ALY – 6080 Integrated Experiential Learning Class

Individual Project Proposal

Implications of Agrivoltaics and Floating Solar Farms for Project Investment Feasibility and Their Potential Sustainable Development Benefits

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Abstract:

This study investigates the financial feasibility and social impacts of innovative solar power generation techniques, specifically agrivoltaics and floating solar farms. These technologies, which combine solar power generation with agricultural production or water-based installations, offer potential improvements in energy efficiency and provide social benefits such as enhanced food security, water conservation, and access to electricity in underdeveloped communities. The analysis employs statistical methodologies, including linear regression and Monte Carlo simulations, to assess the economic viability of these projects in comparison to traditional solar farms. The results show that agrivoltaic systems, with reduced construction costs due to shared land use, offer faster return on investment, while floating solar farms, although requiring higher initial construction costs, demonstrate higher power generation efficiency and greater potential for carbon dioxide emission reduction. In addition to inherent financial feasibility gains of these novel solar power generations techniques, this study also explores their potential social benefits. These social benefits range a multitude of aspects of development ranging from water preservation, food security, education and gender equality in under developed communities. Overall, both agrivoltaic and floating solar power generation technologies offer unique social benefits that are vital for tackling global sustainable development challenges.

Statement of Purpose

This study was conducted to explore the potential implications of agrivoltaics and floating solar farm projects on such clean energy generation projects' financial feasibility for investors and their impacts on social benefits to local communities in terms of access to electricity, food security, education levels and water scarcity in applicable locations. The increasing investments for these novel project types in the solar electricity production sector in the recent years already provide sufficient evidence for the power generation efficiency gains these projects yields thus increasing their profitability compared to traditional projects. However, such projects are almost exclusively enacted with the consideration of financial feasibility and profitability alone with some level of consideration for the additional value of carbon dioxide emissions avoided.

The main deliverable of this project, the projections of financial feasibility and their social impacts, were formulated for the purpose of providing evidence in support of proliferation of such projects whilst highlighting their societal development benefits.

Methodology

The results presented in this article were obtained through utilization of statistical methodologies such as Linear Regression and Monte Carlo simulations in order to provide data driven guidance to support potential future investment projects. Linear regression models are used to describe the relationships between variables, multiple linear regression is used when relationship between two or more independent variables and a dependent variable is being investigated (Bevans R, 2024). In this study, multiple linear regression was utilized to extract the range of monthly power generation based on installed capacity and ratio of energy generated in terms of peak sun hours to total day light hours. This range was later used in the Monte Carlo simulations for the power generation parameter values.

Monte Carlo simulations, also known as multiple probability simulations, is a statistical technique used to predict the probability of different outcomes influenced by random variables. The technique is particularly useful for prediction and forecasting models where impact uncertainty is a significant element (Kenton W, 2024). This study heavily relies on this technique, where probabilistic outcomes of three different solar farm configurations are investigated to guide investment decision making process.

All calculations presented in this document are completed in python programming language version 3.10 and its related libraries.

Project Scope

The introduction of carbon taxes and increased social pressure placed on corporations to decrease their carbon dioxide emissions led to the emergence of clean energy procurement sector and its intermediary actors. Powertrust, a Canadian clean energy procurement platform, offers such services to large corporations in countries where these clients have operations. By identifying suitable clean energy producers and certifying the electricity outputs of these partners, Powertrust and others in this sector also play a significant role in contributing to accountability of corporate sustainability reporting. The analysis presented in this report is largely based on the electricity generation metrics recorded at Powertrust's clean energy producer partner sites in 2023 with additional data sources imputated into the dataset for composition of site performance evaluation performance indicators.

Agrivoltaics is a recent trend in solar power generation projects where solar panel arrays are placed on top of food production farms to establish a mutually beneficial relationship for both activities. By providing shade over the food crops, the food production amounts observed to be increased in hot climates for certain produce items and via the evaporation of the moisture from the soil below, operating temperature of solar panels are observed to be lower yielding higher power generation efficiency levels with expanded operational life spans. Furthermore, due the shading provided by the over head solar panels, the water needs for the crops below observed to be decreased due to lower water loss to evaporation from direct sunlight exposure. (Williams, Hashad, Wang, Zhang, 2022).

The symbiotic relationship between energy and food production in agrivoltaic projects offers key benefits in under developed communities, the most important of which is the lack of competition over land use. In the past, some clean energy sources such as power generation dam construction and biofuel production projects came under public scrutiny and backlash due to their conflicting outcomes with agricultural food production that led to harmful implications for low income communities. When coupled with the suitable type of food crop production farms in locations that experience high weather temperatures, agrivoltaic projects provide production gains in both fronts and result in higher contribution to overall development of their communities.

Home grown school feeding (HGSF) activities are also a recent development in the nexus of development support and humanitarian assistance. HGSF projects involve inclusion of local farmers in the food supply chains of school meal activities that aim to elevate nutritional intake of school children and increase school attendance. (WFP, 2017) HGSF projects are often implemented in remote small communities that suffer from poverty and scarcity. Implementation of agrivoltaic for HGSF farms in such communities can deliver vital developmental gains to these communities through electrification in addition to the support it can provide to the HGSF activities in terms of higher crop yields.

Empirical evidence from multiple studies suggests that the potential gains in agricultural crop yields may lie between 20 percent to 60 percent for certain types of crops such as eggplant, strawberries, aloe, peppers (Enel, 2024). there are further studies which also concluded that there are positive gains in other food crops yields such as lettuce, spinach, tomatoes and carrots. (Enel, 2024). However, implementation of agrivoltaics in different shading configurations also resulted in decline of crop yields according to several studies hence prior to implementation establishing a targeted design specific to the crop type is crucial for obtaining positive gains. (Widmer, J., Christ, B., Grenz, J., & Norgrove, L., 2024) Furthermore, cultivation of certain food crops such as rice are found to be reduced in agrivoltaic configurations therefore significant consideration should be placed on avoiding detrimental returns for communities relying on such food crop production (Widmer, J., Christ, B., Grenz, J., & Norgrove, L., 2024). It should also be noted that most studies were conducted in optimum climatic environments in developed countries, thus the focus of the studies are placed on measuring the impact of agrivoltaic systems in such conditions. In locations where high weather temperatures are detrimental to agricultural production, the additional shading provided by the solar panels may lead to consistent improvements in crop yields and help tackle food insecurity.

Electrification of such communities can also lead to lower dependence on fuel generators, which is often the common practice in remote small communities that are not connected to the grid and decrease the cost of utilization of cold storage systems which are a crucial element in strengthening the food supply chains in low income communities. Inclusion of local farmers for HGSF activities already provides a higher sense of importance and ownership community members place on the education of children in these communities and with the additional benefits of electrification, the significance placed on schools in these communities is likely to be elevated potentially resulting in higher attendance rates. Home grown school feeding activities are often implemented by United Nations organizations and local ministries of education, potential partnership with such entities would also contribute to accountability aspects of the projects.

Floating photovoltaics is the second type of the suggested project configuration by this proposal. Solar panel arrays placed over large bodies of water such as lakes, reservoirs and channels gain power generation efficiency from the decreased operating temperatures of their environments while decreasing water loss to evaporation up to 70 percent (Perera, 2020). Similar to the agrivoltaic plants, a symbiotic synergy can be achieved where the mutual benefits of increased power generation efficiencies and lower water loss to evaporation can be obtained in the suitable locations. Empirical evidence from academic studies suggest power generation gains up to 10 percent (Kamuyu, W. C. L., Lim, J., Won, C., & Ahn, H., 2018). Water scarcity is an issue plaquing communities of all sizes and development levels. In the recent years many innovative solutions were explored to tackle water loss to evaporation due to rising temperatures in certain locations, including placing millions of black floating balls to cover the surface area of a key city water reservoir in Los Angeles, USA.

Underdeveloped communities however are far less under equipped to tackle this issue with such costly solutions. In poverty stricken communities higher levels of water scarcity further inflates food insecurity and poverty levels. When floating solar power plants implemented in such locations the shade provided by the solar arrays can decrease the water loss from evaporation thus help local economy via improving agricultural irrigation capacity. (Ilgen, Schindler, Wieland, 2023)

There two key potential benefits of solar power generation in this configuration, first the already mentioned higher efficiency of solar panels hence increased electricity output. The second is the potential to expand the locations in which solar power projects are profitable, previously deemed not financially viable sites can now be profitable if constructed in this manner. Due to efficiency losses to high temperatures, solar projects often avoid locations that experience high weather temperatures, However, in locations where large bodies of water exists, the power generation efficiency losses can be avoided hence rendering these locations financially feasible for realization of floating solar farm projects. Furthermore, if such systems are implemented where the reservoirs are suitable for conversion to pumped hydro storage systems, another additional benefit, storing energy on site and serving it throughout the day cycle is also gained. (energy.gov, 2024)

Background research and supporting literature

The following articles from previous academic studies were utilized to support the arguments put forward in this study. These studies present findings regarding the areas of solar power generation efficiency and financial gains in different project types as well as their potential benefits on linked social percussions.

Investigating the benefits of agrivoltaics applications in their article "The potential for agrivoltaics to enhance solar farm cooling" the authors, Henry J. Williams, Khaled Hashad, Haomiao Wang, K. Max Zhang, examine the potential improvements to solar farm power generation performance and social gains aspect of such installations by studying the evidence generated at an experimental agrivoltaics site. The article emphasizes the following two main points as an argument for the benefits observed. The first one is the lower ambient temperature levels which could enable longer life spans for solar panels. Their findings include up to 10 centigrade decrease in solar panel operating temperatures which could yield considerable extension of life over extended periods. The second, the added benefit of sharing the land, a limited resource, for growing food crops, agrivoltaics solar farms avoid competition for use of land between energy generation and food production which can be vital in less developed rural areas.

Studying the water evaporation rates and environmental impacts of floating photovoltaic systems in the article “Hybrid Floating Solar Plant Designs: A review.” The authors, Solomin, E., Sirotkin, E., Cuce, E., Selvanathan, S. P., & Kumarasamy, S. investigate a variety of floating solar farm installation configurations and provide an outlook for this growing segment of industry. Main findings of the article include power generation gain levels and water evaporation prevention levels at different study sites. The authors also include cost bearings of such installments and gains from the extended operational life of these site for related to investment costs and benefits of floating photovoltaic power generation farms. Amongst the high levels findings from their studies, they include water evaporation rate prevention up to 70 percent and additional installation cost up to 15 percent.

In his article “Access to electricity for all and the role of decentralized solar power in sub-Saharan Africa” the author, Kirsten Ulsrud, examines the challenges of achieving universal electricity access in sub-Saharan Africa, emphasizing the role of decentralized solar power. The author reflects on three research projects, which aimed to identify success factors and barriers to decentralized solar electricity provision in rural areas. Findings underline that a significant portion of the rural population remains without electricity, primarily due to poverty, geographical dispersion, and socio-economic factors. The research highlights that while decentralized solar power could complement centralized systems, it is often viewed as a competitive threat by energy sector stakeholders. Furthermore, the study reveals that gender plays a critical role in electricity access, with single women facing substantial barriers compared to men and couples. The gender income / pay gap in research locations directly affects their ability to secure electricity for essential services such as water, healthcare, and education.

The conclusions of the article call for enhanced institutional efforts and a shift in perception towards small-scale solar solutions, which are currently underrepresented in governmental and financing structures, in order to build a more inclusive energy framework that adequately supports vulnerable populations, particularly women. The article's focus on under developed countries makes it a valuable source for understanding the factors impacting the development of decentralized solar power generation plants in locations where Powertrust conducts business.

In their article, Agrivoltaics, a promising new tool for electricity and food production: A systematic review, authors Widmer, J., Christ, B., Grenz, J., & Norgrove, L. synthesizes findings form multiple studies on the symbiotic relationship between food and power generation in agrivoltaic solar power generations farms. Furthermore, the studies included in the article also contain mix of agrivoltaics with animal husbandry studies for expanded coverage on the subject.

The article presents key findings from the studies its based on in the form or data tables where the specific finding measurements are shared in detail such as percentage of crop yield changes, the size of installation area, change in crop yield growth such as leaf, fruit and stem sizes. The detailed listing of findings from the studies included provide valuable insights for which combinations of food crops and agrivoltaics yield higher benefits. The findings listed in the article contribute significantly to the suggestions made in the project proposal.

In the article, Prediction model of photovoltaic module temperature for power performance of floating PVs, the authors Kamuyu, W. C. L., Lim, J., Won, C., & Ahn, H. explore crafting a model for predicting power generation efficiency gains obtained from floating photovoltaic systems. The article includes findings from multiple floating photovoltaic sites and present their model with technical details. The authors utilized data captured for the following variable values for their statistical model, air and water temperate, humidity, wind speed and photovoltaic panel operating temperature. To expand the scope of their analysis, the authors compare the energy generation outputs from three different locations in two categories of solar panel installations, a single rooftop installation and two floating photovoltaic installations.

Findings from this article was used in the modeling of the Monte Carlo simulations presented in the project proposal. Furthermore, key insight of underlined efficiency gains in temperature over 40 centigrade Celsius was included in the project proposal for additional guidance on site selection for floating photo voltaic systems.

In the article, Designing of 3MW Floating Photovoltaic Power System and its Benefits over Other PV Technologies, the author Perera, H. R presents the benefits of floating photo voltaic systems based on external studies. The external studies included in the article utilize highly technical measurement and scientific simulation results.

The conclusions presented in the articles were utilized for the project proposal in construction the parameters of power generations efficiency gains for the hypothetical simulation. Furthermore, some of the comments on water preservation potential in the proposal was based on the conclusions presented in this article.

Study Design and Data Collection Methods

The findings presented in this study are based on three main pillars of data sources. First, the power generation records dataset provided by Powertrust consisting of capacity, power generation, location and date ranges of data captured from individual solar power generation sites. This dataset is utilized to extract the relationships between variables and statistical summary values for establishing the parameters used in the Manto Carlo simulations. The secondary data sources utilized are the academic articles presented in the earlier section of this study were utilized for variables such as power generation efficiency gains and cost category variables range parameters.

For the social gains measurements further data acquisition is required to obtain quantitative results. For example, impact of HGSF activities on attendance rates and nutritional intake of students is often measured via periodic surveys conducted by local ministries of education partnering with UN organizations. These data collection surveys can be adjusted to capture impact of agrivoltaic solar farms on community development levels. For floating solar farms projects, the impacts can be measured through capturing the difference in water losses to evaporation in the bodies of water they are implemented on, and the social benefits of this water conservation can be measured through a variety of activities water is being used by the communities e.g. agricultural production, drinking water source amongst others.

Implementation methodology and strategies

The implementation of the analysis began with filtering the dataset provided by Powertrust in order to narrow down the scope of analysis. For this purpose, first the dataset was filtered to only include data from solar farms located in India, secondly, the dataset was further filtered down to sites with capacity utilization factors (CUF) above 15 percent. The latter filter was implemented for the analysis to project performance of solar farms to be constructed with newer materials which are often expected to perform at CUF's above this threshold as solar panels lose efficiency over time of their operational lifespans and newer solar panels achieve higher power generation efficiency levels up to 25 percent. Through earlier mentioned dataset adjustments the scope of the study aims to project outcomes for hypothetical projects in India only. However given the expected consistency of solar power generation in similar conditions findings can be useful for other geographical locations as well.

In the following stage a linear equation model was created based on installed capacities of sites and their ratios of power generated in terms of peak sun hours to average day light hours as independent variables targeting the power generation amount as the dependent variable. These two independent variables were selected because of the inherent role installed capacity has on power generation output and the random nature of power generation in terms of peak sun hours captured to average day light hours (DL/PSH) ratio as this variable can be affected by external factors such as solar altitude angle and cloud coverage.

In the next stage coefficients values at 95% confidence intervals for the independent values extracted earlier in the analysis were plugged into the linear equation with 400kw capacity and .41 mean DL/PSH value extracted from the dataset. The range obtained from the linear regression model was 50,542 Kwh for minimum monthly power generation, 51,931 Kwh for maximum monthly generation and mean value was calculated as the mean of the two. The values were used as the range of monthly power generation amounts in the Monte Carlo simulations which were also used as the basis for calculating the monthly revenues.

The cost parameters used in the simulations were obtained through external online sources cited in the references section of this study. The minimum cost for 1kw of installed capacity was

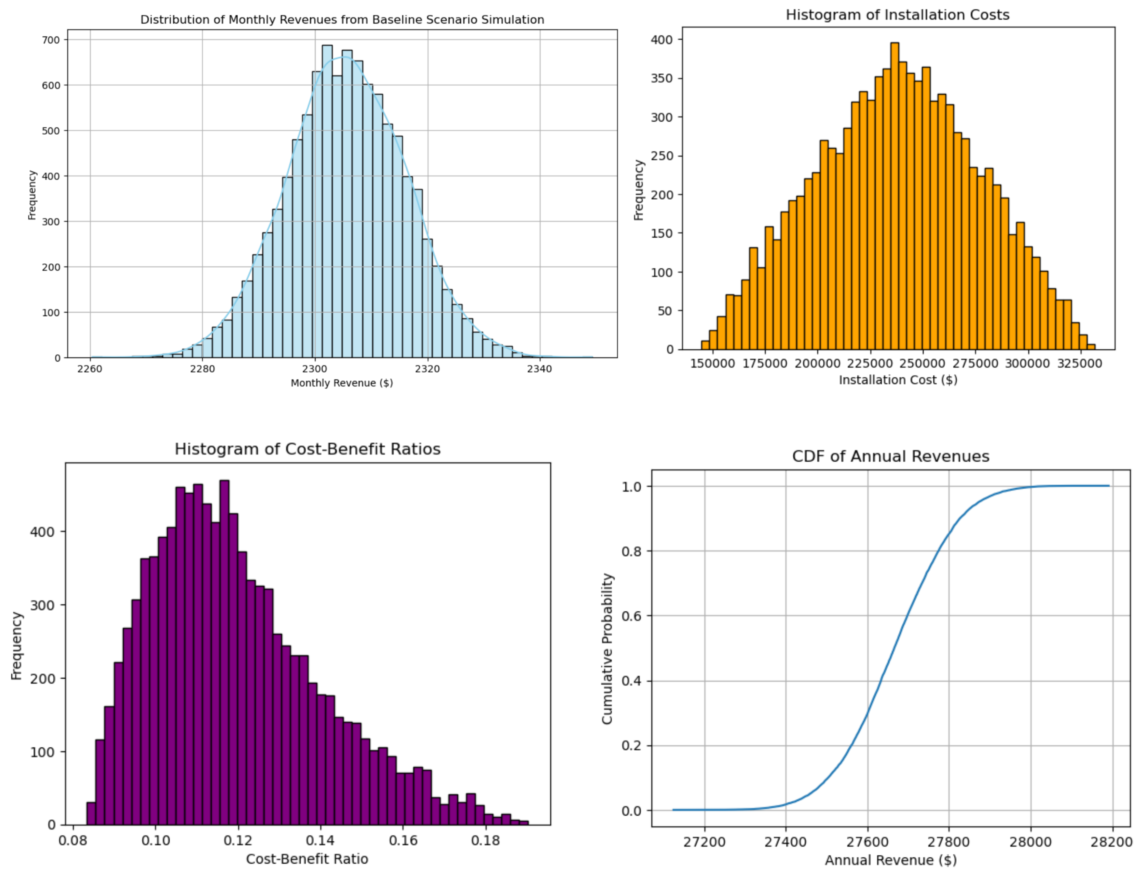
360 USD for minimum value, the mean value was 595 USD, and the max value was 830 USD (Prefuel, 2024).

Baseline Scenario Simulation

Baseline Monte Carlo Simulation Parameters			
	Baseline Scenario		
	Min	Mean	Max
Monthly Power Generation Parameters	**50,542**	**51,237**	**51,931**
Fixed Cost Parameters (USD per Kw)	**360**	**595**	**830**

All simulations were conducted for a hypothetical solar farm with 400 Kw capacity at a purchasing price agreement (PPA) rate of .045 USD (Jowett, P, 2024). This price value was also obtained from online sources, this is the price in a given country grid operators purchase power from the power suppliers and not to be confused with the grid value of electricity charged to households or enterprises at different rates. The results of the baseline simulation provided a mean monthly revenue of 2,305 USD or 27,667 USD mean annual revenue as well as a mean construction cost of 237,972 USD. When the mean construction cost is divided by the mean annual revenue value, an annual cost benefit ratio of .12 was obtained. At this cost benefit ratio, the simulated power plant is expected to recover all investment costs in 8.33 years.

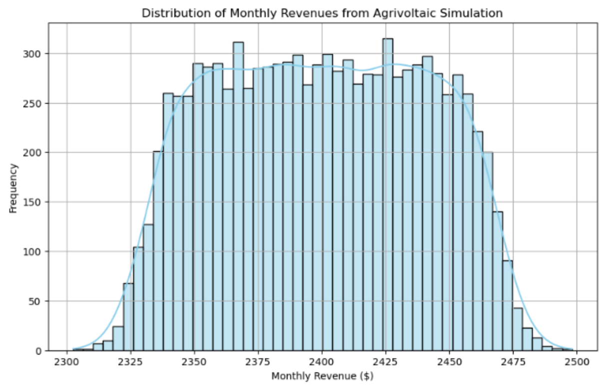
The results from this initial simulation were calculated as the baseline for the purpose of comparing the impact of different cost and benefit characteristics of agrivoltaics and floating solar power farms.

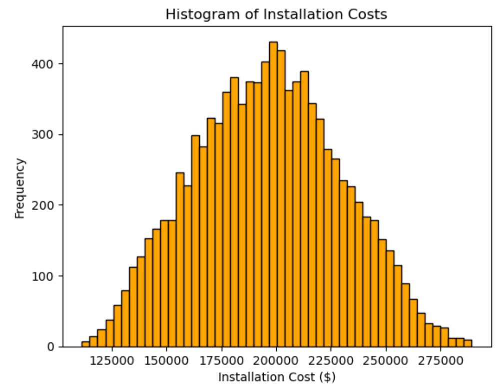


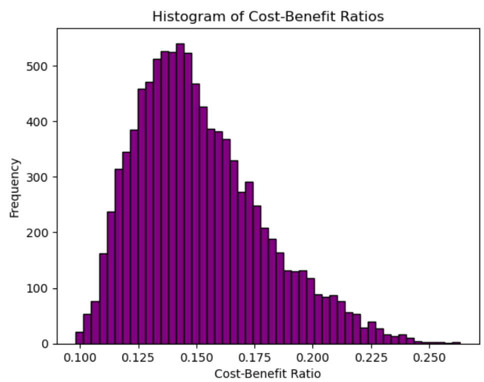
Agrivoltaics Scenario Simulation

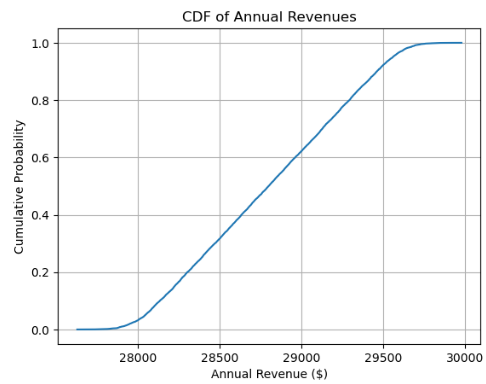
In the next round of simulations parameters of the baseline scenario were adjusted to reflect the performance characteristics and cost parameters of agrivoltaics solar farms. To achieve this, a range of cost reductions parameter was introduced between 10 percent to 25 percent to reflect the lack of land purchase cost’s share in total costs. Furthermore, based on the findings from the supporting scientific articles, a modest variation in power efficiency gains ranging between 3 percent to 8 percent was injected into the monthly power generation calculations.

The results yielded a mean monthly revenue value of 2,432 USD or mean annual revenue value of 29,194 USD. The fixed costs were considerably lower compared to baseline results at 196,115 USD as expected. The mean annual cost benefit ratio obtained from this scenario was 0.15, indicating this type of project would recover its initial investment costs in 6.6 years.





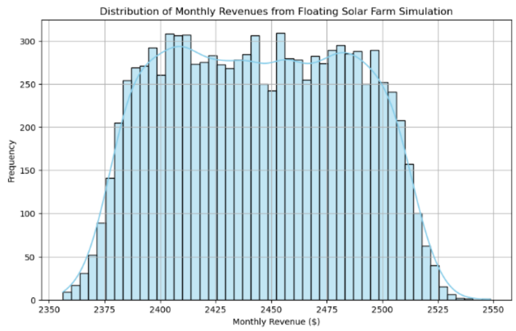


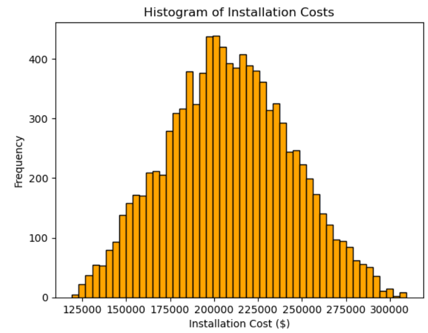


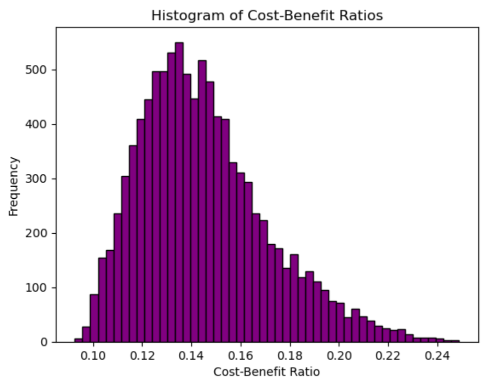
Floating Solar Farm Scenario Simulation

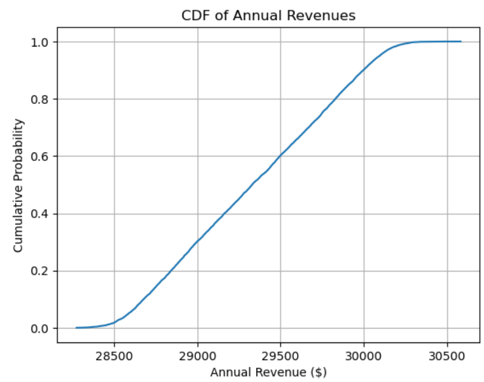
In the last scenario, the parameters of the initial baseline simulation were once again adjusted to reflect the characteristics of expected floating solar farm performance. The initial fixed costs were again reduced, however considering the additional costs of installation over bodies of waters for this type of solar farm configuration the cost reduction range was decreased to 5 percent to 20 percent. However, the power efficiency gain range was also adjusted to fall between 5 percent and 10 percent to reflect higher potential gains obtained from considerably lower operating temperatures obtained from water evaporation in suitable locations.

The results from this scenario yielded a mean monthly revenue value of 2,478 USD or a mean annual revenue value of 29,738 USD with a mean installation cost of 208,535 USD. Mean annual cost benefit ratio was calculated to be .14 indicating 7.1 years for this type of project to recover its original investment costs.









Comparative Interpretation of Simulation Results

	Baseline Scenario	Agrivoltaic Scenario	Floating Solar Scenario
Mean Monthly (Kwh)	51,235	53,332	54,325
Mean Monthly Revenue (USD)	2305.58	2399.92	2444.64
Mean Co2 Savings (Kg)	47649	49598	50523
Mean Fixed Costs (USD)	237,972	196,115	208,535
Mean Cost Benefit Ratio	0.12	0.15	0.14
Mean Investment Recovery Time (years)	8.3	6.7	7.1

According to the results from simulations, agrivoltaics solar farm model was the highest performant in terms of recovery of investment value speed however it should be noted that this was obtained due to added advantage of significantly lower installations costs. Although the floating solar farm model was behind of agrivoltaic systems in terms of financial recovery of its investment value, it outperformed both other models in terms of power generation, hence would yield higher monetary gains over its lifespan. Furthermore, this configuration would also yield higher carbon dioxide emissions savings for the same reasons.

It should be noted that the key variable element across all scenarios is the fixed cost savings obtained from reduced cost of land acquisitions. Agrivoltaic systems provide higher benefits in this area with an average 6 percent lower fixed costs compared to floating solar systems and over 17 percent against baseline scenario. This comparative advantage may be considered as a significant edge in scenarios where multiple project investments are targeted to be realized from a limited pool of financial resources.

Limitations

There are several areas that can be improved in future iterations of this study. The findings are currently limited to hypothetical solar farm in India, although these findings can be informative for other geographical locations, depending on the data availability, other countries may be included in the study for comparative analysis.

The socials gains resulting from implementation of such solar farm models were largely neglected in this version of the study. This is partly due to limited data availability on the subject, however through cooperation with local authorities and international entities such metrics can also be calculated via quantitative analysis and utilized in follow up studies during the project monitoring phases as mentioned in the methodology and data collection section of this study.

Lastly, there are several key cost parameters that were not included in the simulations such as maintenance and other operational costs as well as interest rates calculations for fixed investments costs. Addition of these elements may impact the results presented earlier and further studies should include these elements for real world applications.

Conclusion

In summary, this study presented example applications of statistical modeling methodologies such as linear regression models and Monte Carlo simulations as a real world industry solution. The analysis of simulation results demonstrates that both agrivoltaics and floating solar farms offer promising financial returns, with agrivoltaics showing a faster investment recovery period due to estimated lower construction costs. Floating solar farms, while slightly slower in terms of investment recovery, show a higher potential for power generation and carbon dioxide emissions reduction. These results underline the viability of these innovative solar power plant configurations as attractive investments compared to traditional solar farms, particularly in regions where space, land use, and water scarcity present additional challenges to development.

In future versions of this study, the structures of the simulations should be revised to expand the potential social gains aspect of the study to provide further guidance and contribute to the comparative analysis of investigated solar farm models.

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