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Agri-voltaic System: A Sustainable Approach for Enhancing Farm Income in Arid Western Regions of India

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The concept of integrating both food production and energy generation through agri-voltaic system (AVS) has been evolved in recent times considering the increasing demands for the land resources and energy, especially electricity. At ICAR-Central Arid Zone Research Institute, Jodhpur, India, an AVS of 105 kW capacity has been established with three experimental designs in three separate blocks. In all these three blocks, two different designs were followed: few arrays with gap in between PV modules and few arrays covered fully with PV module which allows receiving different amount of intercepted solar irradiation on ground surface, which is required for crop cultivation in between PV arrays and also below PV panel areas. For cultivation in areas below PV modules, aromatic grasses viz. *Cymbopogon citratus* (lemon grass) and *Cymbopogon martini* (palmarosa) were grown. Apart from different arable crops, medicinal plant, e.g. *Aloe vera* and vegetables *Solanum melongena* (brinjal), *Spinacia oleracea* (spinach) and snapmelon (*Cucumis melo* L. Momordica group) were grown.

Introduction

In arid parts of India *i.e.* in Rajasthan, solar irradiations are available in abundance for almost 300 days clear sky. The average irradiance on horizontal surface in arid Rajasthan is 5.6 kWh m^{-2} day^{-1} and at Jodhpur 6.0 kWh m^{-2} day^{-1}, which can be harnessed to fulfill a part of energy needs of rural communities. Looking to these potentials the Government of India has set ambitious targets of achieving 100,000 MW of solar photovoltaic (PV) based power generation capacity in the country and doubling the farmer's income by the year 2022. Agri-voltaic system, which is an integration of PV generation and crop production, has the potential for achieving the above targets. The concept of integrating both food production and energy generation through agri-voltaic system (AVS) has been evolved in recent times considering the increasing demands for the land resources and energy especially electricity. Solar PV generation is a land intensive venture and it needs around two hectares of land per megawatt of power generation and so is the case with crop production.

Design of Agri-voltaic System

PV module installation: Installation of solar power plants of 1 MW capacity requires about 2 ha area. Design parameters for erecting solar panels in AVS are slightly different from that in a conventional solar power plant. At ICAR-CAZRI, Jodhpur, India an AV systems of 105 kW capacity has been established with three experimental designs in three separate blocks. The size of the experimental farm is 68 m × 68 m and the size of the each block is 28 m × 28 m. These are (i) PV arrays of one row PV module and 3 m interspaces between arrays (ii) PV arrays of two row PV modules and 6 m interspaces between arrays and (iii) PV arrays of three row PV modules and 9 m interspaces between arrays (Fig. 1). In all these three blocks, two different designs were followed: few arrays with gap in between PV modules and few arrays covered fully with PV module which allows receiving different amount of intercepted solar irradiation on ground surface, which is required for crop cultivation in between PV arrays and also below PV panel areas. The shading from the PV module varied according to the time of year and height of the crops planted between the module rows. Solar PV modules were installed on fixed MS iron angle structure facing perpendicular to south and inclination of 26° at both the sites (Fig. 2).

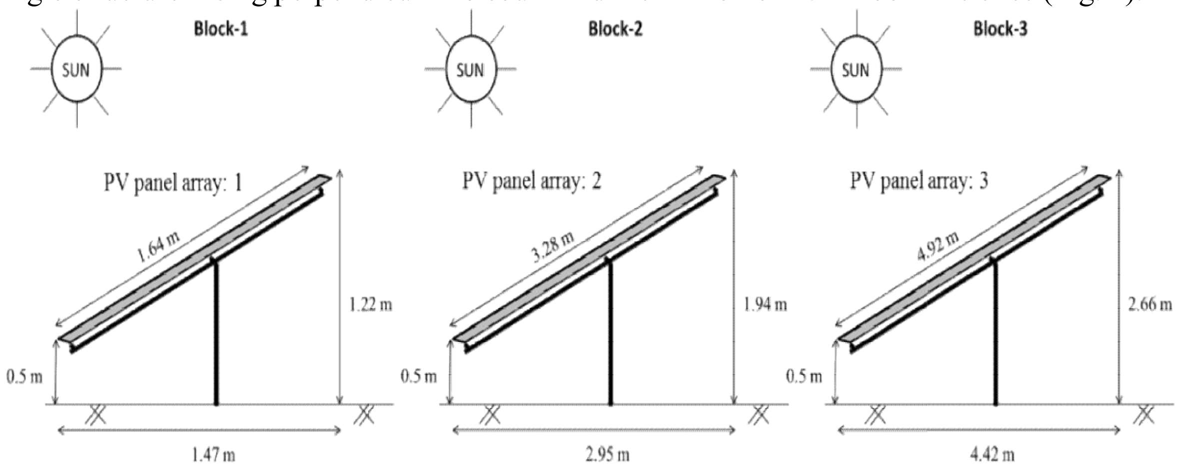

Fig. 1. Schematic design of PV module installations for AVS

Fig. 2. Installed agri-voltaic system at ICAR-CAZRI, Jodhpur, India

Cropping options: In the present AV system, the PV modules created shade on ground surface on leeward side as per the movement of sun. To avoid the shade of one PV array on the next array, a separation distance between two arrays is maintained. This interspaces area between two PV arrays was utilized to grow suitable crops. Moreover, area below the PV module was also used to grow crops since PV modules are fixed over mounting structure at a certain height from ground surface. However, growing crops in between the arrays of PV modules requires selection of suitable crops which have certain degree of shade tolerance and shorter in height to avoid shade on PV panels. The shaded portion at interspaces area varies from morning to evening as per zenith angle and azimuth angle of Sun's position. Available amount of solar irradiation both under direct (open sun) and diffused conditions governs plant growth because the amount of photosynthetically active radiation (PAR) is different under both these conditions. Height of crops is a key parameter for selection of crops for AVS because high crops may create shade on PV modules and thus reduce the PV generation. Therefore, crops with low height (preferably shorter than 50 cm) which can tolerate certain degree of shade and require less amount of water are most suitable for AVS in arid ecosystem. Following crops are initially chosen to grow in agri-voltaic system. Under rainfed situation, moong bean (*Vigna radiata*), moth bean (*Vigna aconitifolia*), and cluster bean (*Cyamopsis tetragonoloba*) have been selected as arable crop, whereas under irrigated situation during *Rabi* season isabgol (*Plantago ovata*), cumin (*Cuminum cyminum*) and chickpea (*Cicer arietinum*) have been selected. Apart from these arable crops, medicinal plant, e.g. *Aloe vera* and *Solanum melongena* (brinjal) have been selected as perennial and *Spinacia oleracea* (spinach) and snapmelon (*Cucumis melo* L. Momordica group) as annual vegetables crop components. For cultivation in areas below PV modules, aromatic grasses viz. *Cymbopogon citratus* (lemon grass) and *Cymbopogon martini* (palmarosa) have been selected. These crops are expected to modify the microclimates below PV modules and thus help in optimum PV generation in arid ecosystem. Moreover, the coverage of crops on soil surface in between PV arrays will also check the erosion of soil by wind action and thus will reduce the dust load on PV module. A field view of different *kharif* and *rabi* crops grown in the AVS is shown in Fig. 3 and Fig. 4.

Fig. 3. Field view of different *Kharif* and *Rabi* crops grown in agri-voltaic system during 2019-20

Fig. 4. Field view of different vegetables and aromatic grasses grown in agri-voltaic system during 2019-20

PV Based Electricity Generation from Agri-voltaic System

Solar PV generation and solar irradiation has been regularly monitored through SCADA (Supervisory Control and Data Acquisition) facility and automatic weather station. The installed AVS has been connected to local electricity grid through net metering system. Therefore, the generated electricity is directly sold to state electricity board at a fixed tariff which varies across different states of India. The average tariff rate of INR 5 per kWh may be considered to calculate the income from PV-generated electricity. The schematic diagram of the PV based electricity generation from the installed AVS and its supply to grid is depicted in Fig. 5. At Jodhpur (India), effective solar irradiation to generate electricity is available for an average of 4–5 h in a day. Therefore, 1 kW PV system is expected to generate 4–5 kWh unit of electricity per day. Thus, 100 kW AVS in Jodhpur will generate at least 400 kWh unit of electricity in a clear sunny day. Monthly PV generation and solar irradiation during 2018-19 is shown in Fig. 5. During the year 2019, month wise, highest PV generation was observed during April 2019 and average PV generation has been observed as 331 kWh month^{-1}. The annual power output generated by AV system was 1,20,779 kWh and the total revenue generated was Rs. 6,03,895 during the year 2019.

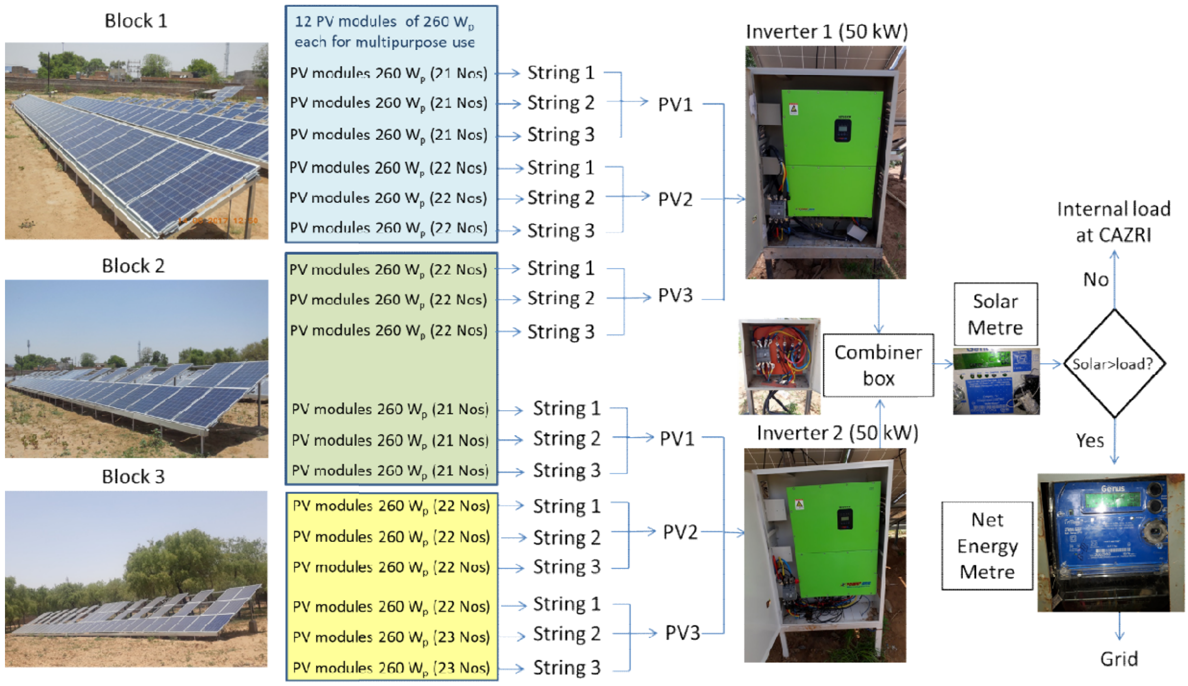

Fig. 5. Schematic diagram of PV based electricity generation in AVS and its supply to local grid

Water Harvesting System

It is possible to collect and store rain water from the top surface of PV modules in AVS. Therefore, in this AVS rainwater harvesting system was also designed and developed by rectangular MS sheet as water collection channels (Fig. 6), underground water conveying PVC pipes of 4″diameter and an underground water storage tank of 1 lakh litre capacity. Surface area of a solar PV module of 260 W capacity is 1.64 m × 0.992 m. Thus, total surface area of 105 kW capacity agri-voltaic system is about 651 m. The total quantity of water received as rain cannot be harvested from PV module surface because of splash loss, evaporation loss, etc. Therefore, a factor of 0.8 may be considered to estimate the total harvested water from rainfall amount. Again, 10% conveyance loss of the collected water to rainwater storage reservoir needs to be considered. Therefore, about 72% of annual rainfall is expected to be collected in water reservoir. Thus, about 180,000 litre of water can be harvested from 105 kW agri-voltaic system. Field observations revealed that solar PV top area harvested 93.3 m^3 of water against a rainfall of about 221.2 mm during the period from June 1- 31 July 2019 with an efficiency of 65.8%. The stored water in water reservoir can be used for supplemental irrigation to crops and have potential to provide 37.5 mm irrigation over an area of 1 acre. Hence, in arid region with severe challenge of water scarcity for agriculture, the agri-voltaic system is a feasible and sustainable option for meeting both food and energy demand in future.

Fig. 6. Rain water harvesting system from top surface of PV module

Economic Analysis of AVS

The economic analysis of the present AVS was carried out by computing the life cycle cost (LCC) and life cycle benefit (LCB) of the system. In addition, five economic attributes, namely, Benefit-cost ratio (BCR), Net present worth (NPW), Annuity (A), Internal rate of return (IRR) and Pay back period (PBP) were also determined for judging the economic viability of the system. The values of five economic attributes, namely, benefit-cost ratio (BCR), net present worth (NPW), annuity (A), internal rate of return (IRR) and payback period (PBP) are presented in Table 1.

Table 1. Values of different economic attributes of AVS project.

S. No.	Economics Attributes	Values
1	BCR	1.46
2	NPW (INR)	25,83,888
3	A (INR)	3,99,920
4	PBP (years)	11.21
	Simple PBP (years)	7.58
5	IRR (per cent)	21.67

Conclusion

Establishments of AVS in arid regions of the country would not only be a source of income by electricity generation (about 400 kWh electricity in a clear sunny day) but also means for rain water harvesting during rainy season. About 180,000 liters of water can be harvested from 105 kW agri-voltaic system. Thus, it would be meeting the demand of water as well as electricity. The stored water in water reservoir can be used for supplemental irrigation to crops which have potential to provide 37.5 mm irrigation over an area of one acre. Thus, in arid region with severe challenge of water scarcity for agriculture, the agri-voltaic system would be a feasible and sustainable option for meeting both food and energy demand in future.