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AgriVoltaics: Economic Viability of a Synergistic System in the Sugarcane Bioenergy Sector in Brazil

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Abstract. This study presents an analysis of the economic viability of AgriVoltaics (AV) applied in the sugarcane-bioenergy sector in a hypothetical plant in the central region of the state of São Paulo, Brazil, using modal values and performance parameters typical of the 2019/2020 harvest season. The objective is to verify the economic viability, considering the technical aspects of the project, and agronomic, operational, and systemic requirements. The obtained results show a substantial increase in the combined economic margin, at 33,5%, a land use efficiency ratio (LER) of 108,6%, and a payback of investments around 9 years. The approach proved feasible for energy prices above US$ 49.21 MWh^{-1}. The greater operational gain was due to the optimization of land use, and the sharing of costs with the existing thermoelectric generation that uses residual sugarcane biomass, which allowed centralized management and a substantial increase in electrical generation. The higher relative incremental cost was resulting from the AgriVoltaics installation, adapted appropriately to the specific agronomic management practices required by sugarcane crops. The cost of the adapted AgriVoltaics installation found was US$ 0.96 per Watt peak. The approach proved economically viable, respecting the agronomic conditions of the crop and the optimized use of biomass-driven electrical thermal generation infrastructure.

Keywords: Sugarcane Biomass; Optimization of Land Use; Renewable Energy; Solar Energy.

1. Introduction

The present work proposes the application of a specific AgriVoltaics approach on a typical Brazilian sugarcane bioenergy installation (Stefani and Felema [1]). AgriVoltaics (AV) is the strategy of using the same area of land both for agricultural production and photovoltaics energy generation. To get positive results a careful analysis is required (Weselek et al. [2]). A specific architecture must be elaborated, this being especially true for sugarcane, which needs very specialized practices to allow yield with a positive economic margin. Pecege [3].

In Brazil, sugarcane is a particularly important crop, whose products include the production of sugar, ethanol as a fuel for cars, and thermal electrical energy [3]. A typical sugarcane installation has a sophisticated agro-industrial plant, that is, it is an installation that can transform sugarcane juice into sugar or ethanol, in a ratio based on decisions that follow market prospects and prices. In turn, the electrical energy is a by-product resulting from burning residual sugarcane biomass [3].

However, one problem observed in the Sugarcane Biomass thermal electricity plants is that the availability of biomass depends on the yield of the harvest and, thus, suffers cycles of unavailability between seasons. Therefore, it is necessary to find alternative sources to keep the levels of electricity generation constant throughout the year. In recent years, during off-season harvest periods, sugarcane biomass availability has been scarce, and, in these cases, alternative biomasses must be used to keep the electrical plants running and maintain the energy supply [3]. That necessity would justify the implementation of the AgriVoltaics approach, as most sugarcane bioenergy plants already have thermal power generation facilities with certified access to the electrical grid and this can open opportunities for synergistic exploration with photovoltaic energy. The proposed approach is to share sugarcane plot areas with AgriVoltaics installations and explore synergies with the electrical generation of thermal biomass. As an example of opportunity, energy from photovoltaic energy during the day could allow substantial biomass savings, which then become reserved for use at night, or when cyclical shortages of biomass supply occur due to the harvest off-season.

Therefore, the objective is to find if there is economic feasibility of the AgriVoltaics approach on sugarcane bioenergy system considering the agronomic, operational, and systemic effects. If so, then, find which are the feasibility-promoting factors, and which items are to be pursued as success conditioners.

2. Materials and Methods

For the application of AV technology in the sugarcane bioenergy sector, two aspects were observed: technical feasibility and economic viability. The methodologies and techniques (Stefani and Felema [1]), are adapted from those used by Weselek et al. [2], Dupraz et al. [4], Trommsdorff [5], and Schindele et al. [6].

The source of data used in this study comes from sectorial reports like those published by the PECEGE institute [3], Brazilian sectorial associations of Solar Energy as ABSOLAR [7] and Greener [8], the Brazilian Chamber for Electrical Energy Trade CCEE [9], and the Brazilian Bank for Development BNDES [10].

The methodology applied was based on systematically analysing the mutual influences, cost impacts and consequences of the presence of photovoltaic modules positioned above the crop. Effects like those expected to affect plant physiology, microclimate, agronomics procedures, installations, process modifications, management practices, and how all those relate to economic aspects.

The main aspects of the detailing of materials and methods according to the premises of a technical and economic feasibility analysis are described below. A complete explanation of the support procedures can be found in Stefani and Felema [1].

- For the desired plot region, the availability of solar energy, and the average irradiance throughout the year were verified. The result was normalized to one hectare, that is, obtaining the available solar energy in one hectare per crop harvesting season in one year.
- A hypothetical sugarcane bioenergy plant was configured, using the typical parameters, the most probable mode results in sugarcane yield in tons per hectare (TCH), total recoverable sugar levels (ATR), and typical sugar and ethanol productive yields of the sector. That data comes from the last sectoral reports presented in the Pecege Institute, [3], a specialized data centre, numbers from the 2019/2020 harvest season. Those numbers were considered the sugarcane baseline performance figure.
- To evaluate the probable effects of the AV approach on sugarcane yields, each element, influence, or item of cost, is evaluated. Results either coming from the physiological needs of the plant, or agronomics practices, management requirements, and each performance factors were estimated.

- To estimate AV shadow effects on sugarcane yields, results coming from agroforestry are extrapolated, based on similar results from experimental plots of sugarcane with trees. For a more detailed explanation, see the next chapter.
- An evaluation of the probable effects applicable in a photovoltaic generation, either due to agronomic or system requirements, also was performed.
- The AV architecture conceived was installed incrementally in the normalized area of one hectare, using the same sugarcane plot area, that is, a certain area of sugarcane plot will be superposed by photovoltaic modules, in a specific number per hectare, without reducing the sugarcane planted area.
- CAPEX, Capital expenditures, was estimated using typical figures of photovoltaic installations, based on data from sectoral reports, like the periodic studies published by the industry association ABSOLAR [7], and the data analysis centre Greener [8]. Each cost item mentioned in the above reports was duly adjusted by the requirements of the AV project proposed while carefully considering the cost effects.
- All components, systems, and equipment have been designed to support a 25-year life cycle, typical for the photovoltaic sector.
- With all the cost effects considered and applying the estimative on probable effects on sugar and ethanol yield, also combining biomass energy generation with photovoltaic energy generation, the revenue of the new combined sugarcane biomass thermal energy plant plus AV was calculated. It was always considered the period of one crop harvest season year, normalized per hectare.
- The energy price considered was the CCEE Brazilian Trade Chamber of Electrical Energy (CCEE [9]) known by the acronym PLD energy price. It was considered the same average value found by Pecege [3] in the sectorial report.
- Finally, cash flow was elaborated, considering a period of 25 years. Net Present Value (NPV), Internal Rate of Return (IRR), and Payback were calculated for the case of self-equity investment. The NPV, IRR, and Payback formulations follow standard definitions, the same as used by [5], and for the sake of brevity were not repeated here.
- An alternative cash flow was made using a specific state-sponsored financing product tailored for photovoltaic plants, Brazilian Bank for Investment BNDES FINEM Energia (BNDES [10]).
- The results were compared between the pure sugarcane energy baseline and the combined sugarcane-energy plus AV installation for three area ratio of photovoltaic modules per proportional crop area. More details are in the next chapter.
- Based on the results, a sensitivity analysis was made on the main influencing factors on feasibility, such as currency exchange ratio, energy price, and equipment cost.
- For the sake of integrated performance comparison, an evaluation of energy and crop yields in a combined index was calculated. Using AV performance indicators such as LER, Land Equivalent Ratio, formulated by Willockx et al. [11].
- Also, for a comparative analysis, a hypothetical conventional Photovoltaic (PV) installation, near ground mounted, was conceived. In this case, conventional PV was mounted on clear ground, with the same number of PV modules employed on the AV approach, but now with the sugarcane crop area reduced, no crop under photovoltaic modules, on the same plot. Conventional PV practices and rules were applied. The reduced crop area in a one-hectare area was considered to behave with the same productivity per area of the sugarcane yield baseline. Both Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) are adjusted using PV common numbers and practices.
- With the AV performance results, and their equivalent from the conventional ground-mounted PV, a comparison of the AV feasibility approach on sugarcane was presented compared with the baseline.

3. Results and Discussion

According to the methodology, the first step was to establish the mutual influences of the AV approach on agricultural practices and crop yield, handling and management practices, and the mutual cross-effects. The first analysis was related to the effects on photovoltaic productivity and costs caused by sugarcane crops, i.e., refers to the effects caused by agricultural influences applicable to the installation of photovoltaic modules. A set of 16 effects were identified [1]. The cost of installation, poles, structures, cabling by underground conduits, fences, and insurance were some of the effects considered. Also, a symmetric analysis was performed, like changes in the routes of the harvesting machines and changes in irrigation practices. Furthermore, the effects caused by the AV approach on agricultural crop productivity were analysed. It refers to the probable effects that the presence of photovoltaic modules would have on crops. A total of 18 effects have been studied [1], like shadow effects, microclimate, water stress, etc. For brevity, some of the factors and cost impacts were not presented here, and complete argumentation and supporting data can be found in [1].

To estimate the effect of the AV shadow on sugarcane yield, specific research was performed, and the methodology used an extrapolation from experiments with sugarcane in agroforestry systems.

The sugarcane, according to Rodrigues et al. [12] is a typical C4 plant, a class that indicates the behaviour and by which means photosynthesis occurs. Sugarcane is considered an example of high photosynthetic efficiency in the capture of CO2 and its transformation into biomass. For this reason, this author argued that any reduction in solar irradiance could cause a decrease in biomass yield. According to Sage et al. [13], there is evidence that sugarcane undergoes some saturation at high levels of irradiance in its photosynthetic capabilities of absorbing CO2. In both studies, leaf temperatures above 34ºC reduce the absorption capacity of CO2 by the photosynthetic pathway. Both studies report that there is energy expenditure when sweating occurs at higher temperatures.

Dupraz et al. [4] showed a possible correlation between AV results and agroforestry systems. Agroforestry systems are those where an agricultural crop coexists with another forest crop, in arrangements optimized for land use, the share of nutrients, and especially sunlight. In Brazil, studies of agroforestry arrangements with sugarcane were carried out, as found in the works of Schwerz et al. [14]; and Pinto et al. [15]. In those experiments, trees of the species *Aleuritis fordii* (*tungue*) were planted at distances of 12m x 12m, or 6m x 6m, measured between sugarcane lines, and the effects on its productivity were analysed. According to the report, using *tungue*, in the spacing of 12m x 12m, there was a small reduction in biomass production, about -8%, but there was an increase in sucrose content, +11%. In the case of 6m x 6m spacing, there was a reduction of both - 27% in biomass productivity and -21% in sucrose levels. As the size of the *tungue* tree canopy, height, diameter, and relative positions of this species are documented, it was possible to estimate by optical simulation which size or equivalent dimension of photovoltaic modules would be, i.e., cause the same shadow effects. By the average shade size calculations, it was found that the 12m x 12m arrangement would be equivalent to a photovoltaic module's coverage area of 1.8% of the hectare. The coverage of 6 m x 6 m is equivalent to 16% of the area in the hectare.

Thus, the strategy here was to design the photovoltaic module sizes to produce the same shadows as the trees reported in Schwarz et al. [14] experiment. It means around 88 modules (~2.04m^2 each) per hectare in the 1.8% coverage in the area. Making the necessary estimations and results based on [14] and [15], it is possible to estimate a sugarcane yield productivity reduction of ~8% on TCH and an increase of sugar contents ATR of ~11%. Photovoltaic modules do not compete for nutrients and water, and therefore those extrapolated results can be considered pessimistic.

The proposed setup for the AgriVoltaics system applied to the sugarcane crop is presented in Figures 1 and 2, and these configurations were the ones used for the entire cost estimation, investments, and feasibility analysis. See [1] for a complete description and data.

In Figure 1, photovoltaic modules are housed on top of poles, 8m in height. This height was necessary to allow clearance for the transit of automated harvesting equipment, which creates the need to install tall and robust structures. It also imposes specific ground anchors, selected to be screw piles, helical anchors, and not concrete pads. The height allows the transit of the automatic harvester truck, their stems lifting conveyor, and trailers for harvest transhipments. Each pole contains 8 photovoltaic modules and is oriented so that the top faces are tilted in their normal north, in Brazil, according to the local latitude. Photovoltaic modules were distributed and oriented so that the sun, in its trajectory throughout the day, did not produce a superposition of shadows, and the paths of these shadows were homogeneously distributed on the sugarcane plot. This allows a good capture of solar irradiation throughout the day and seasons.

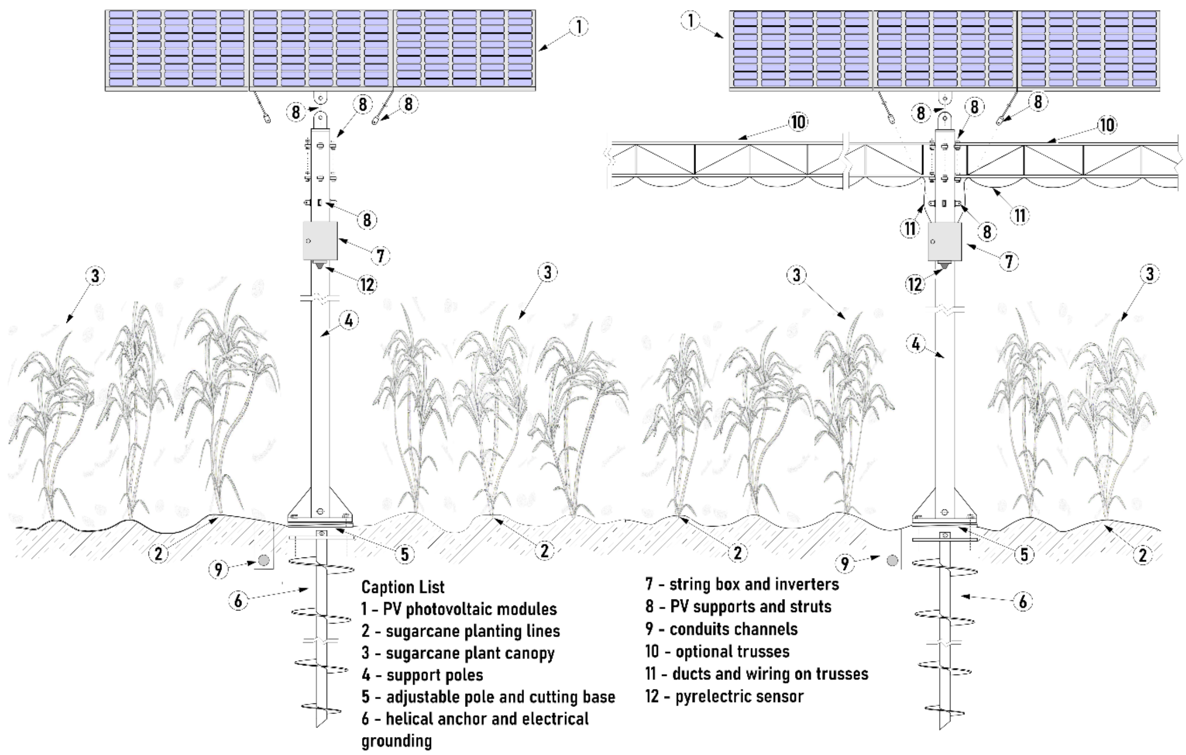

Figure 1. Concept of the AV structures to be installed on the sugarcane plot area.
Source: Stefani and Felema [1].

AV mounted on 8 m high poles, produces a very interesting behaviour on photovoltaic performance. Using the manufacturer's data and design charts, it presented a reduced operating temperature, and due to that, an increased photoconversion efficiency. It was also noted the reduction in dust accumulation. The most important influence was the increased capture of the optical omnidirectional irradiation coming from sunlight scattering on the sugarcane canopy. This justifies the use of bifacial photovoltaic modules, and it caused a significant increase in efficiency. As the typical sugarcane albedo is significant, around ~0.2, it allowed an increase in photovoltaic bifacial efficiency. Using manufacturer charts and optical simulation, photovoltaic modules efficiency found was 21.37%.

Figure 2 shows the distribution of the modules in the top view in a plot, as well as the positioning of the poles in the spaces between rows of sugarcane lines. The project complies with one of the primary requirements, the non-reduction of the planted crop area. Enough spacing allows the passage of harvesters, wagons, sprayers, and fertigation machines. But there was an increase in installation costs due to the need to keep the sugarcane crop management as close as possible to the original practices.

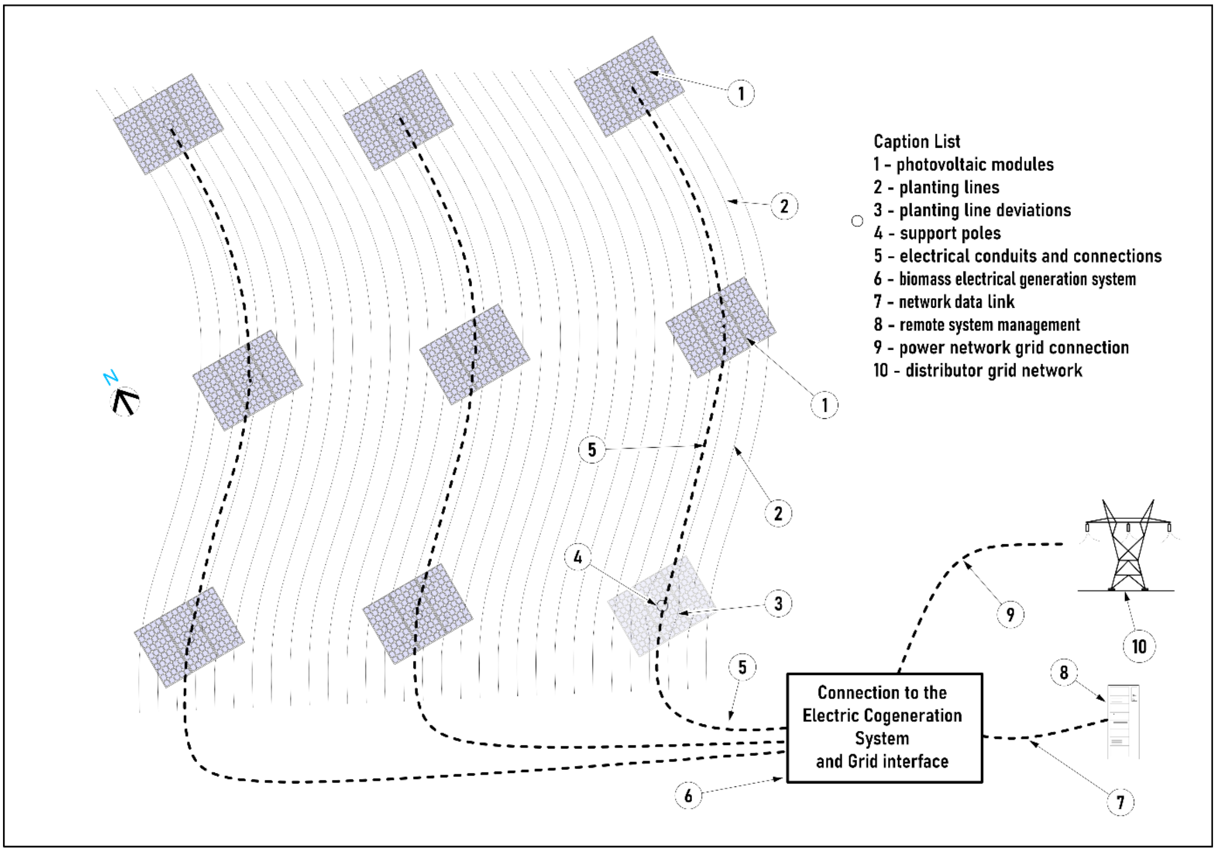

Figure 2. Concept of the AV plant installed on the sugarcane plot area.
Source: Stefani and Felema [1].

In the cost estimation, it was found that the greatest cost increase was caused by the modifications for use of the higher-height pole and associated underground cabling and conduit structures. See [1] for details.

Figure 3 shows that the AV system integrates the sugar and ethanol operation and thermal electrical generation by residual biomass, allowing centralized management. This conception brings savings in the necessary investments, as well in the OPEX, e.g., flexibility in management, same human labour, same energy delivery system, same control station, all exploring systemic synergies.

Cash flow and economic analysis were performed, and for complete numbers, see [1]. Three scenarios were simulated: coverage of 1.3%, 1.8%, and 16% of photovoltaics modules area per hectare, as per the before mentioned, extrapolation of agroforests experimental results. For the sake of brevity, only the results of 1.8% were detailed here. It corresponds to 88 photovoltaic modules per hectare, 8 per pole.

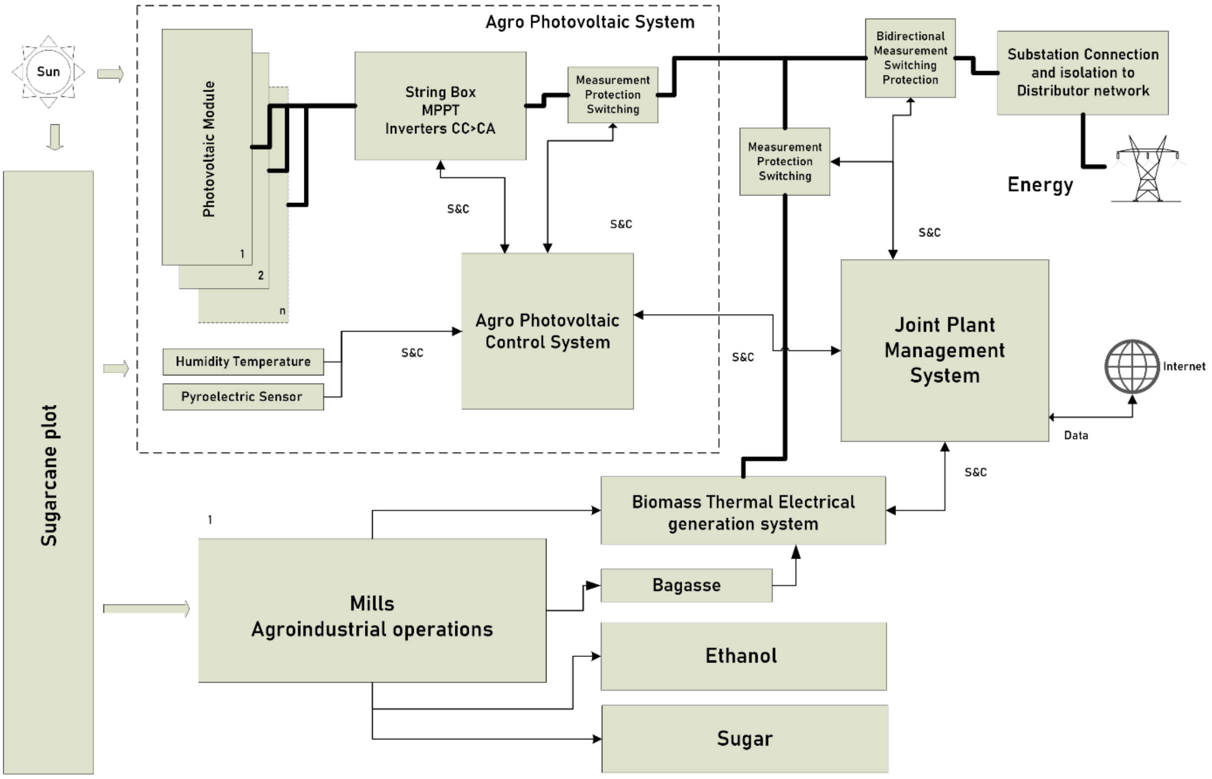

Figure 3. Systemic Overview AV Design applied to sugarcane energy plant.
Source: Stefani and Felema [1].

The economic margin of 10.4% was the baseline found in the sectorial data, average results in sugarcane bioenergy according to the Pecege [3] report. For the AV concept installed above the sugarcane plot, using an area coverage of 1.8% proposed here, the estimated combined economic margin found was increased to 33.5%, a significant improvement. In this 1.8% area coverage ratio, there was a small increase in sugar and ethanol revenue, and an improvement in ATR (recoverable sugar total) sucrose levels, even with a small reduction in TCH (tons of sugarcane per hectare). Higher ATR means a more valued and profitable harvest. Coverage of 16% was performed and resulted in a major revenue increase, but shows a significantly reduced sugar and ethanol performance, reducing yield, due to a substantial reduction in photosynthetic response, whose details can be found at [1].

The bifacial module efficiency found by simulations was around 21.37% in all AV scenarios with sugarcane under photovoltaic modules and allowed a good performance. That result was based on the use of optical irradiation from omnidirectional scattering coming from the sugarcane canopy, and the reduced operating temperature. In conventional PV installations, using the same bifacial photovoltaic module, 1m above ground, there is an increase in operating temperature, and the lowered irradiation coming from the ground backscattering, both resulting in a reduced overall panel conversion efficiency of 20.47%, as per the manufacturer´s data charts and simulations.

Simulating the installation of a conventional PV approach, coverage of 1.8% achieved a combined economic margin of 29.5%. Note that there was found a decrease in agro-industrial revenue, i.e., those coming from sugar and ethanol, due to the reduction of crop area and thus the reduction in harvest yield.

In all AV scenarios above, when compared with the conventional PV approach, it is evident that selected AV strategies applied to the sugarcane bioenergy sector could allow a substantial increase in energy income, with some improved agro-industrial results, sugar, and ethanol, even with photovoltaic area coverage of only 1.8% of the sugarcane plot area.

CAPEX of the Agrivoltaics plant shows that for a typical conventional photovoltaic installation, medium-sized, according to Greener [8] it has an average cost of US$ 0.76 per Wp (Watt peak). In the hypothetical AV installation presented here, 1.8% coverage case, the cost was US$ 0.96 per Wp, showing that there is a need to explore ways of cost reduction via technological development, mainly on the structural poles. (Currency ratio April/22, 1US$ ~5,1R$ Brazilian Real).

Economic feasibility analyses were made, both for the case of own equity capital investment and the financing case, using state-sponsored funding products. In all cases, it is verified that the Net Present Value NPV [5], for the estimated system life cycle at 25 years, always presented positive results in the three AV coverage scenarios, either using own equity capital or funded by state-sponsored investment products. For the analysis, it was used the sector's average energy price PLD [9] in the 2019/2020 harvest season, at around US$ 54.0 MWh^{-1} [3].

For the coverage of 1.8%, the NPV was US$ 10601.09 ha^{-1} (per one-hectare area), and the Internal Rate of Return IRR [5] was 6.93%. The Payback time was 11.55 years. For the financed case, AV coverage of 1.8%, the NPV was US$ 12363.18 ha^{-1}, and the IRR was 14.88%. The Payback time was 8.36 years. In this scenario, a general increase in the efficiency of the combined sugarcane system with AV was highlighted as the first option scenario to be implemented experimentally. Here, the LER index obtained was 108.6%, meaning the highest land-use efficiency [11].

Compared to the conventional PV approach, with a coverage of 1.8%, the NPV was US$ 8411.33 ha^{-1}, and the IRR was 6.92%. The Payback was 11.54 years. Noticeable in this scenario, the lower CAPEX had been compensated for the reduced land-use efficiency, reduced crop harvest area, and the reduced photovoltaic efficiency remaining in the same figure as the AV approach. The lower LER [11] index found of 100.4%, points to reduced land efficiency, the same as the baseline of sole sugarcane land use. In both cases, the conventional PV approach here resulted in lower efficiency compared with AV due to the reduced agro-industrial sugar and ethanol income as well the reduced photovoltaic production, a long-term penalty.

The sensitivity analysis found that the combined AV approach will only be feasible if the energy price PLD [9] remains above ~US$ 45.09 $MWh^{-1.}$ The 2021-year average energy price PLD [9] was US$ 55.39 MWh^{-1}. Another way to look at this factor is to evaluate the Levelized Cost of Electricity (LCOE), a common index on the renewable energy sector, used to compare different approaches. Using the methodology pointed out by Schindele et al. [6] and Trommsdorf [5], the LCOE for all those AV scenarios suggested above, the LCOE range from ~US$ 40.39 MWh^{-1} up to ~US$ 49.21 MWh^{-1}, suggesting a higher minimum PLD.

4. Conclusions

The AgriVoltaics approach applied in sugarcane bioenergy resulted in a promising strategy, provided that its architectures are adapted to agronomic constraints and the nature of sugarcane bioenergy activity. It has been shown that the proposed architecture explores synergies and can adapt to mutual constraints. In the proposed scenarios, the AV approach combined with sugarcane bioenergy activities can earn significantly higher revenues. The results suggest that for sugarcane crops, a small AgriVoltaics coverage area of around 1.8% in photovoltaics panels above the crop area can be advantageous.

The results also showed significant additional economic gains by photoelectric generation, some improvement of sugar and ethanol yields, and significant improvement of land use ratio, increasing its usage efficiency. It was found that the strategy has an average period of return on investment of around 12 years, in the case of self-equity, and around 9 years for the funded case using existing state-sponsored financial products.

The feasibility constraints in cost are those related to the CAPEX of the installation. The greatest cost increase was caused by required modifications in the installation, the higher height pole, and associated cabling structures adapted in appropriate design to reduce interference on the crop handling. The price of electricity is the greatest feasibility constraint, being the primary decision factor for investment. The AV approach is feasible for energy prices above US$ 45 MWh^{-1}. Comparing AV with conventional PV, in the sugarcane bioenergy system, the PV approach here resulted in lower efficiency and returns when compared with AV. The main reason for that is the reduced sugar and ethanol income and the reduced photovoltaic production.

Therefore, the economic feasibility found in the present study, justifies investments in the development of AV technology in the sugarcane bioenergy sector, whether in pilot plants or at reduced scales, aiming at validating the assumptions and the proposed architecture.

Data availability statement

This article is an overview of a complete work based on the monography to earn MBA degree at USP ESALQ authored by Mario Antonio Stefani, and as adviser Prof. João Felema. Original data, tables, figures, analysis, cash flow, economic feasibility data, and a full reference list can be found at Stefani and Felema [1].

Author contributions

Mario Antonio Stefani: *Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Supervision, Writing Original, Writing Review, and Editing.*

João Felema: *Validation, Writing Review, Adviser*.

Competing interests

The authors declare no competing interests.

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