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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, a 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

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

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

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

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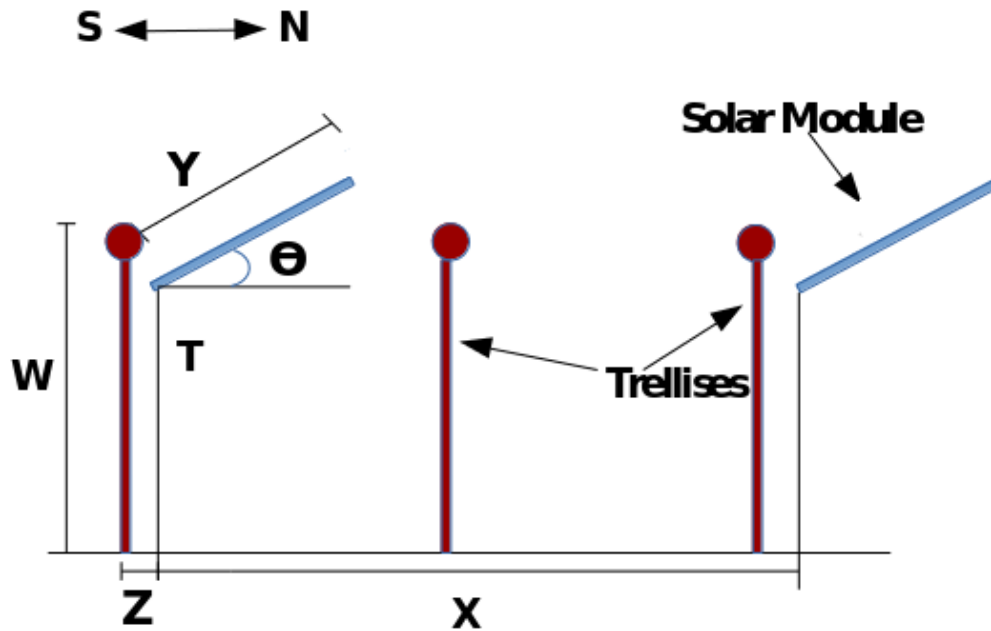
77 2. Background

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79 Grape farms offer considerable promise for agrivoltaic farms. First, grape farms are
80 generally located in areas having a 15-40°C temperature range over a reasonable duration of
81 sunlight hours [46, 47]. Grapes are grown on trellises and the layout of grape farms is such that
82 there is an underutilized gap of about 1.5m to 2.5m between the trellises. Although grapes are
83 normally considered a full sun plant, even in the absence of full sunlight all day long (e.g. even
84 7-8 hours), it is still possible to grow grapes in mostly shade with some preparation and
85 forethought to maximize yield [48].

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

94 the width of the module. Finally, as can be seen in Figure 1, the angle, θ , is define as the tilt
95 angle of the solar module with respect to a plane parallel to the ground.
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101 **Figure 1.** Side view schematic arrangement of solar modules between grape trellises. Note that
102 the middle of the PV module is positioned at approximately the top of the grape crop.
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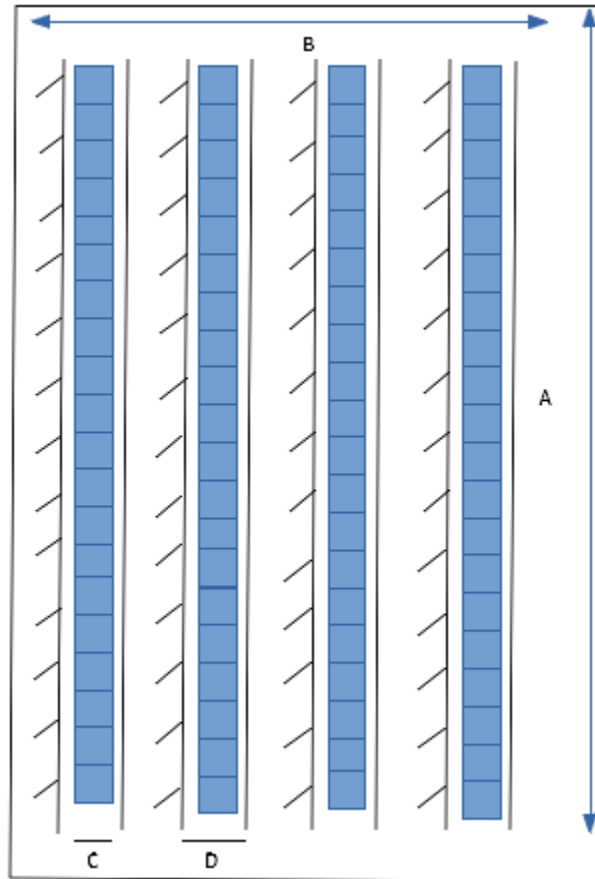
104 Grape farms in India are predominantly located in the Northwestern part of the State of
105 Maharashtra (known as the “the grape capital of India”), particularly in Nashik [49]. Surrounding
106 industries can be supplied with the electricity from these farms during peak load demands,
107 helping to increase grid reliability [39], while decreasing greenhouse gas emissions from
108 conventional power plants that use fossil-fuel combustion. In this way, the sale of PV electricity
109 can operate as a second source of income for farmers from their existing grape fields. In addition,
110 the irrigation cost of grape farms is a substantial fraction of the farm input costs [64] and there is
111 a considerable evidence that farmers can benefit from using the electricity generated from the
112 solar PV for water pumping for their own needs directly [51-55].

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

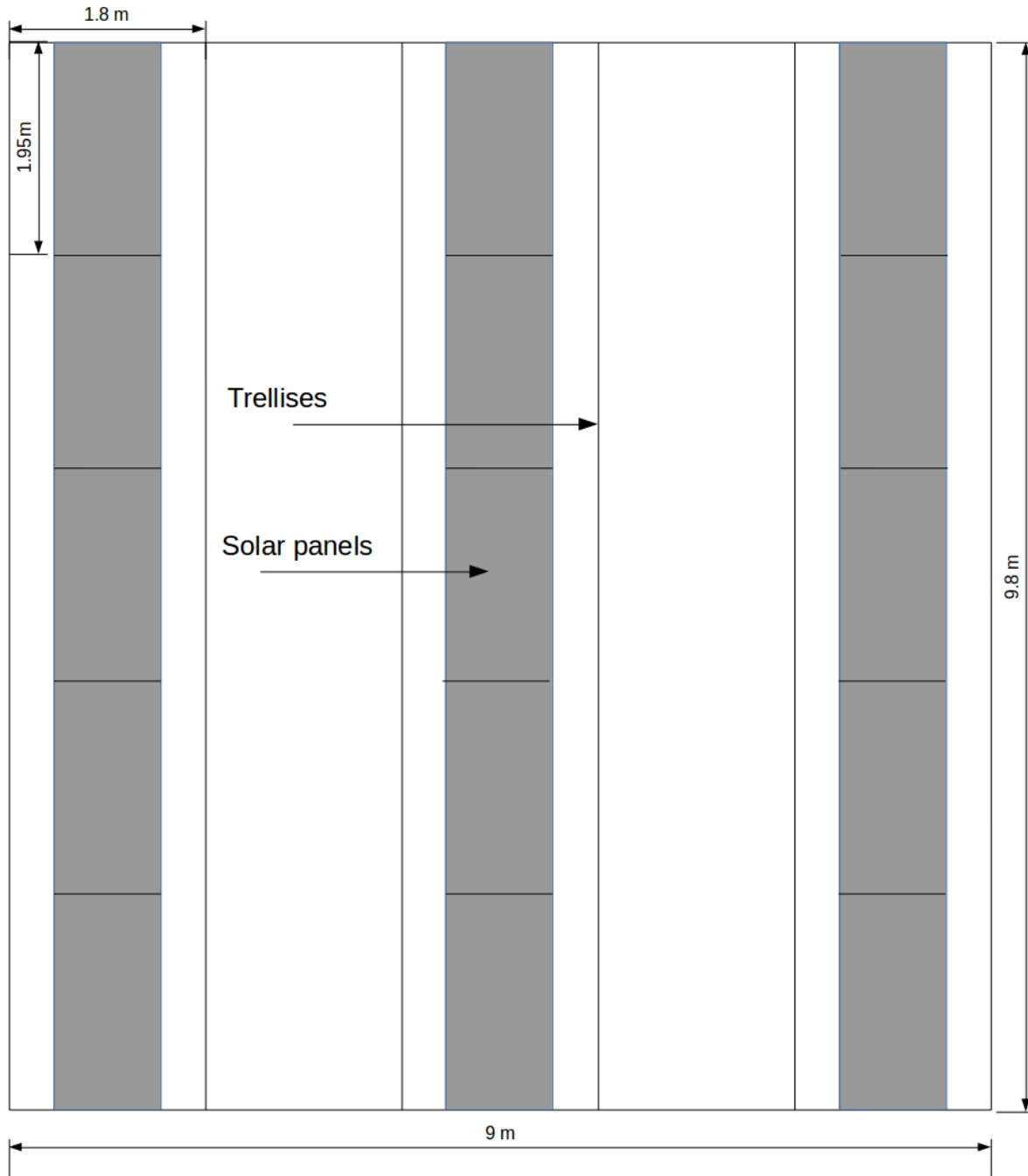
121 and D is the inter-trellis spacing $(X-2Z)/2$. A scaled-down detail section (9.0m X 9.78m) of an
122 agrivoltaic PV acre array used in the simulations is shown in Figure 2b.

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

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3. Methods

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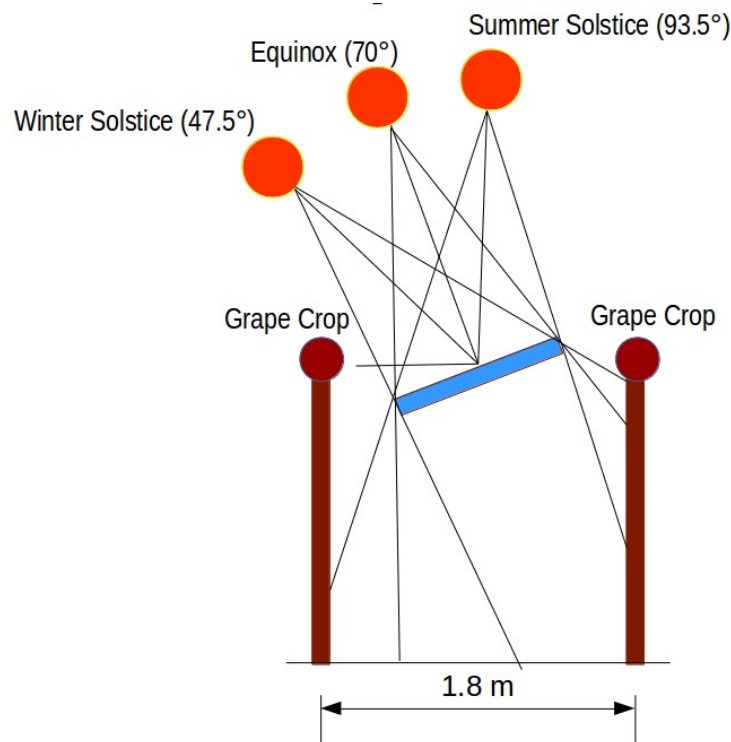
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A combination solar PV and grape farm agrivoltaic system is modeled to study the energy aspects and expected output per acre of farmland with the dual use of land in Nashik district of Maharashtra state of India (Lat: 19°59'0" Long: 73°48'0" E Alt: 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

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

158 The PV module considered (Trina Solar 310W TSM-310-PD14 polycrystalline silicon) is
159 representative of an average performing module with an efficiency of 15.7% and dimensions
160 1956 mm × 992 mm × 40 mm [57]. The modules were arranged between the trellises, at the same
161 height as that of the grapes, such that the center of the module is at the height of the grapes. The
162 farm considered for this case study is a square farm of 1 acre (i.e. 4,046 square meters). With the
163 side A measuring 63.6 m, the number of PV modules that could be arranged along the width are
164 32, whereas the number of rows assuming the widest inter-trellis spacing normally observed of
165 1.8m provides 17 rows.

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



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

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

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

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

195 4. Results and Discussion

196 4.1. Technical Performance of Grape-Based Agrivoltaic Systems

197 For a 1-acre farm with solar modules alone where modules are arranged in 17 rows and
198 32 columns physically, the potential array output is calculated to be 168.64 kW dc as the Trina
199 Solar TSM 310PD14 module has a maximum power output of 310W. The 1-acre farm
200 considered is assumed to be square and there must be a gap between the rows of modules to
201 prevent row to row shading and to allow for maintenance.

202 Next the agrivoltaic farm is considered with grape trellises spaced at 1.8 m. As the solar
203 modules are mounted in the row spacing between the trellises the desired array capacity is
204 expected to be low in comparison to the fully acquitted solar module field. But there would be an
205 added benefit of reduced inter-row shading on the modules (and the height is such that there is no
206 shading of the PV from the grape vines). A sensitivity was run on the annual electricity
207 generation as a function of tilt angles of the solar modules in both agrivoltaic setup and pure
208 solar farm. The results showed that a fixed optimal tilt angle of 21° maximized PV output
209 (259,826 kWhr/year) in an agrivoltaic farm setup in Nagpur, India using a Trina Solar TSM
210 -310PD14 (1920 \times 992 \times 40) mm which is 32 modules wide and 17 rows facing due south. This
211 is the physical arrangement of the modules considered for maximum land coverage. The ground
212 coverage ratio (GCR) is assumed to be 0.26 to avoid shading as much as possible. The monthly
213 solar energy generation at the case location and can be seen in Figure 4. It should be noted that
214 the monsoon season is responsible for the reduction in output during June, July and August.

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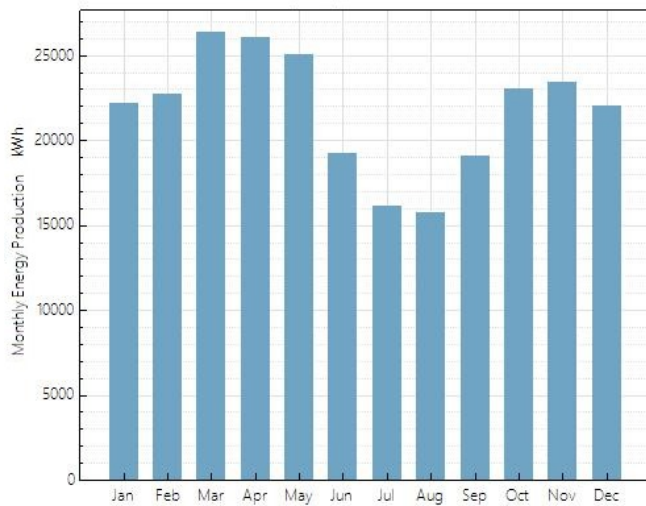


Figure 4. Monthly energy production from an acre of agrivoltaic solar farm in Nagpur, India.

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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.

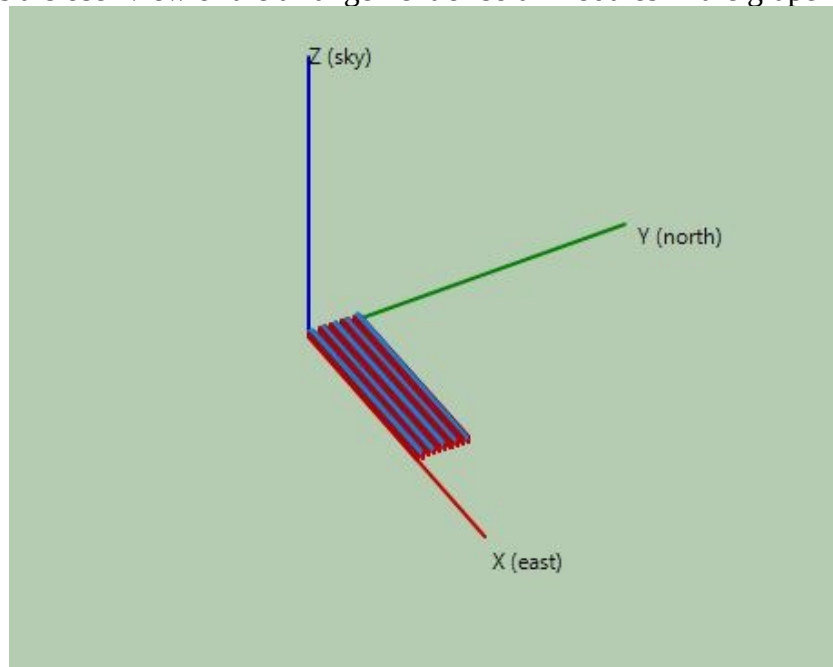


Figure 5a. Arrangement of solar modules (Bird's eye view)

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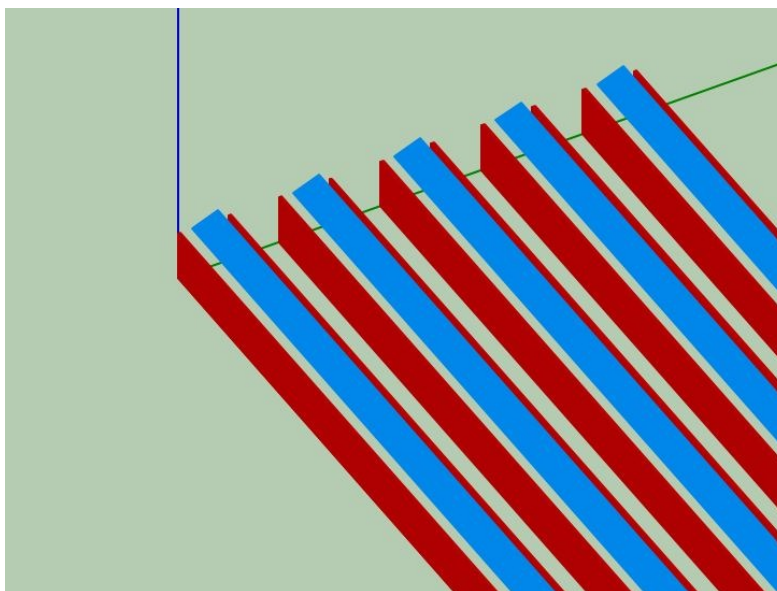


Figure 5b. Closer view of solar modules with trellises

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248 For the 84,015 acres of farm in India [61], the total maximum potential energy production
249 in grape farms with installation of solar PV panels can be scaled up to 21,829 GWh, which is
250 1.97% of 1107 billion units of energy produced in India in 2015-16 [44]. This energy is roughly
251 equivalent to the output of 3GW of coal plants working at 85%. This is the idealistic maximum
252 figure and to find the practical potential, various factors must also be considered. The most
253 important factor is the orientation of the grape crops.

254
255 This preliminary evaluation of orientation-based lost areas with Google Earth appeared
256 that there was no orientation bias in Indian vineyards. This resulted in a loss of approximately
257 23-25% of energy to the aligned direction farmlands. It should be pointed out that this was a
258 preliminary study and that future work using a more sophisticated statistical survey of all Indian
259 grape farms is needed. However, using these preliminary values as a base and including these
260 losses still could provide over 16,000 GWh a year of PV potential. According to the Central
261 Electricity Authority of India, the per capita electricity demand had reached 1,010 kWh in the
262 year 2014 [65], which means that agrivoltaic grape systems could conservatively service 15.8
263 million people. Lastly it should be pointed out that the case considered is for the city of Nagpur,
264 where the annual solar irradiation is above the average solar irradiation for India, so there would
265 also be large geographic variability on solar potential depending on the location, which could
266 again be determined with a more focused GIS-based study.

267 268 **4.2. Economic Performance of Grape-Based Agrivoltaic Systems**

269 Table 1 summarizes the revenue generated by the dual use of land for PV and grape
270 production. The total annual gross revenue from an acre of grape farm is \$1,420.93 (~INR
271 94981.84) [66] (using an exchange rate of ~66 Indian rupees per U.S. dollar), whereas that of
272 solar energy is the product of annual energy generated and cost of electricity. This comes out to
273 be \$20,786.06. Thus from the Table 1, it can be seen that the annual revenue for the grape
274 cultivator is increased by over 15 times if PV is installed between selected rows on a 1 acre farm.

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277 **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%

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

284
 285 **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

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

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

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

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

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331 4.3. Future Work

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

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

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

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

378

379 5. Conclusions

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

390

391 6. Acknowledgements

392

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395 about grape farms.

396

397 7. References

- 398 1. Solomon, S., Plattner, G.-K., Knutti, R., & Friedlingstein, P. (2009). Irreversible climate
399 change due to carbon dioxide emissions. *Proceedings of the National Academy of*
400 *Sciences*, 106(6), 1704–1709.
- 401 2. R.H. Moss, J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren the
402 next generation of scenarios for climate change research and assessment *Nature*, 463
403 (7282) (2010), pp. 747–756.
- 404 3. Mach, K. and Mastrandrea, M., 2014. *Climate change 2014: impacts, adaptation, and*
405 *vulnerability* (Vol. 1). Cambridge, New York, NY: Cambridge University Press.

- 406 4. Hansen, J., Kharecha, P., Sato, M., Masson-Delmotte, V., Ackerman, F., Beerling, D.J.,
407 Hearty, P.J., Hoegh-Guldberg, O., Hsu, S.L., Parmesan, C. and Rockstrom, J., 2013.
408 Assessing “dangerous climate change”: required reduction of carbon emissions to protect
409 young people, future generations and nature. *PloS one*, 8(12), p.e. 81648.
- 410 5. Stern, N.H., 2007. The economics of climate change: the Stern review. Cambridge
411 University press.
- 412 6. Droege P, Renewable Energy and the City: Urban Life in an Age of Fossil Fuel Depletion
413 and Climate Change, *Bulletin of Science, Technology & Society* 2002; 22(2),87–99.
- 414 7. Pimentel D., Ethanol Fuels: Energy balance, economics and environmental impacts are
415 negative, *Natural Resources Research*, June 2003; Volume 12, Issue 2, pp 127-134
- 416 8. El-Fadel M, Chedid R, Zeinati M, Hmaidan W. Mitigating energy-related GHG
417 emissions through renewable energy. *Renewable Energy*, 2003; 28(8), 1257–1276.
- 418 9. Sims REH. Renewable energy: a response to climate change. *Solar Energy*, 2004; 76(1-
419 3), 9–17.
- 420 10. Longo A, Markandya A, Petrucci M. The internalization of externalities in the
421 production of electricity: Willingness to pay for the attributes of a policy for renewable
422 energy. *Ecological Economics*, 2008; 67(1), 140–152.
- 423 11. Tsoutsos T, Papadopoulou E, Katsiri A, Papadopoulos AM. Supporting schemes for
424 renewable energy sources and their impact on reducing the emissions of greenhouse
425 gases in Greece. *Renewable and Sustainable Energy Reviews*, 2008; 12(7), 1767–1788.
- 426 12. Pandey A.K, Tyagi V.V, Sevaraj A/L Jayaraj, Rahim N.A, Tyagi S.K, Recent advances in
427 solar photovoltaic systems for emerging trends and advanced applications, *Renewable and
428 Sustainable Energy Reviews* 53 (2016) 859–884
- 429 13. Barker PP, Bing JM. Advances in Solar Photovoltaic Technology: An Applications
430 Perspective, *IEEE Power Engineering Society General Meeting*, 2005; 2, 1955–60.
- 431 14. Pearce JM, Photovoltaics - A Path to Sustainable Futures, *Futures*, 2002; 34(7), 663-674.
432
- 433 15. Feldman, D., Barbose, G., Margolis, R., James, T., Weaver, S., Darghouth, N., Fu, R.,
434 Davidson, C. and Wiser, R., 2014. Photovoltaic System Pricing Trends: Historical,
435 Recent, and Near-Term Projections. 2014 Edition. *Presentation by SunShot, US
436 Department of Energy, NREL/PR-6A20-62558*.
- 437 16. IEA. Technology Roadmap: Solar Photovoltaic Energy, 2014.
- 438 17. Prasad, D. and Snow, M., 2014. *Designing with solar power: a source book for building
439 integrated photovoltaics (BiPV)*. Routledge.
- 440 18. Jelle, B.P. and Breivik, C., 2012. State-of-the-art building integrated photovoltaics.
441 *Energy Procedia*, 20, pp.68-77.
- 442 19. Heinstejn, P., Ballif, C. and Perret-Aebi, L.E., 2013. Building integrated photovoltaics
443 (BIPV): review, potentials, barriers and myths. *Green*, 3(2), pp.125-156.
444
- 445 20. Wiginton LK, Nguyen HT, Pearce JM. Quantifying rooftop solar photovoltaic potential
446 for regional renewable energy policy, *Computers, Environment and Urban Systems* 2010;
447 34, 345-357.
- 448
- 449 21. Strzalka, A., Alam, N., Duminil, E., Coors, V. and Eicker, U., 2012. Large scale
450 integration of photovoltaics in cities. *Applied Energy*, 93, pp.413-421.

- 451 22. Nguyen HT, Pearce JM. Automated Quantification of Solar Photovoltaic Potential in
452 Cities International Review for Spatial Planning and Sustainable Development. 2013;
453 1(1), 57-70.
- 454 23. Bergamasco, L. and Asinari, P., 2011. Scalable methodology for the photovoltaic solar
455 energy potential assessment based on available roof surface area: further improvements
456 by ortho-image analysis and application to Turin (Italy). *Solar Energy*, 85(11), pp.2741-
457 2756.
- 458 24. Nguyen HT, Pearce JM, Harrap R, Barber G, The Application of LiDAR to Assessment
459 of Rooftop Solar Photovoltaic Deployment Potential on a Municipal District Unit,
460 Sensors. 2012; 12, 4534-4558.
- 461 25. Kodysh, J.B., Omitaomu, O.A., Bhaduri, B.L. and Neish, B.S., 2013. Methodology for
462 estimating solar potential on multiple building rooftops for photovoltaic systems.
463 *Sustainable Cities and Society*, 8, pp.31-41.
- 464 26. Nguyen HT, Pearce JM. Estimating Potential Photovoltaic Yield with r.sun and the Open
465 Source Geographical Resources Analysis Support System Solar Energy. 2010; 84, 831-
466 843.
- 467 27. de Wild-Scholten MJ, Alasema EA, ter Horst EW, Bachler M, Fthenakis VM. A Cost and
468 Environmental Impact Comparison of Grid-Connected of Rooftop and Ground Based PV
469 Systems, 21st European Solar Photovoltaic Energy Conference. 2006.
- 470 28. Bolinger M. Utility-Scale Solar 2012: An Empirical Analysis of Project Cost,
471 Performance, and Pricing Trends in the United States. 2012.
- 472 29. Fairley P. Big Solar's big surge, Spectrum, IEEE, 2015; 52(1), 41-44.
- 473 30. Nonhebel S. Renewable Energy and Food Supply: Will There Be Enough Land?
474 Renewable and Sustainable Energy Reviews. 2005; 9(2) 191–201.
- 475 31. Calvert K, Pearce JM, Mabee WE. Toward renewable energy geo-information
476 infrastructures: Applications of GIScience and remote sensing that can build institutional
477 capacity, Renewable and Sustainable Energy Reviews. 2013; 18, 416–429.
- 478 32. S. Nonhebel Renewable energy and food supply: will there be enough land? *Renew*
479 *Sustain Energy Rev*, 9 (2) (2005), pp. 191–201
- 480 33. United Nations Dept. of Economic and Social Affairs, 2014, Concise Report on the World
481 Population Situation in 2014. UN.
- 482 34. Denholm, P. and Margolis, R.M., 2008. Land-use requirements and the per-capita solar
483 footprint for photovoltaic generation in the United States. *Energy Policy*, 36(9), pp.3531-
484 3543.
- 485 35. Brown, L.R., 2008. Why ethanol production will drive world food prices even higher in
486 2008. *Earth Policy Institute*, 24.
- 487 36. Ford, C. and Senauer, B., 2007. How biofuels could starve the poor. *Foreign affairs*,
488 86(3), pp.41-53.
- 489 37. Tenenbaum D., Fuel vs Food: Diversion of crops could cause more hunger, *Environ*
490 *Health Perspect*, 2008; 116(6): A254-A257.
- 491 38. Dinesh, H. and Pearce, J.M., 2016. The potential of agrivoltaic systems. *Renewable and*
492 *Sustainable Energy Reviews*, 54, pp.299-308.
- 493 39. Ravi, S., Macknick, J., Lobell, D., Field, C., Ganesan, K., Jain, R., Elchinger, M. and
494 Stoltenberg, B., 2016. Colocation opportunities for large solar infrastructures and
495 agriculture in drylands. *Applied Energy*, 165, pp.383-392.

- 496 40. Marrou H, Wery J, Dufour L, Dupraz C. Productivity and Radiation Use Efficiency of
497 Lettuces Grown in the Partial Shade of Photovoltaic Panels, *European Journal of*
498 *Agronomy*. 2013; 44, 54–66.
- 499 41. Cossu Marco, Murgia Lelia, Ledda Luigi, DeligiosA. Paola, Sirigu Antonella, Chessa
500 Franseco, Pazzona Antonio, Solar radiation distribution inside a greenhouse with south-
501 oriented photovoltaic roofs and effects on crop productivity, *Applied Energy* 133 (2014)
502 89–100
- 503 42. Chhablani J., October 20 2012, Occupation of India, Available at
504 <http://www.slideshare.net/jashithchhablani/occupation-of-india>
- 505 43. The World Bank, Access to electricity (% of population), Available at
506 <http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS>, (accessed on 11th April, 2016)
- 507 44. Ministry of New and Renewable Energy, Government of India, <http://www.mnre.gov.in/>
- 508 45. Phukan R. S., 30 July 2014, Solar Energy in India – Pros, Cons and the future,
509 MapsofIndia.com, Available at [http://www.mapsofindia.com/my-india/india/scope-of-](http://www.mapsofindia.com/my-india/india/scope-of-solar-energy-in-india-pros-cons-and-the-future)
510 [solar-energy-in-india-pros-cons-and-the-future](http://www.mapsofindia.com/my-india/india/scope-of-solar-energy-in-india-pros-cons-and-the-future)
- 511 46. GAF Contributor, 26 August 2015, how much sun do grapevines need? Available at
512 http://www.gardenandflowers.com/info_8558829_much-sun-do-grapevines-need.html
- 513 47. National Horticulture Board Ministry of Agriculture and Farmers’ Welfare, Government
514 of India, <http://nhb.gov.in/pdf/fruits/grape/gra012.pdf>
- 515 48. Rodriguez A., How to grow grapes in mostly shade, Home Guides, SF Gate, Available at
516 <http://homeguides.sfgate.com/grow-grapes-mostly-shade-33175.html>, (last accessed 1
517 March, 2016)
- 518 49. Discovered India, Nashik. [http://www.discoveredindia.com/maharashtra/cities-and-](http://www.discoveredindia.com/maharashtra/cities-and-destinations-in-maharashtra/nashik.htm)
519 [destinations-in-maharashtra/nashik.htm](http://www.discoveredindia.com/maharashtra/cities-and-destinations-in-maharashtra/nashik.htm)
- 520 50. Personal communication with Mr. Gopal Bhattad, grape cultivator from Vinchur, Nashik,
521 India.
- 522 51. Bhave, A.G., 1994. Potential for solar water-pumping systems in India. *Applied energy*,
523 48(3), pp.197-200.
- 524 52. Kumar, A. and Kandpal, T.C., 2007. Renewable energy technologies for irrigation water
525 pumping in India: a preliminary attempt towards potential estimation. *Energy*, 32(5),
526 pp.861-870.
- 527 53. Surendra, T.S. and Subbaraman, S.V.V., 2002, May. Solar PV water pumping comes of
528 age in India. In *Photovoltaic Specialists Conference, 2002. Conference Record of the*
529 *Twenty-Ninth IEEE* (pp. 1485-1488). IEEE.
- 530 54. Purohit, P. and Kandpal, T.C., 2005. Solar photovoltaic water pumping in India: a
531 financial evaluation. *International Journal of Ambient Energy*, 26(3), pp.135-146.
- 532 55. Meah, K., Ula, S. and Barrett, S., 2008. Solar photovoltaic water pumping—opportunities
533 and challenges. *Renewable and Sustainable Energy Reviews*, 12(4), pp.1162-1175.
- 534 56. National Renewable Energy Lab. System Advisor Model (SAM). <https://sam.nrel.gov/>
- 535 57. Trina Solar, Trina Solar TSM-310PD14 (310W) Solar Panel. Specification sheet.
- 536 58. GAF Contributor, 26 August 2015, how much sun do grapevines need? Available at
537 http://www.gardenandflowers.com/info_8558829_much-sun-do-grapevines-need.html
- 538 59. timeanddate.com, <http://www.timeanddate.com/sun/india/nashik?month=12&year=2015>,
539 (last accessed 6 March, 2017)
- 540 60. Buckley T., Briefing Note, Indian Power Prices. May 6, 2014. Institute for Energy
541 Economics and Financial Analysis.

- 542 61. Shikhamany S. D., 'Grape production in India', National Research Centre for Grapes,
543 India, Available at <http://www.fao.org/docrep/003/x6897E/x6897e06.htm>, (last accessed
544 30th March, 2016)
- 545 62. Philip, V.V. India's per capita electricity consumption touches 1010 kWh. Indian power
546 sector. Available: [http://indianpowersector.com/2015/07/indias-per-capita-electricity-](http://indianpowersector.com/2015/07/indias-per-capita-electricity-consumption-touches-1010-kwh/)
547 [consumption-touches-1010-kwh/](http://indianpowersector.com/2015/07/indias-per-capita-electricity-consumption-touches-1010-kwh/)
- 548 63. Central Electricity Authority of India Power Sector at a Glance.
549 <http://powermin.nic.in/power-sector-glance-all-india>
- 550 64. Shah D, 'Assessing economics of grape cultivation in India', 9th July 2007, Munich
551 RePEcArchive, Available at [https://mpra.ub.uni-](https://mpra.ub.uni-muenchen.de/3927/1/MPRA_paper_3927.pdf)
552 [muenchen.de/3927/1/MPRA_paper_3927.pdf](https://mpra.ub.uni-muenchen.de/3927/1/MPRA_paper_3927.pdf)
- 553 65. Phinikarides, A., Kindyni, N., Makrides, G. and Georghiou, G.E., 2014. Review of
554 photovoltaic degradation rate methodologies. *Renewable and Sustainable Energy*
555 *Reviews*, 40, pp.143-152. Jordan, D.C. and Kurtz, S.R., 2013. Photovoltaic degradation
556 rates—an analytical review. *Progress in photovoltaics: Research and Applications*, 21(1),
557 pp.12-29.
- 558 66. Branker, K., Pathak, M.J.M. and Pearce, J.M., 2011. A review of solar photovoltaic
559 levelized cost of electricity. *Renewable and Sustainable Energy Reviews*, 15(9), pp.4470-
560 4482.
- 561 67. Domingues, F. and del Aguila, J.S., 2016. The cost of grape mechanical harvesting is
562 more economical than the manual harvest?. In *BIO Web of Conferences* (Vol. 7, p.
563 01023). EDP Sciences.
- 564 68. Pellenc. Self-propelled OPTIMUM. Available at
565 <http://www.pellenc.com/agri/produits/self-propelled-optimum/?lang=en> (last accessed 9
566 July 2017).
- 567 69. Guha P., 2006, 'Betel leaf: the neglected gold of India', Agricultural and Food Safety
568 Department, Indian Institute of Technology, Kharagpur, *J. Hum. Ecol.*, 19(2): 87-93.
- 569 70. Pin, K.Y., Chuah, T.G., Rashih, A.A., Law, C.L., Rasadah, M.A. and Choong, T.S.Y., 2009.
570 Drying of betel leaves (*Piper betle* L.): Quality and drying kinetics. *Drying Technology*, 27(1),
571 pp.149-155.
- 572 71. Ripoche, A., Celette, F., Cinna, J.P. and Gary, C., 2010. Design of intercrop management plans to
573 fulfil production and environmental objectives in vineyards. *European Journal of Agronomy*,
574 32(1), pp.30-39.