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Price for Covering Cropland with an Agrivoltaic System: PV Panels Replacing Shading Nets in Chilean Blueberry Cultivation

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Abstract. Agrivoltaic has no commercial application in South America due to higher capital expenditure compared to traditional photovoltaic systems. Currently, Chilean farmers use plastic crop covers to protect fruits from adverse weather impacts such as excessive irradiation, avoiding sunstrokes in crops, and to use water more efficiently, limiting evapotranspiration. Since agrivoltaic could serve as an alternative for crop cover, we analyze and compare the costs for agrivoltaic with the cost of plastic covers, introducing a metric to calculate the price for covering cropland with an agrivoltaic system. Based on a selected case we demonstrate that the price of covering cropland with agrivoltaic is still higher than the price of covering cropland with shading nets and thus additional costs or design modifications for agrivoltaic systems cannot solely be justified based on the provided economic benefit of shading. Still, depending on the local cost structure of crop protection with plastic cover, agrivoltaic can create notable synergies. Also, we conclude that the price for covering cropland with agrivoltaic can further be reduced when capacity density of agrivoltaic is decreased. Still, further research is needed to investigate on the physical aspects of photovoltaic panels replacing plastic covers to protect crops.

INTRODUCTION

Agrivoltaic, which combines photovoltaic (PV) energy generation with agricultural production on the same land, has no commercial application in South America as higher capital expenditure (CAPEX) leads to worse economic performance in comparison with traditional PV projects. Yet, the sole consideration of PV economics does not do justice to the synergetic effects that agrivoltaic can have on agriculture. Various researches have stated that agrivoltaic could serve as an alternative for crop protection in (semi)-arid and dry regions: While PV modules intercept light for energy generation, they provide shade and thus protect crops from intense solar irradiation[1–4]. Additionally, shading decreases evaporation from soil and transpiration of crops leading to higher efficiencies of water used for irrigation[5].

FIGURE 1. Blueberry plantations in central Chile without (left) and with shading nets (right)

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The use of plastic covers has developed strongly in Chilean fruticulture in the last years, due to the need to protect valuable fruits from adverse weather impact, ensuring a steady production flow, while maintaining product quality requirements. We highlight the case of blueberry production in central Chile, where shading nets with shading rates of up to 30 % are used to protect against high solar radiation, since excess radiation will cause a shortening of the fruit ripening period, reducing fruit quality and harvest[6]. Also, losses because of sunstrokes can reach levels of 20 % to 30 %[7]. In this context, we assume that the synergetic value of agrivoltaic is not only to enable a dual-use of land but to enhance agricultural production, as PV panels could function as an alternative for crop protection.

In previous work we found that the monetization of the synergetic characteristics of agrivoltaic such as dual use of land and providing shading can lead to a higher Net Present Value and shorter payback period for an agrivoltaic system compared to a ground-mounted PV system[8]. Still, while comparing costs of agrivoltaic systems with costs for traditional shading solutions, such as plastic cover we face two substantial differences between the PV and the agriculture sector: PV costs are commonly stated as a monetary value in relation to the installed peak capacity ($/kWp) while agricultural costs are stated as a monetary value in relation to an area ($/ha). Also, while PV costs can be translated to costs per area, there is an asymmetry regarding the magnitude of the costs, with PV costs being significantly higher. These discrepancies complicate not only economic analysis, but in general the communication and creation of business models between farmers and PV developers.

Consequently, we identify the need for metrics that enable the comparison of costs for covering crops with agrivoltaic systems and the costs for covering crops with plastic cover. In the following, we first describe related work before proposing corresponding metrics and demonstrate application.

RELATED WORK

PV projects require significant upfront CAPEX, while operational expenditure (OPEX) is meager by comparison[9,10]. Project finance is used to realize the vast majority of PV projects and several financial indicators are used to assess their economic viability[11].

All indicators consider initial CAPEX as well as OPEX and expected revenues throughout the lifetime of the project. Revenue directly correlates to the generated energy and the price for energy. To determine a price for the generated energy, the Levelized Costs of Electricity (LCOE) method is used[12]. The sum of the generated energy (M) over the lifetime of a plant (N), up-front CAPEX (I_o) and annual OPEX (A_t) are the main parameters. The weighted average cost of capital (WACC) (i) is used as the discounting factor. LCOE calculates as

$$LCOE = \frac{I_o + \sum_{t=1}^{N} A_t * (1+i)^{-t}}{\sum_{t=1}^{N} M * (1+i)^{-t}} \quad (1)$$

LCOE is often used to determine the price of energy in long-term power purchase agreements (PPA). Hence the actual price fixed in PPAs should be equal to or higher than the LCOE to provide economic viability. Among some of the most common indicators to further evaluate PV projects are Net Present Value (NPV), payback period, and internal rate of return (IRR).

Economic studies on agrivoltaic use these metrics to compare economic viability with traditional, ground-mounted PV systems: Obergfell studied the economic situation of APV in Germany and analyzed the cost and revenue structure, with the result that agrivoltaic wasn't competitive against ground-mounted PV systems[13]. Trommsdorff also focused on the situation of agrivoltaic in Germany, referring to local feed-in-tariffs to evaluate the profitability of agrivoltaic compared to rooftop PV and utility-scale PV projects[14]. His findings indicate that agrivoltaic systems are only expected to operate profitably if subsidized feed-in tariffs can be obtained. Agostini estimated specific CAPEX for agrivoltaic systems about 33% more expensive than ground-mounted systems leading to a higher LCOE for agrivoltaic systems than for ground-mounted and roof-mounted PV systems[15].

While some of the described studies incorporated revenue streams from agricultural activities on the land below the agrivoltaic system in their analysis, difficulties of incorporating agronomic values in metrics used for PV project decision making arise: Uncertainty regarding crop yield in general and the impact of the agrivoltaic system on crop yield as well as different orders of magnitude regarding costs and revenues. Schindele et al. recently did propose a new metric for agrivoltaic systems to enable decision making. They calculate a price for maintaining cropland (p) as the difference of the product of LCOE and annual energy generation per hectare for an agrivoltaic and a ground-mounted PV system[16]:

$$p = LCOE_{APV} * M_{APV} - LCOE_{GMPV} * M_{GMPV} \quad (2)$$

Extra costs are then compared to the annual revenues of agricultural activities (pb) on the land below the agrivoltaic system to calculate price-performance ratio (ppr).

$$ppr = \frac{p}{pb} \tag{3}$$

If the ppr exceeds the value of 1, the benefits of agricultural activity do not justify additional costs in comparison to ground-mounted systems, while a value of 1 and lower implies economic viability as the income of the farmer is diversified and an increase in revenues can be expected[16].

Applying the metric, we find a strong dependency on the annual energy generation per hectare, resulting in negative values for the price for maintaining cropland when agrivoltaic systems have a significantly lower density of installed capacity. Since lowering the density in agrivoltaic systems is a common measure to provide sufficient irradiation below PV panels, we will introduce a new metric that expresses the additional cost of an agrivoltaic system in comparison to a ground-mounted PV system for an area, based on capacity specific values.

PROPOSED METRIC

We introduce the price for covering cropland with an agrivoltaic system (p_{APVcc}) over the lifetime of the project per hectare [USD/ha] as

$$p_{APVcc} = \left[\left(i_{0,APV} - i_{0,GMPV}\right) + \sum_{t=1}^{T} \frac{\left(a_{t,APV} - a_{t,GMPV}\right)}{(1+i)^t}\right] * \frac{m_{GMPV}}{m_{APV}} * d_{APV} \tag{4}$$

where

i_0	= capacity specific capital expenditure for PV system	[USD/kWp]
a_t	= capacity specific operating expenses for PV system	[USD/kWp/a]
T	= lifetime of the PV system	[years]
i	= calculation interest rate	[%]
m	= capacity specific electric yield in the first year of operation	[kWh/kWp]
d	= density of installed capacity of PV system	[kWp/ha]

The price for agrivoltaic cropland cover is related to LCOE methodology, as it calculates the capacity-specific difference in capital and operational expenditure over the lifetime of an agrivoltaic and a Gound Mounted (GM) PV system. By multiplying with the ratio of specific electric yield, the calculated cost difference is adjusted to disparities in energy output. Specific generation of agrivoltaic systems can be lower due to adaption to the agricultural context or also higher due to cooler microclimate. Hence, we assure that both systems provide the same amount of energy. Finally, by multiplying the density of agrivoltaic capacity, we obtain the area-specific additional cost of installing PV panels over crops.

The price for plastic cover cropland protection (p_{PCcp}) throughout the same period calculates as

$$p_{Pcc} = i_{Pcc} + \sum_{t=1}^{T} \frac{a_{t,Pcc}}{(1+i)^t} \tag{5}$$

where

i_{Pcc}	= area specific installation cost for plastic cover	[$/ha]
$a_{t,Pcc}$	= area specific operating expenses for plastic cover	[$/ha/a]

The price for crop protection with plastic cover can be compared directly to the price for crop protection with an agrivoltaic system.

Alternatively, the price for crop protection with plastic cover (p_{PCcp}) can be translated in a PV capacity specific value based on a selected agrivoltaic system, representing the increase in CAPEX of agrivoltaic system (i^*_{0cc}) by

$$i^*_{0cc} = p_{Pcc} * \frac{1}{d_{APV}} * \frac{m_{APV}}{m_{GMPV}} \tag{6}$$

Hence, i^*_{0cc} solely depends on the density of the agrivoltaic system and the difference in specific generation of the agrivoltaic system compared to a ground-mounted system.

DATA FOR CASE STUDY

As a study location, we chose a blueberry orchard in Ovalle, Coquimbo Region, Chile. The orchard is located at 250 m above sea level and about 35 km from the pacific coast. Solar irradiation is high with an annual average of Global Horizontal Irradiation (GHI) of 5.69 kWh/m^2/day. Ovalle has a desert climate which can be classified by the Köppen-Geiger scale as cold desert climate (BWk). The average annual temperature is 17.0 °C and rainfall averages 155 mm[17]. Between 2013 and 2018 minimum annual precipitation was 72 mm and the maximum annual precipitation was 257 mm[18].

The blueberry orchard has an extension of 20 hectares (ha), uses organic practices, and produces for exportation. The orchard is organized with a distance of 2.5 m between rows going from south to north and 0.4 m between blueberry bushes. Blueberry bushes have a maximum height of 1.8 m. All 20 hectares of the orchard are covered with shading nets, type Raschel in a height of 2.2 m with a shading rate of 30 %, as excessive solar radiation causes sunburns and a shortening of the fruit ripening period, and therefore to lower fruit quality[19].

Costs for different shading nets are summarized in TABLE 1: Total costs for the installation of shading nets type "Raschel" sum up to 7,000 USD/ha and replacement costs are about 2,500 USD/ha, while lifetime can be up to 5 years. It is noteworthy that we also observed a lifetime for shading nets type Raschel of just 1 year. Since there are more materials for plastic cover available, we also present data for plastic covers type Monofilament, Raffia and Polyethylene which can provide additional protection such as wavelength filtering or rain protection but also come with a higher cost.

TABLE 1. Costs for plastic cover. Based on data from Bastias (2019)[20], Salazar-Parra et al. (2019)[21] and own data from contact with farmers

Shading Nets		Raschel	Monofilament	Raffia	Polyethylene
Installation costs	USD/ha	7,000	17,000	22,000	22,000
Exchange costs	USD/ha	2,500	6,000	11,000	11,000
Lifetime Nets	a	5	7	5	3

The industry standard for ground-mounted PV systems consists of bifacial PV panels that are installed on a horizontal single-axis tracker: PV panels are fixed in portrait format on a rotating D-tube in a height of 2.5 m that has a tracking range of ± 60°.

Agrivoltaic design is not specified in detail as there are various possibilities to provide the desired shading: the north-south orientation of the ground-mounted PV system design might be modified to coincide with the alignment of the rows of bushes, and the installation height must be increased to enable crop growth and accessibility. While an elevated north-south orientated row of PV panels generally can provide an even distribution of sunlight, spacing between PV panels or horizontal PV panel installation must be considered to increase the total amount of sunlight available below the agrivoltaic plant.

Density is 650 kWp/ha for the ground-mounted PV system, while it is 550 kWh/ha for the agrivoltaic system. Specific generation is 2,250 kWh/kWp for both ground-mounted PV system and agrivoltaic system with one-axis tracking, as no deviation in azimuth is needed. TABLE 2 shows estimated CAPEX values for ground-mounted PV system with 1 axis tracking All the above design measures only influence the CAPEX items "Mounting Structure" and "Ramming and Installation".

TABLE 2. Costs for a ground mounted PV system with 1 axis tracking

Item	unit	Ground-mounted PV	Agrivoltaic
PV Panels	\$/kWp	300	300
Inverter	\$/kWp	100	100
other BOS	\$/kWp	50	50
Mounting Structure	\$/kWp	100	*200*
Ramming and Installation	\$/kWp	200	*300*
Soft costs	\$/kWp	150	150
Total CAPEX	**\$/kWp**	**900**	**1,100**

We assume that the OPEX for an APV system does not differ significantly from a GM PV system so that for both systems, yearly specific OPEX is set at $18/kWp.

All costs and prices are calculated in $ US-Dollars, yearly inflation of 3% is applied to all occurring costs and revenues and we apply a calculation interest rate of 6.15%.

RESULTS AND DISCUSSION

Price for Covering Cropland

TABLE 3 shows prices for different solutions to protect blueberries from excessive sunlight over 25 years: Plastic covers Raschel, Monofilament, Raffia, Polyethylene, and an agrivoltaic system. The price for covering cropland is the lowest for the shading net-type Raschel" with 15,133 $/ha. While plastic covers Raffia and Polyethylene have the same cost structure, the price of covering cropland with Polyethylene is higher, as it is less durable. The cost for covering cropland by an agrivoltaic system is 110,000 $/ha when we assume a density of 550 kWp/ha and CAPEX increases of 200 $/kWp, compared to a ground-mounted PV system while OPEX and specific generation are equal.

TABLE 3. Price of covering cropland for different plastic covers and agrivoltaic system

Item	Price for covering cropland ($/ha)	(Equivalent) ΔCAPEX of agrivoltaic system ($/kWp)
Raschel	15,133	33.63
Monofilament	28,977	64.39
Raffia	57,787	128.42
Polyethylene	81,835	181.86
Agrivoltaic	110,000	200.00

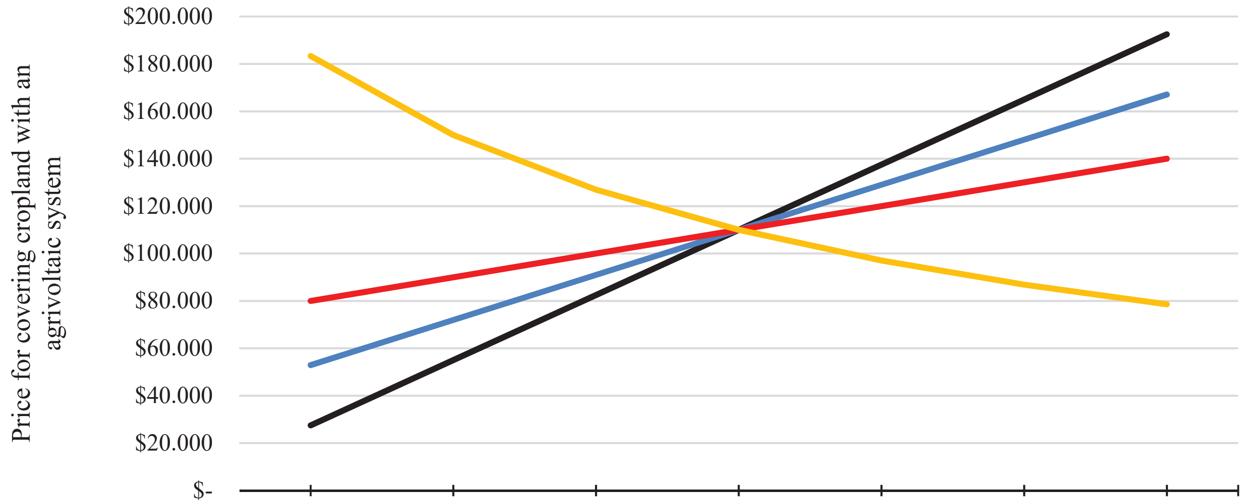
Based on the prices for covering cropland of the shading nets we can calculate the corresponding CAPEX increase for an agrivoltaic system with a density of 550 kWp/ha that leads to an equivalent price for covering cropland if OPEX and specific generation do not differ compared to a ground-mounted PV system. While for the cheapest shading net Raschel equivalent ΔCAPEX is 33.63 $/kWp, we obtain values for equivalent ΔCAPEX of 181.86 $/kWp for shading net "Red Agricola".

Sensitivity of the Price for Covering Cropland

FIGURE 2 shows results of a sensitivity analysis on the variables CAPEX, OPEX, density, and specific yield regarding their impact on the price for covering cropland with an agrivoltaic system. We set a range for the variables considering the baseline values between a minimum and a maximum value.

We see that CAPEX has the strongest impact, as a price for covering cropland with an agrivoltaic system of 27,500 $/ha can be achieved with a ΔCAPEX of +50 $/kWp compared to ground-mounted PV, resulting in total CAPEX for an agrivoltaic system of 950 $/kWp. A CAPEX of 1,050 $/kWp results in a price for covering cropland for agrivoltaic of 82,500 $/ha, thus nearly equal the costs of covering cropland with Polyethylene. Decreases in OPEX also show significant potential as OPEX of 12 $/kWp/a (6 $/kWp/a lower than ground-mounted PV) leads to a price of 52,930 $/ha.

Also, we see that decreases in specific yield should be avoided as the price for covering cropland with an agrivoltaic system shoots up to 150,000 $/ha for a decrease in the specific yield of -900 kWh/kWp compared to the baseline. Changes in density of installed capacity of ±150 kWp/ha result in deviation of the price for covering cropland with an agrivoltaic system of ± 30,000 $/ha.



Parameter	Unit	min			Baseline*			max
ΔCAPEX	$/kWp	950	1,000	1,050	1,100	1,150	1,200	1,250
ΔOPEX	$/kWp/a	12	14	16	18	20	22	24
ΔDensity	kWp/ha	400	450	500	550	600	650	700
ΔS. Yield	kWh/kWp	1,350	1,650	1,950	2,250	2,550	2,850	3,150

FIGURE 2. Results of sensitivity analysis of CAPEX, OPEX, density, and specific yield regarding their impact on the price for covering cropland

Discussion

The presented results show that the price of covering cropland with agrivoltaic is higher than the price of covering cropland with shading nets and thus additional costs or design modifications for agrivoltaic systems cannot solely be justified based on the provided economic benefit of shading. Still, depending on the local cost structure of crop protection with plastic cover, agrivoltaic can create notable synergies when the plastic cover and thus corresponding costs can be avoided. Other impacts like the avoidance of waste are still to be incorporated in economic analysis.

Presented results can be a decisive step towards economically viable agrivoltaic systems since the value of shading can be communicated between the PV and agriculture sectors. Further, the price for covering cropland with an agrivoltaic system allows us to analyze easily how the economic feasibility of agrivoltaic can be increased: Lowering CAPEX and OPEX has the biggest impact. While a lower specific generation of an agrivoltaic system compared to a ground-mounted system amplifies the effect of higher CAPEX (or OPEX), a higher specific generation dampers differences in CAPEX.

We see also that a higher density of the agrivoltaic system leads to an increase in the price for covering cropland, which seems counterintuitive. But it finally makes sense as it is beneficial to provide protection for a large area with few PV panels, hence material. Here PV developers must make a mindset shift when developing agrivoltaic solutions since it was always the focus to minimize needed land area. With an agrivoltaic system that is designed to protect crops, we want to cover as many crops and thereby land, as possible with the least amount of PV panels, always under the conditions that the needed crop protection is provided.

Some limitations of the presented study should be noted: We did not compare in detail the impact of shading by PV panels and shading by shading nets, here further research is needed. Further we assume in the sensitivity analysis that a decrease in density doesn't impact CAPEX, which is true if the design measures to decrease density are minor, such as an increase in pitch distance. If the density is decreased by more complex design measures such as spacing between PV panels or semi-transparent PV panels, the CAPEX would increase. Also, we assume similar degradation of PV efficiency when comparing ground-mounted PV systems to agrivoltaic systems, hence we exclude degradation from the price for covering cropland with agrivoltaic.

CONCLUSION

Agrivoltaic brings together two distinctly different industries, the PV sector, and agriculture. Different cultures and different decision-making practices are an obstacle for agrivoltaic implementation. While the PV sector decides based on capacity-specific prices, agriculture is used to area-specific prices.

We use a metric to calculate the area-specific cost of covering cropland with an agrivoltaic system based on cost differences, deviations in specific generation, and density compared to a traditional ground-mounted PV system. The metric allows comparing additional costs of agrivoltaic with the cost for plastic covers for cropland. Further, we describe data for a case study in Ovalle, Coquimbo Region, Chile, where a farmer is utilizing shading nets in a blueberry orchard. We highlight different shading nets and their cost structure. We describe a state-of-the-art ground-mounted PV system and estimate costs. We elaborate on possible modifications of PV design to enable blueberry cultivation underneath PV panels providing needed shading. Based on the proposed modifications we estimate additional costs compared to the ground-mounted PV system.

Our results show that the price of covering cropland with agrivoltaic is higher than the price of covering cropland with shading nets. Still, while the cost for the initial installation of shading nets is very low, shorter durability and needed replacement increase total spending over 25 years, while additional costs for agrivoltaic (under our assumptions) only occur at the installation. We highlight the impact of reducing additional CAPEX and conclude that if additional CAPEX can be limited to about under 150 $/kWp, the price for crop cover with agrivoltaic systems can compete with the price for crop cover with shading nets. Further, we conclude that agrivoltaic system design should not focus on maximizing capacity per area since the price for covering cropland decreases with lower densities. This conclusion may seem counterintuitive, but it finally makes sense as it is beneficial to provide protection for a large area with few PV panels, hence material. Here PV developers may make a mindset shift when designing agrivoltaic solutions since it was always the focus to minimize needed land area. Also, we conclude based on our results, that losses in specific yield should be avoided, as they amplify the existing differences in costs.

Since this study focuses solely on shading nets in central Chile, it is noteworthy that other possible applications of agrivoltaic as a crop cover and respective plastic covers should be analyzed.

Finally, our study shows that agrivoltaic crop protection can create economic value for agriculture and thus we conclude that further research should be dedicated to investigating the physical aspects of PV panels replacing plastic covers to protect crops.

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