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Renewable energy integration in agricultural practices: Assessing the energy generation performance of agrivoltaic greenhouse system

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Abstract
The agrivoltaic greenhouse was designed and developed at the Department of Renewable Energy Engineering, Junagadh Agricultural University, Junagadh (Gujarat). The solar photovoltaic panels were installed on the greenhouse roof in a chessboard configuration to minimize shading effects and efficient crop cultivation. The total solar power capacity of the developed agrivoltaic greenhouse was 4.8 kW. The energy generation performance of the developed agrivoltaic greenhouse was evaluated from March to May duration. The maximum energy output from the agrivoltaic greenhouse was observed in March at 512.78 kWh, followed by 509.28 kWh in May and 501.5 kWh in April, respectively. The overall final energy yield and reference energy yield were recorded as 3.45 h/d and 5.06 h/d, respectively, for the entire experimental duration. The performance ratio of the agrivoltaic greenhouse in energy output was observed higher in April at 0.71, while the overall performance ratio was recorded as 0.68.

Keywords: Agrivoltaic, photovoltaic system, greenhouse, energy yield, performance ratio

1. Introduction

Addressing the global challenges posed by population growth and climate change involves mitigating the considerable environmental and socioeconomic impacts associated with the use of fossil fuels in food production. This necessitates the adoption of renewable energy sources in agriculture (Keating *et al.*, 2014) [3]. Notably, solar photovoltaic (SPV) energy emerges as a highly successful renewable option, propelled by recent technological advancements, durability, versatility, low carbon emissions, and cost-effectiveness (Tripathy *et al.*, 2017) [7].

Agrivoltaics is the integration of solar energy production and agriculture on the same land, where solar panels receive some portion of sunlight to generate power while allowing the rest to pass through for crop cultivation (Dupraz *et al.*, 2011) [1].

Recently, the rising energy costs and environmental issues in agricultural greenhouses have prompted a search for clean energy alternatives. Integrating agrivoltaic systems within greenhouses is a noteworthy solution, facilitating both agricultural production and photovoltaic electrical generation (Kaiser *et al.*, 2019) [2]. This approach seeks to enhance sustainability and efficiency while reducing reliance on non-renewable energy sources. Photovoltaic technology applied to agricultural greenhouses has led to the creation of "Agrivoltaic Greenhouses." This innovative approach involves installing solar panels on greenhouse roofs, employing various designs and arrangements.

Yildirim and Bilir (2017) [8] evaluated a green energy solution for a greenhouse, covering half of the roof area with solar photovoltaic panels and produced an annual energy output of 21, 510.4 kWh. In summer, solar panels met 33.2 to 67.2% of the energy demand of the greenhouse, supporting the greenhouse's clean energy concept.

Li *et al*. (2018) [4] studied a semi-transparent photovoltaic blind system designed for greenhouses. These blinds, automatically adapting to solar irradiance levels, offered 42% shading as required. The system's operations were powered by the electrical energy generated from the PV modules, and any surplus energy could potentially support extra greenhouse appliances. The research proposes that greenhouses with integrated PV systems, particularly in regions with high insolation, could serve as autonomous dynamic shading systems, improving the crop's light environment.

Salman *et al*. (2020) [6] investigated the integration of photovoltaic panels on greenhouse roofs in the Iraqi climate. The study identified that solar panels generate income with minimal impact on agricultural output.

The combination of PV panels and the greenhouse reduced sunbeam intensity by 35 to 45%, beneficial for mitigating overheating in hot climates and consequently reducing water consumption. This research aims to evaluate the feasibility of incorporating solar photovoltaic technology into greenhouses, investigating its effects on both energy generation and crop performance. The primary objective of this study is to demonstrate the technical, economic and environmental viability of integrating solar panels onto the greenhouse roof.

2. Methodology

2.1 Description of agrivoltaic greenhouse

The agrivoltaic greenhouse was designed and developed in the experimental field of the Department of Renewable Energy Engineering, CAET, Junagadh Agricultural University, Junagadh (Gujarat). The developed agrivoltaic greenhouse has a length of 12 m and a width of 5 m, occupying a total surface area of 60 m^2. The agrivoltaic greenhouse featured a curved roof covered with a UV-stabilized polyethylene sheet, 200 μ-thicks, on both the roof and sides. To facilitate cooling, a forced convection cooling system employing fans and pads was implemented within the developed agrivoltaic greenhouse. Solar photovoltaic panels were arranged on the greenhouse roof in a chessboard pattern to minimize shading on the cultivated crop beneath. The installation included a total of 32 solar panels, each with a capacity of 150 W, resulting in a combined installed solar power capacity of 4.8 kW.

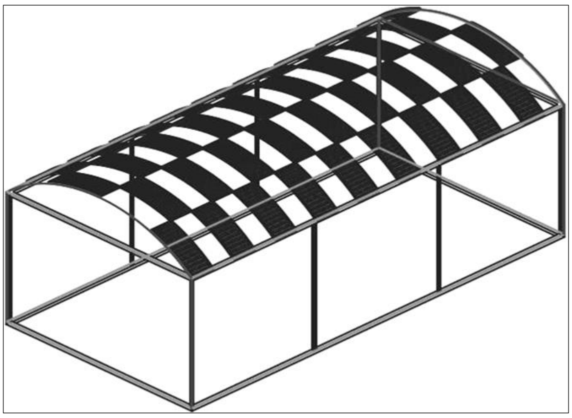

Fig 1: Developed agrivoltaic greenhouse

In Figure 1, the solar photovoltaic panels are represented by shaded boxes on the roof of the agrivoltaic greenhouse system. The gap between the two solar panels was maintained at the same width as the panels themselves. The technical specifications of solar photovoltaic panels installed over the roof of the agrivoltaic greenhouse are presented in Table 1.

Table 1: Technical specifications of solar photovoltaic panel

Sr. No.	Particulars	Specifications
1	Type of material	Polycrystalline material
2	Manufacturer	Australian Premium Solar Pvt. Ltd.
3	Model	APSP6 -150/36
4	Maximum power (P_{MAX})	150 W
5	Maximum power voltage (V_{MAX})	18.5 V
6	Maximum power current (I_{MAX})	8.13 A
7	Open circuit voltage (V_{OC})	21.83 V
8	Short circuit current (I_{SC})	8.53 A
9	Module Efficiency	15.8%
10	Module dimensions	1485 x 675 x 35 mm
11	No. of cells in a module	36 cells (9 x 4)

2.2 Energy generation analysis

The energy generation performance was analyzed according to the International Energy Agency (IEA), taking into account the following parameters for energy generation.

2.2.1 Total energy generation

The daily energy output of the agrivoltaic greenhouse was determined by measuring the energy generated by the PV system after the DC-AC inverter on a daily basis. The total energy generated in a day ($E_{AC,d}$) and in a month ($E_{AC,m}$) by the agrivoltaic greenhouse was calculated as follows:

$$E_{AC,\,d} = \sum_{t=1}^{24} E_{AC,\,h} \quad (1)$$

$$E_{AC,\,m} = \sum_{t=1}^{n} E_{AC,\,d} \quad (2)$$

Where,
$E_{AC,\,h}$ = Total hourly energy output (kWh),

2.2.2 Final yield

The final yield (Y_F) of the agrivoltaic greenhouse is defined as the total energy generated by the PV system for a specific period (day, month, or year) divided by the rated output power of the installed PV system. Final yield was calculated as follows:

$$Y_F = \frac{E_{AC}}{P_{PV,\,Rated}} \quad (3)$$

2.2.3 Reference yield

The reference yield (Y_R) of the agrivoltaic greenhouse is defined as the ratio of the total in-plane solar insolation (Ht) to the reference irradiance (G). This parameter represents the equivalent number of hours at the reference irradiance and was calculated as follows:

$$Y_R = \frac{H_t}{G} \quad (4)$$

Where,
H_t = Total in-plane solar insolation (kWh/m^2),
G = Reference irradiance (kWh/m^2).

2.2.4 Performance ratio

The performance ratio (PR) of the agrivoltaic greenhouse is defined as the ratio of the final yield (Y_F) to the reference yield (Y_R). It represents the overall efficiency of the system, taking into account the losses incurred during the conversion of the DC rating to AC output. The performance ratio was calculated using the following formula:

$$PR\ (\%) = \frac{Y_F}{Y_R} \quad (5)$$

3. Results and Discussion

The energy generation from the agrivoltaic greenhouse from March to May duration was evaluated and various parameters were considered for the performance analysis, including monthly energy generation, final yield, reference yield, and performance ratio. These parameters offer valuable insights into the efficiency and effectiveness of the agrivoltaic greenhouse in energy generation and optimizing its overall performance.

3.1 Total energy generation

The agrivoltaic greenhouse's daily energy ($E_{AC,\ d}$) and monthly energy ($E_{AC,\ m}$) were computed in kilowatt-hours (kWh). The total monthly energy output for March, April, and May was determined to be 512.78 kWh, 501.50 kWh, and 509.28 kWh, respectively, as illustrated in Figure 2. These calculations pertain to the developed agrivoltaic greenhouse with a 4.8 kW capacity.

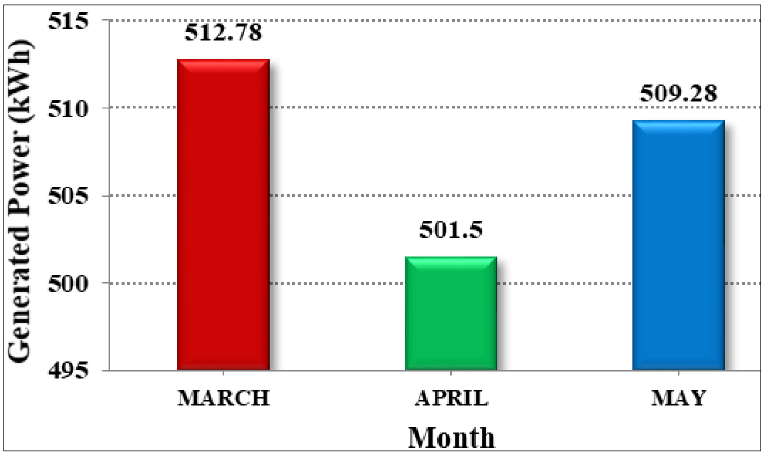

Fig 2: Monthly energy generation

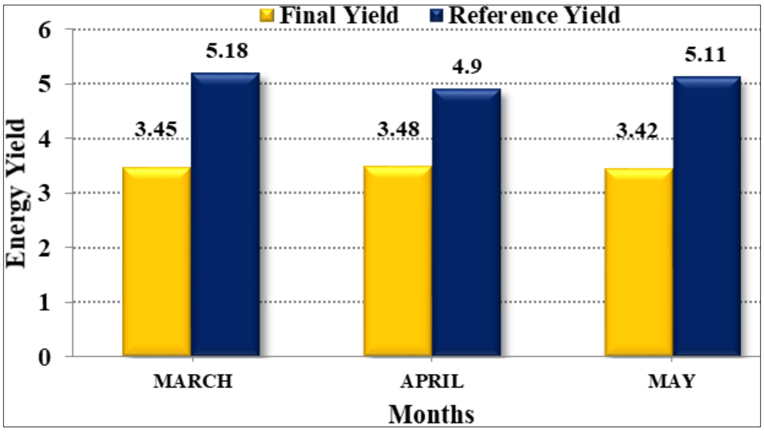

Fig 3: Energy generation yield

3.2 Final yield

The energy yield from the agrivoltaic greenhouse during March, April, and May was found to be 3.45, 3.48, and 3.42, respectively. The overall final yield for the entire experimental period was documented as 3.45. Figure 3 illustrates the calculated final yield for each specific month, showcasing the average daily hours of energy generation relative to the rated power of the installed PV system.

3.3 Reference yield

The reference yield for the agrivoltaic greenhouse during March, April, and May was computed as 5.18, 4.9, and 5.11, respectively. The cumulative reference yield for the entire experimental duration was noted as 5.06. Table 2 presents the energy yield, facilitating a comparison between the final yield and reference yield values.

Table 2: Energy generation parameters

Months	Final Yield	Reference Yield	Performance Ratio
March	3.45	5.18	0.67
April	3.48	4.9	0.71
May	3.42	5.11	0.67
Overall	3.45	5.06	0.68

3.4 Performance ratio

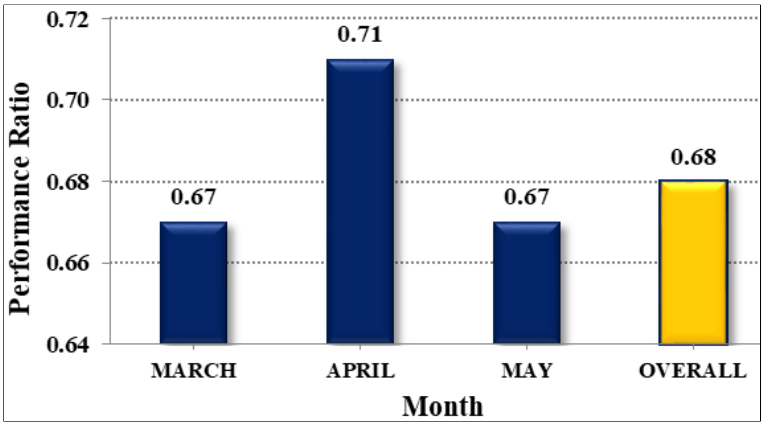

Fig 4: Performance ratio

The performance ratio of the agrivoltaic greenhouse during March, April, and May was observed to be 0.67, 0.71, and 0.67, respectively. The overall performance ratio was recorded as 0.68, as illustrated in Figure 4.

3.5 Net energy generation from agrivoltaic greenhouse

The net electricity generation from the agrivoltaic greenhouse was calculated by subtracting the energy consumed by the cooling and irrigation systems from the total solar energy generated through the installed solar power capacity on the roof of the agrivoltaic greenhouse. The daily electricity consumption for these systems was recorded as 6 kWh.

Table 3: Net energy generation

Months	Energy Generation (kWh)	Energy Consumption (kWh)	Net Energy (kWh)
March	512.78	186	326.78
April	501.5	180	321.5
May	509.28	186	323.28
Overall	1523.56	552	971.56

Table 3 reveals that the net energy generated by the agrivoltaic greenhouse surpassed energy consumption by 1.75 times. The greenhouse's total energy consumption accounted for around 40% of its total energy generation. Consequently, the designed agrivoltaic greenhouse boasted a surplus energy equivalent to 60% of the total energy generated from the solar panels installed on its roof.

4. Conclusions

The following conclusions were derived from the designed and developed agrivoltaic greenhouse throughout the study.

1. The total energy generation output from the agrivoltaic greenhouse with a capacity of 4.8 kW was obtained as 1523.56 kWh and daily energy output was observed higher in March month during the experiment.
2. The overall final energy yield and reference energy yield were recorded as 3.45 h/d and 5.06 h/d, respectively, for the entire experimental duration.
3. The performance ratio of the agrivoltaic greenhouse in energy output was observed higher in April at 0.71, while the overall performance ratio was recorded as 0.68.
4. The net energy generated from the agrivoltaic greenhouse was observed 1.75 times higher than the energy consumption within it. This indicates a promising energy surplus, highlighting the effectiveness of the agrivoltaic greenhouse system in both energy production and crop cultivation.

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