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Assessment of Economic Synergies of Agrivoltaics in the Distributed Generation Segment in Chile

Techno-Economic Analysis and Policy Recommendation

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Abstract. Agrivoltaics (AV) combines photovoltaic (PV) electricity generation with agriculture on the same land. In Chile, despite high potential, AV is not yet commercialized due to high investment cost. To close the remaining cost gap to conventional PV, we shed light on a set of AV specific synergies in the market segment of Small Distributed Generation Facilities. Through a techno-economic model, this paper monetizes AV synergies to derive the economic performance of a sun tracked AV system over blueberries for the PV stakeholder. The study reveals that tracked AV systems can be operated with an Internal Rate of Return (IRR) of 5.2% at the threshold of profitability. This is enabled due to the exploitation of synergies within the market segment that improve IRR for the PV stakeholder by 2.5%. Still, sun-tracked AV requires compulsory technology grants between 5 – 10 USD/MWh to be economically implemented. The results indicate the necessity for regulative adaption. Legislation must open agricultural land for AV project development to enable the commercialization.

Keywords: Agrivoltaics, Techno-Economic Analysis, Policy Recommendation

1. Introduction

1.1 Baseline Situation

Chile is among the most affected countries by climate change worldwide. To date, the country meets seven of the nine vulnerability criteria, including arid and semi-arid zones, territory sensibility to natural disasters and areas endangered to drought and desertification [1]. This reality has already today an impact on agriculture. In the northern and central part of the country, especially small-scale farmers suffer from regional water shortages due to an ongoing 12-year hydrological crisis [2]. Apart of water shortages, agriculture faces unpredictable weather patterns such as hail, frost, high humidity, heavy rain falls and excessive solar irradiation. Corresponding harvest shortfalls affect the income of the sector and the employed rural population. To cope with increasing effects of climate change farmers apply technology to maintain their productivity. Among the applied solutions, plastic and net covers have been developed strongly in the last 10 years [3].

In the wake of cross-sectoral challenges induced by climate change, agrivoltaics (AV) represents an innovative solution to increase resilience in agriculture and enable PV development to cope with national deployment targets. AV is the concept of using the same area of land for agricultural and PV electricity production [5]. The technology experiences increasing attention as exploiting land for energy and food production not solely improves land-use efficiency but also provides synergetic effects for agriculture in arid and semi-arid climates. While PV modules exploit high incoming light to generate electricity, crops are protected from excess solar irradiation and harmful weather phenomena. Through the partial shading of farmland, the irrigation water consumption can be reduced addressing one of the major challenges of agriculture in dry regions. However, up till now AV is not commercialized in Chile and rather a niche solution worldwide. This is mainly due to high upfront capital cost (CAPEX) and uncertain regulative environments. As an AV project includes with agriculture, energy, and construction three main legal sectors, the regulatory framework is often not yet fully defined or unclear [6].

1.2 Small Distributed Generation

In Chile, the Small Distributed Generation Facilities segment administers distributed generation plants between 300 – 9,000 kWp. The segment has experienced strong growth in recent years with a total installed capacity of 1.1 GWp contemplating the overall PV capacity of 4.9 GWp in Chile as of 2022 [7]. Still its future is uncertain as a legislation change in May 2022 (Decreto Supremo 88/2019) introduced hourly band prices considering six different 4 h time intervals during a given day. The electricity remunerations are determined with respect to the average forecasted marginal cost at nodal points throughout the country, with lower prices at daytime for areas with high solar energy generation capacity [8].

In Chile, soils are classified with respect to their capacity for agricultural exploitation [9]. In the case of the construction of a PV plant in the Small Distributed Generation segment, the land use form must be obligatorily changed from agricultural to industrial usage in front of legislation [10].The probability of approval for PV projects on soil with relevant agricultural potential (class I – III) is very low. If a project does get approved, environmental compensation measures are obligatory. The Agriculture and Livestock Service determines the size of the area to be compensated and approves proposed measures [11].

2. Related Literature

To date, few publications investigated the economic performance of AV in Chile. In 2021, Jung et al. conducted a techno-economic assessment in the own-consumption market segment for a horticulture farm assessing the AV business case from the perspective of a small-scale farmer. The authors monetized AV synergies with agriculture accounting for opportunity cost of maintaining cropland and for the substitution of shading nets by PV modules [12]. Subsequently, Jung & Salmon proposed in 2021 a metric to calculate the price for covering cropland of an AV system in comparison to the cost of conventional shading nets in blueberry farming [13]. Hence, the research conducted explored AV business cases predominantly from the perspective of farmers examining synergies between PV and agriculture.

3. Methods and Data

3.1 Case Study

We investigate the economic performance of AV in a hypothetical case study in blueberry farming. For the modeled blueberry system, we apply a baseline case with Raschel type shading nets in vertical clearance of 2.5 m and a shading rate of 30%. This shading net type is a widely applied cost-effective measure in Chilean fruticulture to protect crops of excessive sun and eventual moderate rain and hail events [14].

We suppose the agricultural case study at the two locations indicated in Figure 1. Location 1 (L1) is situated in the commune Ovalle in the region Coquimbo about 450 km north of Santiago and characterized by an average Global Horizontal Irradiation (GHI) of 5.88 kWh/m2/day. Location 2 (L2) is situated in the commune Lampa in the Metropolitan Region of Santiago with a slightly lower GHI of 5.65 kWh/m2/day. At L1 Ovalle, space for conventional PV is available while at L2 Lampa land faces high pressure by urbanization and agriculture which makes ground-mounted PV (PV-GM) impossible to develop as there is no space available. The agricultural yields are assumed to be equal in the conventional shading net and AV system. Respective assumption is justified through a literature comparison of the Ground Cover Ratio (GCR) of AV systems in fruticulture as further specified in the following section.

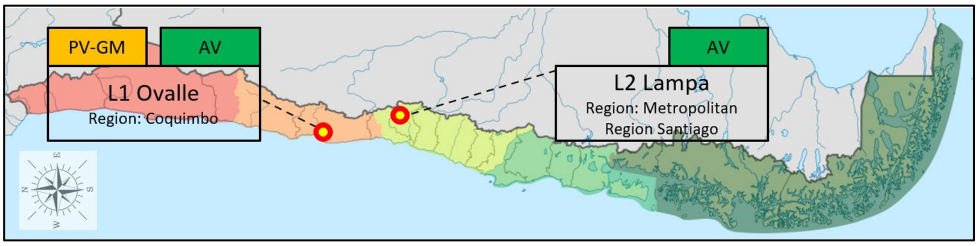

Figure 1. Map of Chile indicating the ubications of the two study locations L1 Ovalle and L2 Lampa and the and the availability of land for PV-GM or AV. Map adapted based on [15].

3.2 Technical Model

We design a Horizontal Single Axis Solar Tracker (HSAT) AV system, referred to as Tracked AV with a total installed capacity of 9 MWp. Bifacial PV panels trace the sun from east to west within a single panel landscape layout to align the PV modules to the 3 m blueberry row distance predefined in the agricultural system. Due to the lack of literature data for AV over blueberry cultures, we consider a tracked AV facility in apple fruticulture with a GCR of 41% in southern France under a GHI of 4.2 kWh/m2/day as a GCR benchmark [16]. The benchmarked system uses dynamic tracking that can increase light availability for the crops instead of solely optimizing electricity yield. However, in accordance with the significantly higher Chilean GHI levels, we assume that a GCR of 41% results in maintaining the cuantity and quality of agricultural production compared to the baseline scenario with shading nets. Assumed cover ratio is within the range of the fixed northeast facing APV plant in horticulture by Fraunhofer CSET in Chile that demonstrated positive yield results for lettuce with a GCR of 38% [17]. By placing the modules directly above the crop rows, the plants are protected from extreme weather conditions. Taking the installation height of conventional shading nets in blueberry cropping as a reference, we set vertical clearance for the AV system at 2.5 m.

Furthermore, we delineate a 9 MWp Tracked PV-GM baseline system according to the industry standard in Chile. HSAT east-west systems are predominant for grid injecting power plants in the local PV market. We employ bifacial PV panels in a single portrait module layout with a row distance of 5,5 m resulting in a GCR of 43%. We model energy generation with the System Advisor Model provided by National Renewable Energy Laboratory. Table 1 indicates modelled annual energy generation in the first year of production for the technical set-ups.

Table 1. Specific generation per technical case for the 1st year. All plants have an installed capacity of 9 MWp. Shading effects of adjacent PV panels lower specific yield of AV slightly.

Location	Tracked PV-GM	Tracked AV	Unit
L1 Ovalle	2,380	2,360	kWh/kWp
L2 Lampa	2,330	2,310	kWh/kWp

3.3 Economic Model

The economic model assigns cost and revenue data to the technical sy21240/stems to derive profitability within the Internal Rate of Return (IRR). The IRR measures the profitability of an investment by assessing the required discount factor to realize a Net Present Value (NPV) of zero representing essentially the annual rate of growth that an investment is expected to generate over lifetime. The higher IRR, the more desirable is an investment. The IRR is written as [18]

$$NPV = \sum_{t=0}^{n} \frac{NetCF_t}{(1+IRR)^t} = 0 \tag{1}$$

with $NetCF_t$ being the net cash flow at time t and NPV the Net Present Value.

Figure 2 indicates the incremental steps of the economic model: PV yield and design parameters are the basis to assign financial data to develop net cash flows over the system lifetime of 25 years. Cash flows are developed individually for a set of economic scenarios to investigate the monetary implications of AV synergies.

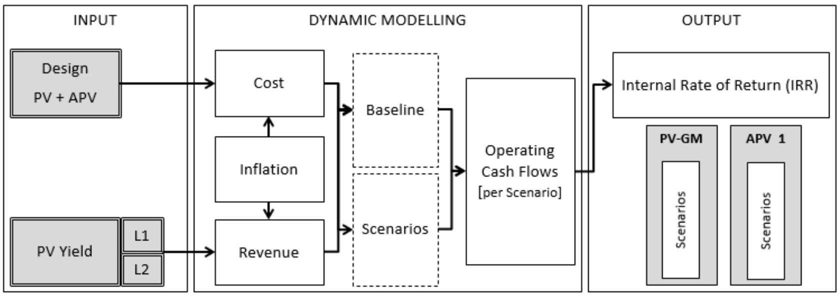

Figure 2. Flow chart economic model.

Table 2 indicates CAPEX derived from current market-specific industry data for the technical cases. The elevated tracker support configuration is the main cost driver for AV as it more than triples mounting structure cost for AV. Respective cost is obtained from quoted proposals from AV support structure providers. OPEX is assumed as 17.9 USD/kWp equal for PV-GM and AV. The fact that the Tracked AV system necessitates a 0,2 ha greater surface area to inhabit 9 MWp due to the lower realized GCR can be neglected due to present low land rents. We apply an annual debt interest rate of 6.5% at a debt tenor of 15 years. The Weighted Average Cost of Capital (WACC) of the project developing company is 5.5%. We apply the 2021 Chilean annual average inflation rate of 3.1% on all prices [19]. Value-added tax is not considered. All cost is provided in USD. Cost accessed in Chilean Pesos (CLP) is converted to USD at an exchange rate of 1 USD = 809 CLP on the 14th of April 2022 [4].

Table 2. CAPEX composition for the technical cases Tracked PV-GM and Tracked AV.

Item	Tracked PV-GM	Tracked AV
	USD/kWp	
PV Modules	300	300
Mounting Structure	100	320
Installation	80	190
Inverter	30	30
BOS		
Grid Connection	60	60
Fencing	10	10
Other BOS	80	80
Soft Cost		
Environmental Management	100	100
Other Soft Cost	50	50
Total	**810**	**1,140**

We consider the hourly band price valid for the 1st and 2nd semester 2021 issued by the National Energy Commission as electricity remuneration for the first year of operation. Hourly band prices at daytime at L2 Lampa are higher compared to L1 Ovalle which is triggered by variations in regional marginal cost between the two ubications. The found price differences are forecasted to stay present until 2031 due to limiting grid capacity that hinders the transmission of high amounts of renewable electricity from the north to the load points in the central part of the country. We assume an Average Annual Growth Rate (AAGR) of electricity remuneration of + 1.3% from Start o Production (SOP) in 2024 until 2031 for L1 Ovalle and L2 Lampa retrieved from a study conducted by the National Electric Coordinator that simulates marginal cost of the energy system until 2031 indicating respective price increases [20]. From 2032 to 2048, we assume an AAGR of – 1% due to the system wide expansion of renewable energy generation in the grid that induces steady decrease of marginal cost.

3.4 Scenarios

The modified cost and revenue parameters for two economic scenarios are presented in Table 3. The first scenario includes the CAPEX and revenue parameters of the Tracked AV system without accounted synergies and the PV-GM baseline plant at L1 (compare Figure 1). The second scenario illustrates the synergies enabled through the installation of the AV system at L2, where PV-GM cannot be developed due to the described land restrictions in the Metropolitan Region of Santiago. AV may be developed on novel sites due to the access to agricultural land which enables the possibility to install systems close to sub-stations and the mid-voltage grid which is numerically captured under the sub-item “Grid Connection” in Table 3. Respectively, we include the option of cost savings for grid connection. The assumed cost data is retrieved from industry exchange. Since the land will continuously exploited for agricultural purposes, we assume environmental compensation measures, that are obligatory for PV projects on land classes I – III, to be obsolete. Fencing cost can be neglected as fruticulture gardens are commonly hedged in Chile. Moreover, through the installation of AV on agricultural land L2 Lampa becomes accessible for PV development. Consequently, AV can access higher remuneration tariffs in the Metropolitan Region of Santiago. Considering the average of the daily hourly band prices for L2 Lampa, a 14% higher electricity remuneration is obtained.

Table 3. Altered parameters for scenario analysis. The average hourly band prices for 2021 for the daylight price bands are presented [8].

Item	Sub-Item	Symbols	AV at L1 w/o synergies PV-GM at L1	Δ	AV at L2 w/ synergies
CAPEX	Grid Connection		570,000 USD	- 450,000 USD	120,000 USD
	Environmental Compensation		100,000 USD	- 100,000 USD	-
	Fencing		130,000 USD	- 130,000 USD	-
	Total Δ			**- 680,000 USD**	
Revenue	Average Hourly Band Prices		43 USD/MWh	+ 14%	49 USD/MWh

4. Results and Discussion

4.1 Economic Performance

Figure 3 indicates an IRR of 2.6% for Tracked AV if no AV synergies are considered. Thus, AV results in a considerably lower profitability compared to conventional Tracked PV with an IRR of 11.2% shown on the far right of the diagram. The profitability of the AV business case is particularly diminished by higher CAPEX.

Within the identified AV synergies, cost savings in grid connection increase the business case strongest by + 1.1% IRR. While the access to higher remuneration tariffs at L2 Lampa increases IRR by + 0.9%, the omission of environmental compensation accounts for + 0.2% and savings in fencing for + 0.3% improvement in IRR. Overall, the identified AV synergies increase IRR by + 2.5% to a total of 5.2%. Comparing this value to WACC for PV assets of 5.5% as the hurdle rate for a feasible investment project, the results demonstrate that Tracked AV can be operated on the edge of profitability. However, the monetized synergies are insufficient to lift the AV business case to a comparable profitability level as conventional PV-GM. To bridge this profitability gap, we derive three major industry recommendations for the Small Distributed Generation Facilities market segment.

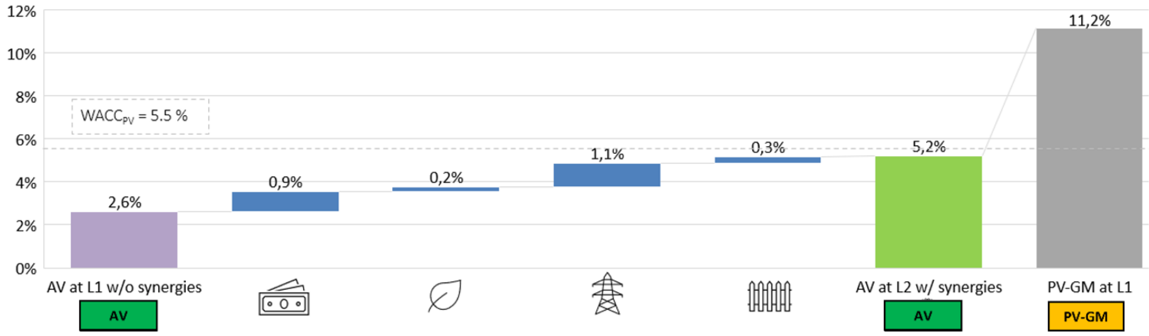

Figure 3. IRR of Tracked AV for PV stakeholder with WACC = 5.5%, plant lifetime = 25 yr.

4.2 Policy Recommendations

4.2.1 Access to Farmland

To permit AV technology to utilize the demonstrated synergies for PV stakeholders and to drive climate resilience in agriculture, it is recommended to open agricultural land for AV project development. It is crucial that this is performed after a standard is introduced that technically defines AV and delineates performance indicators that must be met to protect agricultural practice. Current legislation implies the transformation from agricultural land to industrial land if conventional PV systems are installed [21]. It is either recommended to maintain agricultural land status in the case of AV to account for the continuation of agricultural practice or to introduce a novel land use class for dual land usage.

4.2.2 Debt Financing under the Chilean Green Bond Framework

The provision of advantageous financing conditions may be a valid option to incentivize AV project development without burdening government budgets. In this light, Chile is the first country in Latin America that introduced green governmental bonds to finance sustainable and social projects [22]. To incentivize AV, guarantees can be issued on public loans to reduce the operational risk for investors leveraging private capital investment or projects may be financed in entirety from the green bond. The Ministry of Finance states as eligible expenditures investments in real assets for renewable generation technologies which undoubtedly imply AV. The Chilean Green Bond Framework entails a key performance indicator model to evaluate eligibility and to track the impact of funded projects [22]. Hence, it is recommended to evaluate AV projects on their provided benefits for agriculture, the energy system and innovation to ensure a commercialization with the greatest possible added value for society. Sensitivity analysis reveals low policy support requirements with an annual debt interest rate of 5.5% and a debt tenor of 20 years already enabling an implementation of Tracked AV at an IRR > 9%.

4.2.3 AV Fixed Market Premium

A fixed market premium on electricity remuneration prices under the hourly band price regime denotes an alternative to increase returns for AV projects. We assume an IRR > 9% as the profitability threshold to decide in favor of a project. The consideration of a CAPEX range between 1,050 USD/kWp - 1,150 USD/kWp accounts for cost driving system adaptions to the agricultural context. Proceeding with these values, we derive an AV fixed market premium of between 5 – 10 USD/MWh with WACC = 5.5% and a plant lifetime of 25 years. In accordance with international incentive programmes for renewable energies in distributed generation and utility-scale PV, we recommend a separate tendering scheme to assign technology bonuses to AV projects. As technology-open electricity tenders are already being carried out, legislation may build up on gained experiences. A separate AV tender may award a fixed market premium paid on top of the hourly band prices. Herewith, AV systems can still be incentivized through the price bands to align generation to regional marginal cost. Merely additional cost to adapt AV systems to the agricultural context must be awarded in the tender.

5. Conclusion

Conducted analysis shows that Tracked AV can be operated at the threshold of profitability in the distributed generation segment in Chile. This is achieved through the monetization of synergies with the PV market itself that imply cost reductions and revenue increases. However, AV is still less profitable compared to Tracked PV-GM. Investors would rather remain financing well-known conventional PV projects as they are the economically better choice. Respective results exhibit the necessity for regulative support which in the wake of a liberal Chilean energy policy evidently imposes a challenge for practical implementation. Within the interpretation of the results is to be considered that present analysis lacks a detailed consideration of agricultural yields, as these were assumed to be the equal under the AV system compared to land covered with 30% shading nets referring to literature GCR values from apple-fruticulture in France and horticulture in Chile.

However, since Chile is one of the most endangered countries by climate change worldwide, the expansion of climate resilience in agricultural already is a major concern on the political agenda. The fundamental policy instruments to incentivize AV are already present in the market design. Policy experience in electricity tender schemes and green financing are a vivid point of departure to derive AV tailored instruments. Ultimately, the present study reveals AV to be capable to reach commercial implication in distributed generation in short term with corresponding regulative policy support. The elaboration of an AV standard and a subsequent legislatively controlled opening of agricultural land for AV project development are decisive first steps for a cost-effective and policy goal-oriented introduction of the technology. The present impacts of climate change in Chile and the decarbonization goals of the government require urgent action. In this context, prompt promotion of AV can help to comply with the cross-sectoral governmental goals of renewable energy deployment and climate resilience in agriculture.

Data availability statement

The datasets generated in the present study are available from the corresponding author on reasonable request.

Author contributions

F Schönberger: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. D. Jung: Conceptualization, Methodology, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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