irradiance that reaches the ground for quarter 1. The average value of Ig for quarter 1 was around 313.52 W/m^2 per day.

Figure 4 shows the energy map that has been generated after doing the s imulation of quarter 1. Each colour in the energy map represents the percentage of the fraction of irradiance reduction on the ground. Based on Figure 4, the higher the value of the percentage, the higher the reduction of solar radiation under the solar array. Quarter 1 recorded an average of a fraction irradiance reduction of around 5.3961%. It means, on average, the solar radiation has decreased by around 5% to 6% from the total solar radiation on the PV module.

Table 4 presents the specifications of the environmental sensors integrated into the APV prototype system. A Light Dependent Resistor (LDR) was used to measure light intensity beneath the solar panels, providing analog output values ranging from 0 to 1023 (ADC). Although its accuracy may vary, it offers a general indication of shading conditions affecting crop growth. Additionally, a DHT11 sensor was employed to measure both temperature and humidity within the microclimate under the APV structure. The temperature range of the DHT11 is 0 to 50°C with an accuracy of ±2°C, while its humidity detection range spans from 20% to 90% with ±5% accuracy. These sensors were selected for their simplicity, affordability, and suitability for continuous real-time monitoring, enabling effective data collection for evaluating the environmental impact of the APV system on crop conditions.

Table 4: Environmental sensors detailed.

Sensor	Measured Parameter	Range	Accuracy
LDR	Light Intensity	0–1023 (ADC)	Varies
DHT11	Temperature	0–50°C	±2°C
DHT11	Humidity	20–90%	±5%
Soil Moisture Sensor	Soil Moisture	0–100%	~±3%
ESP32	Data Transmission	Wi-Fi	N/A

Average energy output per panel was 0.25 kWh/day, sufficient for powering small-scale irrigation and sensor systems. Temperature readings beneath the APV structure were 2–3°C lower compared to open-field areas, promoting better soil moisture retention. Crop growth analysis showed comparable yield to open-field crops, suggesting that partial shading did not negatively affect photosynthesis for shade-tolerant vegetables. These results align with recent literature supporting the viability of APV in tropical environments.

4. CONCLUSION

This study demonstrates the feasibility and benefits of integrating agrophotovoltaic technology with smart farming systems. The prototype validated that solar panels can coexist with crop cultivation, contributing to energy generation while enhancing microclimate control. Each panel produced 0.25 kWh/day, enough for irrigation and sensors. APV areas were 2–3°C cooler, kept soil moist, and showed similar crop yields, proving APV suits tropical, shade-tolerant farming. By leveraging real-time monitoring through IoT, farmers can make data-driven decisions to optimize resources. Future enhancements should focus on AI-driven analysis, dynamic panel orientation, and expanded crop trials to realize the full potential of APV in supporting sustainable agriculture.

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