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Agri-voltaic system:

crop production and photovoltaic-based electricity generation from a single land unit

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*Generation of renewable energy has currently gained more importance in India than ever before. Photovoltaic (PV)-based electricity generation shares a major portion of renewable energy generation in India. PV-based electricity generation requires land at a rate of about 2 ha per megawatt (MW) of installation. Since both food and energy are required for human population, a concept of integrating PV-based electricity generation and crop production from a single land unit, commonly referred to as agri-voltaic system, has been designed and developed with a capacity of 105 kW at the Central Arid Zone Research Institute, Jodhpur. Rainwater harvesting system from top surface of PV-module has also been designed and developed with an estimated annual rainwater harvest of 1.5 lakh litres from 105 kW system. The harvested water is enough to provide supplemental irrigation of about 37.5 mm in 1 acre (0.404 ha) land. Suitable crops for agri-voltaic include mungbean (*Vigna radiata*), mothbean (*Vigna aconitifolia*), cluster bean (*Cyamopsis tetragonoloba*), isabgol (*Plantago ovata*), cumin (*Cuminum cyminum*), Aloe vera etc.*

Key words: Agri-voltic system, Crop production, Photovoltic-based electricity

ENERGY and food are the two main requirements for human population and demands for these two resources are increasing at a fast rate. Fossil fuels are being exhausted rapidly and energy from biomass is claimed to be a possible substitutes to fossil fuel. Land area required to replace fossil fuel with biofuels largely exceeds the cropland area of the planet. Biofuels from cereals or oil crops are generally produced through ethanol pathway or transesterification pathway and it was estimated that a hectare of cereals will be sufficient to produce bioenergy which allow running a car for about 18,000 km and it will be about 22,000 km, if most efficient transesterification pathway is adopted. The low efficiency of the photosynthetic process of most energy crops which is about 3% will not be able to cope up with increasing energy demand. In contrast, commercially available photovoltaic panels have an efficiency of 12-15% and can supply the future energy needs. Therefore, solar power plants with photo-voltaic (PV) panels are envisaged to compete with agriculture and even with bioenergy crops for land. The issue of land utilization for future food and energy production is being debated at several platforms.

In view of the future requirement of energy and food production, Agri-voltaic system (AVS) has been proposed as a mixed system associating solar panels and crop at the same time on the same land area. Keeping in mind the importance of AVS in future, 105 kW and 25 kW capacity systems has been designed and installed at Central Arid Zone Research Institute, Jodhpur and its Regional Research Station at Bhuj, respectively. The potential role of AVS has been discussed in enhancing farmers' income and in improving livelihood.

Availability of solar irradiation in western Rajasthan

Arid western India mainly comprise of the western part of Rajasthan and north-western part of Gujarat with some parts of Haryana and Punjab. It lies between 21°17'-31°12'N and 688-76°20'E covering an area of 32 million ha. The arid part of the country receives more radiation as compared to the rest of the country. The average irradiance on horizontal surface in India is 5.6 kWh m^{-2} day^{-1} whereas at Jodhpur, which lies at the arid part of the country, it is 6.11 kWh m^{-2} day^{-1}. Spatial pattern on availability of solar irradiation in western Rajasthan is depicted in Fig. 1. Maximum amount of irradiation is received during April

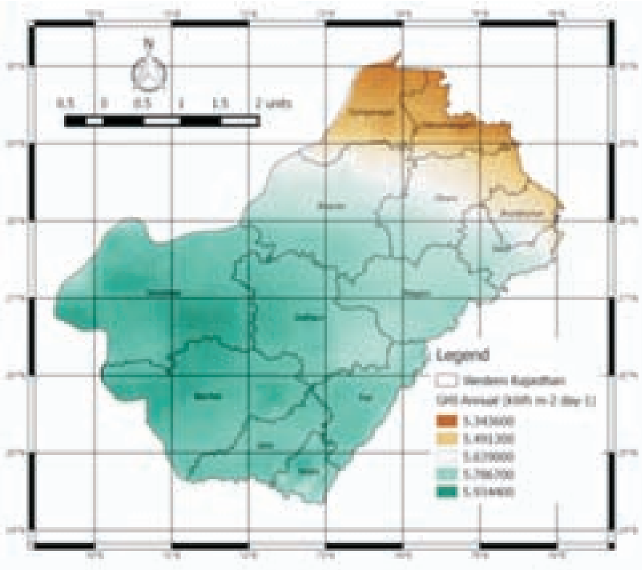

Fig. 1. Availability of solar irradiation in western Rajasthan and at Jodhpur.

(7.17 kWh m^{-2} day^{-1}), whereas the minimum amount of irradiation is received during December (5.12 kWh m^{-2} day^{-1}). Most of the days (more than 300) in a calendar year at western Rajasthan are cloud free, which makes this region more advantageous in harnessing solar energy.

Design criteria of AVS

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 (Fig. 2). Installation of such systems in farmers' field may fetch additional income from sale of electricity in addition to crop production. It has been estimated that 240 to 480 kW capacity system may be established in 1 ha cropped field. At CAZRI, Jodhpur, 105 kW capacity AVS has been established with three experimental designs, viz. PV arrays of one-row PV module and 3 m interspaces between arrays; PV arrays of two-row PV modules and 6 m interspaces between arrays and PV arrays of three-row PV modules and 9 m interspaces between arrays. Solar PV modules were installed on fixed MS iron angle structure facing perpendicular to south and inclination of 26 at both the sites. The schematic diagram of the PV based electricity generation from the installed AVS and its supply to grid is depicted in Fig. 3.

Cropping options in AVS

PV-module are installed in AVS at an inclination angle equal to the latitude of the place of installation. Thus, shade of PV-module is generated at leeward side on ground surface 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. The interspace area between two PV arrays may be utilized to grow suitable crops. Moreover, area below the PV module can also be used to grow crops since PV modules are fixed over mounting structure at a certain height from ground surface. However, growing crops under shade requires selection of suitable crops which have certain degree of shade tolerance. The shaded portion at interspace area varies from morning to evening as per zenith angle and azimuth angle of sun's position. Therefore, the available amount of solar irradiation and photosynthetically active radiation both under direct (open

Table 1. Agri-voltaic system (AVS) for crop production and photovoltaic-based electricity generation from a single land unit of 1 ha land

Item	Value
Dimension of solar PV module of 250 W_p capacity; W_p stands for peak wattage capacity at standard condition (1 atm pressure, 25°C ambient temp and 1000 W m^{-2} solar irradiance)	~100 cm ´ 165 cm
Diurnal variation of solar irradiance	Reaches its peak of 700-900 W m^{-2} during 12:00-1:00 PM
Annual average availability of solar radiation in India	~5.6 kWh m^{-2} day^{-1}
Annual average availability of solar radiation at Jodhpur	~6.0 kWh m^{-2} day^{-1}
Inclination of solar PV module	Latitude of the place of installation (26° at Jodhpur)
Area for 1 MW_p (~1000 kW_p) installation including accessory space for roads, inverter etc.	2 ha
Maximum capacity of solar PV module installation in 1 ha land	0.5 MW_p (500 kW_p)
Average effective availability of solar radiation in hours per day for electricity generation in India	3-5 hrs
Average effective availability of solar radiation in hours per day for electricity generation at Jodhpur	4 hrs
Electricity generation per day per kWp installation at Jodhpur	1 kW ´4hrs = 4 kWh or 4 unit
Electricity generation from 1 ha land at Jodhpur (500 kW ´ 4 kWh/kW/day)	2000 kWh/day
PV generated electricity tariff	₹ 5/kWh
Approximate annual income from PV generated electricity in 1 ha at Jodhpur (2000 kWh/day´‘ 5/kWh´300 effective days in a year at Jodhpur)	₹ 30 lakhs
Cost for establishment of PV plants in 1 ha = Rs.2.5 crores	₹ 200-250 lakhs
Interspace and below panel area for cultivation in agrivoltaic system	49% interspace and 24% below panel
Potential amount of rainwater harvesting from 500 kW agrivoltaic system in 1 ha land at Jodhpur	~7.5 lakh litre
Potential income from crop yield (e.g moong bean-cumin)	₹ 0.5-0.6 lakhs

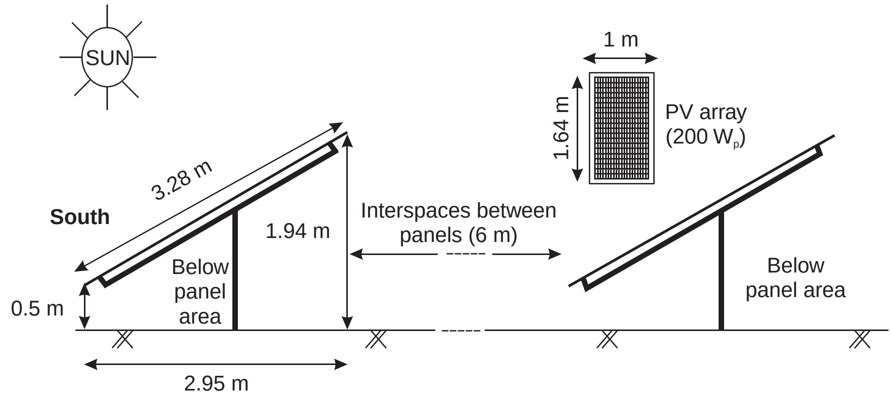

Fig. 2. Design of typical agri-voltaic system.

sun) and diffused conditions governs plant growth. For example, net radiation at Jodhpur during a clear sunny winter days varied from 32.8Wm^{-2} during morning to 328 Wm^{-2} during afternoon under open sun condition whereas under shade it is about 8.2-46.9 Wm^{-2}, which shows that the shade created by PV-module significantly reduced the available net radiation. However, the shade is dynamic following the sun's movement and thus the shaded portion on ground surface does not remain static but changes with time in a day. Available photosynthetically active radiation (PAR) on shaded ground surface was also found significantly lower (84.5 to 127 mmol cm^{-2} s^{-1}) than open sun condition (243-1296 mmol cm^{-2} s^{-1}).

Height of crops is a key parameter for selection of crops for agri-voltaic system because tall-growing crops may create shade on PV-module and thus reduce the PV-based electricity generation. Therefore, crops with low height (preferably shorter than 50 cm) and which tolerates certain degree of shade and require less amount of water are most suitable for AVS. Crops can be cultivated in AVS at interspace areas between PV arrays and at areas below the PV arrays. Area available for cropping purpose changes as per design of the installation. The interspace areas and below PV module areas available for cultivation of crops in a typical agri-voltaic system are about 49% and 24% of the total block area, respectively.

Crops that can be successfully grown in interspaces of the established AVS at Jodhpur during *kharif* include mungbean (*Vigna radiata*), moth bean (*Vigna aconitifolia*) and clusterbean (*Cyamopsis tetragonoloba*) Fig. 4. Apart from these rainfed crops, *isabgol* (*Plantago ovata*), cumin (*Cuminum cyminum*) and chickpea (*Cicer arietinum*) can be grown under irrigated situations during *rabi*. Apart from arable crops, a few medicinal plants of perennial nature e.g. *Aloe vera*, *sonamukhi* (*Cassia angustifolia*) and *sankhpuspi* (*Convolvulus pluricaulis*) can also be grown. For cultivation in below panel areas, few vegetable crops e.g. chilli (*Capsicum annum*), cabbage (*Brassica oleracea* var. *capitata*), onion (*Allium cepa*) and garlic (*Allium sativum*) may be selected. These crops are expected to modify the micro-climates below PV-module in reducing the temperature and thus PV-based electricity generation will be optimum. Moreover, the crop coverage in between PV arrays will also check the erosion of soil and thus will reduce the dust load on PV module.

PV-based electricity generation from agri-voltaic system

At Jodhpur, effective solar irradiation to generate electricity is available for an average of 4 to 5 hr in a day. Therefore, 1 kW PV system is expected to generate 4-5 kWh unit of electricity per day. Thus, 105 kW agri-voltaic system in Jodhpur is capable of generating at least 420 kWh unit of electricity in a clear sunny day. 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 ₹ 5/kWh may be considered to calculate the income from PV-generated electricity.

Rainwater harvesting in AVS

It is possible to collect and store rainwater from the top surface of PV modules in AVS. Therefore, rain-water harvesting system in the developed AVS has also been designed and developed. The water harvesting system consists of rectangular MS sheet water collector channels (Fig. 5), underground water conveying PVC pipes of 4" dia and an underground water storage tank of 1 lakh litre capacity. The stored water is to be used for washing PV panels and to provide supplemental irrigation the crops to be grown in the AVS as well as to clean the

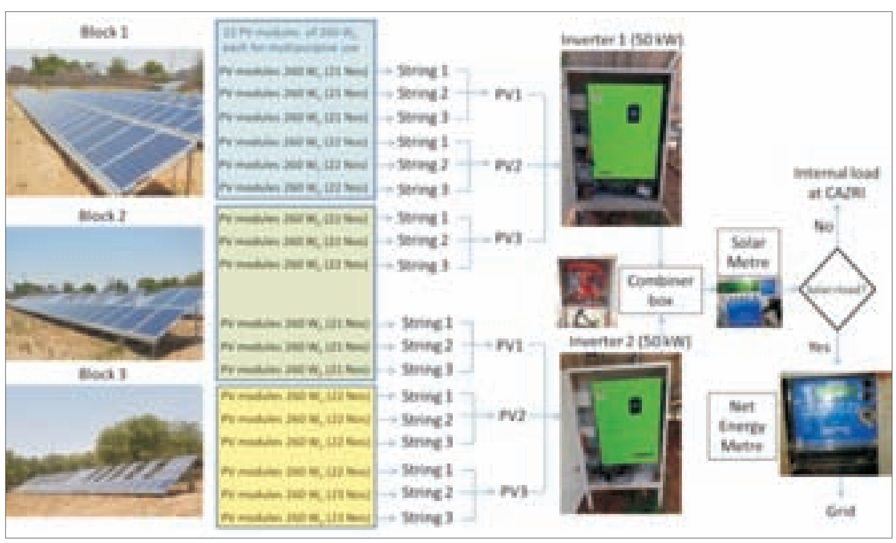

Fig. 3. Schematic diagram of PV based electricity generation in agri-voltaic system and its supply to local grid.

Fig. 4. Crops grown at interspace area of agri-voltaic system

deposited dust from top surface of PV modules.

Surface area of solar PV module of 260 W_p capacity is 1.64 m ₹ 0.992 m and thus, a total surface area of 651 m^2 is available in the developed 105 kW capacity AVS. Considering the splashing loss and water conveyance loss factor, the efficiency of developed rainwater harvesting system is about 70-80%. 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.

Potential economics of AVS

PV modules of AVS has been installed at a price rate of ₹ 49.84 per W_p, thus a cost of ₹ 52,33,200 has been incurred to install 105 kW capacity AVS. Establishing water harvesting system and water storage structure needs additional costs of about ₹ 7 lakhs. Thus the total system cost was about ₹ 60 lakhs at a rate of about ₹ 57,000 per kW of AVS. The income from selling of PV-generated electricity will be about ₹ 7,60,000/- per year considering a minimum generation of 4 kWh unit of electricity per kW system per day and for 300 clear sunny days in a year while average selling price of PV generated electricity is considered as ₹ 5 per kWh. From agricultural activity within the agri-voltaic system, an income of ₹ 8,235/- from *Vigna radiata* (mung bean) during *kharif* and ₹ 23,339/- from *isabgol* during *rabi* can be generated if mungbean-*isabgol* crop rotation is followed. As compared to the income from PV generated electricity, income from agricultural activity is quite less but it has several environmental and societal benefit. For example, cropping activity in AVS will judiciously use the scarce rainwater of arid region, it will control soil erosion through wind action and thus reduce the dust load on PV-module, improvement of microclimate surrounding the PV-module and thus helps in optimum generation of electricity from PV module, and finally the land equivalent ratio (LER) will be improved. The breakeven period of AVS is roughly calculated as 9 to 10 years. Whereas the life-cycle period of PV module is 25 years with efficiency of not less than 90% at the end of 10th years, not less than 80% at the end of 20 years and not less than 75% at the end of life cycle. Therefore, installation of agri-voltaic system may be viable option for future specifically in arid regions of the country.

Fig. 5 Rain water harvesting system from top surface of PV module

SUMMARY

Agri-voltaic system is designed and developed at Central Arid Zone Research Institute, Jodhpur through which electricity can be generated, crops can be cultivated at interspace area and rainwater can be harvested from top surface of PV-module. About 49% land area of a solar PV-installation system can be used to cultivate crops, which is otherwise left as fallow. Few of the selected crops are mungbean, mothbean, clusterbean, isabgol, cumin, and chickpea. Apart from these, medicinal plants e.g. *Aloe vera*, sonamukhi, sankhpuspi etc. can be grown. All these crops are generally low height crops and require less amount of water and thus are suitable for AVS. Apart from crop production, about 1,50,000 litre of rainwater on one acre can be harvested. The stored water can be used as supplemental irrigation to crops during *rabi*. Annual income from PV generated electricity has been estimated as ₹ 7,00,000 per acre, whereas cost involved for installation of such system is ₹ 55,00,000 and thus the breakeven period of the system is about 9-10 years.

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