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ORIGINAL PAPER

Design of agrivoltaic system to optimize land use for clean energy-food production: a socio-economic and environmental assessment

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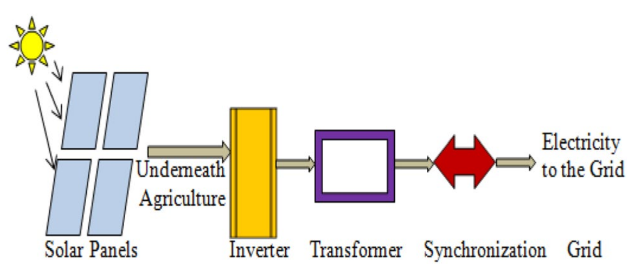
Abstract

Accessing solar photovoltaic energy is a key point to develop sustainable energy and the economy of a developing country like India. The country has set a target of 100 GW of power production from solar photovoltaics to double the farmer's income by 2022, out of which 50 GW has been achieved by 2021. As an evolving economy, demand for energy and foods has improved by almost 40% and 25%, respectively. This transition will add to the global competition in land use issues. In this perspective, a dual land use approach, 'agrivoltaic system' is essential to secure land tenure as well as enhance energy-food security, socio-economic feasibility, and livelihoods of the country. In the present study, three different types of design techniques have been demonstrated to obtain an efficient system. A double row array design capacity of a 6 kWp agrivoltaic system is found as the best system in terms of average annual revenue, land equivalent ratio, and payback period resulting in 2308.9 USD, 1.42, and up to 7.6 years, respectively. Further, the socio-economic parameters such as revenue, benefit–cost ratio, and price–performance ratio of turmeric are found to be 187.3 USD, 1.86, and 0.75, respectively, in the same land use. This work can be extended to a different technology of panels, more seasonal crops, and photosynthesis responses in medium and large-scale AVS.

Graphical abstract



Keywords Agrivoltaic · Clean energy-food production · Land use · Socio-economic

Introduction

Globally, it is estimated that about 1 billion people are not able to harness electricity, and 0.7 billion people are still hungry by 2021. The sustainable development goal 13 (SDG-13) reported urgent action to mitigate climate change joined with SDG-7 which ensures affordable, reliable, sustainable, and modern energy access to all by 2030 (SDGs

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2021). But the majority of the world's starving is about 380 million found in Asia and more than 250 million live in Africa. SDG-15 report highlights that about 0.012 billion hectares of land are lost per year in terms of drought and desertification (UNECE 2020). This is due to the population growth and traditional technology used in maximum countries. Simultaneously, the demand for energy-food production and socio-economic value is increasing rapidly. The primary sources of greenhouse gas emissions (GHGs) from electricity and heat are about 31%, and agriculture is about 12% (UN 2021; Kumar and Majid 2020). Clean and sustainable energy generations, especially solar energy, is emerging solutions to cut down the carbon footprint, energy-food demand, and livelihood. This system can cut down carbon footprint by 0.82 kg/kWh (Sreenath et al. 2021). For human welfare, both energy and food securities are very essential for the country. Rising demand for clean energy, solar photovoltaic (SPV) and agricultural productions, will entail a techno-economic sustainable system for livelihood, land use, and social necessity of the human race (Pascaris et al. 2021). Almost 100 countries privilege admirable status for photovoltaic installations, and their average output is 4.5 kWh/kW/day (Awan et al. 2020; GoI 2021). In 2021, the top installer of solar PV (SPV) capacity was China, the US, Japan, Germany, and India (Giri et al. 2021; Ray 2019). India is vastly populated, and the numbers are gradually increasing, government must develop its GDP and SDGs proportionately. However, the rise in GDP and energy would arise at a cost. It is predicted that a 1.3% rise in the economy will consequence in a 1% progress in CO_2 emission (SDGs 2021).

The scarcity of arable land and overpopulation leads to a new approach to land use, farm income, and environmental conflicts. These issues can be mitigated by adopting a sustainable agrivoltaic system (AVS) or agriphotovoltaic (APV) system, where sunlight is mutually used for photovoltaic energy as well as for agriculture productions from the same land (Choi et al. 2021; Adeh et al. 2019). The system is best acceptable for those locations where the availability of solar irradiation is sufficient and land productivity capacity is relatively low (Bist et al. 2021; Miskin et al. 2019). An additional benefit of AVS is to harvest rainwater from the top of solar panels (Amaducci et al. 2018). The collected rainwater can be used for cleaning solar panels and delivering supplemental irrigation to crops. This system can be connected to a nearby grid to supply the generated electricity and earn an income of 81.88 USD/kW/year. Otherwise, the off-grid AVS can be used for irrigation purposes on farmers' land (Poonia et al. 2021). Apart from income by selling the electricity, farmers can also earn income from agriculture production.

The AVS market share has been increasing sustainably, world organizations have given attention to better system adoption, and different characteristics of the systems have newly been published (Campana et al. 2021; Jain et al. 2021). Policy and framework on AVS differ from one country to another. Based on technology and configuration, the AVS systems are two types, namely (a) fixed AVS and (b) dynamic AVS. The most common type of system is fixed solar panels installed on the same agricultural land (Raiz et al. 2020). However, the modern AVS design uses a tracking and/or adjustable system either manually or automatically that optimizes the harvesting of solar radiation for better production of energy and food from the same land. But the design, installation, and maintenance costs are more than the fixed type (Abidin et al. 2021). The governments of many countries such as Japan in 2004, the USA in 2008, Germany in 2015, China in 2016, and South Korea in 2019 have already introduced policies for AVS innovation and implementation (Weselek et al. 2021; Naguyen and Su 2021; Agostini et al. 2021; Dinesh and Pearce 2016). Several studies illustrated the techno-ecological and socio-economic viability of AVS (Schindelea et al. 2020; Irie et al. 2019). Studies also cover the selection of shade-tolerant crops for agricultural production, photosynthesis process, soil quality aspects, solar panel selection, combinations, energy generation, efficiency, feasibility, environmental impact, and policy considerations of AVS (Honsberget et al. 2021). Other studies covered the performance analysis of different SPV systems (Elamathi et al. 2021; Srivastava et al. 2020).

India is geographically located above the equator leading to good solar radiation and clean energy production across the country. The equivalent energy capacity is predicted at about 6,000,106 GWh/year (GoI 2021; Praveen et al. 2021). The daily average global radiation varies from 4.5 to 7.0 kWh/m^2/year (Magadley et al. 2020; Ouammi et al. 2020). Looking at these possibilities, the Indian government has approved a scheme 'Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan" (PM-KUSUM) through the Ministry of Agriculture & Farmers Welfare to double farmers' income and provide solar PV energy options for irrigation (GoI 2021). The country is motivated toward sustainable development and has achieved 4th and 2nd positions globally in clean energy and agricultural production, respectively (Ravishankar et al. 2021; Selvaraj et al. 2021). In 2021, the country's solar power installed capacity was around 55 GW (including 45 GW of ground-mounted), whereas the target is to achieve 100 GW by next year for reliable energy production and to double the farmer's income (GoI 2021; Chakraborty and Bandopadhyay 2021). In 2017, a 105 kW AVS was designed, implemented, and verified for real settings at the Indian Council of Agricultural Research (ICAR) and the Central Arid Zone Research Institute (CAZRI), Jodhpur, India (Poonia et al. 2021). Apart from this capacity, more than twenty grid-connected AVS has been implemented in India by 2021 (Giri et al. 2021; Dinesh and Pearce

2016). This system can be connected to a nearby grid for selling electricity to the respective State Electricity Regulatory Commissions (SERC, for Odisha- OERC) at the current fixed tariff rate of 0.040–0.066 USD/kWh (GoI 2021), as presented in Table 4.

One of the Indian states, Odisha, receives an average solar irradiance of 5.5 kWh/m^2/year from around 320 clear days (Proctor et al. 2021; Bhandari et al. 2021). The innovative design and implementation of solar photovoltaic (SPV)-based electricity production over agricultural land (i.e., AVS) are very essential to mitigate the environmental issues, land tenure, and economy in Odisha, India (GoO 2021). In this study, three different types of designing techniques for AVS have been designed using the software SOLIDWORKS Premium 2020. It is found that a double row array design capacity of 6 kWp AVS with turmeric crops provides better performance in terms of benefit–cost ratio, land equivalent ratio, and payback period of the system. This creativity improves the gradation of sustainability along with local employment in both rural and urban areas. Hence, AVS is a co-developing of solar PV energy and food productions system, which has the potential to reach the above-said targets and enhance the livelihoods security of the country.

Materials and methods

The design of an AVS serves to share light between solar panels and crops for the production of energy and food from the same land use. In the present study, experimental work has been conducted to find out the production capacity of energy and food from an AVS in Odisha, India. For an efficient AVS, the following aspects need to be considered before the implementation of the system by a farmer or an investor.

- The suitable gap between solar panels for proper photosynthesis of the plant
- Tilt angle and supportive elevation for better farming
- Cultivation of suitable crops/rhizomes for better production and revenue

Design of agrivoltaic system

The AVS is best suitable for those locations where sun radiation is better and land may be barren or fallow or cultivable lands. In the case of cultivated lands, the elevation of solar panels or arrays needs to be maintained above a suitable height from the ground so that sufficient light will pass for the growing of crops and farming equipment. Design factors for installing solar panels in AVS are slightly different from the traditional SPV system. It comprises several apparatuses, including solar panels to absorb and convert solar into electrical energy, a solar inverter to convert the output from DC to AC, a mounting structure, cabling, and other electrical accessories to set up a working system. Installation of a 1 MW SPV system with crystalline panels will require 3–4 acres, while the thin-film panels will need 4–6 acres of land (UNECE 2021; Giri and Mohanty 2020). In the world, both tenders and pilot projects are started with a capacity from kW to MW range (Malu et al. 2017), as illustrated in Fig. 1.

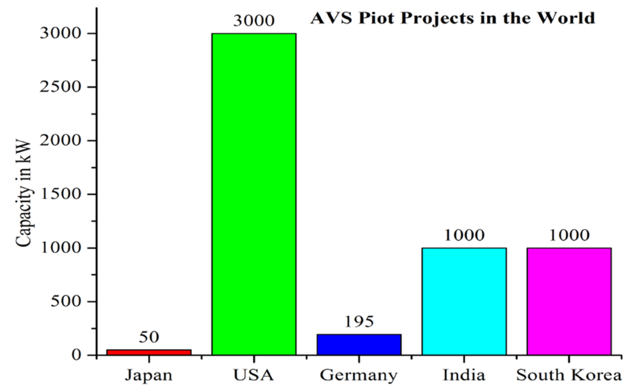


Fig. 1 World's AVS pilot projects

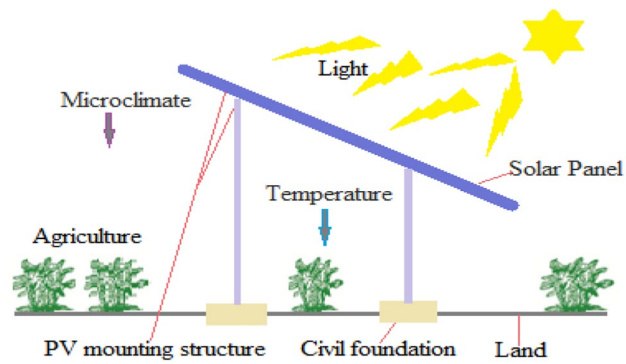


Fig. 2 Concept design of agrivoltaic system

The innovative design and installation of panels over crops lead to optimizing the production of energy and food in the country. The solar panels should be installed toward the southeast face of India for producing the optimum output of the system. The basic design for solar panel installation in an AVS comprises location, site assessment, structure, orientation, SPV system components, and plantations as illustrated in Fig. 2. Spacing between the panels is very essential to obtain sufficient light for photosynthesis and moderate the micro-climate thereby reducing the panel's temperature by 1-2^{0}C lower than ambient temperature, which helps in optimum electricity generation. This electricity generation will help to reduce the CO_2 emission from the same land use by half as against fossil fuel-based electricity generation.

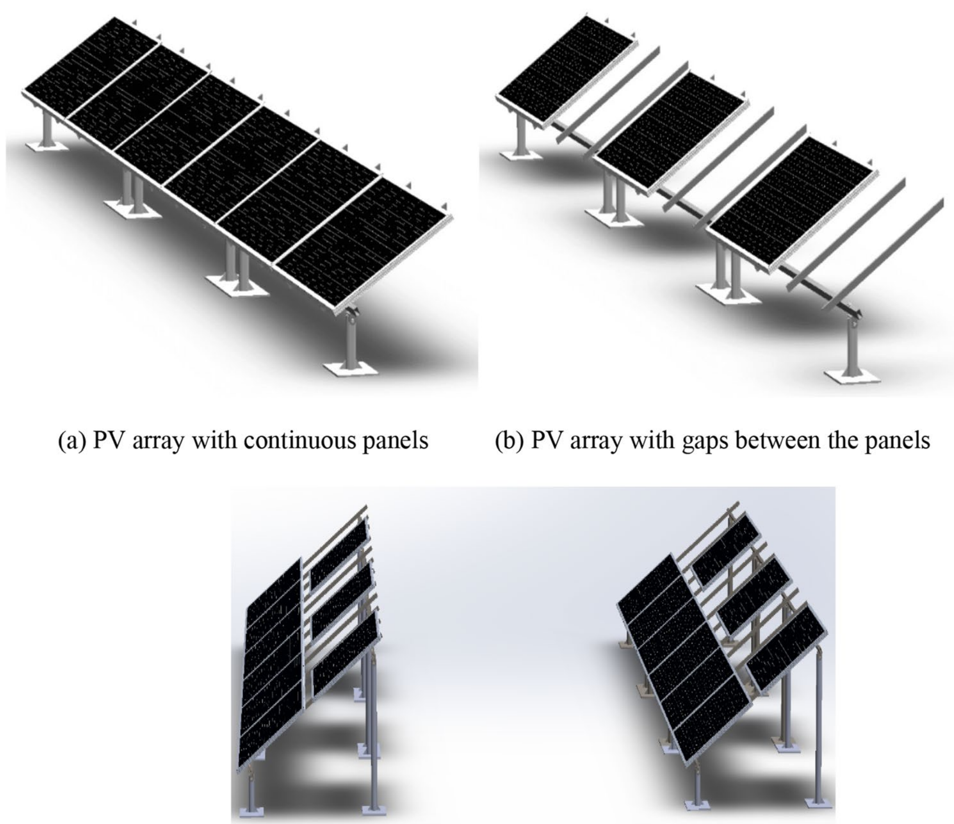
In this research, three experimental designs in three separate configurations have been investigated such as (a) single row PV array with continuous panels, (b) single row PV array with gaps between the panels, and (c) double row PV array with continuous panels in the lower row and upper row panels with uniform gaps. The design has been created using the software SOLIDWORKS Premium 2020 as displayed in Fig. 3. The purpose of different designs is to access sufficient light for better farming and power production from the same land use. A suitable gap between the PV strings/arrays (Fig. 3 (c)) is considered for AVS and then coupled with agricultural activities at Centurion University Technology and Management (CUTM), Bhubaneswar (20.2961° N, 85.8245° E) Odisha, India. This design also avoids the shading effect on the next strings/arrays of the SPV structure. The location experiences average radiation of 5 kWh/m^2/day, temperature varies from 20-32^{0}C, humidity from 50 to 80%, wind speed from 7 to 15 km/h, and annual rainfall from 1200 to 1400 mm (GoO 2021). The farming site is nearly flat with well-drained sandy soil. Considering the above characteristics, and concept design (Fig. 2), a ground-mounted double row AVS has been selected for better energy-food production and revenue.

The AVS structure is designed with 75 Wp (Dimensions L x H x W = 0.66 m × 0.75 m × 0.03 m) polycrystalline solar panels. The selected solar panel (NOVASYS) specifications are given in Table 1.

The structure dimensions (L x H) of 4.01 m (3.96 m + 0.05 m) × 0.75 m and 4.01 m × 0.76 m (0.75 m + 0.01 m) have been used for designing of Fig. 3a and b and Fig. 3c, respectively. The surrounding gap in the design of panels is taken as 0.01 m for light passing to the plant. For better farming and production in an AVS, the inter-row spacing needs to be 1.5–2 times the height of solar panels from the ground.

Table 1 Selected solar panel specifications

Electrical characteristics	Rating
Peak power (P_{max})	75 Wp
Rated voltage (V_{mp})	18.21
Rated current (I_{mp})	4.12 A
Open circuit voltage (V_{oc})	22.20 V
Short circuit current (I_{sc})	4.42 A
Efficiency (η)	14%
Application	Class A



(a) PV array with continuous panels (b) PV array with gaps between the panels

(c) Combined design of a and b

Fig. 3 Schematic design model and open-field application of AVS

Energy production from AVS

The state of Odisha receives average solar irradiation and sunny hour of about 5.5 kWh/m^2/day and 7 to 8 h/day, respectively (GoI 2021; GoO 2021). It is estimated that a 1 kW solar power plant can generate 4–6 kWh (Units) per day with suitable installation and tilt angle (Latitude 20.9517°N and longitude 85.0985°E). The AVS is capable of generating electricity from its solar panel as a key output. The generated energy from the solar power plant needs to be connected with the nearby grid for selling electricity with the current tariff rate ranging from 0.040–0.067 USD/kWh. A 6 kW capacity of double row SPV structure has been implemented in 14 m^2 of land for energy generation at CUTM, Odisha, India, as presented in Fig. 4. As it is a dynamic type AVS, the different capacity of panels and suitable configuration can be possible for further research and development in Odisha.

The maximum energy production aspect of AVS at CUTM is accompanied by R&D institutions like Central Arid Zone Research Institute (CAZRI), and the National Institute of Solar Energy (NISE), India, set up projects. However, PV energy production could also offset global energy demand if $<1\%$ of agricultural land were converted to an AVS. In addition, food production consumes less than 1% of the total energy generated by AVS (Adeh et al. 2019).

Food production from AVS

The choice of land, cultivation, and harvesting of suitable crops under solar panel(s) projects in Odisha is a vital task. These are the environmental issues, microclimatic effects, soil conditions, technology, height, and space of the panels. The solar panels are installed in AVS at a tilt angle equal to the latitude of the location. Thus, the shade of panels or arrays is created at the leeward side of the ground surface. The interspace area between the SPV arrays is suitable for crops cultivation. Underneath-based farming structure varies from plant to plant and variety to variety in different shading percentages such as 30, 40, 50 60, 70, and 80%. The shade structure with 40–60% as shown in Fig. 3c is more suitable for better farming with proper sustaining of microclimatic elements in different locations. As reported in different literature and implementation of projects, the suitable seasonal categorization crops are illustrated in Table 2 (Bhandari et al. 2021). Farming of turmeric, ginger, potato, vegetables, etc., is suitable as per the climatic conditions of Odisha for underneath practice. However, in this research, the performance indicators of AVS have been calculated for the turmeric crop cultivated in Kharif (rainy) season.

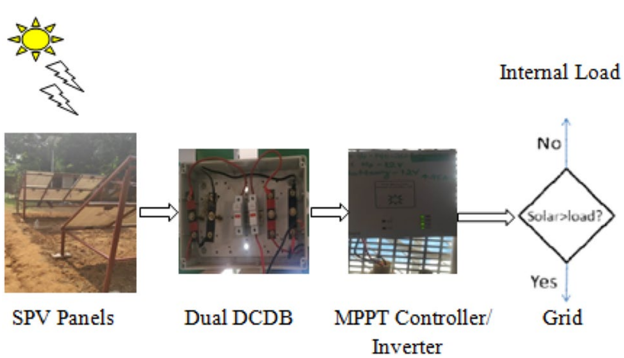


Fig. 4 Schematic diagram of on-grid AVS system for energy production in CUTM campus, Odisha

For overall farming and production, the 'green' category crops (shade-tolerant) are performing better; the 'orange' category is performing moderate, whereas the lower performing crops (shade-intolerant) are considered under the 'red' category. However, field experiments are very important to select any of the above crops for suitable locations around the world.

Combined energy and food production

Energy and food production can be optimized by co-development with the sunlight sharing method on the same land area. This abundant solar radiation will be used in two ways, such as light energy converted to electricity through solar panels and visible light energy converted to food production through the photosynthesis process of the plant, presented in Fig. 5a. Most solar cells use unseen ultraviolet (UV) and infrared light (IR) to generate electricity (Aklin et al. 2018). For this system, maximum oxygen-producing plants are widely suitable to balance microclimatic elements and improve the efficiency of the AVS.

In 2017, the first AVS prototype with a capacity of 105 kW was commissioned with an average tariff rate of 0.067 USD/kWh at ICAR-CAZRI, Jodhpur, India (Poonia et al. 2021), presented in Fig. 5b. At the place, the operative average solar irradiation is 4–6 h/day to generate electrical energy of 120,779 kWh, and the total revenue was 8696.09 USD in 2019. Few suitable crops were chosen for food production such as beans, isabgol, tomato, watermelon, brinjal, medicinal plants, leafy vegetables, and aromatic grasses. It is found that the double row design has better production and revenue capacity as compared to others.

The energy-food production can be calculated by using the land equivalent ratio (LER) (Trommsdorff et al. 2021). The LER of an AVS can be defined as in Eq. (1):

$$\mathrm{LER} = \frac{\text{PV electricity production in dual use}}{\text{PV electricity production in single use}} + \frac{\text{Crop production in dual use}}{\text{Crop production in single use}} \quad (1)$$

Table 2 Suitable seasonal categorization crops for AVS system

Seasons	Suitable crops	Green	Orange	Red
Summer (Zaid)	Tomato, Chili, Aloe Vera, Watermelon, Brinjal, Isabgol, Leafy Vegetables- Peppers, Celery, Coriander	Potato, Chili, Tomato, Onion, Grapes, Berries, Broccoli, Bean, Turmeric, Ginger, Aloe Vera, Brinjal, Lettuce, Leafy Vegetables,	Cucumber, Watermelon, Isabgol, Beet, Carrot, Cabbage, Fennel, Celery, Areca Nut Nursery	Rice, Corn, Wheat, Fruits, Millet, Sunflower, Olive
Rainy (Kharif)	Turmeric, Ginger, Bean, Areca Nut Nursery, Leafy Vegetables- Water Spinach, Indian Pennywort			
Winter (Rabi)	Potato, Onion, Beets, Carrots, Leafy Vegetables- Spinach, Coriander, Lettuce, Cabbage, Carrots			

If LER > 1, AVS design is more suitable than producing only energy or only crop from the land.

The production value (i.e., revenue) of farming is obtained by multiplying of total production capacity by the unit selling price, as defined in Eq. (2):

$$\text{Production value} = \text{Total production} \times \text{Unit selling price} \tag{2}$$

The total cost (variable and fixed) of production denotes the expenses involved in crop production. Variable cost includes expenditure on crops, harvesting process, daily wage labor, etc. whereas fixed cost includes financing, equipment, depreciation, etc.

The gross margin of farming is calculated using Eq. (3):

$$\text{Gross Margin} = \text{Total production cost} - \text{Variable cost} \tag{3}$$

Farm profit is a crucial factor for a farmer as calculated using Eq. (4):

$$\text{Profit} = \text{Production value} - \text{Total cost} \tag{4}$$

The benefit–cost (B/C) ratio is calculated by dividing the production cost, by the total cost as given in Eq. (5):

$$\text{B/Cratio} = \frac{\text{Production value}}{\text{Total cost}} \tag{5}$$

The AVS should be economically acceptable and can be measured by the price–performance ratio (ppr). The ppr is calculated by taking the ratio of annual extra cost to maintain the land for the farmer's crop production and production value (revenue) as given in Eq. (6):

$$\text{ppr} = \frac{\text{Annual extra cost}}{\text{Production value}} \tag{6}$$

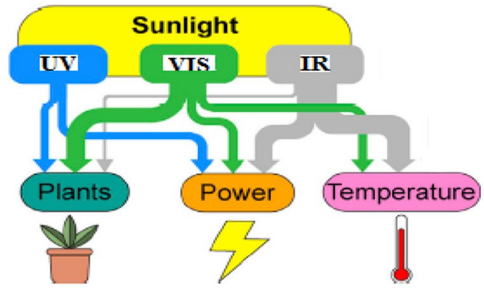
If ppr < 1, the performance benefits of AVS are greater than normal revenues of the agricultural land. The smaller price/performance ratio indicates that the implementation of the project is more interesting.

The payback period (PBP) is also considered in this study, which is an important economic parameter of an SPV system. It is determined by comparing the initial investment of the project with the annual profit or returns from the project. The depreciation method is considered as the life of SPV system assets above one year.

$$\text{PBP} = \frac{\text{Depreciable fixed capital}}{\text{Average profit per year} + \text{Average depreciation per year}} \tag{7}$$

In India, the depreciation allowance of the solar power generating system is 40%. The Return on Investment (ROI) gives an effective return over the 25 to 30 years of a solar plant or agrivoltaic project. The higher is annual profit on energy-food productions indicates the quicker of repaid and the higher ROI of the initial investment.

Fig. 5 Combined energy-food production from AVS



(a) Schematic diagram of sunlight sharing for Energy-Food production

(b) Combined energy-food production at ICAR-CAZRI, Jodhpur, India (Poonia 2021)

Table 3 Possible natural hazards and their phenomena in Odisha, India (Sreenathet al. 2021)

Natural hazards	Phenomena
Cyclone	High
Drought	High
Weather	Moderate
Lightning	Moderate
Flood	Moderate
Hailstorm	Low
Earthquake	Low

Environmental risk and sensitivity assessment

Environmental change is a deviation of the surroundings most often initiated by human influences or natural activities. The performance of an AVS is affected by internal and external factors such as location, radiation, weather, structure, elevation, and shading. Natural factors such as availability of sunlight, temperature, humidity, wind speed, and rainfall are the leading constraint to an integrated energy-food production system. Any type of climate change causes variations in the radiation and the temperature; hence, the PV system and agricultural potential will be reduced. The possible natural hazards and their likelihood of phenomena for the project are displayed in Table 3. This risk can be incorporated through a proper environmental and social risk management (ESRM) practice (Sreenathet al. 2021). The main focus is to identify possible natural hazards and their prior precautions to project planning and development (SDGs 2021). As the SPV structure creates shading on the plant, the sensitivity of the food production to the radiation intensity is observed. 40–60% shade structure as presented in Fig. 3c is more appropriate in terms of panel arrangement, photosynthesis, microclimate, and production capacity of the system. For example, 40% shading means the structure will cut 40% of radiation intensity and would pass 60% of light to the plant.

The above factors lead to mitigating clean energy and an agrarian crisis in an agrarian state like Odisha. Further, several reports suggest that cyclones and droughts may come with higher capacity during the coming years. Solar panel selection is very important for the design, installation, and operation of radiation, withstand wind speed, hailstorms, drought, and cyclones. Furthermore, solar panel sizes ranging from 75–200 Wp will be preferable for most geographical locations and climate conditions of Odisha, India. Therefore, a sensitivity analysis to climate has been performed based on incoming solar radiation and energy production at the output of the AVS, as presented in Fig. 6 under the results and discussions section.

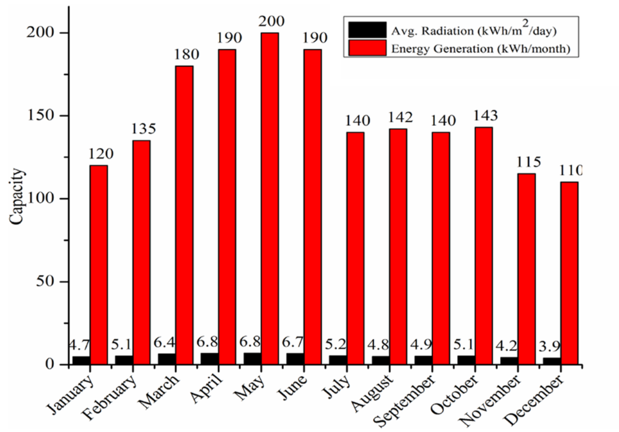


Fig. 6 Sensitivity analysis of SPV (1 kW) output with respect to change in radiation in the year 2021, CUTM, Odisha

Results and discussion

Agrivoltaic system offers a symbiotic approach for both solar energy and food production on the same land area. The solar light is shared and maintained in between the solar panels and crops for better production. The performance of an SPV system directly depends on incident solar radiation for the panels. Similarly, food production is based on radiation conversion efficiency. From the field experiment, it is measured that the highest and lowest amount of radiation received is 6.87 and 3.92 kWh/m^2/day during May and December, respectively. The variation of solar radiation to the solar panels and monthly average power generation of the ground-mounted SPV system (1 kW) at CUTM, Odisha, is illustrated in Fig. 6. The power output is affected more in January, February, November, and December due to lower solar radiation. Other parameters may be weather conditions, design, technology, operation, and maintenance of the system.

The three suitable designs of AVS have been discussed elaborately to find out better systems as well as optimization of energy and food from the same land. It has been observed that the sensitivity of PV array with continuous panels (Fig. 3 (a)) passes less radiation of light and heat below panels in comparison to gaps between the panel's design (Fig. 3b). The suitable gap between the solar panels helps in the passing of sufficient light for photosynthesis, reduction of wind resistance, dust deposition, and evaporation at the same time and location. The inter-row spacing is maintained a little bit more (2.5–3 times the row height) toward the North–South direction to avoid the shading effect and to improve crop farming. For a small system design, reasonably suitable for 40º latitude or that latitude minus 10º is a suitable acceptance tilt angle in a multiple-row fixed-tilt ground-mounted system. The combined design (Fig. 3c) provides better results in terms of panel configuration, installation, energy-food production, soil health, wind speed to crops, and water conservation. These designs maintain the temperature of the solar panels 1–3 °C lower than the ambient temperature resulting in an improvement in power generation capacity (Figs. 2, 5a). The production capacity and revenue calculation are based on the PM-KUSUM framework of a few selected solar power plant capacities in Odisha which are illustrated in Table 4.

One kW capacity of ground-mounted solar power plant requires 7 to 10 m^2 of land for the installation and energy generation capacity up to 1800 kWh per year as presented in Fig. 6. Similarly, around 1 dismil or 40.47 m^2 of land or more is required to install a 6 kWp capacity of the AVS plant with investment. The medicinal crop turmeric has been considered for farming in AVS. This AVS can generate up to 30 Units/day or 49,920 Units per year (6 kW × 26 units × 320 clear days). According to Eq. (2), the annual average revenue will be 2121.6 USD. The maximum annual revenue from the solar power plant of capacity 1, 100, and 1000 kW is illustrated in Fig. 7.

In this field experiment, a few selected crops such as turmeric, ginger, potato, and vegetables have been farmed in 1 dismil or 40.47 m^2 of land area, Odisha, India. The selection of crops is based on local market demand and production capacity. The farming cost, production capacity, and selling price calculation of these crops are illustrated in Table 5. Other intercrops can be planted in parallel for extra adding of income on the same farmer's land. The average results of agriculture revenue (minimum to maximum) and B/C ratio are calculated from Eqs. (2) and (5), as presented in Figs. 8 and 9, respectively.

Table 4 Average production capacity and selling price (tariff rate) of the solar power plant in Odisha

Plant capacity (kW)	Land capacity (m^2)	Production capacity (Unit/day)	Production capacity (Unit/year)	Tariff rate (USD/unit)
1	7–10	4–6	1200–1800	0.040–0.045
100	400–600	400–550	11,50,00–18,05,00	0.040–0.045
1000	16,188–24,281	4000–5000	13,00,000–19,00,000	0.036–0.041

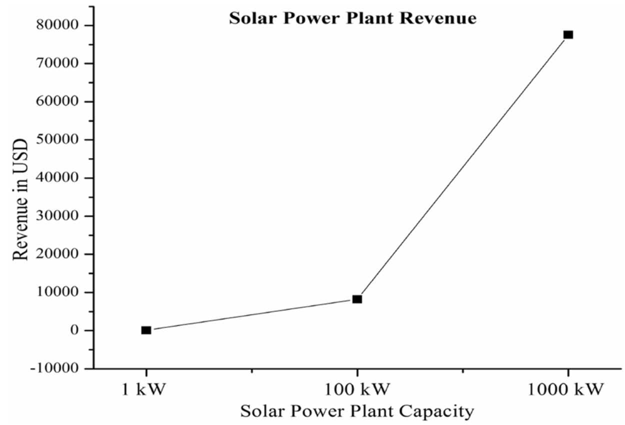


Fig. 7 Solar power plant revenue from 1, 100, and 1000 kW in Odisha

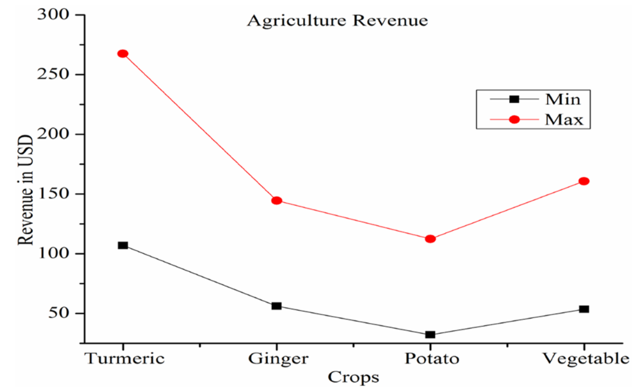


Fig. 8 Agriculture revenue of selected crops in Odisha (40.47 m.^{2} of land)

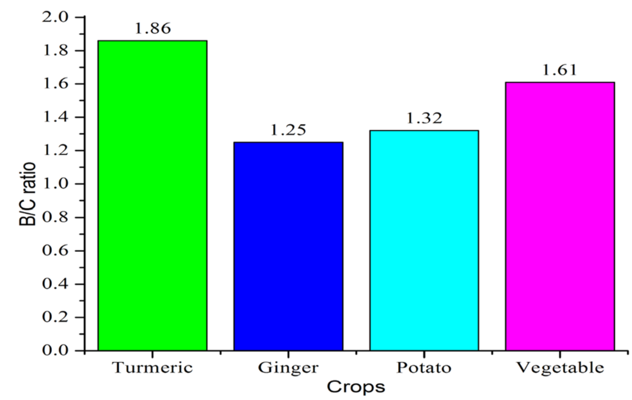


Fig. 9 B/C ratio of selected crops in Odisha (40.47 m.^{2} of land)

The farming economic indicator results are better than traditional farming practices in rural areas of India. It is observed that turmeric farming indicates the highest return, whereas potato produces the lowest revenue, but the demands for potatoes and vegetables are more in Odisha, India. For the short period of farming, a vegetable has a better production capacity and B/C ratio, but it requires more water, pesticides, and labor for the harvesting process and may add extra cost to the investment. Overall, turmeric (tuber) farming performs the best among all these four crops in AVS technology.

For production and economic calculation, the collected data are obtained based on experimental analysis as well as farmers' experiences. The maximum revenue of selected shade-tolerant crops such as turmeric, ginger, potato, and vegetable is 267.57, 144.49, 112.38, and 160.54 USD per year, respectively, as demonstrated in Fig. 8. The maximum revenue from solar power plants 1, 100, and 1000 kW is 81.88, 8210.42, and 77,528.7 USD per year, respectively, in the same farming land as demonstrated in Fig. 7. The average revenue from agriculture (only turmeric) production is around 187.3 USD/dismal per year. The agriculture revenue will be added with an intercropping option on the same land. Overall, the average revenue from 6 kWp AVS will be 2308.9 USD per year with an average tariff rate of 0.042 USD/unit from 1 dismil or 40.47 m^2 of land use. According to Table 4–5 and Eqs. (1), (5), (6), the land equivalent ratio and benefit–cost ratio of AVS are around 1.42 and 1.86, respectively. The annual extra cost for food production (including land preparation, crop production, labor, agri tools, etc.) is around 140.47 USD. According to Eq. (6), the price–performance ratio of turmeric production is around 0.75. From Eq. (7), the average payback period of 6 kWp AVS is 7–8 years. The selling of energy and food from an AVS needs to be addressed more profitably in new government policies.

Table 5 Average farming cost, production capacity, and selling price of selected crops in Odisha

Crops	Quantity (kg)	Harvesting time (months)	Production/farming cost (USD)	Production capacity (kg/dismil)	Selling price (USD/kg)
Turmeric	4–5	6–7	100.43	80–100	1.34–2.68
Ginger	5–6	5–6	80.35	70–90	0.80–1.61
Potato	8–9	3–4	54.90	120–140	0.27–0.80
Vegetable	0.004–0.005	2–3	66.96	100–120	0.54–1.34

In the global context, the UN predicts the growing population will disturb natural activities, especially in the agriculture and energy sectors. To sustain a better lifestyle, integrative, efficient, synergistic, and sustainable uses of land are very essential. The investment in AVS development signifies a useful solution to growing concerns over the clean energy-food crisis and has been validated by this study. The dual land use, socio-economic and environmental benefits of AVS can fulfill the many sustainable development goals (SDGs) of the world. A few advantages of AVS are stated below:

- Dual land use
- Sufficient light transfer for better photosynthesis
- Improvement in microclimate for crop cultivation under raised solar panels
- Tuber crops have maximum energy-food production with minimal water use
- Reduction in dust deposition on solar panels and very less maintenance
- Increase socio-economic value from farmland (for turmeric: B/C ratio is 1.86)
- Improvement in LER and efficiency of the AVS

Although the AVS has feasible advantages, there are a few challenges too. These are initial investment that is a major burden for its adoption in farmers' land, the safety of field workers involved in agricultural activity, ownership issue, and sharing of profits in case of the joint project. Therefore, the government should appraise better policy for tendering AVS pilot projects with the agriculture diversity and environmental risk management to sensitize stakeholders and farmers. As these technologies are very new, the results need to be confirmed with field experiments first before the installation of such projects.

Conclusions

An agrivoltaic system has been discussed for the energy-food production on the same agricultural land, thereby increasing the revenue of the farmers. The results of this study suggest that double row design produces maximum production of energy-food and income among the different AVS designs. Considering turmeric farming in 40.47 m^2 land of AVS, the average income from 6 kWp solar plant and agriculture will be 2121.6 USD and 187.3 USD per year, respectively. The average socio-economic indicators such as LER, B/C ratio, and ppr are found as 1.42, 1.86, and 0.75, respectively. Further, the agriculture production under solar panels leads to moderate microclimate, reduction of temperature level by 1–2° C, and lower the average payback period by 2–3 years. It is found that solar panel output is good at 25 °C and each degree rise in temperature causes the reduction of PV generation. These results imply that the revenue, B/C ratio, and LER, environmental sustainability are improved by a suitable AVS installation compared to the ground-mounted SPV system. India's AVS design is gradually maturing from R&D into the commercial market. However, there are many limitations such as no legal framework for AVS plant design, insufficient R&D efforts, sharing of profits between farmers and solar project developers, and ownership issues. A deeper investigation is required in terms of location, technology, implementation, land productivity, socio-economic value, new jobs, SDGs target, and livelihoods of the country.

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Author contributions Nimay Chandra Giri was involved in conceptualization, resources, data collection, methodology, designing, analysis, visualization, writing, original draft preparation. Ramesh Chandra Mohanty contributed to methodology, software, writing, reviewing, editing, and interpretation, paper correction, and formatting.

Declarations

Competing interest The authors declare that they have no well-known competing financial interests that may have acted to influence the work reported in this article.

Informed consent This article is about consent to solar energy and agricultural research procedures ethics.

Consent to participate The authors mutually agree that they participated in the preparation of the manuscript.

Consent for publication The authors declare that the manuscript is their intellectual property and that they want to publish it in the Journal "Clean Technologies and Environmental Policy."

Data availability Data archiving is not mandated, but data will be made available on reasonable request.

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