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Solar parks: A review on impacts, mitigation mechanism through agrivoltaics and techno-economic analysis

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ABSTRACT

Solar parks are mega solar projects to fast track renewable energy integration, while avoiding redundancy in electro-mechnical infrastruturing and land acquiring procedures. However these ground-mounted grid-integrated solar photovoltaic projects require vast land banks, which remain covered for the lifetime of the project.. The socio-economic and environmental externalities on at micro level affecting livelihoods often go unaccounted. Earlier works on impact assessment of large solar parks have considered environment, ecology, micro-climate at large while impact on livelihoods and long term externalities on socitial issues were not addressed. The effectivnes of agrivolticas as a mitigation mechanism was primarlity focused on type of crops vis-à-vis height of structures, water management and economic outputs. The current work has a reviewed agrivoltaic projects in India and identified the managaement practices, constraints, cost econmoics and policy framework. A review of works done on solar park impact assessment and mitigation mechanism by agrivoltaics are done in detail. The work has considered agrivoltaics from a social aspect and focused on impacts due to loss of livelihoods and associated externalities under social impact classification. A methodology in which agrivoltaics is taken as a self healing mechanism to environment and society is adopted. A conventional solar plant and an agrivoltaic plant are considered for study and three livelihood mechanisms namely medicinal plants, poultry and bee keeping are considered for techno-commecrcial analysis. It is found that while the medicinal plants in PV plants can improve the income by 8%, while poultry in solar parks bring additional income of 83%, considering one lifecycle, while bee keeping bring additional income of 4%. The economic analysis shows that agrivoltaic without workable business models for a captive power plant with 0.14$/kWh FiT breakeven at 3 years and 9 months while a captive plant with the same FiT without agrivoltaics breaks even in 2 years and 4 months. A captive plant with 0.14 $/kWh FiT with a workable business model will breakeven in 3 years and 3 months. A grid tied solar PV plants with a FiT of 0.03 $/kWh which has a breakeven of 13 years without agrivoltaics, may not breakeven within 25 years (plant life) without a workable business model. However, with a workable business model for agrivoltaics the grid tied solar PV plant with a FiT of 0.03 $/kWh will have a breakeven in 17 years and 8 months.

The social impact assessment conclude that, livelihood impacts can lead to extinction of cultures, urban migrations, growth of uncontrolled peri-urban regions, the long term impacts are beyond economics. Thus social impact mitigation cost (SIMC) along with environemental impact mitigation cost (EIMC) are considered as incentives or subsidied and the levelised cost of energy (LCOE) is calculated. It is found that levelised cost of energy for the conventional ground mounted solar PV plant is 0.03 $/kWh while for agrivoltaic plant without subsidies and incentives the LCOE is 0.052 $/kWh. For the agrivoltaic plant with a subsidy of 30% the LCOE is 0.046 $/kWh and with a further green incentive billing the LCOE can be brought down to 0.041 $/ kWh.

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Introduction

Energy is the primary demand to meet rural-urban divergence in an increasing population scenario for a growing economy. Global commitments to mitigate climate change externalities require substantial renewable energy share in the energy resource pool [1]. Ease of installation, technology readiness level (TRL) and plant load factor (PLF) make solar photovoltaics is an easy substitute compared to other renewable energy sources [2]. Agriculture is an energy-intensive industry and is the mainstay of economy in the Indian economic scenario for decades. Erratic climatic cycles, globalization and urbanization have made at least some farmer community to move away to alternate livelihood options [3]. Climate change reduces agricultural productivity while demands larger renewable energy share in energy basket. Thus productive fertile land banks is the key to meet food demand for increased population, while large patches of land need be covered for solar plant lifetime leading to an inherent energy-food-land nexus [4]. Solar parks are solar PV plants where multiple developers put up plants under a common infrastructure development facilitated either by state/central Government in order to avoid redundancy in utility infrastructure [5]. Ultra mega solar parks are in capacities of GW's, while mega solar parks are in capacities of 500 MW and above, while huge patches of land has to be found out that can be used for a period of three decades to promote the scheme of solar parks. Land topography, soil characteristics, geographical location, population demographics, distance to grid infrastructure and availability of water resources are influencing parameters for capital and operation expenses [4]. The solar irradiation, sun hours, wind characteristics and annual rainfall are ruling parameters without compromise. There is a policy by Ministry of new and renewable energy (MNRE) promoting use of fallow, barren and unproductive land for large scale solar parks through viability gap funding (VGF) and generation based incentives (GBI) [6,7]. However the development cost and energy competitive market but agricultural land which are plain and available in large patches, with a proximity to the nearest town are luring for developers. The mandate to use barren land or unutilised land for large solar parks increase the cost of structures for the panels to have maximum efficiency and to provide required angle of tilt [7]. In a competitive energy market, in race with wind energy anywhere timelines to increase the renewable share in the grid are important, agricultural lands have an upper hand. The changing climatic patterns, globalization and urban ingression lure the farmers to give away land for large scale solar projects, often for onetime benefit or annual benefit through lease. While solar parks are an easy method to promote large scale renewable energy in the energy pool, the land coverage for the period of three decades affect the environmental, social and regional climatic patterns, Studies in this regard have been conducted by various researchers, but in-depth analysis on social impacts affecting livelihoods, migration and extinction of rural life have not been done analysed [8]. Agrivoltaics a method to integrate agriculture in solar parks is investigated at research level, leading to pilot plants and a few commercial plants [9,10]. Studies by Pascaris [11] through an extensive survey of developers, policy makers' and local community concluded that while complexity of structures in agrivoltaics is a concern, the environmental benefits and additional income are attractive. The State and Central Governments, the solar developers and the farmers are the key stake holders, while the policy and regulatory framework should address two interdisciplinary sectors, the energy and the agriculture [11]. Terrapon-Pfaffa [8] and Corona [12] has considered the social impacts of the large scale CSP plants in Spain and Morocco, while the later has done specifically on the impact on livelihoods. To arrive at the overall outcome of the large scale solar projects the study should focus beyond economic and ecological studies and focus on detailed social impact analysis (SIA) [13,14]. The rural-urban migration in China during industrial revolution has brought many villages empty, extinction of livelihoods and unstructured growth of urban areas with large scale peri-urban regions with an economic divide. The decision makers in such migration process are the new generation affecting life expectancy, declining population and adapting to unproductive newer livelihood mechanisms [15]. Terrapon-Pfaffa [8] suggests that though renewable energy projects are supposed to bring positive impacts, the actual outcome at local micro level is different. Renewable energy integration with agrivoltaics has the potential to bring positive impacts to socio-economics and environment at local community level while curtail CO_2 reduction to meet global commitments at macro level [16–19].

The present work reviews the work done on agrivoltaics in Indian solar plants, the impact analysis due to solar parks from the environmental, social and microclimate aspects and the existing policies and regulatory mechanisms favoring land usage. The impacts due to social impact analysis (SIA) are looked into detail and the option of agrivoltaics as a mitigation mechanism is explored. The impact on capital and operational expenses are identified. The work also looks into technical viability, economic feasibility and managerial methods to integrate selected livelihood mechanisms, namely medicinal plant vegetation, poultry and bee keeping. A 1 MW solar plant is considered for experimentation analysis to integrate with medicinal plant and poultry for which the cost of generation, breakeven analysis, and levelised cost of energy are identified To make the LCOE more enterprising the cost of mitigation of externalities of concerned with EIA and SIA are considered as a cost component.

Agrivoltaics in India

The agrivoltaics in India have had positive impacts in many carefully designed plants, while in some cases it did not have any positive impact, but has never come across an adverse negative impact, with growing vegetables while major crops like rice and wheat are yet to be tried [9,10]. Stakeholders are keen to work on practical business models for which firm technology, policy and regulatory measures are most important. The outcomes from the pilot studies can be scaled up only through research to finalize location based crops, selection of infrastructure and benefits beyond produce from agrivoltaics [20]. The agrivoltaic solar plants in India are installed as commercial, research or on pilot basis. The list of agrivoltaic plants in India, with the type of soil, agriculture aspects, water management, productivity and challenges are mentioned in Table 1.

It is found that the focus was to select the right crop based on the soil through experimentation in the available space between the arrays and underneath the panels. However, studies on agrivoltaics as a mitigation mechanism to retain the topsoil, increase ground water retention, reduce micro climate changes and increase efficiency of panels were not focused. Experimental studies on the impact on society, through loss of livelihood mechanism, migration to urban areas, productivity of rural areas and growth of peri-urban areas are not included. Recent trends in AI and ML can predict the productivity, irrigation method, water usage, underground water retention and adverse implications based on soil characteristics and climatic conditions. Research work by Khanali [21] has done eco-exergo environmental analysis to find the best irrigation method for sunflower growth with emphasis on water minimization while to keep best practices for environment. Ghasemi-Mobtaker [22] has done a modelling for wheat cultivation to predict economic profit based on climatic pattern during the lifetime of the crop. Studies by Moosavi-Nezhad [23] with water melon seedlings with artificial controlled environment predicted the energy and economic outputs. Saeidi [24] has done modelling to predict the growth of saffron in a controlled environment. Studies by Malka [25] and Alhejji [26] on models created for possibilities of energy harvesting through proper management in the reference region has optimised the use of water and resources to gain maximum economic output keeping the environment balance in the controlled experimental reference area. Thus the modelling of a solar farm with suitable crop beforehand and using prediction methods could help in deciding the feed-in-tariff beforehand and arriving at better business models.

Table 1
Agrivoltaic plants in India with outcome, water management and challenges.

Plant Location (C/R)	Capacity &Year	Structure Height (m)	Agriculture aspects /Land utilisation	Crops	Outcome	Water Management	Challenge
Amrol, GIPCL (C)	1 MW, 2016	3 m	Loamy sand, which require irrigation. Interspace and overhead hybrid cultivation practice.	Groundnut, soybean, chickpea, vegetables -, sesame, fodder, black gram	Not Published	Bore well and drip irrigation	Tractors to move in between and to reach below the panels
Sikka, GSECL (C)	1 MW, 2016	3 m	Sandy, Gritty soil, which require ploughing once a year. Interspace cultivation practice.	Lady fingers, bottle gourd, coriander, beans - Tomato, cucumber, chilli - Mug, tal	However the effect of shadow not studied.	Public utility network water and drip irrigation	Panel cleaning require 10 people to tilt. Sand on panels damages the flowers. AC cables to be relayed once every year.
Pandhro, GSECL (Commercial)	1 MW, 2016	3 m height	Sandy, Gritty soil. Require ploughing once a year. Interspace cultivation practice.	Brinjal, beans, coriander, ladyfinger, bottle gourd - Pulses: Green gram, sesame,	Different crops tired. Investigation on the prospects of shading not studied.	Public utility network and drip irrigation.	Panel cleaning, AC cables relaying.
Jodhpur, CAZRI (Research)	105 kW, 2017	1.22 m to 2.66 m height. Array distance 3 m to 9 m.	Sandy and loamy. Require irrigation. Interspace and overhead	Bean, Cumin, chickpea - Aloe vera, chilli, cabbage, onion, garlic	Mung bean not affected by shade. Moth bean and Cumin affected by shade. Aloevera grew extremely better in interspace region.	Efficient rain water harvesting system.	Large array interspace allow all possible tilling.
Dayalbagh, DEI (R)	200 kW, 2020	6 m and 19 towers of 50 modules with tracking.	Deep loamy sand with easy ploughing. Interspace and overhead cultivation.	Grams, brinjal, tomato, wheat, spinach, cauliflower, carrot, gourds	There is no difference in productivity due to shadow.	Sewerage treatment plant (STP) water with drip irrigation and retention.	Cables have to be laid below 3 ft.
Sardoi, Solar Agri Electric Model (C)	3 MW, 2012	1.5 m	Rocky soil with not water retention. Cotton fibre used for water retention. Interspace cultivation only.	Water melon, ladies finger, bottle guard.	No study done	Water used for cleaning panel used for irrigation	Limitation due to water availability and height restrictions.
Tandur, Clean solar private limited (C&R)	400 kW, 2016	1.5 m height with tractor way in between arrays.	Loamy soil and sandy soil. Cultivation between the arrays.	Lemon grass	Lemon grass grows abundantly, since no water requirement.	Water used for cleaning panels is used for irrigation.	Limitation of veriety of vegetation.
Jalgaon, Jain Irrigation. (R)	200 kW	Transparent, Building Integrated Photovoltaics (BIPV) with 30 ft height greenhouse	Cultivable cured soil. Greenhouse cultivation.	Banana	Greenhouse effect, prepared soil and additional LED lights produce best results	Rainwater and bore well	Expensive infrastructure
Gurugram, NISE (R)	100 kW, 2018	1.5 m height with large inter array space	Loamy sand. Cultivation between the arrays spacing only.	Vegetables and flowers	Flowers and vegetables have shown no change due to shadow.	Utility water and water used for cleaning	Research study on for vertical bifacial panels to reduce land coverage while increase productivity
Cochin, SIAL (C)	4 MW, 2015	1.5 m with 3 m inter array space.	Loamy sand and clay. Cultivation between the array spacing and overhead	Yam, Mountain Ginger, Guards, Curry leaves, Pumpkin, Drumstick, Small mango trees.	Organic farming have produces 60–80 tomes produce per year.	Water from cleaning and abundant rainfall with water ingress.	Nil
Delhi, Sunmaster (C)	2 MW, 2021	4.3 m structural height	Loamy sand. Cultivation at overhead.	Brinjals, Lettuce, Spinach, Lady Finger, Tomatoes, Bottle Guard, Fenugreek, Coriander, Cucumber	Massive structural height permits different crops and with till-ing/ploughing.	Reuse telescoping cleaning water.	Massive structural height and investment cost in telescopic cleaning.
Dhule, Grosolar (C)	7 MW	1.5 m with 3 m interspacing	Loamy sand. Cultivation between the arrays and overhead.	Geranium, Guava, Lemongrass	Rearing of sheep at overheads.	Cleaning water and bore well.	Low height allows grass for rearing of sheep.

adapted from [9,10].

Impact due to land usage for solar parks and possibility of agrivoltaics as a mitigation mechanism

Acquiring big land banks for solar parks can displace men and resources, affecting the livelihood activities of the villages [7], change in land use pattern, loss of topsoil due to erosion, contamination of soil, removal of natural vegetation cover, fragmentation of existing faunal habitats, displacement of manpower & livelihood mechanism and solar PV heat islands are few common impacts due to ultra-mega solar PV power projects [27] The below sessions go through the work done by various researchers on impacts of solar parks in detail under various headings and the work done on mitigation mechanisms.

Environmental impacts of solar parks and agrivoltaics

The expansion of solar parks will curtail the carbon absorption properties of soil, control the emission of greenhouse gases, and regulate the type of species that can grow in the new environment [27], Studies by Trumbore [28] show that land-use change pattern affects the carbon stocks and soil respiration rates, also called soil CO_2 efflux. Vasconcelos [29] point out that soil respiration is influenced by temperature, moisture, vegetation type, and substrate availability. Recent studies have focused on the agri-electric model solar farm as a clean development mechanism, to find CO_2 absorption and the use of biomass residue for power [30] Farming at the PV plant site reduces the desertification process of land, as it increases vegetation cover over the area and it also reduces dust emissions [31]Vegetation reduces the soil erosion process thus improving the water retention capacity of the soil in the surrounding area [32]. According to Machnick [27] solar technologies can be compatible with harvestable crops by modifying panel height and spacing between the panels. Studies done by Santra [33], Patel [34]), Ravi [31] and Harinarayan [35] show that integrating agriculture into mega-scale solar PV power plants is possible by optimizing space and careful selection of crops. According to Patel [34] integrated agriculture practices give a good yield of the crops and generate agricultural residues that can be used for making organic manure through the decomposition process. The crop selection, height of the structures, tilt angle optimization, solar irradiation, soil quality, and climatic patterns play a major role in the success of the agrivoltaic systems [36]. In general, for ground-mounted solar power plants in India, the modules are mounted on metal frames with an average height of 1 m at the tail and 1.75 m at the mouth of the solar arrays, depending on the latitude-longitude. The support of frames for module mounting structures takes less than 5% of the land area [37] and the remaining 95% of the area remains unused, the potential for various activities for a lifespan of 25 years of the solar PV plant. Both research studies and commercial agricultural operations demonstrate that solar technologies can be compatible with harvestable crops by modifying panel height and spacing such that harvestable crops can thrive between them [27]. The studies by Macknick [27] focused on the benefits of integrating agriculture and solar PV from the perspectives of vegetation-centric, energy-centric, and vegetation-energy-centric integrations. The first trials of agrivoltaics done on an experimental basis in France in the year 2010, had structures raised to 4 m and has proven successful, which led to research publications on vegetation to a microclimate. Research done by Fraunhofer University on 3 hectares of solar PV land with 5 m raised structures in 2016 has considered economic benefits and social acceptance [38]. A few research pilot projects are done in India in the recent past in which research is underway to decide the most suitable crop [39] Studies done in Malaysia to grow spinach and aloevera amongst ground-mounted solar panels have shown a higher yield with a temperature reduction of 0.85% to increase annual electricity yield by 2.8%. The studies in India have identified the soil type in existing solar farms and suggested a few crops that are possible to integrate, though the results on the potential of yield is not mentioned [39]. Studies in Japan on various potential crops for agrivoltaics have shown a 15% conversion rate in wheat and an 89% conversion rate in growing ginger. Tuberous crops have predominantly succeeded in agrivoltaic farming [40]

Solar parks and microclimate, mitigation through agrivoltaics

Studies on solar park in UK [41] has shown negative impacts on temperature difference, humidity, biomass species and diversity under the solar panels, which require careful design of solar parks. Barron-Gafford [42] analysed that the temperature below the panels in the arid and semi-arid regions, which are mostly selected for solar parks were always 3–4 °C higher than the surroundings during the night time. Solar panels induce regional cooling by converting incoming solar energy to electricity, however the conversion of this electricity to heat compensate the cooling effect especially in urban areas which increases regional and global temperatures, which thus require careful design considerations [43]. Nguyen [44] investigated the effect of large solar farms across Australia through sensitivity analysis and indicates that the surface temperature will increase by 10 °C, while rainfall can reduce by 30–70%, which will require careful considerations. Haider [45] indicate that radiative balance at the surface atmosphere interface can occur due to large-scale PV deployments and can exert certain impacts on the temperature and flow fields. According to Weselek [46] agrivoltaics with potato and wheat under panels and with reference comparison have shown that photosynthetic active radiation is reduced by 30%, while there is a difference between the productivity under the panels and the reference. There is a difference in soil temperature under the panels during the summer along with changes in rain pattern and atmospheric temperature. Van de Ven [47] in studies suggest that a renewable energy mix of 50% in electricity can occupy 5% of the land, the direct and indirect effects causing release of carbon ranging from 0 to 50 gCO2/kWh, Williams [48] investigated the difference in cooling underneath the panels with agrivoltaics at 0.5 m and 4 m height and found that as the height of structure increase, the cooling beneath the panels gets better. Zainali [49] has used the CFD modelling to investigate the temperature under the solar panels and the ground and found that the margin of error is just 0–2% for the panels and 0–1% for the ground respectively. Investigations by Dhivagar$_a$ [50] and Dhivagar$_b$ [51] have shown that the use of heat transfer materials using polymers can be helpful in controlling the heat and can be tried at micro level. Denise [52] have experimented comparison of crop under the panel and the reference and found that productivity increase is better in reference compared to below panels due to better photosynthesis, while the water usage and moisture of soil is better under the panels, thus making the panel area cooler.

Agrivoltaics and levelised cost of electricity (LCOE)

Agrivoltaics in Germany have achieved an LCOE of $0.1 per kWh and suggest that separate tender be called inside policy framework to make agrivoltaics prosper [53] Experiments done on a 650 kW solar plant has found the cost to implement agrivoltaics will be $ 1332/kW, while a ground mounted conventional plant will cost $ 617/kW and a vertical mounted bifacial plant will cost $ 742/kW [54]. The researchers point out that the cost of agrivoltaic will depend on the structure height which again depends on the type of crop and the soil conditions. Economic analysis done on agrivoltaics with bifacial panels in four different scenarios at 1.25 m height fixed tilt, 1.75 m with tracker, 3.75 m fixed tilt and 3.75 m tracker have shown additional cost increase of 80%, 225%, 300% and 375% respectively, while the IRR at fixed intake of 0.045 $/kWh is derived to be 10.5%,12.75%, 11% and 13.5% respectively. The agricultural yield was obtained in the above cases are $ 2182, $ 4908, $ 12,273 and $ 13,636 respectively [55]. This shows that the selection of crop, the investment of structures and policy recommendations for subsidies in agrivoltaics is important. As of now there are no subsidies prevailing in Agrivoltaics, while there are handholding done to prepare detailed project reports and avail subsidies in agriculture sector, largely for farmers who depend on solar energy for pumping. However the detailed question remains the cost of infrastructure and the method of framing workable business model [56].

Social impacts of solar parks and agrivoltaics

The social impact in large scale solar projects is multifold and often unaccounted. However mitigation of such an impact requires best management practices and investment strategy, to avoid negative publicity leading to scrapping of project. Unmanaged social impacts can lead to loss of livelihood, extreme poverty, unrests and potential suicides [57] According Terrapon-Pfaffa [8], the impact on society die to large scale solar projects are often not considered, while the same is complex and based on sourcing of information, benefit distribution, management of collected information and estimating long term impacts. The same can be mitigated by alternate arrangements and inclusion policy rather than infrastructural or physical aspects. Terrapon-Pfaffa [8] has considered social impact and the cost of mitigation of the same in a cradle to grave approach on a new cost calculation method called social levelised cost approach (S-LCA). This was an alternative to the usual economic levelised cost analysis (E-LCA), which often neglects the hidden social impacts and mitigation costs.

Extensive literature review conclude that agrivoltaic research with respect to impact of solar parks were focused on (i) land coverage and associated environmental issues (ii) microclimate changes (iii) economics of agrivoltaics based on crop selection (iv) Design of structures and levelised cost of energy. The studies related to social impact analysis (SIA) due to solar farms with respect to impact on livelihoods, rural-urban migration, development of *peri* urban regions, anarchy of the displaced and loss of productivity of rural regions are not considered in earlier works. . Research and pilot plant on agrivoltaics conclude that (i) The selection of crop, irrigation management and location are key factors for success (ii) Shadowing on crops affect the productivity (iii) The increase in height of the structures allow variation on crops but a concern for developers (iv) The use of solar panels that can transmit light can increase productivity (v) There is a considerable increase in capital and operational expenses with agrivoltaics compares to conventional solar parks

Considering the conclusions from the review on the agrivoltaics a few livelihood mechanisms beyond conventional agriculture which being poultry, bee keeping and medicinal plants are considered for techno-economic analysis.

Techno-economics of livelihood mechanisms in solar parks

This section investigates the possibilities of co-locating medicinal crop vegetation, poultry and bee keeping in solar PV fields.. Considering 5 acres of land can generate 1MW with solar PV panels, an estimated 16.16 lakh units of electricity could be generated in a year at irradiation levels at 5.5 kWh/m^2/day with polycrystalline technology [7,58]. The location considered for experimentation is Jodhpur district, Rajasthan India, having arid climate and lying between 21°17′- 31°12′N and 688–76°20′E. having an average irradiation of 6.11 kWh m-2 day-1. [59].

For the current work, polycrystalline panels of size 2 m x 1 m with a non-tracking fix-mounted system are considered. These panels can generate 160 Wp per square metre, which amounts to 3330 panels for generating 1MW power, with a requirement of an approximate area of 5-acre land for a 15-degree angle of tilt [7,27]. A typical configuration of a connection of panels in series (string), for a solar park design, is shown in Fig. 1. Usually, a group of 20 panels is connected in series, to form a string, which is terminated to an inverter, which converts direct current (DC) to alternate current (AC), before the step-up to the required voltage to integrate with the grid. As a standard practice, the distance between two consecutive strings is kept at 1.8 m, for easy access of men and machinery during the process of cleaning and maintenance [7]. As a standard practice, a tractor or pickup-vehicle access is provided into the deep pockets of the power plant for the movement of men and machinery to assist in cleaning panels.

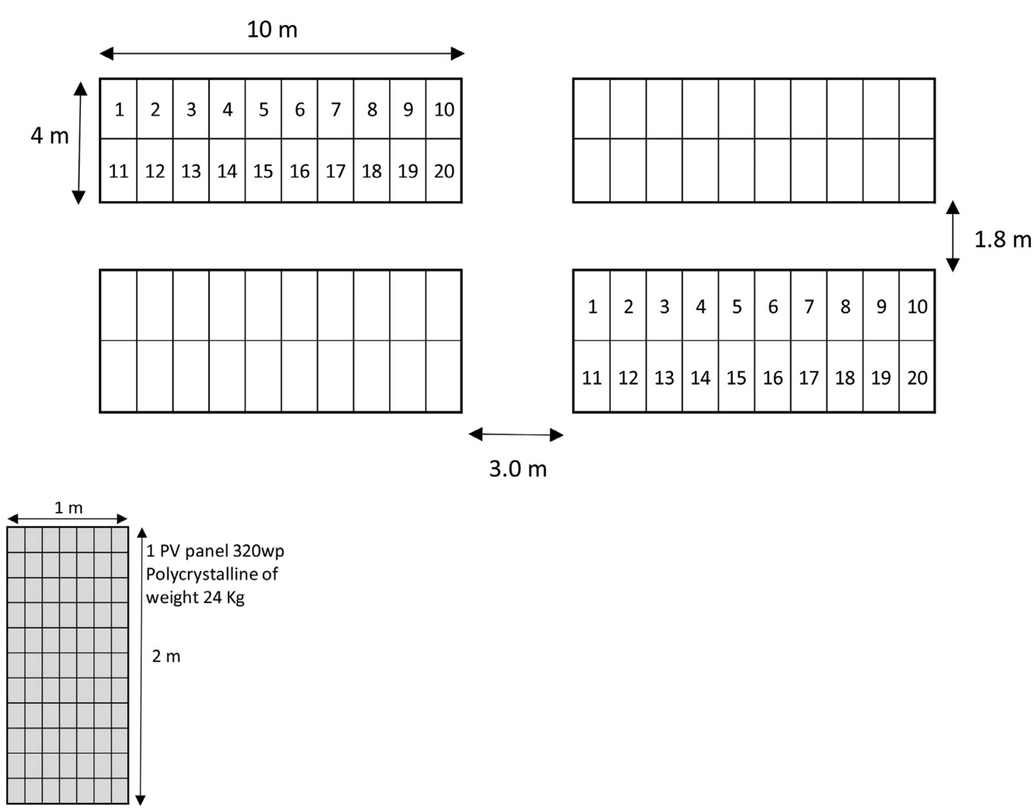

Fig. 1. Typical string layout of a polycrystalline solar panel for a ground mounted solar photovoltaic system [7].

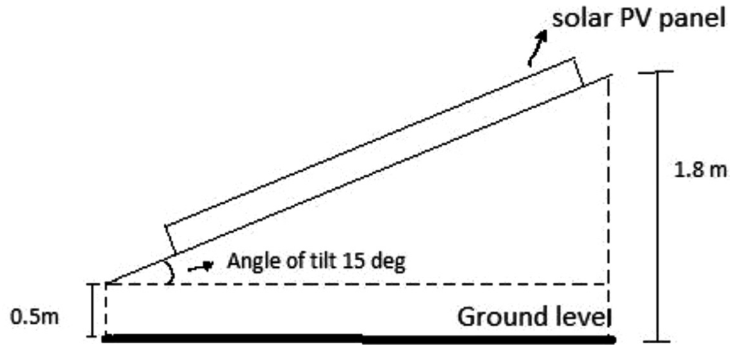

Fig. 2. The standard layout of solar panels at 15° Angle of Tilt.

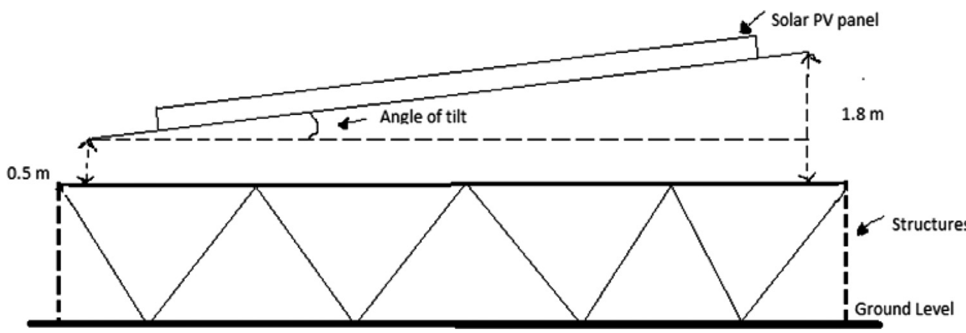

Fig. 3. Solar panels mounted on structures to increase ground clearance.

Table 2
Revenue generated by agriculture in the ground mounted solar PV plant from 1 acre of land.

Crop Name (Medicinal name)	Seasonal Water Requirement (in mm) [a,c,e]	Yield (in tons per acre) [b,d,e]	Revenue Generated ($ in thousands peracre)[a,c,d,]
Mungbean (Vigna radiata),	150 to 450	0.6–1.0	−550–750
Isabgol (Plantago ovata)	200 to 500	0.9–1.5	750–935
Cumin (Cuminum cyminum)	200 to 400	0.5–0.6	250–375

[a] Steduto [61].
[b] [62].
[c] [63].
[d] Madhusudhana [64].
[e] [65].

To collect maximum solar radiation, solar panels must be kept at the correct orientation and slope. Single and dual-axis, solar tracking is used for increasing the panel efficiency; however, the technology is expensive and requires more land area. Non-tracking installations are mounted to land using proper panel mounting structures, on an optimum 'Angle of tilt, to intercept maximum solar irradiation [7]. A typical solar panel mounting is shown in Fig. 2, with 0.5 m ground clearance, at one end with a 15° angle of tilt, leaving a height of 1.8 m ground clearance at the other end.

For the current analysis of integrated agriculture and solar photovoltaics, crops with a maximum height of 1.5 m, are considered with standard mounting structures. In climatic regions, where the selection of crops is constrained by height, additional structures can be introduced, increasing the height of panels from the ground, to accommodate vegetation of a different kind as shown in Fig. 3.

Integrating agriculture and livelihood activities in ground-mounted solar photovoltaic power plants

A feed-in-tariff (FiT) of $0.031 / kWh Saran, [60], with a yearly escalation of 2% on the Feed-in Tariff and a 3% escalation on revenue from agriculture yield is considered for calculations. Rainwater hervesting of 15 lakh litre capacity per year is considerd from the location, used for cleaning of panels and for irrigation [59]. Shade-tolerant vegetation, poultry, and beekeeping are considered potential livelihood mechanisms for integration in solar PV parks. Considering, the wide geographical topography, the actual selection of livelihood activities and crops will depend on solar irradiation, land terrain, soil characteristics, culture, and the climatic zone.

The approximate revenue generated fromland required for 1 MW solar PV land by cultivating different medicinal plants between solar arrayis indicated in Table 2. Mungbean (Vigna radiata), Isabgol (Plantago ovata) and Cumin (Cuminum cyminum)are considered as medicinal plants. The plants are randomly chosen, but every soil and climatic region will have a set of medicinal plants that can grow with little care, but will have a regional or global market.

The comparison of revenue generated from 5 acre of land through the production of solar PV power and integrated medicinal plant in solar PV farms is shown in Fig. 4. The comparison shows that there is a considerable difference in the revenue, which can compensate for additional expenses incurred under the capital and operational heads during the life of the solar plant. If cultivation of conventional crops are done the agricultural residue generated after harvesting can be used as biomass fuel. Biomass can be converted into heat energy through the combustion process since it is considered the most developed process of energy generation from the agricultural residue [67]Crops like groundnut and cotton produce high calorific value residues [68] and therefore are used as main biofuels. The amount of heat energy that can be generated from the agricultural residue of high calorific value tuberous crops from one acre of land is given in Table 3.

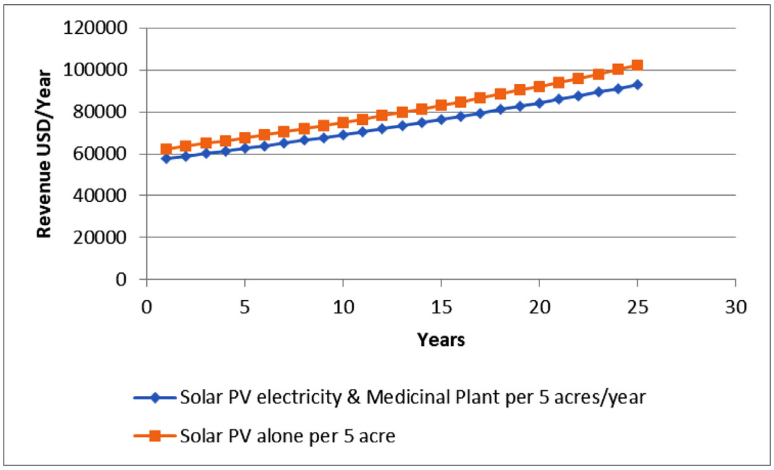

Fig. 4. Comparison of revenue generated in 5 acre of ground mounted solar PV plant and integrated agriculture.

Table 3
Heat energy potential from biomass residues.

Sl. No.	Crop	Residue production per acre(tons)[g]	Calorific value(MJ/kg)[g]	Heat energy (MJ)
1	Soya bean husk	1.4–1.5	19.4	27,160–29,100
2	Wheat straw	0.94–1	17.9	16,826–17,900
3	Cotton stalks	3–3.2	18.2	54,600–58,240
4	Groundnut shells	0.4–0.5	20.74	8296–10,370

[g] [68].

Table 4
Revenue generated in one acre of land from poultry.

Number of hens in 5 acre [h]	Number of eggs produced per hen per year [h]	Average chicken dropping in a month/hen (Kg)[i]	Average Selling Price /Egg ($) [j]	Average Selling Price Poultry manure/kg ($)	Revenue generated by egg and poultry waste production first year ($)
2000	220	5	0.05	0.36	19,023

[h] [69]).
[i] [70].
[j] [71].

Studies related to the integration of poultry into the solar park were undertaken through earlier studies [37]The revenue generated from poultry from 5 acre of land and the effects of integrated solar and poultry are indicated in Table 4 and Fig. 5 respectively. The analysis shows that there is a considerable increase in profit by integrating poultry in solar farms, even by considering the revenue from the eggs and the poultry manure alone. There will be an additional income if the revenue from meat is considered farm produce.

The revenue from 5 acre of land with beekeeping and the effect of integrated solar and beekeeping is indicated in Table 4 and Fig. 6 re-

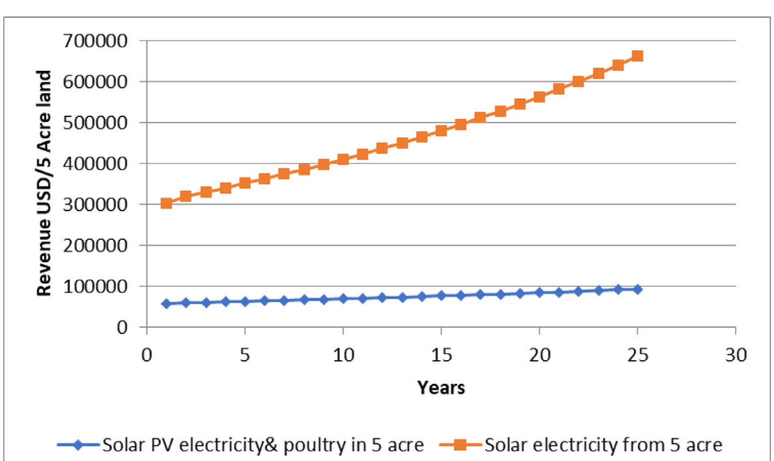

Fig. 5. Revenues generated with integrated poultry farming in 5 acre of ground mounted solar PV plant land.

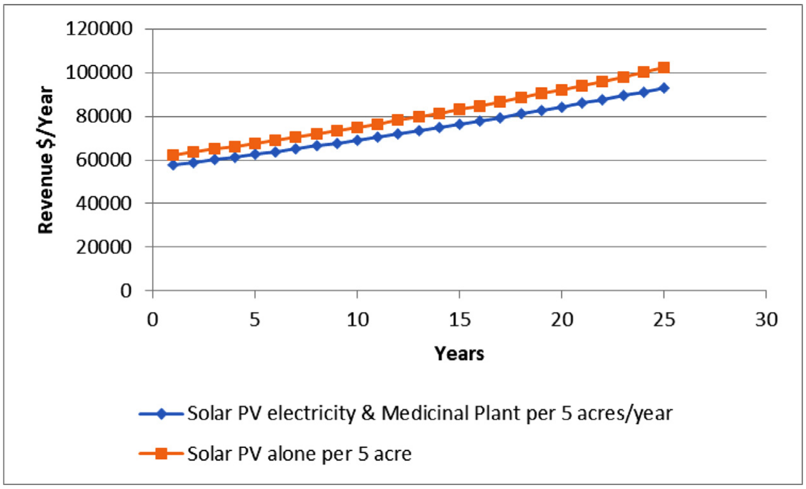

Fig. 6. Revenue generated from solar and beekeeping in 5acre of PV land.

Table 5
Revenue generated through beekeeping in 5 acres of land.

Average production of honey/beehive/year (in kg)	Number of beehives that can be put in 5 acre of land [k]	Total production of honey in 5acre of land(in kg) [j]	Price of 1 kg of honey[l] ($)	Total revenue generated by beekeeping in 1 acre of land($)
10	50	500	2.60	1300

[k] [66].
[l] [72].

spectively. The restrictions on number of beehives and harvest per year are restricted. Thus, integration of solar PV and beekeeping is not as prospective as medicinal plants and poultry (Table 5).

This session has analysed the possibilities of integrating medicinal plants, poultry and bee keeping as livelihood activities into land allotted for solar parks. The analysis shows, that integrating solar and livelihood are having the potential for additional income. The analysis arrives to a conclusion that poultry is a feasible option with respect to medicinal plants and beekeeping. However the purpose of agrivoltaics as a mechanism to mitigate topsoil degradation, water retention and micro climate conditioning may not be feasible. One option being a mix of medicinal plants and poultry that can coexist with the solar farms.

Results and discussion

A comparative analysis on the economic feasibility of agrivoltaics is done with the following specific cases.

(i) Captive solar PV power plant with a FiT of $ 0.14/kWh without agrivoltaics, with conventional structures as in Fig. 1.
(ii) Captive solar PV power plant with a FiT of $ 0.14/kWh with agrivoltaics with raised structures as in Fig. 3, without working business model for implementing agrivoltaics
(iii) Grid tied solar PV power plant with FiT of $ 0.03/kWh without agrivoltaics and conventional structures as in Fig. 2
(iv) Grid tied solar PV power plant with FiT of $ 0.03/kWh with agrivoltaics and raised structures as in Fig. 3 without business model for implementing agrivoltaics.
(v) Captive solar PV power plant with FiT of $ 0.14/kWh with raised structures as in Fig. 3 for agrivoltaics and workable business model
(vi) Grid tied solar PV plant with FiT of $ 0.03/kWh with raised structures as in Fig. 3 for agrivoltaics and workable business model.

The solar plant considered was 1 MW capacity with an average irradiation of 5.5 kWh/m^2 irradiation to produce 1.61 million kWh/year [7] and loamy soil to grow a combination of medicinal plant between the arrays and poultry underneath the solar panels. The considerations for the plant and agrivoltaics are as per section4.0 above with medicinal plant and poultry considered as livelihood mechanisms.

The capital expenditure for the conventional plant is considered as 0.49 million $ with polycrystalline panels and capacity utilization factor 18.4% [73]. The debt equity ratio considered is 70:30 at a term loan interest rate of 10% and working capital interest rate of 12.80%. Repayment period considered is 12 years and operation maintenance cost of 2.5% of the capital cost with 5% annual escalation. The feed-in-tariff considered for captive and grid tied were fixed for a period of 25 years, while a rate of 5% increase is considered for the income from the agrivoltaics. An 80% increase in capital cost is considered for the agrivoltaic structures at a height of 3 m from the ground (Fig. 7).

The economic analysis for the payback and cumulative annual return shows that agrivoltaic without workable business models for a captive power plant with 0.14$/kWh FiT can have a breakeven in 3 years and 9 months while a captive plant with the same FiT without agrivoltaics breaks even in 2 years and 4 months. A captive plant with 0.14 $/kWh FiT with a workable business model will have a breakeven in 3 years and 3 months. A grid tied solar PV plants with a FiT of 0.03 $/kWh which has a breakeven of 13 years without agrivoltaics, may not breakeven within 25 years without a workable business model. However, with a workable business model for agrivoltaics the grid tied solar PV plant with a FiT of 0.03 $/kWh will have a breakeven in 17 years and 8 months.

The payback period of beyond 17 years will not be an attractive scenario for the developers, considering high interest rates for a 70:30 debt equity ratio.

Agrivoltaics – tradeoff in energy, land and food nexus

Subsidies by the Government are also unlikely, considering the fact that wind power is an alternative source where many of the factors of land coverage issues can be neglected. One option is to consider the cost of mitigation of externalities into the cost economics of the solar parks. Table 6 shows how the potential impacts of solar parks and how agrivoltaics mitigate the externalities to the environment, microclimatic changes and socio-economics of the society.

Table 6
Impact mitigation matrix to co-locate livelihood activities in solar parks.

Segment	Potential Impacts	Impact	Mitigation measure	Management for Implementation	Impact on Capex	Impact on Opex
Socio-economics	Loss of land for produce from cultivation	Social	Find alternate land banks for re-settlement	Policy guidelines for resettlement. Find locally adaptable livelihood mechanisms that can be integrated	High	N/A
	Loss of livelihood activities	Social	Integrate livelihood activities in solar parks	Energy – Agriculture-centric approach to redesign the solar park for adaptability.	High	Medium
	Scaling down of efficiency of villages	Social	Integrate livelihood activities into solar PV farms	Incentivise the local population through training, provision of jobs.	High	Medium
	Land grab, Loss of jobs and farmer suicides	Social	Policy implementation for solar parks to use fallow/ scrap lands for solar parks	Phase out conventional agriculture practices to agrivoltaics. Training to adapt new livelihood activities.	Low	High
	Rural-urban migration	Social	Enhance the rural productivity, skilling, enhance natural resources. Negotiate policy frameworks	Skill the local manpower to adapt to new technology practices in energy and agriculture. Provide subsidies	Low	High
	Creation of peri-urban regions and imbalance urban infrastructure	Social	Strengthen the rural-urban divide through infrastructure, (transport, health and economic balance)	The Non-Government organisations who work amongst the villagers strengthen the confidence and pilot projects to convince the farmer community	High	High
Environment	Soil Erosion affecting water retention properties	Social /Ecology	Reduce grubbing areas. Reduce land levelling by removal of local vegetation	Use specially designed panel mounting structures to include the natural slope of land into the required system design slope.	Medium	Low
	Alteration of natural drainage due to module mounting structures.	Social /Ecology	Natural waterways should not be blocked	Use existing water channels for rain harvesting to be used for cleaning of solar panels	Medium	Low
	The exploitation of naturally available water bodies/ bore wells	Social/ Ecology	Investigate waterless cleaning mechanisms	Pressure cleaning of panels using pneumatics can be implemented	High	Medium
	Loss of topsoil characteristics	Ecology	Limit removal of local vegetation and soil cover	Use well designed prefabricated/cast structures to carry the load	High	Low
			Stockpile topsoil & gravel for remediation	Collect topsoil during the construction phase, to spread underneath the panels for reuse and re-vegetation.	Medium	N/A
			Modify foundation design for minimal impact on topsoil	Precast structures, with high-strength materials, have minimal footprints during construction activities.	High	Medium
	Loss of vegetation cover	Ecology	Minimize cut & fill by limiting grubbing areas	Increase the height of the structures, to have minimal losses/damage to existing vegetation	High	Medium
	Removal of natural vegetation cover	Ecology	Maintain the removed topsoil for re-vegetation to maintain the original ecology	Refrain from the conventional practice of grading. Carefully remove the topsoil / preserve the topsoil for agriculture.	Medium	N/A
	Fragmentation of existing faunal habitat	Ecology	Remove topsoil carefully, retain the properties and reuse efficiently	Remove the topsoil through grading; preserve the soil characteristics through aeration, the addition of nutrients.	Medium	N/A
	Loss of local vegetation leads to the end of terrestrial species	Ecology	Use the topsoil to have the same terrestrial species through re-vegetation	Use the preserved topsoil to re-vegetate the land by carefully integrating for a better blend.	Medium	N/A
	Disturbance of site-specific animal population	Ecology	Preserve local animal habitat, through artificial mechanisms to maintain animal movements undisturbed	Every solar park should have a green buffer to preserve regional animal species, which can naturally survive and breed.	High	Medium
Climate change	Heat islands will reduce the life and efficiency of the panels	Energy	Integrated agriculture practices will induce natural breeze and evaporation bringing a cooling effect.	Grow height constrained shadow crops underneath the panels. Provide enough area around the solar park, in between the rows of panels, without shadow effect.	High	Medium
	Carbon Dioxide Sequestration - solar panels covering vast lands for decades can affect the carbon sequestration cycle.	Energy	Integrated agriculture below the solar panels, between the rows, and at solar park boundaries will compensate carbon trap capacity.	The vegetation below the panels should be carefully selected to optimize height, shade, and carbon trap potential. Minimize soil tillage, practice cover cropping, and investigate crop rotation	High	Medium
	Absorption of GHG emissions - Absorption of carbon dioxide influences nitrous oxide and methane composition.	Energy	Grow plants having high Carbon cycling efficiency to check GHG ratios.	The type of vegetation is constrained by soil properties and sunlight. Possibilities for high carbon trap vegetation to be practiced.	Medium	Low

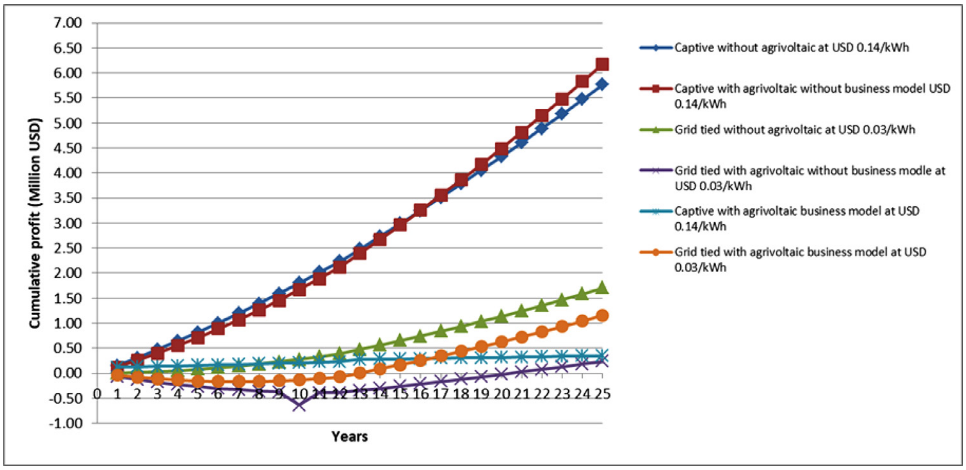

Fig. 7. Cumulative profit with different scenarios of conventional and agrivoltaic plants.

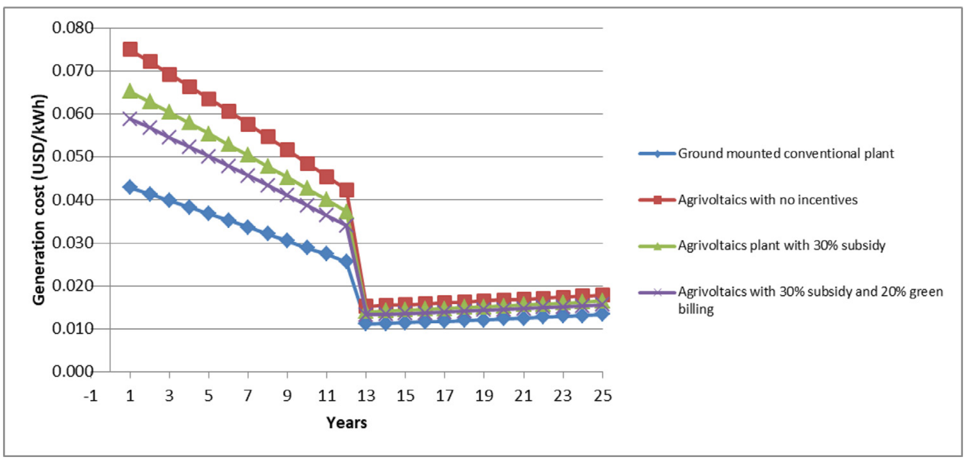

Fig. 8. Generation cost of conventional solar plant and agrivoltaic plant with and without subsidy and incentives.

The key stakeholders of the agrivoltaic based solar PV parks will be central and state Governments, policy makes, developers and farmers. Increase of renewable energy share in the energy pool is a global mandate and commitment by the country. Agriculture is the mainstay of the economy with rural regions many fold the urban areas. Globalization and climate change is luring farmers to shift to alternate livelihood options. Implementing agrivoltaics as a mandate will require contribution from the Government as a subsidy, which in turn can be adjusted against green energy bills. An 80% increase in capital cost and 2.5% additional operation and maintenance cost has to be absorbed either in form of subsidies or levied as an environmental impact mitigation cost (EIMC) and a social impact mitigation cost (SIMC). The generation cost analysis of a conventional ground mounted solar PV plant, agrivoltaic plant without subsidies and incentives; agrivoltaic plant with 30% subsidy and agrivoltaic plant with 30% subsidy and 20% green billing are shown in Fig. 8.

From the analysis it is found that the generation cost can be reduced only if the subsidies and green energy billing in form of EIMC and SIMC can be levied. The levelised cost of energy for the conventional ground mounted solar PV plant considered is 0.03 $/kWh while for agrivoltaic plant without subsidies and incentives the LCOE is 0.052 $/kWh. For the agrivoltaic plant with a subsidy of 30% the LCOE is 0.046 $/kWh and with a further green incentive billing the LCOE can be brought down to 0.041 $/kWh.

Conclusion

The growing population and urbanization increase the energy demand, while the climate changes and global warming demand green energy. Renewable energy has relied on solar photovoltaics considering easy installation and technology readiness levels (TRL). However the land utilisation of solar photovoltaics plant is a factor, especially when large solar parks are planned which avoids redundancy in pooling and wheeling infrastructure. The externalities caused by land coverage of solar parks are divided over environmental and social along with changes in micro climate. Research in agrivoltaics has considered the prospects of different crops vis-à-vis the soil conditions. There are no concrete outcomes on the benefit of agrivoltaics to work on a workable business model to bring down the capital and operational cost of agrivoltaics. The current work has done a review on the agrivoltaic plants in India, and concludes that the focus was to look into the economics of the agrivoltaic plant to lure the farmers to practice. However the complexity of the environmental externalities and social externalities, with focus on livelihoods, rural-urban migration were not looked into. The present study has considered agrivoltaics as a mitigation mechanism of EIA (Environmental impact analysis) and SIA (Social impact analysis) and looked into the techno-commercial viabilities of the same. The impact due to land coverage has been classified under three broad spectrums namely, environment, social and microclimate changes. Three livelihood mechanisms are considered and technical and economic feasibilities are carried out. It is identified that a mix of medicinal plants and poultry is beneficial and the break even can be achieved in 17 years for an additional capital investment of 80% and operational expenses of 2.5%. However considering the breakeven of 17 years may not attract investors, for a 70:30 debt equity ratio with a term interest of 10%, the inclusion of subsidies and green billing was considered and it is found that the LCOE can be brought down to $ 0.041/kWh from $ 0.053/kWh, thus bringing the better breakeven .

As a future scope of research it will be interesting to have a practical investigation on pilot plants with hybrid livelihood mechanisms, with minimal modifications of structures. As a policy recommendation it is suggested that separate tenders with FiT's that are made feasible with at least 30% subsides may be considered with focus on fallow and waste lands.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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