Agri-voltaics or Solar farming: the Concept of Integrating Solar PV Based Electricity Generation and Crop Production in a Single Land use System

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Abstract- In view of future requirement of both energy and food, agri-voltaic system (AVS) has been proposed as a “mixed systems associating solar panels and crop at the same time on the same land area”. Considering the available land area between PV rows and wash out water from PV panels along with harvested rainwater from panel, few crops which can be grown in agri-voltaic system were screened based on their height, water requirement and shade tolerance characteristics. However, for future establishment of agri-voltaic system in India, performance of crops at different agro-climatic zones needs to be carried out through field experimentation.

Keywords Agri-voltaic system; PV based electricity generation; Food production; Land productivity; Renewable energy.

1. Introduction

Energy and food are the two main requirements for human civilization; however the demands for these two resources are increasing with a fast rate. Fossil fuels are being exhausted rapidly and sometimes energy from biomass is claimed to be a possible substitute to fossil fuel. However, the 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 allows running a car for about 18,000 km and it will be about 22,000 km if most efficient transesterification pathway is adopted. Low efficiency of the photosynthetic process of most energy crops which is about 1-3% [1] 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 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 discussed recently in several literatures [2, 3, 4, 5, 6]. It was also reported that in near future energy from biomass is the most likely renewable energy source; however, this source cannot fulfil all the energy requirements [7]. For future, energy from PVsystems seems to have the largest potential, however, implementation requires large amount of land @ 2 ha MW^{-1}. To meet the national solar mission target of 60 GW PV based electricity generation by 2022 in India, total required amount of land is about 1.2 lakh ha or 1,200 sq. km. Future potential of renewable sources for electricity generation in India is reported in Sukhatme [8, 9] and it was estimated that 788.4 TWh electricity can be generated annually from 10,000 sq km area. It is to be noted here that open lands without tree or short bushes are best suitable for PV panel based electricity generation. It has been also observed that demands for energy are increasing for meeting domestic and industrial needs as well as for different agricultural operations e.g. pumping irrigation water, operating post-harvest processing machines etc. Average solar irradiance on horizontal surface in India is about 5.6 $kWhm^{-2}day^{-1}$ and in western Rajasthan it is higher than national average, which is about 6.0 $kWhm^{-2}day^{-1}$. It is therefore pragmatically envisaged in national solar mission of India to produce 100,000 MW grid connected and 2000 MW off-grid solar power by 2022 in three phases. Total 3062 MW grid connected solar power plants have already been installed in the country till December, 2014, whereas, cumulatively 227.12 MW off-grid SPV generations have been achieved including 19501 solar PV pumps of 2200 or 3000 W_p capacity, decentralized systems, solar lighting etc. Keeping in mind the future demand of energy as well as food and the requirement of land for it as mentioned above, the concept of integrating them in a single land use are being discussed recently. In this paper, the potential of food production by growing crops in land areas between PV arrays in solar PV installation site is discussed.

2. Solar PV based Electricity Generation: Requirement of Land and Water

Solar PV panels are generally installed at fixed inclination angle equal to latitude of the location for optimum harnessing of solar irradiation throughout the year. Provision may also be kept for change of zenith and azimuth angle of solar PV panel fixture so as to harness greater amount of solar energy considering the diurnal and seasonal variation of solar irradiance, but the cost for installation will be higher. In general, 6-12 m spaces between two rows of PV arrays are kept in conventional solar power plants to avoid shadow of it on next row. Low height mounting structures are now preferred because of low cost involved for it with a space of 6 m between two rows (Fig. 1). Two rows of solar polycrystalline PV module of 200-250 W_p capacity with vertical alignment are suggested in the design. The length of such PV array depends on number of PV modules connected in series. Ground clearance of 0.5 m is kept so that crops grown in between two rows of PV array in field cannot create shade on top of PV modules. Considering above characteristic features of solar PV panels and their requirement for harnessing solar energy, establishment of solar PV power plant requires about 2 ha land area per MW capacity.

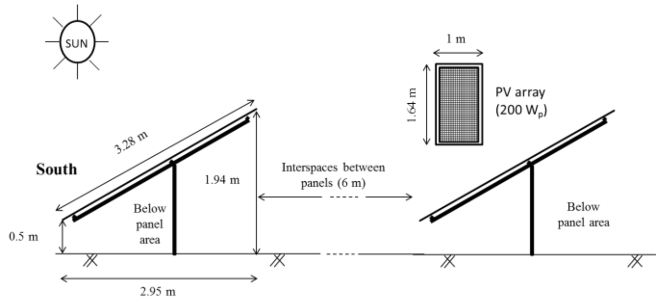

Fig. 1: Basic design of solar PV installation in an agri-voltaic system

Moreover, the problems of dust deposition on solar panels require regular washing with water, which is again a scarce resource in arid region. It was reported in literature that the amount of deposited dust is higher during summer periods in arid region however its effect in reducing PV output is more during winter season because of formation of a sticky dusty layer on PV panel top surface after mixing with dew during night time [10]. From the field observations in a solar power plant at Jodhpur, it was noted that to maintain PV generation at economical level four times cleaning per month is required during summer season and two times during winter, whereas for one time cleaning about 20,000 litre of water is required per 0.5 MW block.

3. Shade Created by Solar PV Panels on Ground Surface and its Variation

Shade of solar panel on ground surface depends on sun's position, which is mainly defined by azimuth angle and zenith angle [11]. Azimuth angle (ϕ) is defined as the angle between a line due south and the shadow cast by a vertical rod on earth (Fig. 2). Solar zenith angle (θ_s) is the angle measured from directly overhead to the geometric centre of the sun's disc (Fig. 2). Solar elevation angle (α_s) is complementary of zenith angle, which can be defined as the angle between the horizon and the centre of the sun's disc. If we write θ_s for the solar zenith angle, then the solar elevation angle $\alpha_s = 90°–\theta s$. Graphical representation of solar azimuth, zenith and elevation angle is illustrated in Fig. 2.

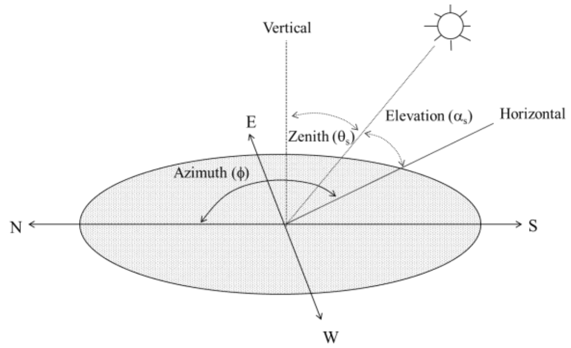

Fig. 2: Schematic diagram of solar azimuth and zenith angle

Solar zenith angle and azimuth angle can be calculated for a particular location and for a particular time in a day using the following set of equations [11, http://pveducation.org/]:

$$\cos\theta_s = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cosh \quad (1)$$

$$\cos\emptyset_s = \frac{\sin\delta \cos\varphi - \cos\delta \sin\varphi \cosh}{\cos\theta_s} \quad (2)$$

$$\delta = 23.45 \sin(B) \quad (3)$$

$$B = \frac{360}{365}(d - 81) \quad (4)$$

$$h = 15(\text{LST} - 12) \quad (5)$$

$$\text{LST} = \text{LT} + \frac{\text{TC}}{60} \quad (6)$$

$$\text{TC} = 4(\text{Longitude} - \text{LSTM}) + \text{EoT} \quad (7)$$

$$\text{LSTM} = 15\ \Delta\text{GMT} \quad (8)$$

$$\text{EoT} = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B \quad (9)$$

Where, θ_s is solar zenith angle, φ is latitude of location, δ is the solar declination, h is the hour angle at local solar time indicating the angular motion of sun which is 0° at noon whereas negative during morning and positive during afternoon, ϕ is the solar azimuth angle, B is a factor which corrects the ecentricity of earth's orbit and earth's axial tilt, d is the Julian day in a year by representing its value from 1 and 365 at 1st January and 31st December, respectively, LST is the local solar time, LT is the local time, TC is the time correction factor in minutes which accounts for the variation of LST within a time zone, LSTM is the local standard time meridian, ΔGMT is the time difference with Greenich Mean Time in hour, EoT is the equation of time in minutes. LST and LT as mentioned earlier are different in the sense that at twelve noon LST the sun is highest in the sky but the LT is different than LST because of ecentricity of earth's orbit, time zones and daylight saving etc. EoT is an empirical equation that corrects the ecentricity of earth's orbit and earth's axial tilt.

Following the above equations, variation of solar zenith angle and azimuth angle throughout the year can be quantified for any location. Here, θ_s and ϕ were calculated for Jodhpur for which geographic coordinates are 73°E and 26.2°N. From solar elevation angle, length of shade created by solar PV array in a field can be calculated by the following equation:

$$D' = \frac{z}{\tan \alpha} \quad (10)$$

Where D′ is the maximum shade length for a particular solar elevation angle α and z is the height of PV array. Height of PV array can be calculated from tilting angle ψ using z = x sinψ, where x is the width of the PV array. If two lines of PV panel each of 200 W_p capacity and having dimension of 1.64 m × 1 m is used in a PV array then total width of the PV array is 3.28 m.

Maximum length of shade created by above set of PV arrays during different times in a year at Jodhpur is plotted in Fig. 3. During vernal equinox and autumnal equinox on 22 March and 23 September, respectively, the length of shade varies from 1 to 6 m with its minimum value during 12:00-14:00 hr. During summer solstice, when sun lies at top of 23.5°N, maximum shade length will be 4 m during morning 8:00 hr and almost negligible during noon time. Maximum shade length in a year is observed during winter solstice and it is ~ 6 m during morning and late afternoon hours. For designing the PV array installation in northern hemisphere, maximum shade length on 22 December is considered as a critical parameter to decide the separation distance between two PV arrays.

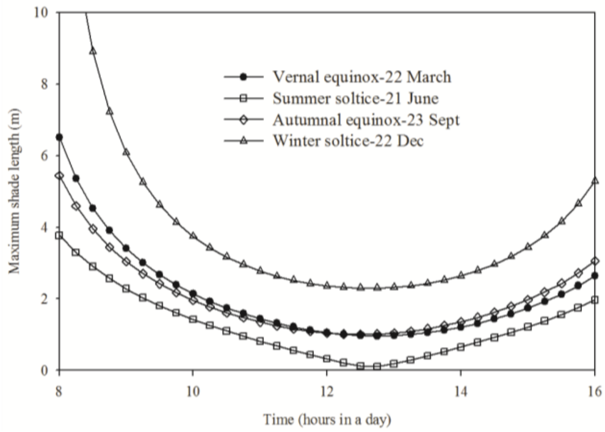

Fig. 3: Variation of maximum shade length created by PV array in a day during different time of a year at Jodhpur (PV array height: 1.94 m)

Spatial coverage of shade on ground surface in X-Y plane can be calculated from D′ by correcting it with azimuth angle as follows:

$$D_x = D' \sin\ (180 - \emptyset) \quad (11)$$

$$D_y = D' \cos(180 - \emptyset) \quad (12)$$

Where D_x is the horizontal distance of shade edge from PV array at X-direction and D_y is the perpendicular distance of shade edge from PV array. Spatial distribution of shade during different times in a day on 22 December is presented in Fig. 4. In the figure, solid dark line at middle of x-axis represents the PV array of 10 m length. The length of PV array is aligned with east-west direction which is represented by x-axis. Top surface of PV modules is inclined towards south with an inclination angle of 26° therefore, y-axis represents the south-north direction. It is observed that if two PV array rows are installed 6 m apart, about 25-30% area near PV array is always covered by shade, whereas a portion is covered by partial shade and rest is not shaded at all.

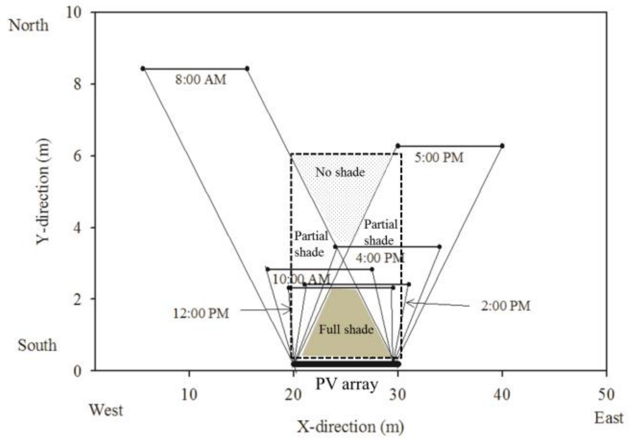

Fig. 4: Shaded portion in land areas between two PV arrays during different time in a day on winter solstice (22 December) at Jodhpur (PV array height: 1.94 m); dotted rectangle represents the area between two rows of PV array

4. Solar Farming

Agri-voltaic land utilisation system: In view of the future requirement of energy and food production, agri-voltaic systems (AVS) were proposed by Dupraz et al. [12], which is defined as "mixed systems associating solar panels and crop at the same time on the same land area". By adopting such system in agricultural land, farmers can generate income from their land through sale of PV generated electricity along with the crop production. Even in case of total crop failure during drought or aberrant weather events which is frequent in arid region, the income from PV system is ensured. Therefore, the solar farming system may be effective approach of mitigating climate change and drought in fragile arid lands. However, long before this, the concept of producing energy and food from a single piece of land was coined by Goetzberger and Zastrow [13] and Kuemmel et al., [14]. Goetzberger and Zastrow [13] proposed a configuration of solar photovoltaic power plant, which allows for additional agricultural use of the land. They proposed that if the collectors are not installed directly on the ground, but are elevated by about 2 m above the ground with the periodic distance between collector rows of about three times the height of the collectors, one achieves nearly uniform radiation, on the ground of a value of about two-thirds of the global radiation without solar collectors. Kuemmel et al., [14] proposed an integrated agricultural system with the goal of neutralizing the energy-related CO_2 emissions from agriculture by substituting fossil with biofuel energy produced on mandatory set-aside areas, which was further demonstrated as economically viable both from a farmer's point of view and from a social point of view.

Feasibility of agri-voltaic system in terms of radiation use efficiency, shade effect on crops and water flows in soil-crop system etc. was experimentally tested in European conditions by Marrou et al., [15, 16, 17]. Use of PV panels in greenhouse and the effect of its shade on crop productivity were also tested at different conditions [18, 19, 20]. Recently, semi-transparent organic PV panel was reported as a unique solution for greenhouse cultivation by Emmott et al., [21]. Brudermann et al. [22] analysed to identify the success factors, incentives, barriers and challenges in the adoption process of photovoltaics (PV) in the agricultural sector, with particular focus placed on decision making of individual farmers and network effects.

Solar PV pumping cooperative systems: Decentralized small PV power plants may be collectively installed at agricultural field to supply electricity for cluster of pumps (~10-15 farmers) in nearby areas. A cooperative model may be developed comprising benefited farmers for this purpose. Apart from this, use of solar PV pumping systems on individual basis are also required to be promoted by optimizing the land, water and energy productivity using advanced technologies of solar PV operated protected cultivation. This will enhance the energy security at agricultural farms alongside food security.

5. Crop Production Options in Agri-voltaic System

There is an availability of partially shaded space and recurrently available washout water in solar PV power plants, which can both be harnessed for growing crops in agri-voltaic system. Ideally, crops for these sites should be such that it is not tall, preferably perennial (life cycle is more than a year), spreading, and do not interfere in any way with the functional efficiency of solar power plant. In arid zone, partial or full shading (see Fig. 3) actually serves as a boon by stopping evaporation of water as well as reducing transpiration losses. Height and spacing of the panels may also be adjusted to grow different type of crops in an agri-voltaic system. Even, agri-PV parks may be developed in hot arid and semi-arid Indian situation depending on land capability class (LCC).

PV panel water wash will require to be harvested in suitably designed slopes as catchments with plastic or other sealed surface. Such water can be ponded, recycled and distributed through drips for irrigation purpose. Based on field performance, crop height and water requirement, few crops and vegetables are screened as suitable for cultivation in agri-voltaic system. Selected annual crops require less than 200-250 mm water in their life cycle so that available scare water through rainfall, which is about 285 mm annually at the region, may be used for growing these crops by efficient water harvestung system. Maximum height of these crops during its peak vegetative growth stage does not cross 0.75 m height so that the crop shade on PV modules may be avoided. Few of the selected crops and vegetables are also shade loving or tolerate shade too some extent. Here, few selected crops and vegetables are mentioned, which can be grown in an agri-voltaic system. Following spice crops may be successfully grown in blank spaces between two PV rows since they are short height in nature e.g. *Coriandrum sativum* Linn. (coriander or 'dhania'), *Anethum graveolens* (dill), *Trigonella foenum-graecum* Linn.('methi'), *Plantago* *ovata* Forsk. ('isabgol'), *Foeniculum vulgare* Mill. (fennel or 'saunf') etc. Following vegetable crops also have the potential to grow in an agri-voltaic system e.g. *Cyamopsis tetragonoloba* (l.) Taub. (clusterbean or 'guar'), *Brassica oleracea* var. botrytis (cauliflower), *Brassica oleracea* var. capitate (cabbage), *Pisum sativum* Linn., (pea), *Allium cepa* Linn. (onion), *Allium sativum* (garlic), *Vigna unguiculata* (Linn.) Walp. (Cowpea), *Capsicum annum* Linn.(chilli) etc.

Land area below PV panels may also be exploited to grow vegetable crops of family Cucurbitaceae e.g. *Cucurbita pepo* Linn.('kakri'), *Cucumis callosus* (Rottl.) Cong. ('kachri'), *Luffa acutangula* Linn. (ridged gourd), *Lagenaria siceraria* ('lauki'), *Citrullus fistulosus* Stocks.('tinda'), *Citrullus lanatus* (Thunb.) Matsumara & Nakai ('matira'), *Momordica charantia* Linn.(Karela), *Momordica dioica* Roxb.ex Willd. ('kankero') etc. Cultivating crops in areas below PV panel has the additional advantage of reducing heat load on bottom surface of solar PV panel by modifying the microclimatic conditions and thus helps in generating optimum electric output.

Medicinal plants can also be the potential crops if the PV plant is located on rocky scrubs or degraded lands e.g. *Cassia angustifolia* (senna), *Convolvulus microphyllus* Sieb.ex Spreng., (shankhpushpi), *Aloe vera* ('gwarpatha'), *Withania somnifera* (Linn.) Dunal (ashwa gandha), *Barleria acanthoides* Vahl.('vazradanti'), etc.

In order to reduce the dust settling on solar panels, there is also a need to develop shelter belts of suitable plant species of that height which do not interfere solar irradiance on PV panel surface. Fruit trees e.g. *Ziziphus sp*. ('ber'), *Cordia myxa* ('gonda'), *Carisa carandas* ('karonda'), *Ficus carica* (fig) can be used as component plants in tree belt. Those solar PV plant sites located in areas having LCC VI-VIII and unfit for agriculture can become ideal sites for ex-situ conservation of threatened plant species of the region.

6. Conclusion

Agri-voltaic system is the future land use system from where both food and energy can be produced. In this paper, different options for an agri-voltaic system in hot arid western India have been discussed which may be different for other agro-ecological regions of the country. Moreover, suitable crops for agri-voltaic system suggested here is applicable for arid western India and hence for other regions different crops need to be identified as per prevailing rainfall and weather conditions. Lastly, performance of the selected crops under shade condition needs to be experimentally tested under field conditions. Therefore, there is a need for research work to develop parameters and management options for future establishment of agri-voltaic system in India.

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