Potential of Agrivoltaics to Contribute to Socio-Economic Sustainability: A Case Study in Maharashtra / India

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Abstract. In the ongoing energy transition in India, ground mounted photovoltaic (GM-PV) plays a crucial role which becomes evident when looking at both governmental PV targets and recent developments. Despite cost-effectiveness speaking in favor of GM-PV, generally, a major drawback of GM-PV is the high land usage. One possibility to overcome conflicting interests of land use is agrivoltaics – a combined land-use for food and electricity production.

This paper summarizes the findings of a feasibility study on a 50 MWp agrivoltaic project in Maharashtra conducted by Fraunhofer ISE in 2018/2019 focusing on social impact and economic viability. The analyses indicate that an agrivoltaic system appears economically feasible with expected levelized cost of electricity (LCOE) of INR 2.02 (EUR 0.0243) already including cost on water management, rainwater harvesting, water storage, and irrigation. Depending on the institutional arrangement between the farming community and the investor, the social impact is expected to vary from high benefits to risk of severe poverty among affected farmers.

Further findings indicate that the use of bifacial glass-glass PV modules raises electrical yield by 6.4% compared to mono facial modules. Regarding land use, the study suggests that the analyzed agrivoltaic system is likely to almost double average land use efficiency measured by the combined output of electricity and agriculture per unit of land (+94%).

INTRODUCTION

While recent developments in photovoltaics (PV) generally facilitate a more sustainable power generation, large ground-mounted PV (GM-PV) systems frequently seal arable causing a realistic threat to farmers who, in densely populated regions, compete with PV investors. Considering the predicted rise of global PV capacity from 385 GWp in 2017 to 8,500 GWp in 2050, this situation is expected to aggravate within the next decades [1].

In the ongoing energy transition in India, these challenges become evident when looking at both governmental PV targets and recent developments. While land-neutral roof-top PV accounts for 40% of India's 2022 development goals, with 60% the largest share of all PV technologies is designated for utility-scale GM-PV [2]. The growing population and adverse effects of climate change are further challenging Indian's agriculture sector leading to a substantial decline of arable land per capita on the subcontinent within the last 50 year.

One possibility to overcome conflicting interests of land use is agrivoltaics – a combined land-use of food and electricity production. In recent years, agrivoltaics has experienced a very dynamic development and spread in almost all regions of the world. The installed agrivoltaic capacity increased exponentially from approx. 5 MWp in 2012 to approx. 2,2 GWp in 2018, with governmental support schemes in Japan (since 2013), China (approx. 2014), France (since 2017), the Massachusetts/USA (since 2018), and, most recently, Korea [3].

This paper summarizes the results of an agrivoltaic feasibility study conducted for a project site in Maharashtra, Western India, where an investor considered installing a GM-PV system on more than 100 ha of fertile agricultural land which today serves as the livelihood of more than 100 farmers and their families. Main aim of the study is to assess the economic and technical viability and to scope the potential of agrivoltaics to contribute to socio-economic sustainability in the project region.

After providing an overview of the of the project site, in Section 3 we present the proposed technical design of the agrivoltaic system highlighting the expected performance of the PV system. Section 4 sheds light on the institutional setup of the involved stakeholders assessing the different motivations of and incentives for participating in an agrivoltaic solution. Section 5 presents the results of a detailed analysis of cost and revenues of the agrivoltaic system considering typical expected yields of both the agricultural and electrical layer. A final section discusses the results and concludes.

The results of the study indicate expected levelized cost of electricity (LCOE) of INR 2.02 (EUR 0.0243) already including cost on water management and irrigation. Regarding socio-economic sustainability, the agrivoltaic system is expected to largely raise employment compared to a mono land use and to strongly increase land use efficiency. Further, the results suggest the installation of bifacial PV modules.

Overall, if social criteria are considered and affected farmers are involved in the decision making, a realization of the agrivoltaic system appears eligible to serve as a lighthouse project for future activities with high expected reputational benefits for involved stakeholders and effective contributions to the Sustainable Development Goals (SDGs) of the United Nations.

PROJECT SITE AND SOCIAL BACKGROUND

Since several decades, the investor of the intended agrivoltaic project owns and runs a thermal power plant (TPP) close to the project site. The TPP has been boosting the economy of the small village in myriad ways and there has been a symbiotic relationship between the farming community and the TPP management as reported by members of the local community.

The operator of the TPP has acquired land from farmers multiple times since its beginning i.e. before the first commissioning and for later expansions of its capacity. Additional to compensation commensurate, the TTP management provided jobs for affected farmers. Today, more than 1,500 workers are employed at the TTP. According to interviews with stakeholders and given the long-term benefits and steady income, a job at the TPP holds a high aspirational value for the agrarian community in the region as reported in interviews with farmers. A strong desire for a steady income and a relatively high level of despair among the rural population appears plausible as the region suffers a high number of suicides of farmers.

In 2011 and 2012, further expansion of the TPP was envisaged and the neighboring 125 hectares of land belonging to 124 farmers were acquired. According to information gathered during the fieldwork done in September 2018, in which informal and unstructured interviews were conducted with individual farmers, farmers groups, local staff of the TPP and local residents, it was evident that farmers were not keen to part with their land as this was the most fertile land parcel in the vicinity. However, appropriate compensation and the perspective of getting employment at the TPP were the incentives committed, if farmers agreed to give away their land. Subsequently, leaving aside 2-4 families, the majority of farmers agreed to give up their land entitlements. For some farmers, this resulted in becoming entirely landless or homeless.

As in the following years the Indian energy policy changed starting to support the deployment of renewable energies, the envisaged expansion of the TPP did not happen but, instead, plans for installing a GM-PV arose. Meanwhile, the farmers were allowed to continue farming on the land without paying land rent to the TTP as the land owner. Due to uncertainty, no farmer invested in irrigation arrangements or wells. Farmers reported that only a few farmers could get a permanent job at the TTP. According to the TTP management, the reason for his low engagement rate was due to the low education level of most farmers.

For the analyses in this report, we assume that from the 125 ha of acquired land 100 ha will be used for PV generation. The inclination profile is relatively flat with slopes not exceeding 4%. The climate is semi-arid with a dry and a wet season. The dry season from November to May is especially water scarce with almost no precipitation at all. Following climate change perspectives, the historical average precipitation of 891 mm will decrease in future

[4,5]. Already today, the groundwater is under stress and future availability for irrigation is categorized only as medium. Hence, ground water extraction seems recommendable neither for panel cleaning nor for crop irrigation in order to assure sustainability of the agrivoltaic project.

PROPOSED TECHNICAL AND AGRICULTURAL DESIGN

Cotton, soybean, sorghum and pigeon peas are the main crops grown in the studied region. During the investigations, present agriculture at the project site was primarily based on low mechanized pulse cropping largely growing soybean and pigeon peas. Yields were mainly marketed at two local markets in a distance of 30 and 50 kilometers, respectively.

For our analyses, we targeted at crops that appear promising with respect shade tolerances and sheltering benefits, local growing conditions, and farmers' agricultural skills. Further, we selected analyzed crops to represent a sufficient range of different requirements and economic characteristics to set up an agrivoltaic system that appears flexible enough to allow for different agricultural approaches regarding irrigation needs, investment requirements, marketing opportunities, and profit margins. The selected crops are cotton (Gossypiumarboreum), soybean (Glycine max), tomato (Solanum lycopersicum), and banana (Musa acuminate).

Generally, whether crops benefit from shade or shelter does not only depend on crops' characteristic but also on the local climate and weather conditions. A crop generally regarded as sun-loving might produce higher yields even in the shade of PV panels if there is too much heat and sun or too little rain during the growing period and vice versa. Still, according to shadow and shelter experiments, yields of cotton and tomato tend to be more suitable for agrivoltaic applications than soybean and banana in most conditions (for cotton see [6]; for tomato see [7], and [8] for soybean see [9], [10], and [11]; for banana see [12], [13], and [14]). Table 1 illustrates stylized characteristics of selected crops.

	Cotton	**Soybean**	**Tomato**	**Banana**
Shading and sheltering benefit	High	Low	High	Medium
Irrigation need	Low	Low	Medium	High
Farmers' agricultural know-how	High	High	Low	Low
Marketing opportunities	High	High	Low	Low
Investment requirements	Low	Low	Medium	High
Profit margin	Medium	Low	High	High

TABLE 1: Main criteria for the selection of analyzed crops.

The irrigation requirements represent additional water that must be added to the precipitation to ensure theoretical optimal crop growth. The requirements stayed the same for the 1st and 2nd year. For cotton, tomato and soy bean 249, 83.6 and 14 mm per m^2 respectively must be added.

As tomato and soybean seem theoretically feasible without or only marginal additional irrigation during wet season, cotton would require additional water resources of at least 500 to 1,000 m³ per ha. The cultivation of banana on 100 ha would heavily impact the ground water resources of the district. With an annual ground water recharge rate of about 5.25 MCM, the required 1.2 MCM of annual irrigation of banana plantation clearly indicates that a cultivation of banana is not sustainable in this water-stressed region[15]. Smaller plots of bananas might still be feasible if rainwater or surface waters are used in combination with drip irrigation. As the soil at project site is generally well suited for Banana and may generate high revenues we consider Banana growing to some extent.

The technical agrivoltaic design (see figure 1) deviates from purely south oriented PV modules in order to ensure a homogenous distribution of sunlight below the PV modules. The geometric parameters are specified at a vertical clearance of 4 meters, a row distance of 5 meters, an orientation towards south west of 208 degree (corresponding to a 28 degree deviation from full south), and a fixed tilt of PV modules of 22 degree. Further, we considered bifacial PV modules as our analyses clearly favored them compared to monofacial modules from both technical and economic perspective. Table 3 provides an overview of the agrivoltaic system's parameters.

Geometry parameters	**Unit**	**Value**
PV module row width	[m]	1.85
Row distance	[m]	5.00
Vertical clearance	[m]	4.00
Distance between pillars (vertical to rows)	[m]	7.00
Distance between pillars (horizontal to rows)	[m]	5.00
Coverage rate, birds-eye perspective	[%]	37.1

PV module parameters	**Unit**	**Value**
Ground albedo	[%]	20
Bifaciality of PV modules	[%]	70
PV module power	[Wp]	370 W
PV cell type	[-]	monocrystalline
Modul width	[mm]	992
Modul length	[mm]	2,000
System parameters	Unit	Value
Number of modules per string	[No.]	20
Number of strings per inverter	[No.]	10
DC-power of inverter	[kW]	67.3
AC-rated power of inverter	[kW]	60

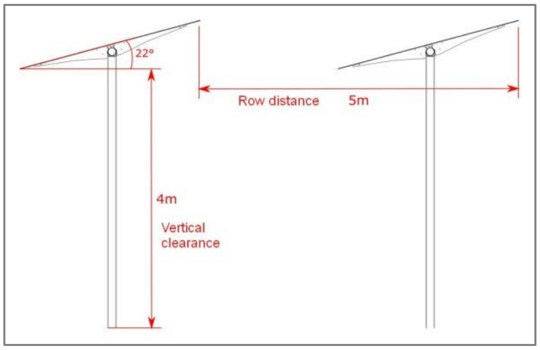

FIGURE 1: Technical design of the agrivoltaic system.

TABLE 2: Overview of the main parameters of the proposed agrivoltaic system.

The theoretic capacity of this system design amounts to 746 kWp per hectare. This does not consider border margins, access routes or facility buildings that might be required and reduce the PV capacity per area of land.

INSTITUTIONAL ANALYSIS

From an institutional perspective, the scoping mission in September 2018 indicated, that the main challenge of the project lies in the present mistrust of farmers against the TPP operator and the threat of farmers' resistance against a PV project. Though, generally, the TPP operator enjoys a good reputation among the local population as the TPP provides jobs and enhances prosperity in the region since several decades. Still, given the political economy associated with land acquisition and assured jobs, utilizing the land without the acceptance of local farmers bears a mentionable economic and reputational risk.

To assess different institutional arrangements, we consider the three involved main stakeholders: The investor and owner of the TPP; the affected farmers and former land owners; and the financier of the project, a German development bank. The financier plays a crucial role in the project since socio-economic sustainability of its investments is of high priority. Accordingly, it was the financier who initially considered the approach of implementing agrivoltaics instead of a GM-PV because sealing of the fertile soil and the loss of livelihoods of farmers could not be reconciled with its investment strategy.

In Table 4 we provide an overview of three possible scenarios.

Scenario	Characteristics
1) No cooperation between farmers and investor, investor tenders land for farming	The investor reinforces the ownership and lances a bidding process to allocate the project to the highest bidder for farming. The investor builds and maintains the agrivoltaic power station. Farmers or land tenants choose the crops they want to grow with the sunlight available. There is minimum transaction and interaction between the electricity and

	agriculture layer. Inhabited houses on the project site will be removed.
2) Basic land agreement between farmers and investor	The investor installs an agrivoltaic power station and allows farmers to continue using the land for agriculture. They allow farming on their land in-lieu of the jobs committed earlier and do not charge land rent from farmers. For hiring staff to protect and maintain the agrivoltaic power station, the investor aims at primarily employing affected farmers. Also, a preliminary agriculture crop plan is suggested to farmers to help them utilize the land efficient according to agrivoltaic growing conditions. Inhabited houses on the project site will be removed but the investor provides land elsewhere for homeless families.
3) Symbiotic relationship between farmers and investor	The investor installs the agrivoltaic power station and shares a small percentage of energy sale revenue with farmers' community as maintenance charge. Farmers organize themselves into a local institution (company or cooperative). The local institution will systematically manage the maintenance, with the support of the investor and apply agricultural strategies tailored to the growing conditions of the agrivoltaic system. Inhabited houses on the project site remain and affected families are employed for staff and security personal.

TABLE 3: Stylized institutional scenarios.

In the following table 5 a comparision of expected qualitative costs and benefits for different stakeholders can be found.

		Stakeholder		
	Scenario	**Investor**	**Financier**	**Farmers**
Financial	(1)	Low cost on the short run. Additional income from land rent. Social unrest in the village may result in difficulty in construction and operational phases.	Higher financing risk due to increased risk of social unrests. No additional investment for training and coordination of farmers required. Negative branding.	Very low chance of being competitive within the tender. Probable (partial) loss of income and livelihood.
	(2)	Higher transaction cost for dealing with farmer. No revenues from land rent. Higher social acceptance might reduce security cost. Still, uncertainties of farmers with respect to the agrivoltaic technology and the future level of agricultural yield might trigger social unrests.	Lower financing risk due to decreased risk of social unrests. Minor increased investment requirements for farmers' training.	Farmers can maintain income from farming but partial adjustment to agrivoltaic growing conditions might be required. Additional income possible for maintenance and security works. Financial risks remain with respect to unknown agrivoltaic technology
	(3)	High transaction cost and no revenues from land rent. Additional costs for PV dividend payments. Higher social acceptance is likely to reduce cost on security and maintenance.	Low financing risk due to little risk of social unrests. Additional investment required for training and organisation of farmers.	High initial in-kind investment needed for training and organisation. Steady income and high financial security. Lower risk of poverty due to income from both crop and energy production.
Social	(1)	High social cost as	High social cost conflicts	Loss of livelihood might

		farmers may lose income from farming.	with investment strategy. This might result in negative publicity for both the financier and the agrivoltaic technology in general.	result in extreme poverty. Risk of unrests and potential suicides among farmers might increase
	(2)	Low social cost and possible strengthening of reputation among local population. Increased but minor risk of envy driven objections against involved farmers from farmers not having sold their land to investor. Lack of proper cultivation techniques might incentivize farmers to sabotage PV panels to maximize sunlight penetration for better yields.	Low social cost and possible gains in reputation for supporting innovative solutions of dual land-use in a sustainable social manner.	Additional income for maintenance and security works enhances social situation of farmers compared to status quo. Still, uncertainties remain with respect to social acceptance of agrivoltaic technology. Reduced income due to lack of proper cultivation techniques.
	(3)	A strong institutional cooperation with farmers' community is expected to increase visibility and social acceptance of the agrivoltaic technology. Project may enhance the investors' CSR reputation in and beyond the project region.	Reputational gains expected for supporting innovative technologies in an innovative and socially sustainable approach. High overlap of project outcome and strategic financing goals.	Reduced vulnerability and good support to challenge uncertainties with respect to agrivoltaic technology. Social advancement due to income diversification and educational trainings.
Political	(1)	Locally, high social cost might result in loss of political power. On state and nation level, still, a general acknowledgement of the project is expected.	High social cost defeats the purpose of development bank and may adversely affect the reputation of German development cooperation strategy.	Farmer may retreat to social unrest and radical political organizations.
	(2)	No or minor cost and benefits on local level expected.	No or minor cost and benefits expected.	Farmers remain sovereign with respect to land and agricultural decisions.
	(3)	Showcase of SCR, lighthouse effect, blueprint for subsequent projects. Emancipated farming community might reduce the investor's power on the long run.	High acknowledgment from stakeholders.	Shift of status increases the political influence of farmers. Social "saboteurs" among community members.

TABLE 4: Qualitative cost and benefit comparison of institutional scenarios.

ECONOMIC ANALYSIS

To assess the typical initial annual electrical yield of the proposed design, we employed the Fraunhofer ISE`s inhouse simulation software ZENIT. A detailed description of the software can be found elsewhere [16][source ISE]. According to our simulations, typical initial annual yield amount to 1,713 kWh per installed kWp, thus a performance ratio of 84.8 %. With an expected probability of 10% the initial annual electrical yield indicates 1,552 kWh per kWp or below. On the other hand, with an expected probability of 10% the initial annual electrical yield amount to 1,874 kWh per kWp or above.

Simulating the same system configuration, bifacial modules produced a result 6.4% above the electric yield of mono-facial modules. A comparative electrical yield assessment for a monofacial module with similar electrical properties results on 1,604.4 kWh/kWp and a performance ratio of 79.4%.

To assess agricultural yield, the irradiation simulation based on the proposed system geometry concluded with an average annual photosynthetically active radiation (PAR) of 62%. We considered high mechanization as a precondition for the expected land losses in order to anticipate further agricultural development. Such land losses were estimated to be 6% for cotton, 4% for tomato, 9% for soy bean and 3% for banana. The agricultural yield assessments suggest a yield increase of 33% for cotton and 11% for tomato. Yield reductions can be expected for soy bean (17%) and for banana (20%). The standard yields were estimated by local agriculture experts. The results of the agricultural yield assessment can be found in Table 6.

Crop	**Total cost [INR/ha]**	**Yield [kg/ha]**	**Sales price [INR/kg]**	**Gross income [INR/ha]**	**Net income [INR/ha]**
Soybean	20,250	2,155	30.5	65,736	45,486
Cotton	59,500	5,002	40.0	200,076	140,576
Tomatoes	78,583	19,993	9.0	179,939	101,355
Banana	87,375	44,928	5.0	224,639	137,264

TABLE 5: Results of agricultural yield assessment.

Most crucial assumptions of the economic performance assessment are a share of debt of 95% with weighted average cost of capital (WACC) of 1.4425%, a debt financing of 95%, and electrical producer prices per kWh of INR 3.79. For the dynamic investment calculation, however, we assumed a slightly higher discount rate of 3% (see figure 7).

Parameter	**Unit**	**Value**	**Parameter**	**Unit**	**Value**
Durability	[a]	25	Corporate tax rate	[%]	35
Share of equity	[%]	5	Cost of debt	[%]	1.0
Share of debt	[%]	95	WACC	[%]	1.4425
Risk factor	[-]	2	Exchange rate	[EUR/INR]	0.012
Risk-free Rate of Interest (rf)	[%]	1.5	General inflation	[%]	3
Expected market return	[%]	9	Inverter replacement reserve inflation	[%]	-7
Market Premium (MP)	[%]	7.5	Crop producer price inflation	[%]	4.0
Cost of equity	[%]	16.5	Electricity producer price	[INR/kWh]	3.79

TABLE 6: Assumptions and Parameters for WACC and CAPM assessment.

In contrast to the report of the pre-feasibility study of 2019[17], we kept the parameters for the dynamic investment calculation the same, changed however the CAPEX and OPEX cost items due to updated benchmark figures (see table 8 & 9).

Capital expenditures (CAPEX)	**INR per kWp**	**INR lakh per ha**	**EUR per kWp**	**% of total CAPEX**
Modules	21,250	107.82	255	43
Inverter, trafo&combiner	5,707	28.96	68.48	11.6

Mounting structure &installation	16,327	82.84	195.93	33.1
Other BoS	797	4.04	9.56	1.6
Management	1,160	5.88	13.92	2.3
Land acquisition	794	4.03	9.53	1.6
Cleaning system	1,770	8.98	21.24	3.6
Water management system	1,535	7.79	18.42	3.2
Total CAPEX	49,383	250.57	592.6	100

TABLE 7: Expected capital expenditures of the proposed agrivoltaic system.

Operational expenditures (OPEX)	**INR per kWp**	**INR lakh per ha**	**EUR per kWp**	**% of total OPEX**
Inverter replacement reserve	100	0.51	1.2	10.8
Provision of repair services	166.67	0.85	2	17.
Management, insurance & other	391.67	1.99	4.7	42.2
Cleaning system	143.92	1.73	1.73	15.5
Water management system	180.56	1.52	1.52	13.6
Total OPEX	928.83	4.71	11.15	100.0

TABLE 8: Expected operational expenditures of the proposed agrivoltaic system over a period of 25 years.

Compared to conventional GM-PV the cost for mounting structures, site preparation and installation as well as for the cleaning and water management system, significantly increases the CAPEX and OPEX. Whereas for a conventional GM-PV power plant the CAPEX would range between INR 28,000 to 34,000, agrivoltaics accounts for around 30 to 40% higher investment excl. cleaning system and water management. At this point, however, it shall be considered that Indian benchmark figures from 2018 for rooftop PV range at fairly similar values between INR 47,153 (< 10 kWp) to INR 39,135 (> 500 kWp) [18].

In order to provide a better impression of the cost structure, the dynamic investment calculation includes different scenarios (see table 10):

- In the Low Cost Scenario we disregard earlier investments made on land acquisition, assume 30% and 15% lower cost on mounting structures and mounting & construction, respectively, and a higher future solar irradiation leading to 2% higher initial annual electric generation compared to the Baseline Scenario.
- In contrast, in the High Cost Scenario we assume 30% and 15% higher cost on mounting structures and on mounting & construction, respectively, and 2% lower initial annual electric generation.
- The “No Subsidy” Scenario includes the same cost figures as Baseline, yet a standard market discount rate of 9% and a electricity producer price of only 3.2 INR/kWh was applied.

	Unit	**Baseline Scenario [INR]**	**Baseline [EUR]**	**Low Cost Scenario**	**High Cost Scenario**	**No Subsidy Scenario**
CAPEX	[INR/kWp]	49,383	592.6	44,053	53,919	49,383
OPEX	[INR/kWp/a]	929	11.15	929	929	929
OPEX (PV)	[INR/kWp over 25 years]	21,039	252.47	21,039	21,039	11,073
Total cost (PV)	[INR/kWp over 25 years]	70,422	845.07	65,092	74,958	60,456
Electricity generation	[kWh/kWp]	1,713	1,713	1,747	1,679	1713
Revenues Electricity Sales (PV)	[INR/kWp over 25 years]	132,065	1,584	134,706	129,424	52,946
Net Earnings (NPV)	[INR/kWp over 25 years]	61,643	739	69,614	54,466	(-) 7,510
LCOE	[INR/kWh]	2.02	2.43	1.83	2.20	3.65
IRR	[%]	12.1	12.1	14.6	10.3	9.0

TABLE 9: Dynamic investment calculation and scenario analysis.

The scenario analysis also shows the significant impact of the low interest rate. The usual LCOE for large scale GM-PV in India at a market discount rate of 9% ranges around 2.6 to 3.0INR/kWh. Therefore LCOE values between INR 1.83 to 2.20 are to be seen in the light of low interest rates and high electricity producer prices. Within the context of real market rates and despite an IRR of 9%, the system would not reach a positive NPV and would not be competitive without lower interest rates and a producer price of above 3.7 INR./kWh. These figures clearly indicate the need for a promotion programme to overcome such financial barriers.

Main uncertainties of the economic analyses remain with respect to cost and revenue items that cannot be assigned clearly to the agricultural or the PV layer and, hence, depend on the business case arrangement with farmers.

DISCUSSION

The above presented LCOE values are far below European standard costs that range between EUR 0.07 to 0.12 [19]. The expected overall capital expenditures without water management and cleaning system range from about INR 41,000 to 49,000 per kWp and internal rates of return (IRR) from 10.3 % to 14.6 %.

The concept of the Land Equivalent Ratio (LER) was introduced by Willey (1985) [20] and enables to quantify land use efficiency of intercropping systems. It is frequently used in agroforestry, aquaponics and recently also agrivoltaics. LER shows the relative land area that is required for mono-production in order to achieve the yield of dual land use [21]. Willey (1985) specified the LER as the sum of the respective yield ratios of dual land use to mono land use:

$$LER = \frac{Yield_a(dual)}{Yield_a(mono)} + \frac{Yield_b(dual)}{Yield_b(mono)}.$$

Here, a and b represent the cultivated crop and electricity, respectively. The concept LER has been applied in this research in order to compare the productivity of the agrivoltaic system to single production of crops and of PV as well as to other agrivoltaic systems. The agricultural and electrical yield assessments suggests that over all four crops the average LER of the analyzed agrivoltaics system ranges around 194% indicating to almost double the land use efficiency compared to a mono cultivation of land.

This seems particularly relevant in the context of Indian’s high population density and – in several regions – its respective fierce scarcity of land. From the investor`s perspective, high initial costs on water management might seem as an unproductive burden at first sight. Though, if employed wisely, this could be a valuable and helpful asset for future discussions with the agricultural and political stakeholders.

Upcoming negotiations with regulatory authorities and stakeholders should clarify whether the required electrical tariff of INR 3.79 can be achieved or not. In the discussion, highlighting the expected beneficial social and environmental aspects as well as the future potential of agrivoltaics systems seems important to justify a higher electrical tariff.

Further studies on quantifying the societal added value of agrivoltaic systems in the Indian context might help to provide a solid basis for public decision makers.

REFERENCES

1. IRENA, *Global Energy Transformation: The REmap transition pathway - A Roadmap to 2050. Background report to 2019 Edition*, 2019.
2. M. K. Hairat and S. Ghosh, “100 GW solar power in India by 2022 – A critical review,” Renewable and Sustainable Energy Reviews **73**, 1041–1050 (2017).
3. S. Schindele, M. Trommsdorff, A. Schlaak, T. Obergfell, G. Bopp, C. Reise, C. Braun, A. Weselek, A. Bauerle, P. Högy, A. Goetzberger, and E. Weber, “Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications,” Applied Energy **265**, 114737 (2020).

4. TERI, *Assessing Climate Change Vulnerability and Adaptation Strategies for Maharashtra: Maharashtra State Adaptation Action Plan on Climate Change (MSAAPC)*, <http://www.moef.gov.in/sites/default/files/Maharashtra%20Climate%20Change%20Final%20Report.pdf>.
5. TERI, *Extreme Risks, Vulnerabilities and Community-based Adaptation in India (EVA). A Pilot Study*. Governing Climate Extremes in Maharashtra, <http://www.teriin.org/projects/eva/>.
6. D. Singh, “Effect of Low Light Intensity on Growth and Yield of Rainfed Cotton,” **Indian Journal for Plant Physiology** (1986).
7. A.M.R. Abdel-Mawgoud, S. O. El-Abd, S. M. Singer, A. F. Abou-Hadid, and T. C. Hsiao, “Effect of shade on the growth and yield of tomato plants,” Acta Hortic. (434), 313–320 (1996).
8. V. Hernández, P. Hellín, J. Fenoll, I. Garrido, J. Cava, and P. Flores, “Impact of Shading on Tomato Yield and Quality Cultivated with Different N Doses Under High Temperature Climate,” Procedia Environmental Sciences **29**, 197–198 (2015).
9. A. M. H. de Avila, J. R. Boucas Farias, H. Silveira, and F. Gustavo, “Climatic Restrictions for Maximizing Soybean Yields,” in *A Comprehensive Survey of International Soybean Research - Genetics, Physiology, Agronomy and Nitrogen Relationships*, edited by J. Board (InTech, 2013).
10. F. O. Odeleye, A. O. Togun, and T. O. Tayo, “Effects of depodding and light intensity on soybean (Glycine Max (L.) Merrill) in South West Nigeria,” Tropical Agriculral Research and Extension **7** (2004).
11. A. J. Zanon, N. A. Streck, and P. Grassini, “Climate and Management Factors Influence Soybean Yield Potential in a Subtropical Environment,” Agronomy Journal **108** (4), 1447 (2016).
12. U. Ghosh, N. Sarkar, K. Biswas, and Ranajit, “A review on performance evaluation of drip irrigation system in banana cultivation,” Journal of Pharmacognosy and Phytochemistry (2018).
13. Y. Israeli, Z. Plaut, and A. Schwartz, “Effect of shade on banana morphology, growth and production,” Scientia Horticulturae **62** (1-2), 45–56 (1995).
14. D. D. Pawar, S. K. Dingre, and P. G. Bhoi, “Productivity and Economics of Drip Irrigated Banana (Musa Spp.) under Different Planting and Fertigation Techniques in Sub Tropical India,” Communications in Soil Science and Plant Analysis **62** (3), 238 (2017).
15. CGWB, *Report On The Dynamic Ground Water Resources Of Maharashtra (2016-2017)*, <http://cgwb.gov.in/Regions/GW-year-Books/GWYB-2015-16/GWYB%20CR%202015-16.pdf>.
16. B. Müller, L. Hardt, A. Armbruster, K. Kiefer, and C. Reise, “Yield predictions for photovoltaic power plants: empirical validation, recent advances and remaining uncertainties,” Prog Photovolt Res Appl **24**, 570-583 (2016).
17. Fraunhofer ISE, *Feasibility and Economic Viability of Horticulture Photovoltaics in Paras, Maharashtra, India*, 2019.
18. UERC, *Public Notice Inviting comments on the Draft Order on Review of the Benchmark Capital Cost for Solar PV*, <http://www.uerc.gov.in/Draft%20documents/2018/26%20Public%20Notice_on%20Benchmark%20Capital%20Cost.pdf>.
19. M. Trommsdorff, “An Economic Analysis of Agrophotovoltaics: Opportunities, Risks and Strategies towards a More Efficient Land Use,” Constitutional Economics Network Working Paper Series (2016).
20. R. Mead, R. W. Willey, “The Concept of a ‘Land Equivalent Ratio’ and Advantages in Yields from Intercropping,” Experimental Agriculture **16**, 217–228 (1980).
21. C. Dupraz, H. Marrou, G. Talbot, L. Dufour, A. Nogier, and Y. Ferard, “Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes,” Renewable Energy **36** (10), 2725–2732 (2011).