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Agrovoltaic systems for crop improvement in Equatorial Andean Regions

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Abstract. The current study evaluates the deployment of a grid-independent agrovoltaic system for maximizing land utilization and crop productivity. Through the utilization of solar energy, an integrated irrigation and monitoring system is incorporated to enhance crop growth. The project's feasibility is evaluated from both technical and economic perspectives. The design of the photovoltaic system and the pumping system is customized to optimize efficient utilization of solar and water resources. The findings of this research demonstrate the viability of adopting an environmentally friendly approach. The utilization of photovoltaic solar energy for electricity generation can coexist with agriculture and complement each other.

Key words.- Agrovoltaic system, solar energy, PVs.

1. Introduction

The inaccessibility of electricity in certain rural and remote regions can pose a significant hindrance to the production of goods and services [1]. In 1982, Goetzberger and Zastrow were the pioneers in proposing the concept of an Agrovoltaic System (AVS). They presented a configuration of a photovoltaic (PV) system designed to enable additional agricultural use of the involved land while optimizing the collectors for solar energy conversion [2]. However, it was only in 2017 that this concept began to gain significant importance.

A recent study conducted a review of the types of AVS technologies, their architectures, and their effectiveness currently employed in agriculture [3]. It also examined the state of Internet of Things (IoT) systems. AVSs are the combination of deploying PV panels with crop cultivation beneath these solar panels. This technology is based on the ability to provide partial shading that can be tolerated by crops, thereby reducing water consumption due to evaporation during drought periods and regulating solar irradiation incidence that is harmful to certain crop requirements [4]. Additionally, this technology enables traditional agricultural practices such as the use of machinery, which is not feasible with ground-level PV installations [4]. It is recommended that the PV panels be installed at a height exceeding 5 meters to avoid interference with agricultural machinery [5].

The primary focus of AVS is to promote continuous agricultural production [6]. To achieve this, specific agricultural practices and machinery involved in the process must be considered. It is advisable to consider a construction height of 5 meters, a distance of 16 meters between two vertical pillars, and a module tilt at 12% slope to limit wind loading and self-shading effects of the module, independent of the chosen Ground Coverage Ratio (GCR) [6]. Reducing wind loading results in a lighter steel structure and smaller foundation, and the use of concrete is discouraged due to its negative impact on the soil [7].

AVSs have gained popularity worldwide, and several significant projects have been implemented. According to [8], a solution to this problem involves the simultaneous production of food and energy using AVSs. Governments such as France, Japan, the USA, China, and South Korea have developed supportive policies for AVS implementation since 2017 [9]. In a specific case in India [10], the authors proposed a PV system for grape cultivation, where PV panels were installed on the unused spaces between trellises to maximize land utilization. A simulation was done using the NREL SAM model, revealing that the economic value of exports can be enhanced by a factor of 15 compared to traditional cultivation methods [11].

In France, a study was conducted on the production of different crops in the same land area subjected to shading by PV panels. The study proved that lettuce and other horticultural crops could achieve high yields under the partial shade generated by the PV panels. AVS has yielded positive results, as it has shown that shading in vegetable crops irrigated with panels allows savings between 14% and 29% as a consequence of reducing the evapotranspiration effect, depending on the level of shading and the type of crop [11].

In this work, we propose a simplified AVS, which delivers electricity to a small-scale lettuce plantation ($20m^2$). Further, it could be scaled to integrate this concept at large-scale crop fields to combine large-scale power production with large-scale agricultural production in equatorial locations.

A. Production of Lettuce with PV Solar Systems

Lettuce, or Lactuca sativa [12], is one of the simplest vegetables to cultivate (see Table I). Factors such as light intensity, day length, colour spectrum, ambient temperature, and humidity, among others, are components that affect the growth and yield of lettuce cultivation [13] [14]. Due to its short vegetative period, lettuce heads can be harvested within 45 to 50 days, and the seeds after 120 days [14].

Table I. Main types of lettuce [14]

COMMON NAME	APPEARANCE
Crisp lettuce	(var.capitata L. nidus jaggeri Helm)
Butterhead lettuce	(var.capitata L. nidus tenerrima Helm)
Romaine lettuce or Cos lettuce	(var.longifolia Lam., var.romana hort. en Bailey)
Leaf or cutting lettuce Latin	(var. acephala Alef., syn. var.secalina Alef. , syn. var. crispa L.)
Stalk or asparagus lettuce	(Asparagus) lettuce (var. angustana Irish ex Bremer,syn. var.asparagina Bailey, syn. L. angustana Hort. In Vilm.)
Latin lettuce	(without scientific name)

B. Solar potential of Ecuador

The solar atlas of Ecuador was created for electricity generation purposes. This atlas contains the average daily solar insolation (direct, diffuse and global insolation) values. In Figure 1, the locations in Ecuador with the highest solar irradiance that can allow feasible PV generation can be observed [15]. The annual global horizontal insolation in Ecuador ranges from 2.8 kWh/m²day to 6.4 kWh/m²day. Being closer to the equator at 2500 meters above sea level produces high solar irradiation levels, providing a good potential to implement solar energy technology for energy harvesting. The solar potential determined the capability of generating power up to 312 GW, which is equivalent to 456 TWh/year. This value is approximately fifteen times the technically and economically exploitable electrical potential of the country. However, the share of solar energy in the electricity matrix was less than 1% until 2023 [15] [16].

The orientation of solar panels is a crucial factor in optimizing their performance and maximizing solar energy production. In [17], five mathematical models were used to estimate the total insolation received by a flat surface, with meteorological variables such as global, direct, diffuse, and reflected irradiation being considered. These estimation models include the Isotropic Diffuse Model (MDI), Liu & Jordan (L&J), Temps & Coulson (T&C), Klucher (K), and Pérez et al. (P) models. Climatic data were obtained from two stations located in the city of Cuenca, belonging to the Universidad Politécnica Salesiana. Data from the years 2014 to 2017 were used for the study. According to the results, the optimal position to capture solar irradiation in the Cuenca city region is 35° orientation relative to the north (NNE), and an inclination angle of 15° [17]. The results of irradiance according to the Klucher model and the Liu and Jordan model in the city of Cuenca, Ecuador, are similar. Therefore, for a flat surface, the most optimal orientation is 34° relative to the north, with an inclination angle of 16° to obtain more significant insolation [18].

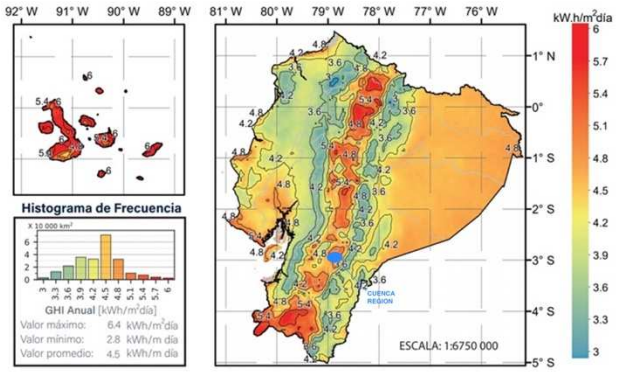

Fig. 1. Annual Global Horizontal Solar Irradiance [15]

2. Sizing of the agrovoltaic system

A. PV System Assessment

This section describes the development of the standalone PV system in a rural zone of the city of Azogues, Ecuador. Specifically, in Zhizhiquin sector at -2.7385° latitude and -78.858° longitude. The experimental system includes an area of 20 m^2 for the lettuce crop, as shown in Figure 2.

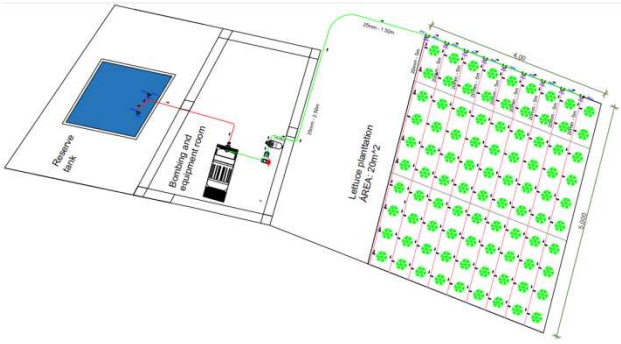

Fig. 2. Lettuce plantation details

Based on the solar atlas of the year 2019, the horizontal global irradiance data of the sector were obtained. The PVGIS software was used to estimate the solar irradiance at different tilt angles with north orientation, as seen in Table II. The global horizontal irradiance data was obtained from the solar atlas of 2019. To get irradiance data at different angles, the PVGIS software was used, obtaining the values shown in the Table II. Based on the data obtained above, the number of panels, battery bank, charge controller, and inverter is calculated. These calculations are based on a solar irradiation value of 3.66 kWh/m²/day, which corresponds to June with panels tilted at 10 degrees to the North.

Table II. Global Irradiation at Zhizhiquin according to the tilt angle to the north [15]

Tilt angle [°]	0°	10°	15°	20°
January	4.72	4.59	4.44	4.27
February	4.9	5.15	5.02	4.87
March	4.3	4.03	3.99	3.93
April	4.5	4.4	4.41	4.39
May	4.3	4.61	4.66	4.68
June	3.9	3.66	3.71	3.75
July	4.5	4.25	4.31	4.35
August	4.3	3.77	3.79	3.75
September	4.8	4.72	4.69	4.63
October	5.1	4.69	4.6	4.49
November	5.1	4.95	4.78	4.59
December	4.9	4.68	4.49	4.29

The energy demand of the irrigation system equipment is shown in Table III.

Table III. Determination of power demand

Equipment	Quantity	Time (h)	Power (W)	Energy (Wh/day)
Programmable irrigation device	1	24	12	288
Solenoid valve	1	1	1.5	1.5
Water pump	1	1	372.85	372.85
Total			386.35	662.35

B. Calculation of the number of PV panels

Using Equation 1, the number of PV panels (Np) required is calculated. The power of each PV panel is 75 W.

$$\boldsymbol{Np} = \frac{\boldsymbol{Energy}}{\boldsymbol{Pmodule * Field\ Efficiency * Irradiation}} \quad (1)$$

$$\boldsymbol{N_p = 4}$$

C. Calculation of the capacity of the battery bank

For the calculation of the capacity of the battery bank (Cbb) of the system, 3 days of autonomy were considered, a battery bank nominal voltage of 12V, and a depth of discharge of 0.7 (See Equation 2).

$$\boldsymbol{Cbb} = \frac{\boldsymbol{Daily\ Energy\ Demand \times Days\ of\ autonomy}}{\boldsymbol{Batery\ bank\ voltage \times Depth\ of\ discharge}} \quad (2)$$

$$\boldsymbol{Cbb = 236.55\ Ah}$$

D. Inverter and battery charge controller capacity

For calculation of the battery charge controller, the maximum current that circulates through this device was determined, resulting in 30A. The inverter should deliver the motor-pump starting currents, therefore, an 800 W inverter was considered.

E. *Evaluation of the pumping system*

Due to the meteorological situation in the location, a water pumping system was incorporated to irrigate the lettuce crop, both in the planting and growing phases of the vegetable. The water pump is powered by the PV system, for this project the water is pumped in the morning and in the afternoon. To implement this pumping system a programmable irrigation device, a water reservoir, piping, solenoid valve and a water reservoir are used. Technical characteristics, such as: the flow rate, pump power, tank head, pump speed, pumping capacity, fluid velocity in the pipeline, friction losses of the fluid in the pipe, among others are defined in order to calculate the pump power (Equation 3), pump head losses (Equation 4), and water speed (Equation 5).

$$\boldsymbol{Pb} = \frac{\boldsymbol{Q * g * \rho * hb}}{\boldsymbol{746 * \eta}}\ [\boldsymbol{hp}] \quad (3)$$

Where, $\boldsymbol{Pb}$ is pump power in *hp*, $\boldsymbol{Q}$ is the water flow rate in m^3/s, $\boldsymbol{g}$ is the gravity acceleration m/s^2, $\boldsymbol{\rho}$ is the water density in kg/m^3, and *hb* is the pump net head in meters.

Knowing the net head of the pump [19], the water drainage in the pipe is determined, using the fluid mechanical energy balance (Equation 4) [19]. Mathematical statement is represented as Bernoulli's equation [20] [19], where the simplified equation is represented as:

$$\boldsymbol{h_b = h_{uz} + \frac{V_{ud}^2}{2 * g} + hf}\ \ [\boldsymbol{m}] \quad (4)$$

Where, h_{uz} is the reference altitude of the level upper zone (3 m), *v* is the fluid speed on the upper deposit, and *hf* is the friction losses.

The altitude of the storage tank h_{st} is calculated as the sum of the head from the tank to the pump h_{PB} (1.5m) and the head from the pump to the upper tank h_{BD} (1m).

The water velocity in the pipe (v) arriving at the inlet of the upper tank [19] is calculated with the Equation 5.

$$\boldsymbol{v} = \frac{4*Q}{\pi*D^2} = \frac{Q}{A}[m/s] \quad (5)$$

Where, D is the pipe diameter (D = 0.02 m).

The primary frictional losses inside the pipe, are determined by Darcy-Weisbach [19]. The total friction losses (H_f) due to fittings correspond to Equation 6.

$$\boldsymbol{hf} = \boldsymbol{F} * \frac{L}{D} * \frac{v^2}{2*g} + \boldsymbol{K_a} * \frac{V^2}{2*g} \ [m] \quad (6)$$

Table IV: Sizing of the pumping system

Event [%]	Flow m^3/s	D [m]	$\boldsymbol{v}$ [m/s]	N_R	h_f [m]	h_b [m]	P_b [Hp]	P_b [kW]
100%	0.000803	0.02	2.55	49900	6.4432	41.0346	0.54	0.4043
90%	0.000723	0.02	2.30	45007	5.2206	33.7146	0.40	0.2990
60%	0.000482	0.02	1.153	29940	2.3203	16.3732	0.13	0.0968
50%	0.000401	0.02	1.275	24950	1.6113	12.1341	0.08	0.0598
30%	0.000241	0.02	0.765	14970	0.5801	5.9683	0.02	0.0176
20%	0.000160	0.02	0.51	9980	0.2578	4.0415	0.01	0.0080

Where, F is the friction coefficient (0.012), L is the pipe lenght, and K_a is the accessories coefficient. The coefficient of friction (F), is determined by means of Reynolds and relative roughness (Equation 7) [19][21]. For this case the relative

roughness of the pipe is ε = 3.0 ×10-7, the roughness will vary according to the pipe material [19] [21], the pipe diameter is D = 0.02m.

$$\boldsymbol{F} = \boldsymbol{1.325}/[\boldsymbol{Log}\left(\frac{1}{3.7*\frac{D}{\varepsilon}} + \frac{5.74}{N_R^{0.9}}\right)]^2 \quad (7)$$

Reynolds coefficient to establish the fluid behaviour makes use of Equation 8 [19] [21].

$$\boldsymbol{N_R} = \frac{v*D*\rho}{\mu} = \boldsymbol{v} * \boldsymbol{D}/\boldsymbol{V} \quad (8)$$

Where, the density of water is ρ = 998 (kg/m3), the dynamic viscosity of the fluid is μ = 1.02×10^{-3} [Pa.s] [21], these data are taken from normalised values at a temperature of 20°C. The fluid velocity is ν = 2.55 m/s and V is the kinematic viscosity of the fluid (m^2/s).

Table IV incorporates the flow rate in percent for analysis. The calculated values correspond to each sizing possibility of the pumping equipment.

F. Assembly of the AVS equipment

The PV modules were installed on a 4-metre-high metal structure as shown in Figure 3, to avoid shading and to allow free accessibility to the agricultural works. The PV panels are oriented towards the North with an inclination of 10 degrees, since it facilitates self-cleaning with rainwater. [22]. The structure on which the PV panels are placed is fixed to the ground with a concrete base for stability.

In order to automate irrigation, a HUNTER programmable irrigation device is used; a WAND module for Wi-Fi is incorporated. This device allows automatic management by means of the Hydrawise software. It was configured an automatic irrigation two times per day, (6 am and 6 pm) with a duration of 5 minutes each. The main advantages of using this equipment are its flexibility to manage 6 stations known as zones, and facilitating the control of irrigation online [23].

Fig 3. View of the PV structure for agrovoltaic system

The hydrawise application used for the Hunter controller allows the irrigation to be programmed and controlled via a mobile phone. As part of the irrigation system, a 0.5 hp pump is responsible for drawing water from the reserve tank as illustrated in Figure 4. Adjacent to it, there is a solenoid valve designed to control the flow of water, allowing or preventing its passage. Additionally, a filter has been incorporated to prevent any impurities in the water from clogging the pipe.

Fig. 4. Connection of the solenoid valve and the 0.5 hp pump.

The PV System consists of the equipment and devices described in Table V, which have a total cost of 1720 USD.

G. Analysis of results with the implementation of solar panels.

The total costs of the devices that integrate the AVS is 2391 US dollars, including the pump and hydraulic system. In this PV off-grid the useful life of the batteries is between 5 and 10 years with proper maintenance. The analysis is taken the most critical case, which is 5 years. Taking into account the useful life of the system, which corresponds to 25 years, it would mean that it should be changed 5 times.

Table V: Components of the PV System

Device	**Brand**	**Model**
Controller	EPSolar	LS3024B
Inverter	Powest	SP-700
Batery	NPP	NPP NPG12-150Ah 12V
PV Panel	Komas Solar	KOMAES SOLAR KM75

Table VI shows the economic results, where the NPV is positive. The investment will be recovered in 9.09 periods and the IRR value exceeds the interest rate of 8.2%. Thus, the project is economically viable. It is important to note that positive cash flow takes into account both the generated productivity and the energy prices of the PV system.

Table VI. Cost and economic indicators of the project

Referential equipment costs (Battery charge controller / Inverter / Battery / Solar Panels)	$ 1,720.00
Material costs (Metallic structure, Switches, Switchgear, Grounding systems)	$ 236.00
Transportation and Labor	$ 435.00

Internal rate of return	11%
Net Present Value	728.14%
Return on Investment	9.09 years

3. Production obtained with the application of the AVS

In order to compare the results, two samples were taken, one corresponding to the traditional crop and the other to the AVS, as seen in Figure 5. The lettuce produced by the AVS increased in size and their ripening time was shorter. The lettuce of the traditional crop takes three months to be ready for consumption, while those cultivated underneath and feed by the AVS system, took only two months.

In local markets, traditionally grown lettuces was sold for 0.3 USD, those produced by the AVS are sold for 0.5 USD because of their robust size. Previously, the same parcel of land produced only 60 plants where the farmer obtained 18 USD with the sale of his production. With the implementation of the AVS, his productivity increased to 125 plants, obtaining 62.50 USD, which means an increase of 44.50 USD for the farmer.

4. Conclusions

The AVS represents an innovative and sustainable approach to utilizing agricultural space and harnessing solar energy. In this study case, the use of an AVS improves crop quality, increasing the sell price of lettuces from 0.3 USD to 0.5 USD each. The payback period has been determined to be a little longer than 9 years, and it has been determined that could be interesting, especially when there is no grid power availability. Even though this analysis was performed in a prototype scale, the expected revenue would be higher in greater crop extent.

Fig. 5. Production of lettuces, left (traditional crop), right (using AVS)

Further work would be to identify the improvement in crop production because of the shading produced by the photovoltaic panel. This analysis was not performed in this work due to the small scale of the system; however, on a large scale its benefits can be better quantified.

AVSs are a good alternative to combine power generation with agriculture, considering that these two industries require space that can be optimized under this scheme. It provides the potential to reduce production costs by generating its own electricity. These advantages make the adoption of AVS an appealing and financially rewarding option for farmers.

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