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Agrivoltaics and Sustainable Energy Production: An Analysis of Theoretical Application on Indian Farms

Introduction & Overview of Problem

In a world where there are increased concerns about food security and availability, evaluations must be made in order to consider concrete solutions. This is especially true in the case of India - a country that is home to one of the world's largest populations (Routley, 2022) and one of the world's most challenging problems: how do we feed a growing population sustainably without using substantial amounts of agricultural land? India's farms are being tasked with feeding a peak estimate of 1.7 billion people by 2064 (Silver et al., 2023), and in order to meet the country's ambitious goals for adapting to the climate crisis, the government and individual farmers will need to work together in order to establish a solution. This solution will need to include renewable energy development to consciously grow India's energy capacity along with an understanding of the land availability needed for energy production projects.

The individuals who are at the forefront of needing change include the families who live throughout India, requiring future-proof methods of social and environmental sustainability. For an individual living in Uttar Pradesh, India's highest-income state on a monthly basis, expectations of a Rs. 20,730 (~\$240) monthly income is common (Acharya, 2024). With India's typical family size sitting at an average of 4.4 individuals (Global Data, 2021), there exists an inherent responsibility for communal care and support, even though services like healthcare sit at a comparatively low cost to other countries (Sengupta & Nundy, 2005). Some of these families could be part of the 39% of Indians who consider themselves vegetarians (PEW, 2021) abstaining from eating meat but still finding nutritious meals elsewhere. These meals could include that of rice, a common staple of several meals and a crop that has seen tremendous increases in yield in India over the past decade (USDA, 2025). Overall, the individuals in India have implications surrounding their livability and wellbeing, establishing importance for future developmental change.

There are notable problems in India existing in the form of environmental conditions. Air pollution is one of the most pressing issues in urban environments such as Delhi, where the air quality index (AQI) frequently exceeds a rating of 100 throughout the year (AQI.in). This issue has been consistent, and could be alleviated with the implementation of general renewable energy targets.

India's governing body has established a goal of achieving 500 GW (gigawatts) of renewable energy electricity generation capacity by the year 2030. As of 2023, the Indian government has reported bids for 50 GW of renewable energy capacity for each of the next 5 years (International Trade Administration, 2023). With the country recently surpassing 200 GW of renewable energy capacity, this puts the sector on pace to meet targets within the next 5 years (Ministry of New and Renewable Energy, 2024). However, this cannot be attained without notable steps in the social sector.

For sustainable development and renewable energy generation to occur, attention must be paid to

the people who are at the forefront of the effects of climate change. India faces issues in the rural sector of life, bringing great difficulty to a significant part of the country's population. The CIA World Factbook projects overall decreasing rural population growth for India in the near term. Regardless of this, the country will still have a large rural population that needs continual attention and support in the time it takes for their renewable energy goals to come to fruition.

Rural regions of India face decreased access to important electricity grid systems, resulting in the need for formation of several microgrid-like groupings. These microgrids will require power systems, which could easily come from renewable sources. Rural settings are often the areas that need important energy generation for places of learning, living, and growth. These are the areas that wouldn't typically have access to a profound grid system, preventing significant development. Unreliable and inefficient power in general has cost India nearly 4% of its annual GDP, signifying a need for change (The World Bank, 2018).

When observing some of the most important concepts in relation to rural development, access to education is apparent as one of the most important factors of analysis. Rural communities in any setting are likely to lack the important infrastructure that provides access to schools, libraries, and other academically-inclined facilities (Wood, 2023). Without this access, there is limited opportunity for students and societies to thrive as much as an urban population might due primarily to the disparity in electricity and infrastructure availability. Furthermore, India's population as a whole is very young, with a quarter (24.5%) being between the ages of 0-14 and with a majority (according to 2023 data) being between the ages of 20-24 (CIA, 2025). This significant statistic emphasizes the importance for education availability throughout the country, but with 64% of the population living in rural communities (World Bank, 2022a), there is an ever present need to address young individuals in less urban regions.

In addition to addressing education and overall infrastructure needs, India's population is notably undernourished. According to 2022 data, 14% of the total population is undernourished, up from 10% in 2018. This is compared to 7% of the total population of Indonesia, a neighboring country, being undernourished (World Bank, 2022b). In a country where 67.6% of land used for photovoltaics could be used for agriculture (Ortiz et al., 2022), this presents a large problem for food security and overall production for a significant population.

Solutions & Evaluation

The two ideas of agriculture and renewable energy can go hand-in-hand, creating a solution that can only be achieved through cohesive effort. Agrivoltaics is a key component of this, best defined as a situation in which a farmer is able to cultivate their crops (mostly shade tolerant) (Stawarz, 2024) while simultaneously hosting solar panels to generate electricity. Agricultural needs are significant in India due to its large population and demands as discussed before. With the introduction of agrivoltaics in several capacities (seemingly with boundless limitations even beyond crops), India will be able to reach its renewable energy capacity goals without worrying about the potential decrease in viable agricultural land. While considerations must be made for the types of crops cultivated based on their general shade tolerance, applications of the technology could be made elsewhere with land that is not cultivated for crops but instead livestock (Stawarz). These applications could also use different orientations of panels and placement based on use case, as seen in Figure 1.

Of course, there will be difficulties in the implementation of this technology. It is expected that the willingness of some individuals to adopt the new technology will be impeded by various outlying circumstances, which could prevent further exploration. However, with enough investment from both the government and private entities, India could see ease of access to more rural areas that may be target regions for implementation. To start, the country could begin by establishing energy rights, ownership of

energy produced at agrivoltaic sites, and how rights will be allocated throughout the country's farmers. This could generally ease the minds of the farmers in question, as their energy generation would be accounted for as an asset of production in addition to crops.

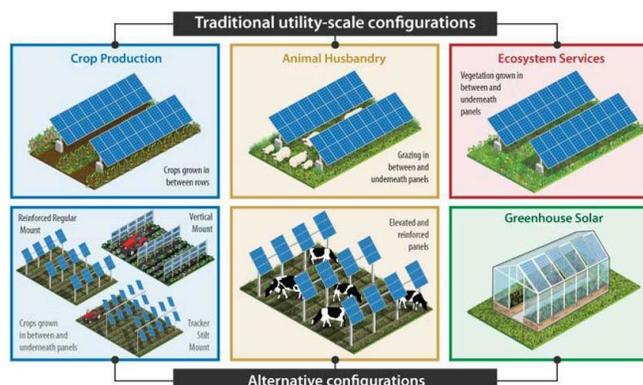


Figure 1. This chart shows the various different ways in which a solar energy system can be configured based on application and use case on farms. (National Renewable Energy Laboratory, 2022).

Furthermore, a financial incentive program could be established to reward farmers who use agrivoltaics in exchange for connections to the grids. A program of similar sorts exists in Massachusetts, where farmers who implement development of agrivoltaic technology can be compensated with up to \$0.06/kWh through the Solar Massachusetts Renewable Target (SMART) program (Williams et al., 2024). Though this particular program has significant barriers to what it classifies as acceptable for rebates, a program with fewer, yet still strict barriers, could be implemented in India to encourage the adoption of such technologies. A program in India could be more focused more directly on farmer compensation rather than the specifics surrounding panel implementation. In other words, as long as the panels are producing power and the farmer is producing product, compensation could occur from government incentive programs.

When looking at European implementation, a program in Germany awards farms implementing agrivoltaics with a “technology bonus” that still allows for 85% of standard agricultural subsidies provided by the EU (New Zealand Berlin Embassy, 2022). With this added incentive that keeps subsidies available, there would be a generally positive response to the benefits, provided they are able to work in conjunction with the agricultural operations undertaken. While the 2022 report says that stakeholders of the program are welcome to the idea, time will tell in terms of analyzing success. Despite these time-based shortcomings surrounding analysis, a program similar to this could be implemented in India without significant drawbacks. A “technology bonus” of sorts could be given to farmers that produce the highest amount of overall kWh, or could be given to the most agriculturally productive farms that are able to continue production with the added components of a photovoltaic system.

In addition to achieving its renewable energy goals through agriculture, India is able to take advantage of the vast amount of wind energy available. The Indian states of Gurjrat and Tamil Nadu are being identified as potentially positive locations for the implementation of offshore wind energy generation, with assessments suggesting that these two locations could provide a combined 71 GW of energy potential (Ministry of New and Renewable Energy, 2017). With India’s goal of achieving 500 GW of clean and renewable energy capacity, it becomes imperative that this concept be taken into account. Not only would the country see a tremendous amount of energy generated from ocean-based wind turbines, but they would also be able to retain the land that is needed for agricultural production. The water provides no feasible agricultural value, and thus can be used for its offering of wind. Furthermore,

offshore wind turbines are able to produce more energy than their onshore counterparts, reaching 15 MW per turbine as opposed to the roughly 3 MW achieved on land. This alone is a substantial reason to explore the potential of wind-based energy. However, with the costs associated with implementing several wind farms and turbines, this is not necessarily the most feasible concept. India has a much better opportunity to reach its goals with implementing solar energy as costs associated with this technology will inherently be lower than water-based technologies. The ease of access to individual grids will also be simpler with solar, allowing communities who may have agrivoltaic projects to directly benefit from their energy generation with increased energy availability and reliability.

With the installation of new wind turbines and solar technology, India can directly maximize its employment opportunities through the implementation of renewable energy infrastructure. With increased investment in infrastructure, there is an opportunity for the government to establish more job availability and further stimulate the economy. Additionally, with governmental assistance in providing incentives for agrivoltaic implementation on Indian farms, there would be an increased demand for employment in order to physically install panels due to an uptick in demand for incentives. Beyond this, governmental investments would require an overall increase in the aggregate supply of public/private partnerships, leading to increased employment on the governmental and organizational levels. These relationships with the government will involve individual action along with the establishment of organizations driven to enact change or install mechanisms to continue technology development, as is seen with programs like the National Solar Energy Federation of India. With the addition of capital investments that are needed to fully implement solutions, production will increase and require a large workforce paid for largely by the government. To fund this, federal taxes could be increased or levied on products that are derived from farms utilizing unsustainable practices identified by national surveying efforts. With this, the country will be able to encourage sustainable development on farms while also broadly funding the agrivoltaics installation incentive program.

While demand may not be initially apparent, there will be opportunity for new groups and organizations to reach rural communities directly and assess the practicality of reaching them. The government will need to invest, though not entirely directly. While India's goals of reaching 500 GW of renewable power generation are being invested in, they don't have to entirely be focused on agrivoltaics. The country is surrounded by ocean, and can take advantage of the potential for wind energy. Additionally, photovoltaic farms can be strategically placed in areas that are not ecologically or agriculturally significant to avoid environmental issues. Many regions in India see between 300 and 330 sunny days per year (Energy Efficiency & Renewable Energy Management Centre, n.d.), so it is important to take advantage of as much energy capacity as possible. Without taking advantage of these concepts and implementing renewable energy technologies, India will face a difficult path towards achieving full renewable capacity.

While India is relatively on track to achieve its renewable energy targets (increasing renewable energy capacity by a staggering 13.5% between 2023 and 2024) (Ministry of New and Renewable Energy, 2024), there are important steps that need to be taken, primarily in the agricultural sector. Agrivoltaics is one of the most practical, feasible, and efficient ways of achieving peak renewable energy capacity by 2030 while providing much-needed jobs and opportunities for investment by the government and private entities. Agricultural production can be managed sustainably while still being able to provide the land required for renewable energy projects, creating more broad food security across the country. With increased solar production in conjunction with a level agricultural sector, there is no doubt that the future will be bright for India's sustainability.

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