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1 **Agrivoltaic Potential on Grape Farms in India**

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8 **Abstract**

9
10 Aggressive growth of land-based solar photovoltaic (PV) farms can create a land use conflict
11 with agricultural production. Fortunately, this issue can be resolved using the concept of
12 agrivoltaics, which is co-development of land area for both solar PV and agriculture. To
13 investigate and quantify PV generation potential, without harming agriculture output, this study
14 explores the viability of agrivoltaic farms deployment on existing grape farms in India.
15 Considering the shade tolerance of grapes, an techno-economic analysis is run for the installation
16 of PV systems in the area available between the trellises on a grape farm. The electrical energy
17 generation potential is determined per unit area and economic benefits for the cultivators is
18 quantified over a number of design options. The results show the economic value of the grape
19 farms deploying the proposed agrivoltaic systems may increase more than 15 times as compared
20 to conventional farming, while maintaining the same grape production. If this dual use of land is
21 implemented nationwide, it can make a significant impact by generating over 16,000 GWh
22 electricity, which has the potential of meeting the energy demands of more than 15 million
23 people. In addition, grape-based agrivoltaics can be implemented in rural areas to enable village
24 electrification.

25
26 **Keywords:** Agrivoltaic; agriculture; photovoltaic; land use; food-energy-water nexus; solar farm

27 **1. Introduction**

28 Fossil fuel combustion for human energy use and concomitant carbon emissions [1] is
29 disturbing the global ecosystem balance [2,3], which threatens future generations [4] the global
30 economy [5]. Fossil fuels are being depleted [6], yet simultaneously there is an increasing
31 negative environmental impact from their continued use [7]. This demands a greater use of
32 renewable energy [8,9] to enable to internalize current externalities [10] and de-carbonize the
33 energy supply [11]. In the past few decades, the continuous technical improvements [12,13] in
34 solar photovoltaic (PV) technology have enabled methods to provide clean and sustainable solar
35 energy [14] while driving down economic costs [15]. The International Energy Agency (IEA) has
36 predicted that 16% of world's energy demand, which would be approximately 6,000 TWh, would
37 be generated using solar PV by 2050 [16]. Because of the rise in capacity for solar power
38 generation studies have focused on aggressive use of new designs [17] building integrated PV
39 (BIPV) [18,19] and more conventional rooftop PV retrofits estimated over regional [20], city
40 [21,22], municipal district [23], or multiple buildings [24,25]. However, rooftop systems cannot
41 provide all the energy necessary for some regions with high population densities and thus land-
42 based solar PV farms have also been investigated in depth on technical [26] and economic
43 [27,28] and future economic [29] grounds. The aggressive growth of land-based PV farms [30]
44 creates a conflict in the use of land [31] for generating energy using solar PV or meeting
45 increasing food production demands of the world population [32]. With the world population
46 increasing at the rate of 1.15% per year [33], and the continued failure to adequately nourish the
47 entire world population [34], this problem is becoming more important. Solar module requires a

relatively large amount of open space [35]. Prior efforts to convert crop lands to energy generation (e.g. the production of ethanol) have driven up the cost of food [36], primarily impacted the poor [36] and aggravated world hunger [37]. Fortunately, this major disputation of land use can be resolved using the concept of agrivoltaics (i.e. co-developing the same area of land for both solar PV and agriculture) [38]. The agrivoltaic concept has proven successful in several systems [38] including solar PV and aloe vera in dry, semi-arid regions [39], lettuce [40], and cherry tomatoes [41]. Most agrivoltaic studies, however, have focused on shade tolerant crops. This study will focus on the potential of a relatively shade *intolerant* crop (grapes) in a promising region for agrivoltaic production (India).

India is a particularly promising region for agrivoltaic production because it has an economy that is made up of many agriculture producers [42], and is rapidly expanding electrical services to the 21.3% of India's population without access to any form of electricity [43]. In addition, India has significant support from the government for PV production and has achieved increasing solar capacities [44]. Finally, India receives a relatively high solar flux. Indian states like Maharashtra, Gujarat, Haryana, Punjab, Rajasthan, Andhra Pradesh, Orissa, Madhya Pradesh, Bihar, and West Bengal, which form the major part of India, receive 4-7 kWh of solar radiation per square meter per day, which is equivalent to 2,300-3,200 hours of sunshine every year [45].

To investigate and quantify some of this agrivoltaic generation potential, without harming the Indian agriculture output even for shade-intolerant crops, for the first time this study explores the viability of agrivoltaic farms deployment on existing grape farms in India. Considering the weak shade tolerance of grapes, an analysis is run for the installation of PV systems in the area available between the trellises on a grape farm without compromising grape production, which represents a novel approach to agrivoltaics in the use of the necessary harvesting space of shade intolerant crops. Then the electrical energy generation potential is determined per unit area and economic benefits for the grape cultivators is quantified. A sensitivity analysis is run on geographical location, selection of module and inverter, row spacing, selection of axis and azimuth angle. The results are discussed and conclusions are drawn to provide best practices.

2. Background

Grape farms offer considerable promise for agrivoltaic farms. First, grape farms are generally located in areas having a 15-40°C temperature range over a reasonable duration of sunlight hours [46, 47]. Grapes are grown on trellises and the layout of grape farms is such that there is an underutilized gap of about 1.5m to 2.5m between the trellises. Although grapes are normally considered a full sun plant, even in the absence of full sunlight all day long (e.g. even 7-8 hours), it is still possible to grow grapes in mostly shade with some preparation and forethought to maximize yield [48].

One of the method is to more fully utilize the sunlight incident on a standard grape farm is to mount and install solar PV modules in the unused space between trellises. This agrivoltaic geometry for grape farms is schematically represented in Figure 1, where X is the horizontal distance between the solar PV rows towards the south direction, Z is the horizontal distance between the trellis and the solar module, W is the height of trellis and T is the distance from the ground to the bottom of the PV array, and Y is the length (vertical height) of the solar module. It should be noted that for grape farms with small inter-trellis spacing $(X-2Z)/2$ the standard modules will need to be mounted in landscape format so that Y is what is normally referred to as

the width of the module. Finally, as can be seen in Figure 1, the angle, θ , is define as the tilt angle of the solar module with respect to a plane parallel to the ground.

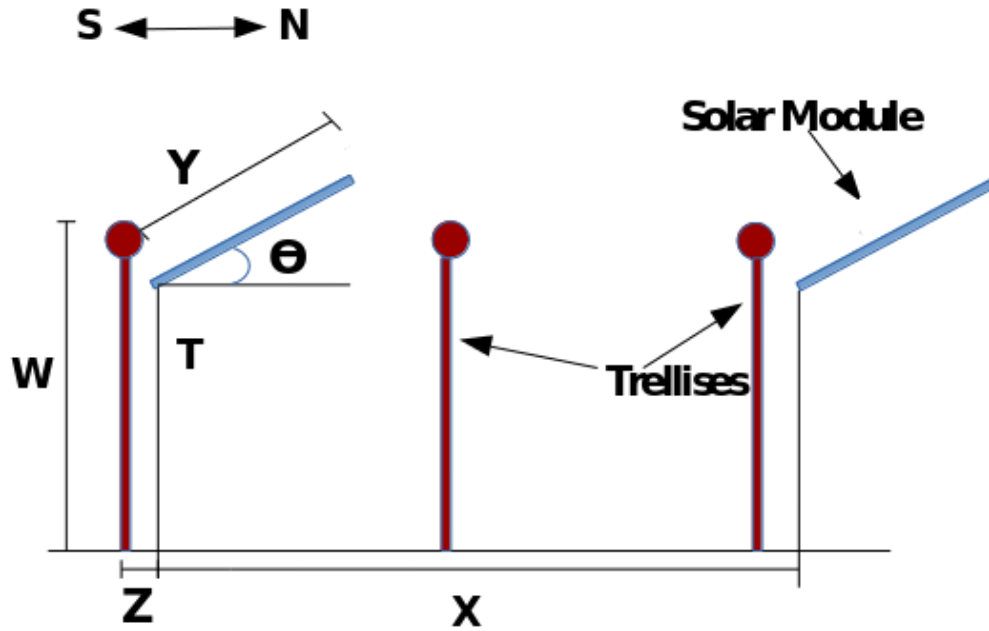


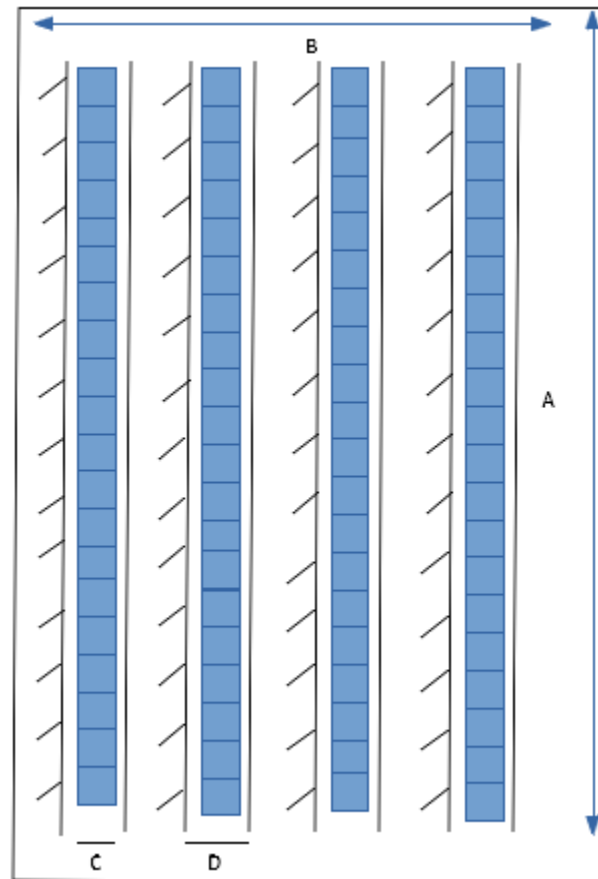
Figure 1. Side view schematic arrangement of solar modules between grape trellises. Note that the middle of the PV module is positioned at approximately the top of the grape crop.

Grape farms in India are predominantly located in the Northwestern part of the State of Maharashtra (known as the “the grape capital of India”), particularly in Nashik [49]. Surrounding industries can be supplied with the electricity from these farms during peak load demands, helping to increase grid reliability [39], while decreasing greenhouse gas emissions from conventional power plants that use fossil-fuel combustion. In this way, the sale of PV electricity can operate as a second source of income for farmers from their existing grape fields. In addition, the irrigation cost of grape farms is a substantial fraction of the farm input costs [64] and there is a considerable evidence that farmers can benefit from using the electricity generated from the solar PV for water pumping for their own needs directly [51-55].

Using the geometry shown in Figure 1, Figure 2a is generated to show the top view arrangement of the solar PV systems in a complete grape-based agrivoltaic system. The PV modules are mounted in series between the trellises in an alternate manner to allow grape farmers access to every plant for pruning, harvesting and other agriculture related tasks. At the same time this allows restricted access to the PV modules for any maintenance related tasks (e.g. periodic cleaning). The variable A describes the width of the farm (east west direction) and the B explains the depth of the farm made up of a multiple of X spacing between rows of modules. The C describes the horizontal width of the PV module projected on the ground, which is $Y\cos(\theta)$

and D is the inter-trellis spacing $(X-2Z)/2$. A scaled-down detail section (9.0m X 9.78m) of an agrivoltaic PV acre array used in the simulations is shown in Figure 2b.

Figure 2a. Top view schematic arrangement of a grape-based agrivoltaic system. Please note that the grape trellises are exaggerated to be seen in the top view. They are conventional trellises and would not need to be modified for agrivoltaic production.



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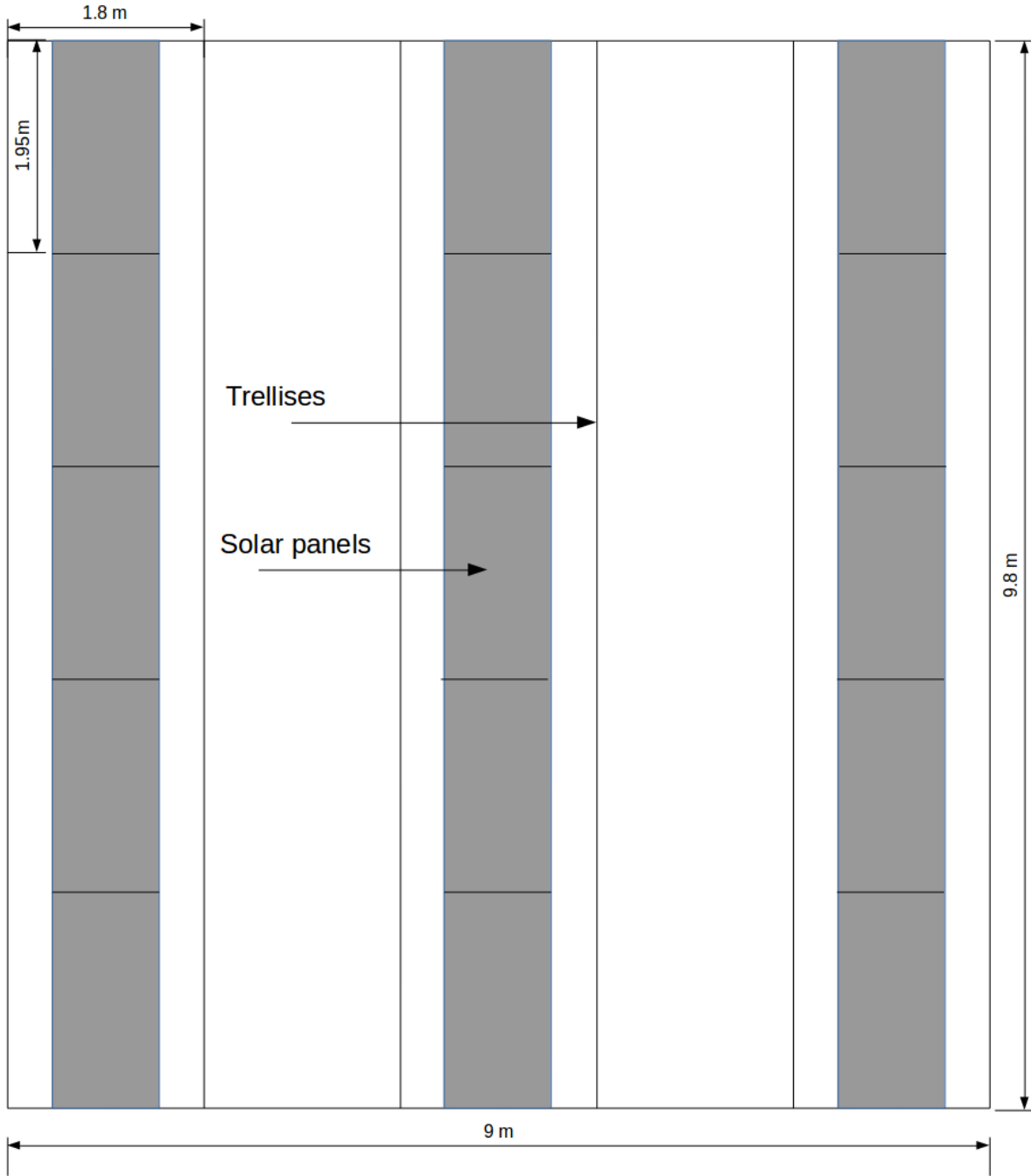


Figure 2b. Scaled down agrivoltaic farm (9.0m X 9.78m)

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146 3. Methods

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A combination solar PV and grape farm agrivoltaic system is modeled to study the energy aspects and expected output per acre of farmland with the dual use of land in Nashik district of Maharashtra state of India (Lat: 19°59'0" Long: 73°48'0" E Alt: 700 m). The National Renewable Energy Lab System Advisory Model (SAM) version 2014.1.14 [56] is used to simulate the performance of the PV system. Since SAM does not have Nashik as a default location due to lack of meteorological data, the location assumed for simulation is Nagpur, which

is close to and has similar climatic conditions as Nashik. The other inputs of system design include the system array size, DC to AC ratio, azimuth angle, required type of axis and the tilt angle (which was optimized with a sensitivity analysis with SAM) are detailed below. The revenue generated through the electricity produced and data from historical grape farming on the grape cultivation revenue are quantified.

The PV module considered (Trina Solar 310W TSM-310-PD14 polycrystalline silicon) is representative of an average performing module with an efficiency of 15.7% and dimensions 1956 mm × 992 mm × 40 mm [57]. The modules were arranged between the trellises, at the same height as that of the grapes, such that the center of the module is at the height of the grapes. The farm considered for this case study is a square farm of 1 acre (i.e. 4,046 square meters). With the side A measuring 63.6 m, the number of PV modules that could be arranged along the width are 32, whereas the number of rows assuming the widest inter-trellis spacing normally observed of 1.8m provides 17 rows.

For the solar module selected, Y is fixed at 0.992 m. This is about half the distance between the trellises and hence, the shade of the solar module will not fall on the grape crop for most the year. This can be seen in Figure 3 where, the extreme solar altitude angles are shown schematically. It should be pointed out that the exact difference in the heights (as measured above the ground) between the PV array and the top of the grape crop would in practice vary with growth and future work is necessary to optimize this value. However, as can be seen in Figure 3, in general, the grapes will be shaded only for a few days around the winter solstice. This position of the module will cause minimal shading on the grape crop, which ensures that direct sunlight is available for the grape vines and thus the quality and quantity of grape production is not compromised.

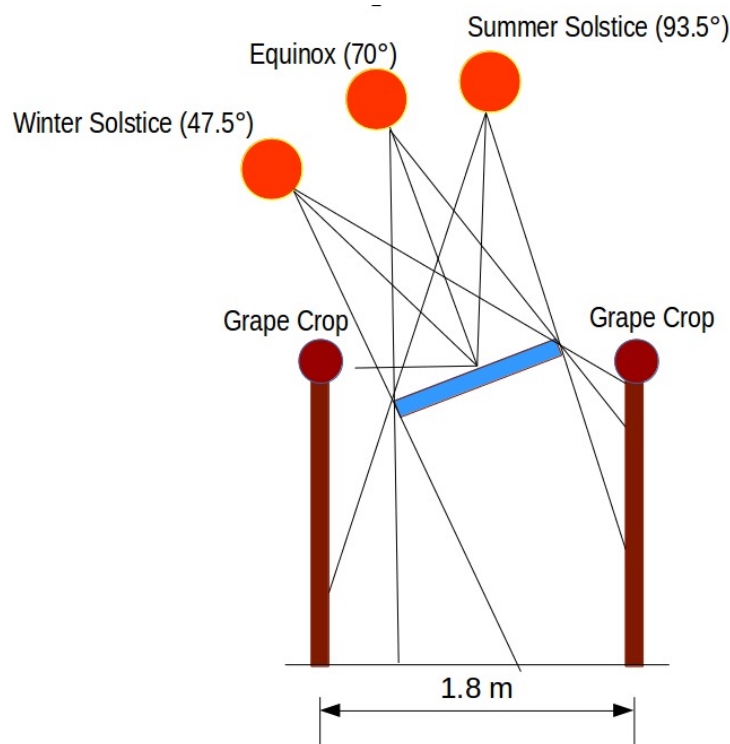


Figure 3. Solar path showing shading of solar module on grape crop in Nashik, India.

The proposed agrivoltaic system yield is determined per unit acre. Then, for agrivoltaic farms the optimum parameters from Figure 1 of X, Y, Z and Θ for a case of combination solar PV and grape farm where the trellises are placed 1.8 meters away from each other is calculated. In this step, no shade constraints and module size constraints are considered and Θ can vary.

Grapes need 7-8 hours of direct sunlight [58] to grow fully to be sold commercially. The average duration of day during the harvesting season of grapes is 11 hours 20 minutes [59] and hence, it can be estimated that grapes are about 30% shade tolerant for practical purposes. Simulations are run using SAM to determine optimum value of Θ . With thesedata, it is possible to calculate the economic benefit incurred by the grape cultivators for a unit acre of grape farm with a combination of grape and solar PV. The average retail electricity price in India has been constant over the last 5 years and for practical purposes, it is \$0.08/kWh [60].

Loss factors that need to be considered for scaling to all of India are the orientation of the grape farm (e.g. rows are ideally east-west allowing PV to be placed appropriately). Finally, the distance between the trellises varies on grape farms and must be wide enough to accommodate conventional PV modules without significant grape yield losses from shading. To make an estimate of these factors, 10 farmlands were evaluated in the region for orientation and spacing with Google Earth.

4. Results and Discussion

4.1. Technical Performance of Grape-Based Agrivoltaic Systems

For a 1-acre farm with solar modules alone where modules are arranged in 17 rows and 32 columns physically, the potential array output is calculated to be 168.64 kW dc as the Trina Solar TSM 310PD14 module has a maximum power output of 310W. The 1-acre farm considered is assumed to be square and there must be a gap between the rows of modules to prevent row to row shading and to allow for maintenance.

Next the agrivoltaic farm is considered with grape trellises spaced at 1.8 m. As the solar modules are mounted in the row spacing between the trellises the desired array capacity is expected to be low in comparison to the fully acquitted solar module field. But there would be an added benefit of reduced inter-row shading on the modules (and the height is such that there is no shading of the PV from the grape vines). A sensitivity was run on the annual electricity generation as a function of tilt angles of the solar modules in both agrivoltaic setup and pure solar farm. The results showed that a fixed optimal tilt angle of 21° maximized PV output (259,826 kWhr/year) in an agrivoltaic farm setup in Nagpur, India using a Trina Solar TSM -310PD14 (1920 × 992 × 40) mm which is 32 modules wide and 17 rows facing due south. This is the physical arrangement of the modules considered for maximum land coverage. The ground coverage ratio (GCR) is assumed to be 0.26 to avoid shading as much as possible. The monthly solar energy generation at the case location and can be seen in Figure 4. It should be noted that the monsoon season is responsible for the reduction in output during June, July and August.

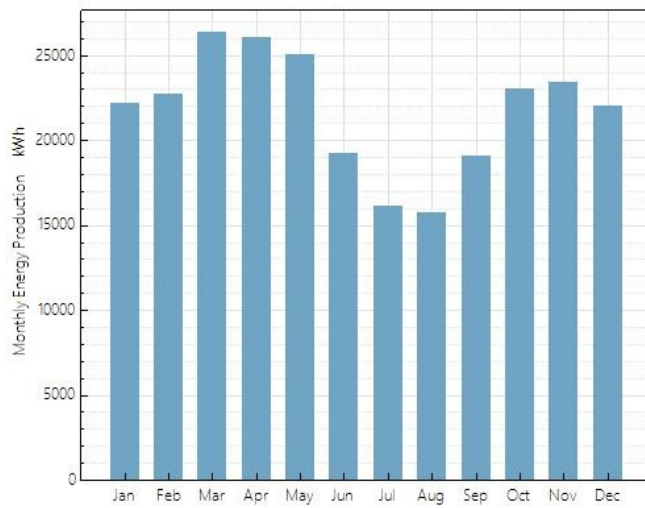


Figure 4. Monthly energy production from an acre of agrivoltaic solar farm in Nagpur, India.

There is negligible shading on the solar panels. It is found that the partial shading occurs only during 5 pm to 6 pm for the months of November and December. This shading can be neglected as most of the solar energy incident on the modules is used. Figure 5 shows the arrangement of solar modules in

a grape farm. Figure 5a shows the Bird's eye view of the arrangement of modules, whereas Figure 5b shows a closer view of the arrangement of solar modules in the grape farm.

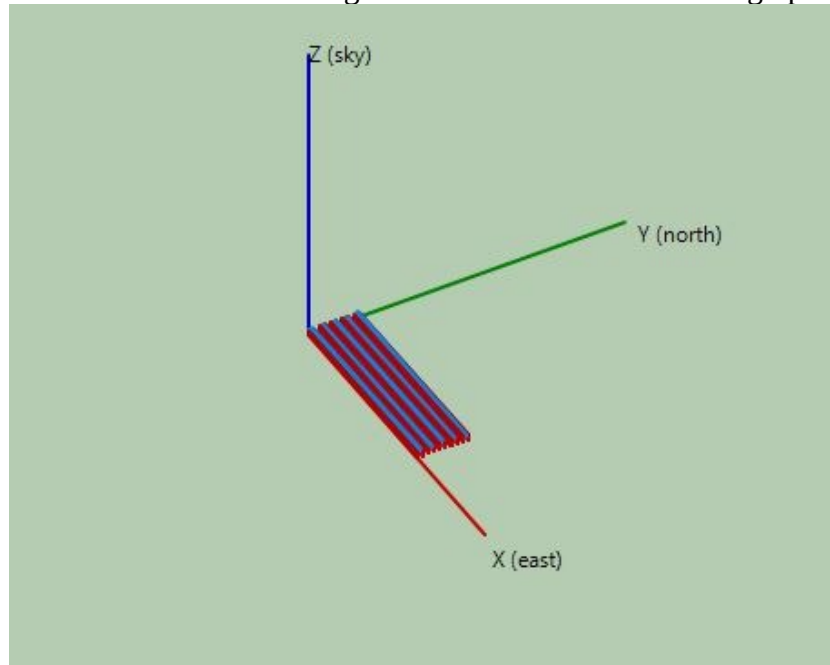


Figure 5a. Arrangement of solar modules (Bird's eye view)

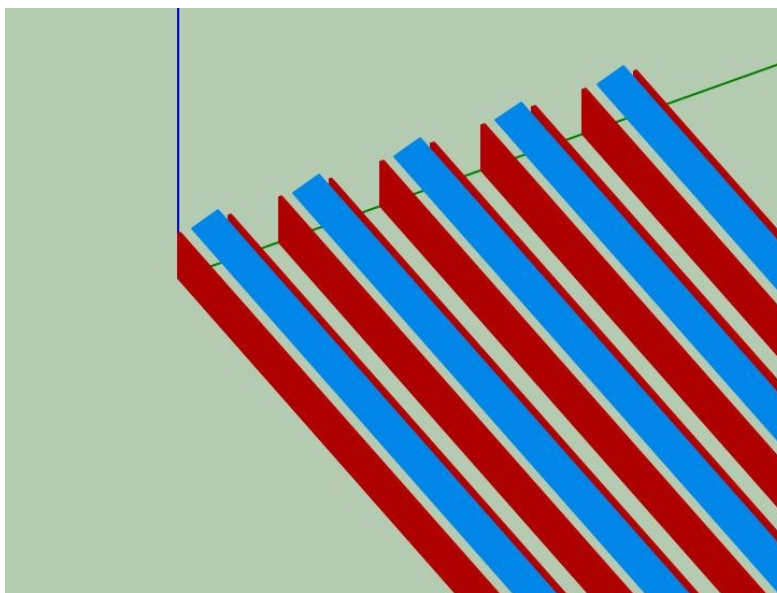


Figure 5b. Closer view of solar modules with trellises

For the 84,015 acres of farm in India [61], the total maximum potential energy production in grape farms with installation of solar PV panels can be scaled up to 21,829 GWh, which is 1.97% of 1107 billion units of energy produced in India in 2015-16 [44]. This energy is roughly equivalent to the output of 3GW of coal plants working at 85%. This is the idealistic maximum figure and to find the practical potential, various factors must also be considered. The most important factor is the orientation of the grape crops.

This preliminary evaluation of orientation-based lost areas with Google Earth appeared that there was no orientation bias in Indian vineyards. This resulted in a loss of approximately 23-25% of energy to the aligned direction farmlands. It should be pointed out that this was a preliminary study and that future work using a more sophisticated statistical survey of all Indian grape farms is needed. However, using these preliminary values as a base and including these losses still could provide over 16,000 GWh a year of PV potential. According to the Central Electricity Authority of India, the per capita electricity demand had reached 1,010 kWh in the year 2014 [65], which means that agrivoltaic grape systems could conservatively service 15.8 million people. Lastly it should be pointed out that the case considered is for the city of Nagpur, where the annual solar irradiation is above the average solar irradiation for India, so there would also be large geographic variability on solar potential depending on the location, which could again be determined with a more focused GIS-based study.

4.2. Economic Performance of Grape-Based Agrivoltaic Systems

Table 1 summarizes the revenue generated by the dual use of land for PV and grape production. The total annual gross revenue from an acre of grape farm is \$1,420.93 (~INR 94981.84) [66] (using an exchange rate of ~66 Indian rupees per U.S. dollar), whereas that of solar energy is the product of annual energy generated and cost of electricity. This comes out to be \$20,786.06. Thus from the Table 1, it can be seen that the annual revenue for the grape cultivator is increased by over 15 times if PV is installed between selected rows on a 1 acre farm.

Table 1: Revenue generated with dual use of land in one acre of farm in India.

	Annual Revenue/acre (in 1st year)	Percent of Agrivoltaic Revenue
Grape Produce	\$1,421	6.3%
Solar Electricity	\$20,786	93.6%
Total	\$22,207	100%

It should be noted that the cost per unit area (e.g. acre) is less for agrivoltaic farms in this setup than conventional solar farms because the packing factor (spacing between rows) of PV is lower for the agrivoltaic farm than for a conventional solar PV farm. The capital costs for such a 1 acre agrivoltaic farm vary by the cost of installation per unit power. Thus a sensitivity analysis was run from \$2/W (~INR 132) to \$0.25/W (~INR 16.5), which is summarized in Table 2.

Table 2: Sensitivity on the capital cost of a one acre agrivoltaic farm

PV System Capital Cost (\$/W)	Total Cost (USD)	Total Cost (INR)	Simple Payback Time (years)
2.00	337280	22260480	15.2
1.75	295120	19477920	13.3
1.50	252960	16695360	11.4
1.25	210800	13912800	9.5
1.00	168640	11130240	7.6
0.75	126480	8347680	5.7
0.50	84320	5565120	3.8
0.25	42160	2782560	1.9

In Table 2 the highest capital cost analyzed is \$2/W, which is a installation cost readily obtained for large ground-mounted PV systems currently in the global market. This provides about a 4% return on investment (ROI) assuming a 25 year lifetime. Again this is a conservative estimation of lifetime and the ROI is provided without taxes if the electricity is used by the farm. This ROI may already be attractive for some investors as the risk is relatively low. For larger systems the installation cost drops with economies of scale. For example, large systems have already been installed for under \$1/W, which in this context would provide a ROI of greater than 12%. This ROI would be attractive to most investors. However, if the agrivoltaic system were optimally constructed using existing trellises as the structure to reduce some of the mounting costs and low-cost high-efficiency PV modules were obtained, in the future \$0.25/W systems are possible. This would drive the ROI over 50%. The total cost comprises the costs of PV modules, land, civil and general works, monitoring, structures, power conditioning units, preliminary & pre-operation expenses including IDC and contingency, project design & management. However, the

Government of India provides support as accelerated depreciation, 10-year tax redemption, and other state specific exemption [66], which could drive up ROIs higher than shown here.

Clearly any reduction in the capital cost that resulted in the same yields would provide higher returns for the farmer and make the system less challenging to finance.

It should be pointed out, however, that the revenue shown in Table 1 is for the first year. Over the span of 25 years (under which the PV is under warranty), the efficiency of solar PV farm will decrease each year of all PV technologies is about 1%/year [67] and the majority of modules should be less than this at around 0.5%/year [68]. However, the functional lifetime of the PV can be much greater than that and with proper care, grapevines can live for 50 to 100 years or more. It is challenging to make projections of cost and value of both grapes and electricity over such time scales and these factors will effect the levelized cost of the electricity from the farm [69] as well as the ROI.

4.3. Future Work

The most pressing area of future work is to develop real-world proof of concepts. This could first be done in a controlled fashion by turning a fraction of a grape vineyard into an agrivoltaic farm and comparing the grape yield from the converted farm to the uncovered farm used as a control. This study had no plant-biology/physiology considerations for the partial shade effects caused by agrivoltaics and such a future proof of concept could begin to quantify the impacts of partial shading from the PV on grape plant health and productivity. Careful records can be kept on any secondary effects both negative (e.g. possible increases in labor costs due to increased harvesting time due to more restricted access to vines for harvesting) or positive effects (e.g. improved microenvironments increasing grape yields due to decreased soil temperatures and thus reduced evaporation from PV-related ground shading). Similarly, such a pilot test bed would also have a co-deployed PV system completely unshaded by grapes to compare solar electric yields to with the agrivoltaic system. Both PV systems could be compared to SAM simulations. These data could then be used to provide a more accurate economic model to create a sound business case for such systems.

If these field studies also prove promising, there are other opportunities to improve the mechanical design of an agrivoltaic system located on a grape farm. The existing structures made for the grape plantations could be used to mount solar panels and thus a major installation cost can be saved. Depending on the mechanical stability of the existing trellises this may only be possible for new installations where the trellises are designed to meet mechanical specifications of both grape and PV production. In this case the trellises can be used as the base structure and solar modules can be fabricated to be mounted on them. This will ensure saving time and energy to dig additional holes in the ground as well as the material cost to hold the solar modules will decrease with an added advantage of free space under the module to facilitate farming. This study assumed human labor for harvesting. However, there are automated harvesting machines for grapes, which are economic on large scale farms [70]. Future work should also consider the design of an agrivoltaic grape farm, which has sufficient spacing to enable automated grape harvesting [71]. This will entail additional spacing between trellises and the impact on grape production per unit area will need to be taken into account and weighed against the additional revenue from the PV electrical production.

There are also several potential integrated benefits such as the use of the sprinklers for irrigating the farms can help in cleaning the dust particles from the solar modules. This loss can be non-trivial in certain areas (e.g. 15-25% decline in annual electricity production from solar PV) [39]. A future study is needed to quantify this benefit for increased solar electric yield in specific regions and then compared to the cost of manual or automated cleaning for dedicated PV cleaning systems.

If the proof of concept study shows an unacceptable decline in grape production cultivators may still be able to use agrivoltaics on grape farms and have added revenue generation by using a tertiary source for intercropping. For example, a 3 part system could be made up of solar PV, grapes and a shade loving crop like the betel leaf, which is also known as the ‘neglected green gold of India’ [72]. Betel leaves are in great demand in several countries of the world apart from India and generate additional revenue after drying [73]. Similarly, the shade occurring due to solar modules can also be used to cultivate medicinal plants like ginger, tulsi (*Ocimum tenuiflorum*), which need shade to proliferate. Farmers have explored intercropping of grape farms with other crops on an experimental basis [74] and this could potentially made the business model of agrivoltaics even more promising as solar PV + grape vineyards can attract tourists and open more opportunities of income.

5. Conclusions

Growing the world's food supply while transitioning to more land-intensive energy sources is a challenge that can be partially overcome by the dual use of land in agrivoltaic systems. This preliminary modeling study showed that for grape crops, food yields in India may be maintained while the revenue of the farms deploying the proposed agrivoltaic systems could increase by over 15 times annually as compared to conventional grape farming. If this dual use of land is implemented nationwide, it could make a significant impact by generating over 16,000 GWh electricity, which could meet the energy demands of more than 15 million people. Future work is needed to experimentally verify the results of this modeling study so that agrivoltaic systems can be implemented in the rural areas and villages, which can be electrified apart from the added advantage of growth in revenue.

6. Acknowledgements

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