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Agrivoltaics Over Berries in Chile: Potential for Clean Energy Generation and Climate Change Adaption

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Abstract. Agrivoltaics (AV), the concept of installing photovoltaic (PV) panels on agricultural land, enabling a dual use of the surface, has the potential to foster renewable energy expansion without land use conflict and to protect water from evapotranspiration. Although there is growing interest in AV, there has been no structured analysis of its potential for clean energy generation and climate change adaptation in Chile. In this paper, we provide the first national-level estimate of the AV potential over blueberries, using a combination of filtered geo-datasets and meteorological data to quantify PV yields and impact on evapotranspiration. We find a theoretical potential of 13.4 GWp for AV over blueberries, predominantly in the central and southern regions. The derived potential for AV could provide 22% of the current national electricity generation while lowering irrigation demand by nearly 18 million m³ per year. Finally, we identify about 8,000 GWh of current annual conventional electricity generation that could be regionally replaced by AV, showing the potential to contribute significantly to the decentralization and decarbonization of the Chilean electricity mix. Further research on the agronomic and economic aspects of AV implementation should be carried out to enable synergetic development.

Keywords: Agrivoltaics Potential, Evapotranspiration, Decentralization

1. Introduction

Both, the Chilean energy and the agriculture sector, are facing interconnected challenges: About 6.89 GWp of subsidy-free solar photovoltaic (PV) capacity, mainly located in the northern desert regions, have been connected to the grid as of April 2023, representing 22% of the national electricity generation capacity [1]. The current energy policy aims at further expanding renewable energy (RE) generation by 30 GWp while focusing on decentralization and implementing generation capacity close to consumption centers in the central and southern regions of the country [2], [3]. When it comes to decentralization, PV projects are projected to face land use conflicts, as fertile soils in central and southern regions are exploited for agricultural purposes. At the national level, agriculture is an important economic sector, accounting for 3.4% of GDP in 2022 and especially fruticulture has developed strongly, increasing the total cultivated area by 88% in the last 20 years to currently over 375,000 ha [4], [5]. This development is threatened by the effects of climate change: the period between 2010 and 2019 is classified as a mega-drought in the central zone of Chile with rainfall deficits of 30% [6]. Water scarcity is directly impacting agriculture which accounts for 88% of the freshwater consumption in the country [7]. In the time between 2008 and 2021 a total of 507 water emergencies have been declared at regional and communal levels [8]. Water emergencies allow the government the application of instruments that seek to reduce the impact of drought on people's lives. These instruments include the limitation of irrigation volumes for agricultural activities, hence could potentially impact crop yields negatively. Consequently, agriculture needs to adapt and build up resilience against the projected sunnier and drier climate.

In this context, Agrivoltaics (AV) could create valuable benefits by installing PV panels over crops on farmland. AV not only has the potential to solve land use conflicts but also to enable efficient water use due to shading that lowers evapotranspiration (ET) rates [9]. Schönberger et al. [10] investigate the economic performance of AV in blueberry farming in Chile and find that AV systems can be operated at the threshold of profitability due to monetizable synergies in the grid-injecting segment. To provide a further understanding of the AV potential as a basis for political decision-making, we conduct this study to quantify for the first time the theoretical potential of AV over berries in Chile for clean energy generation and water protection.

2. Methods and Data

We use and process publicly available Geographic Information System (GIS) and meteorological data with scientifically validated methods to examine the potential implementation and impact of AV systems for berry orchards, as described in the flow chart in Figure 1 (a).

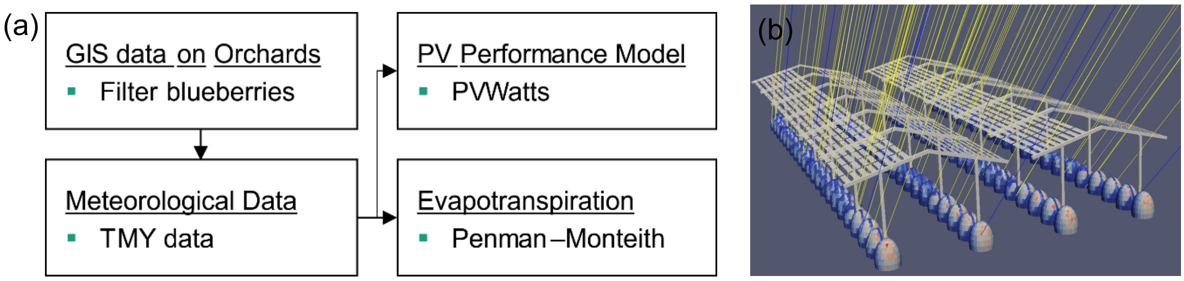

Figure 1. (a) Research methodology flowchart. (b) Ray tracing for crop geometries under a 3D model of applied AV system

2.1 GIS Data on Orchards

We use publicly available GIS data on areas with fruticulture cultivation for 14 of the 16 Chilean regions. Only the desert region Antofagasta and the austral region Magallanes are not represented due to a lack of fruticulture activity. The data is elaborated by the Natural Resources Information Center (CIREN*)* in the years 2020, 2021, and 2022 and provided by the Office of Agricultural Studies and Policies (ODEPA*)* from the Ministry of Agriculture [11]. The datasets of polygons contain information on the species grown for all entries and partially complete information on the irrigation system and plant date. The regional datasets are joined to a national dataset and filtered for the species “American blueberry”.

2.2 Meteorological Data

Based on the GIS data on the blueberry orchards, we extract weather data for a Typical Meteorological Year (TMY) derived from ERA5-Land reanalysis for all coordinates of the identified water bodies with the python library *pvlib* from the publicly available PVGIS version 5.2 [12], [13]. TMY data contains hourly values, selected from historic data (10 years or more), with the premise of considering the statistically most representative year. Relevant parameters are presented in Table 1.

Table 1. Parameters of extracted TMY data.

Symbol	Parameter	Unit
T_a	Ambient air temperature in height of 2 m	[°C]
RH	Relative humidity	[%]
R_s	Global Horizontal Irradiance	[W m^{-2}]
u_{10}	Wind speed in height of 10 m	[m s^{-1}]

We convert wind speed u_{10} [m s^{-1}] at height z = 10 meters to wind speed u_2 [m s^{-1}] at height 2 of 2 meters as described by the Food and Agriculture Organization of the United Nations (FAO) and Allen et al. [14]:

$$u_2 = u_z \frac{4.87}{\ln(67.8\,z - 5.42)} \tag{1}$$

2.3 AV System

To further investigate the potential of the AV system, we defined a conceptual design using semi-transparent PV panels based on c-Si technology with spacing between cells and a light transmittance factor of 45%. The panels were arranged in a roof layout facing east-west with an inclination of 15° respectively to provide homogeneous shading. The design had a vertical clearance of 2.5 m and a row spacing of 3 m, which are common machinery heights and blueberry growing row distances in Chile. These characteristics allowed for the implementation of 0.708 MWp per hectare. Further we compute daily shading rates for every month under consideration of hourly timesteps with an in-house simulation based on the ray tracing tool solstice as shown in Figure 1 (b) [15]. Daily shading rate shows maximum deviation between 31.8% in December and 28.9% in August for an AV systems in the Coquimbo region. Further south, intramonthly changes in shading rate diminish.

2.4 PV Performance Model

We simulate hourly PV performance with functions provided by *pvlib* python [12]: We use TMY data to calculate total plane-of-array irradiance (POA) [W m^{-2}] and its direct, sky diffuse and reflected components [W m^{-2}], using the isotropic sky diffuse irradiance model for defined location, azimuth, panel tilt and albedo of 23%. Further, we obtain effective irradiance by calculating the angle of incidence and incidence angle modifier using the ASHRAE transmission model [16]. We calculate cell temperature T_c [°C] using an empirical heat loss factor model as implemented in pvlib based on the Faiman equation [17]:

$$T_c = T_a + \frac{POA}{U_c + U_v * u_2} \tag{2}$$

where POA is the plane of array irradiance [W m^{-2}], U_c is the constant heat transfer component [W m^{-2} K^{-1}], U_v is the convective heat transfer component [W m^{-2} K^{-1} (m s^{-1})$^{-1}$] and u_2 is the wind speed [m s^{-1}]. Direct Current (DC) output is modeled with NREL's PVWatts DC power model for two PV systems with 0.5 kWp nameplate capacity each, orientated 15° west and 15° east. We consider a temperature coefficient of -0.0037 °C^{-1} [18]. Finally, we add the DC outputs of the two systems and use the PVWatts inverter model for a 1 kW inverter with a nominal inverter efficiency of 96.1% to obtain alternating current (AC) energy output and apply a loss factor of 16.7%, including standard soiling losses of 5%. Hourly values are summed up to yearly values equaling the potential specific generation of an AV system.

2.5 Evapotranspiration

To determine the irrigation demand of crops and the impacts of AV systems, we calculate potential evapotranspiration (PET_{PM_FAO56}) [mm d^{-1}] as described by Penman-Monteith [19], [20] and Allen et al. [14] and as implemented in the python library *pyet* as the FAO-56 function [21]:

$$PET_{PM\_FAO56} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2(e_a^* - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3}$$

with Δ as the slope of saturation vapor pressure curve [kPa °C^{-1}], R_n is daily net radiation at the crop level [MJ m^{-2} d^{-1}], G is the soil heat flux [MJ m^{-2} d^{-1}], γ is the psychrometric constant [kPa °C^{-1}], T_a is air temperature [°C], u_2 is the wind speed in height of 2 meters [m s^{-1}], and finally $(e_s - e_a)$ is the vapor pressure deficit [kPa] with e_a^* as the saturation vapor pressure [kPa] and e_a as the actual vapor pressure [kPa]. The soil heat flux G is assumed to be 0. All variables are calculated based on TMY data according to the methods of Allen et al [14]. Net radiation R_n [MJ m^{-2} d^{-1}] is being calculated based on net incoming solar short-wave radiation R_{ns} and net outgoing thermal long-wave radiation R_{nl}. Net short-wave radiation R_{ns} [MJ m^{-2} d^{-1}] is the difference in incoming and reflected outgoing solar irradiation under consideration of the albedo factor α for a vegetated surface of 23% as indicated by the FAO [14]. Also, we apply the computed shading rate s_{AV} resulting in a decreased incoming short-wave radiation $R_{s\,AV}$ under AV conditions:

$$R_n = R_{ns} - R_{nl} = (1 - \alpha) * R_s - R_{nl} \text{ with } R_{s\,AV} = R_s * (1 - s_{AV}) \tag{4}$$

Further, we apply crop coefficients for different stages of the crop growing season for berries (bushes) as stated by Allen et al. [14]: $k_{c\,ini} = 0.3$ for the initial fase of crop growth in August, $k_{c\,mid} = 1.05$ for the mid-season stage from November to February and $k_{c\,end} = 0.5$ for the late season in April. We exclude the time between growing seasons from the ET calculation. Further, to obtain ET we apply a factor for the effective area planted with $f_c = 0.7$, accounting for space between rows that is not covered with leaves as indicated in Eq. (5):

$$ET = PET_{PM\_FAO56} * k_c * f_c \tag{5}$$

The calculated values for ET can be used as an indication of irrigation demand as the irrigation quantity and frequency should be scheduled to replace water loss of the crops through ET [22]. The efficiency of irrigation systems is not considered.

3. Results and Discussion

The study found a significant potential for the implementation of AV systems over blueberries in Chile, with a theoretical potential for over 13.44 GWp based on about 19,000 ha of orchards distributed in the regions between Coquimbo and Los Lagos. The majority of blueberry orchards are located in the Maule and Ñuble regions, which could allow the implementation of about 4,383 MWp and 3,150 MWp of AV, respectively. Additionally, the study found a theoretical potential for AV implementation of over 0.5 GWp in all regions south of Santiago, except for the austral Aysén and Magallanes regions. This potential represents a sharp contrast to the current installed PV capacity in Chile, as no region south of Santiago inhabits more than 0.5 GWp of grid-connected PV capacity. The results suggest that implementing AV systems in blueberry orchards could significantly contribute to the country's renewable energy goals and provide a potential pathway for increasing PV capacity in the southern regions of Chile.

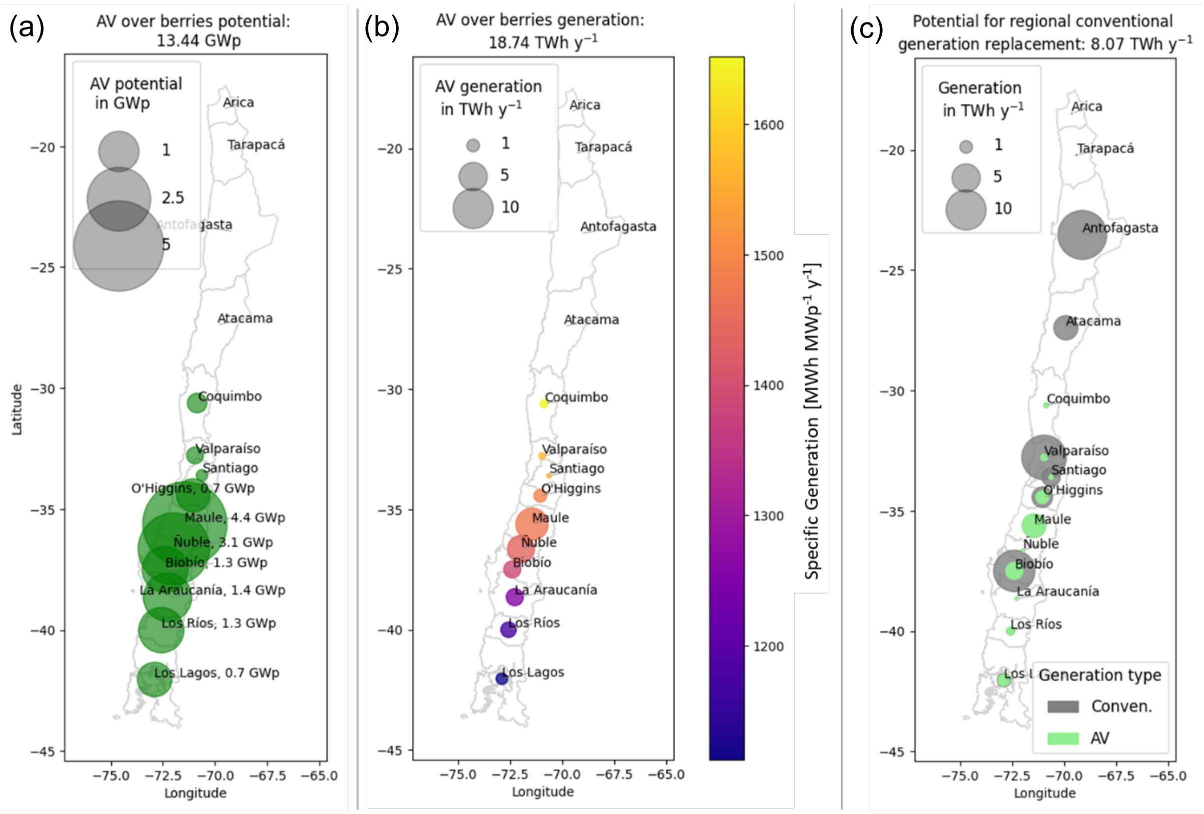

Figure 2. (a) Theoretical capacity potential for AV over blueberries (b) Potential for annual generation with indication of specific generation efficency (c) Potential for regional conventional generation replacement in Chile (all illustrations exclude the austral regions Aysen and Magallanes)

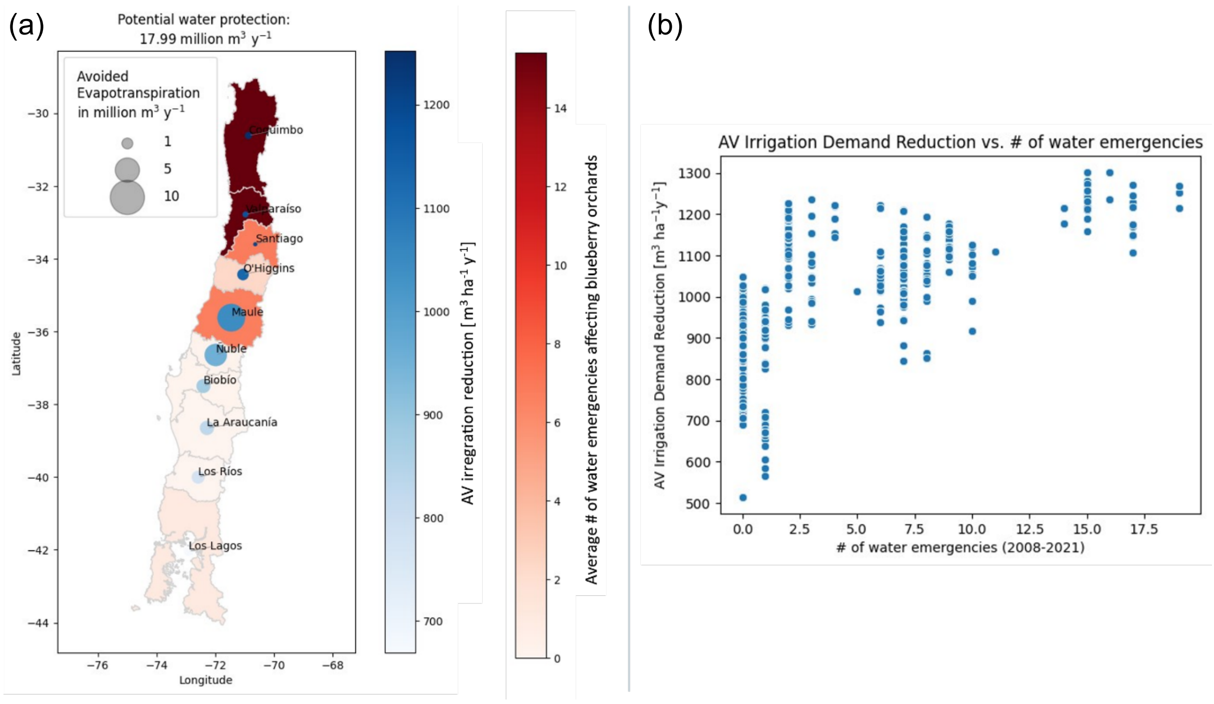

Figure 3. (a) AV evapotranspiration reduction and average number of water emergencies affecting blueberry orchards (only regions that inhabit blueberry orchards are illustrated)
(b) Correlation between irrigation demand reduction due to AV and number of water emergiencies

As shown in Figure 2 (b), the theoretical AV capacity enables an annual generation of about 18,700 GWh, representing about 22% of the total generated electricity in 2022, with specific generation differing highly between regions [1]: The proposed AV system yields 1,113 MWh MWp^{-1} y^{-1} in the Los Lagos region, whereas specific generation is 1,652 MWh MWp^{-1} y^{-1} in the Coquimbo region. Analyzing regional patterns, we find potential to enhance the distributed generation and replace current conventional generation. Figure 2 (c) shows how the derived technical potential of AV relates to the 2022 annual regional conventional and non-conventional renewable generation, as well as to the regional electricity demand (data from 2020, adjusted to match 2022 generation volume) [1], [23]: Nearly 8 TWh y^{-1} of conventional generation, including 1,7 TWh y^{-1} of carbon-based energy generation in the Biobio region could be replaced by AV.

Further, we find that a reduction in irradiation from an AV system results in an average diminution of evapotranspiration and thus irrigation demand by 15%. The difference in ET between unshaded and AV conditions is between 669 and 1,252 m^3 ha^{-1} y^{-1}, with values increasing in northern regions as shown in Figure 3 (a). The total potential to protect water from ET sums to about 18 million m^3, which equals 4.2% of the national domestic freshwater consumption [7]. Also, as shown in Figure 3 (b), orchards that are most affected by regional and communal water emergencies inhabit the highest potential for water savings: While orchards that were affected by less than 2 water emergencies between 2008 and 2021 present a potential for water savings between 500 to 1,100 m^3 ha^{-1} y^{-1}, orchards that were affected by 14 – 17 water emergencies present a potential for water saving through AV shading between 1,100 to 1,300 m^3 ha^{-1} y^{-1}.

4. Conclusion and Outlook

Presented results indicate a high potential for AV over blueberries in Chile, as theoretical AV capacity equals two times the current total Chilean PV capacity [1]. Interpreting the identified theoretical potential within its geospatial distribution reveals the great potential benefits of AV for decentralizing the national electricity grid and fostering the energy transition towards renewable generation. As the major surfaces of blueberry cultivation are located in the central to the southern part of the country, AV enables land renewable energy expansion without land use conflict in regions that are still dominated by conventional generation. Namely in the regions of O'Higgins, Maule, and Biobío electricity generated by AV over blueberries represents an attractive solution to decarbonize the local electricity grid mix. On the agricultural side, the reduction in ET due to shading shows the climate change adaption potential of AV for Chilean agriculture since it allows to lower irrigation demand by about 15%. Further, we found a positive correlation between water scarcity and the ET reduction by AV, indicating the viability of AV to address current challenges of water use efficiency in agriculture. As the effects of climate change are forecasted to further worsen the hydrological situation in the central zone, AV could be a key element to maintain agricultural productivity under challenging future climatical conditions [24].

Still, these results have limitations: Agronomic aspects such as the possible impact on plant growth and physiology are not considered. Technical aspects of AV implementation, including the slope of the terrain, distance to the electricity grid, as well as economic aspects such as the Levelized Cost of Energy (LCOE) and operation type (own consumption vs. grid injection) should be considered in future analysis for AV potential.

The results of this study lead us to the following conclusions and recommendations: In order to leverage the potential for clean energy generation and climate change adaptation identified in this study, Chilean land use legislation needs to be adapted. As of today, conventional PV and AV systems are not legally differentiated. Thus, agricultural land for AV projects in the grid injection segments must be converted to industrial land by law. However, Chilean legislation protects agricultural land with a high potential for crop cultivation from being transformed. Consequently, current land use legislation impedes the implementation of AV systems on agricultural soil outside the own consumption segment.

However, for this legislative vacuum, international experiences reveal solution pathways. In Germany, agricultural land was opened for the development of AV based on standards demarcated in a technical normative (DIN SPEC 91434) that sets minimum requirements for AV system design intending to ensure the unrestricted continuation of agricultural activities on the concerned land [25]. For the elaboration of such a normative, we recommend the creation of a collaboration platform between the industry, research, and public institutions from the agricultural and energy sector to initiate an intersectoral dialog that is needed to develop AV in a target-oriented manner. Ultimately, a legislative process and technical definition must ensure that AV is used in a way that is beneficial to agriculture. Thus, unlike conventional PV, the technology can serve to protect fertile land and optimize water use efficiency under the intensifying effects of climate change.

Data availability statement

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

Author contributions

D. Jung: Conceptualization, data handling & analysis, methodology, validation, visualization, writing; F. Schönberger: Conceptualization, Methodology, Writing – review & editing; F. Moraga: Data handling and analysis, methodology

Competing interests

The authors declare that they have no competing interests.

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