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Reducing CO_2 Emissions by Off-Grid Photovoltaic Systems: A Case Study in the Departamento del Magdalena - Colombia

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ABSTRACT

This paper presents projections on the reduction of CO_2 emissions through the implementation of off-grid PV systems on 33 farms located in rural areas of the Departamento del Magdalena, where horticultural activities are performed by small local producers. To achieve this, the emission reduction was estimated for a period of 25 years using the installed PV peak power on each farm, data from the Global Solar Atlas, the emission factor in Colombia for electricity generation and information established in the harmonization project of the National Renewable Energy Laboratory (NREL). In order to compare the estimations, temperature and solar irradiance data were obtained from 10 farms near the installations, located in 8 municipalities within the department. With these data and through mathematical modeling, the energy generated by each PV system and the projection of non-emitted CO_2 emissions were calculated. The results obtained demonstrated that, in both cases, the projections for emission reduction are similar, highlighting that the municipalities of Ciénaga and Sitio Nuevo contribute the highest amount of saved CO_2 due to the projections of higher energy production in these locations.

Keywords: CO_2 Emissions, Photovoltaic Systems, Off-grid System, Rural Agriculture
JEL Classifications: C10, C60, C80, Q42

1. INTRODUCTION

According to the Food and Agriculture Organization of the United Nations (FAO), the agricultural sector is responsible for approximately 23% of global greenhouse gas (GHG) emissions. The main sources of GHG emissions in agriculture include soil management, use of fertilizer and agricultural machinery, livestock breeding, food transportation, and energy use for food processing and refrigeration (Trivelli and Berdegué, 2019). In the case of Colombia, the agricultural sector is among those that generate the most GHGs in Latin America, ranking third after Uruguay and Argentina. In the country, agricultural activity generates 38% of total GHGs (OECD/FAO, 2020).

The Department of Magdalena is in northeastern Colombia, in the Caribbean Region, with a predominantly intertropical climate, and is characterized by its strong agricultural and livestock vocation. According to the Gobernación del Magdalena, the department has 1,723,384 hectares available for this type of activity, with the greatest vocation for agricultural use (50.8%). One of the great strengths of this area of the country is the diversity of production of permanent and transitory crops, and the potential for expansion of agricultural activity due to the richness of the soils, which generates challenges in order to strengthen the agricultural sector, guaranteeing sustainable production that minimizes GHG emissions that contribute to climate change (Gobernación del Magdalena, 2020).

In general, the department's agricultural potential is concentrated in rural areas, where the productive matrix includes permanent crops such as Banana (*Musas acuminatas*) (47.1%), Cassava (*Manihot esculenta*) (20.6%), Palm oil (*Elaeis guineensis*)

(15.9%), Citrus (*Citrus aurantifolia* and *Citrus limon*) (4.3%), and Mango (*Mangifera indica* L.) (3.9%). There are also transitory crops such as Corn (*Zea mays* L.) (43%), Rice (*Oryza sativa*) (18.8%), Ahuyama (*Cucurbita maxima*) (8.2%), Chili (*Capsicum annuum*) (6.8%) and Watermelon (*Citrullus lanatus*) (6.6%). In the current situation and the post-COVID-19 economy, it has become clear that food production must be a priority on the reactivation agenda. It requires support and conditions that guarantee increased productivity and the development of competitive capacities in the region (Gobernación del Magdalena, 2020).

In this scenario, the agricultural sector in the department of Magdalena faces several challenges, including land distribution, low implementation of production systems, disarticulation between some links in the production chain, low connectivity and problems with access to reliable electricity. Energy supply is of vital importance for agriculture, as it is an indispensable input for the production, processing and marketing of many products. Without an adequate supply of electricity, rural producers face barriers to the development of new production processes and to the development of climate change mitigation strategies. One of the main uses of electric power in the rural agricultural sector is for water pumping systems; however, due to the low quality or, directly, the non-existence of electric power service from the grid, many farmers find it necessary to implement diesel engines or use gasoline to power pumping systems, generating extra costs in the production chain and increasing pollution levels and GHG emissions (Lozano-Espitia and Restrepo-Salazar, 2016). Additionally, other processes such as the storage of fruits and vegetables and the refrigeration of many products require constant use of electrical energy.

Considering the aforementioned scenario, all efforts made to improve the quality of energy services or electrify rural areas with agricultural potential are crucial, as they contribute to enhancing various production processes. In this context, solar photovoltaic energy becomes significant as it is regarded as a solution that provides reliable energy services for rural areas in the Departamento del Magdalena. This region of the country benefits from good solar potential, with levels of global solar radiation ranging between 4.5 kWh/m^2 and 5.5 kWh/m^2/day. Furthermore, PV solar energy has the advantage of not emitting CO_2 during its operation, making it one of the most efficient renewable technologies in the fight against climate change.

CO_2 emissions are considered to have the greatest impact in terms of global warming, and as a result, efforts worldwide are focusing on reducing this pollutant (Issayeva et al., 2023). When CO_2 emissions increase, solar radiation becomes trapped in the atmosphere, leading to a rise in the planet's temperature and flooding. In a country like Colombia, CO_2 emissions in 2021 amounted to approximately 77.57 megatons, representing a carbon footprint of approximately 1.6 tons per person per year (Ministerio de Ambiente y Desarrollo Sostenible, 2022).

A major factor in CO_2 emissions into the atmosphere is electricity generation through combustion when non-conventional energy sources based on fossil fuels are used. Additionally, it is important to consider carbon emissions resulting from electricity consumption. In the case of the Departamento del Magdalena, understanding the process of CO_2 emissions generated from thermal power plants is crucial. Being a coastal region, it faces significant disruptions due to climate change, ultimately leading to an increase in the demand for thermal electricity. This is a result of the various impacts on the water resource, and consequently, on hydropower plants.

In this context, the present research offers an analysis of carbon footprint reduction through the implementation of 33 off-grid PV systems used to power 33 drip irrigation systems located in 11 municipalities in the Departamento del Magdalena. This analysis considers factors such as the energy that was no longer consumed from non-conventional sources like thermal power. Such studies become significant considering the Colombian government's goals aimed at reducing greenhouse gas emissions by 51% by 2030, with a priority on energy transition and deforestation reduction.

2. GEI EMISSIONS HARMONIZATION PROJECT

The National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy led an important harmonization project that made it possible to unify the information reported in the scientific literature in order to make more accurate estimates of GHG emissions in the life cycle of photovoltaic systems. This way, the harmonization parameters shown in Table 1 were obtained, related to the lifespan of PV systems and solar module efficiency. Percentages are also unified for the performance ratio considering losses. This parameter was considered as the ratio between the actual AC electricity produced by the PV system and the electricity calculated based on PV module DC efficiency and irradiance.

The harmonization project also establishes an approximate value of CO_2 equivalent emissions for PV systems during the manufacturing, installation, generation, operation, maintenance, decommissioning and final disposal phases. Thus, the emission factor shown in equation (1) was established according to the percentages illustrated in Figure 1 for each of the three phases of the PV systems life cycle.

$$\text{Emission Factor PV Systems} = 40\text{g}CO_2\ \text{eq/kWh} \quad (1)$$

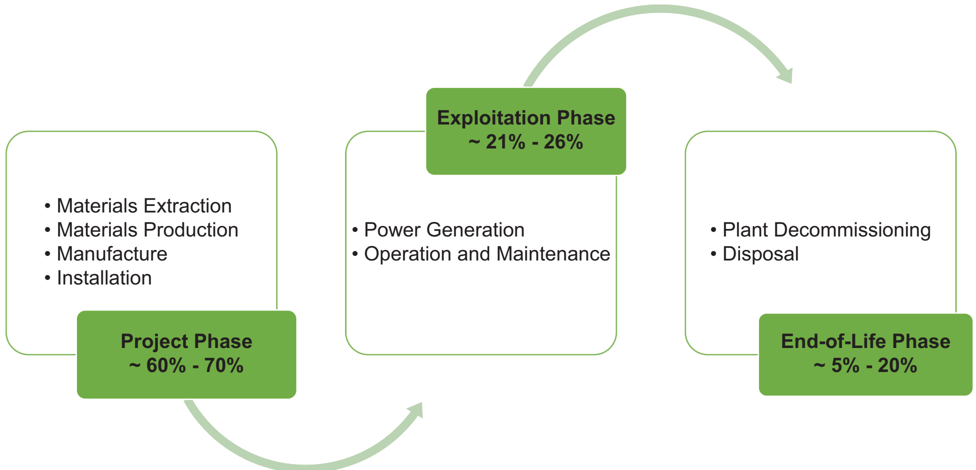
3. CO_2 REDUCTION WITH THE IMPLEMENTATION OF PV SYSTEMS

Climate change and the reduction of CO_2 emissions have become priority issues on the global agenda. The burning of fossil fuels

Table 1: GHG Emission Harmonization Parameters

Parameter	Value
System Lifetime	30 years
Mono-crystalline module efficiency	14.0%
Multi-crystalline module efficiency	13.2%
Performance ratio of ground-mounted	0.80
Performance ratio of rooftop	0.75

Figure 1: CO_2 emissions during the life cycle phases of a photovoltaic system



such as coal, oil and natural gas for electricity generation and heat production is one of the main sources of CO_2 emissions. Faced with this challenge, the implementation of photovoltaic systems has emerged as a promising solution to reduce CO_2 emissions and mitigate the effects of climate change.

CO_2 is a greenhouse gas that traps heat in the atmosphere, contributing to global warming and climate change. Coal-fired power plants emit large amounts of CO_2 per unit of electricity generated. In addition to CO_2, electricity generation with fossil fuels also produces other greenhouse gases, such as sulfur dioxide (SO_2) and nitrogen oxide (NO_x). These gases contribute to the formation of acid rain and air pollution, with negative impacts on human health and the environment.

To estimate the reduction of CO_2 emissions through the implementation of PV systems, it is necessary to have information about the conventional electricity generation that is being replaced by PV systems. This involves knowing the energy source used, such as coal, oil, or natural gas, as well as the amount of electricity generated from that source. Furthermore, it is crucial to determine the amount of CO_2 emitted per unit of electricity generated from the conventional source. This information can be obtained by using standard emission factors provided by government agencies or specialized institutions. These emission factors quantify the amount of CO_2 released per unit of energy produced.

Using the estimated electricity generation by photovoltaic systems and the emission factors, the amount of CO_2 that will be avoided by replacing conventional generation can be calculated. This estimate is determined by multiplying the estimated generation by the CO_2 emission factors of conventional systems. In addition to electricity generation, photovoltaic systems also have emissions associated with their life cycle, such as those from the manufacture of solar panels and other components. It is important to consider these emissions in the total carbon footprint calculation and subtract them from the avoided emissions mentioned above to obtain a value that fits reality. This procedure was used in the present study to calculate the project's impact on reducing CO_2 emissions.

To assess the efficiency of photovoltaic systems in comparison to traditional non-sustainable energy systems, it is essential to consider the available information concerning the CO_2 emissions associated with the manufacturing and maintenance of PV systems. In the case of conventional PV panels, the process begins with the extraction of metallurgical-grade silicon or high-purity silicon (approximately 99% purity) from quartz mines. This material is then transformed into semiconductor-grade silicon through a chemical process, ensuring a minimum concentration of impurities suitable for electronic applications. This stage significantly impacts the environment and results in the highest emissions of CO_2. Nevertheless, it is a necessary step for the crystallization process and the production of wafers, which are used in the subsequent manufacturing of complete PV modules (Seigneur et al., 2016).

With the use of a renewable energy it is expected that the planet will improve and greenhouse gases will be considerably decreased, with respect to photovoltaic energy it is estimated that CO_2 emissions will be decreased to 18.8% (Hernandez et al., 2014) since as expected, even first generation PV panels have a minimal carbon footprint compared to that emitted in the extraction of energy by the use of fossil fuels in areas of residential electricity and business machinery. With PV technology having an average manufacturing carbon footprint value per panel of 498 $kgeCO_2$ (Nugent and Sovacool, 2014).

According to the Renewable Capacity Statistics 2021 report by the International Renewable Energy Agency (IRENA), increased adoption of renewable energy can potentially reduce global CO_2 emissions in 2050 by approximately 70%, compared to a scenario based on fossil fuels. This scenario is visualized at scale in Figure 2. It is important to note that prompt actions are essential, and the energy sector should ideally transition to a renewable-dominant state exponentially over the next 30 years. This transition implies the need for the implementation of the right policies and accelerating the shift (IRENA, 2021).

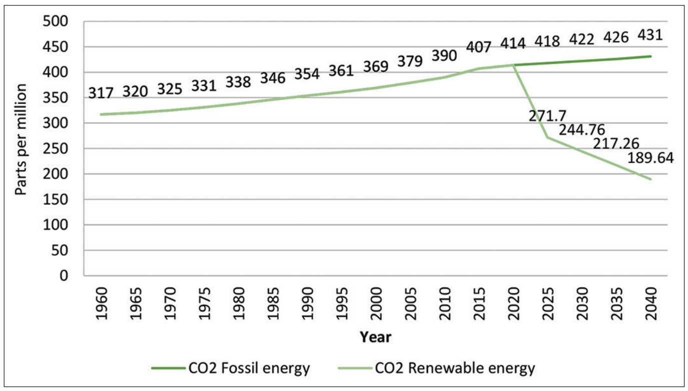
3.1. CO_2 Emission Factor in Colombia

The Mining and Energy Planning Unit - UPME through resolution 320 of 2022 updated the emission factor of the National Interconnected System for Greenhouse Gas (GHG) emission inventories and GHG mitigation projects. Thus, the emission factor for GHG inventories was established as shown in equation (2) (UPME, 2015; UPME, 2020).

$$\text{Emission Factor for Electricity Generation} = 126 gCO_2\ eq/kWh \quad (2)$$

The emission factors defined in equations (1) and (2) were used to calculate the CO_2 reduction considering the emissions in the distinct phases of the PV systems, from the extraction of materials to the final disposal.

Figure 2: Average CO_2 levels in the atmosphere and the impact that can be generated by the exponential implementation of sustainable energies in the coming years. Modified from: (Statista, 2023)



4. MATERIALS AND METHODS

4.1. PV Systems Implemented

The declaration of an economic, social and ecological emergency due to COVID-19 has shed light on the vulnerability of the agri-food system in the Departamento del Magdalena. The Territorial Development Plans (PDT) of the municipalities in the department have identified several key limitations preventing them from achieving competitiveness and reducing crop wastage. These limitations include technological gaps in agriculture, a high number of intermediaries, inadequate rural infrastructure, limited access to water, insufficient business training and poor-quality energy services in rural areas.

To reduce the limitations, 11 municipalities were selected (Ariguaní, Ciénaga, Plato, Pivijay, El Piñón, Zona Bananera, Santa Marta, Sitionuevo, Santa Ana, Guamal, San Sebastián) distributed in the five sub-regions of the Departamento del Magdalena (River, South, Center, North and Santa Marta). The choice was based on their representation of the edaphoclimatic conditions in each subregion and their strong horticultural focus. Within these 11 municipalities, a total of 33 farms, associated with local agricultural groups, were chosen for intervention. These farms had off-grid PV systems installed to power irrigation modules. For a detailed overview of the farm locations involved in the project, please refer to Table 2.

Table 2: Location of the 33 properties intervened with PV systems

Municipality	Associations - properties	Latitude	Longitude
Guamal	Asoproagro – Dios da para todos	9°20'01.2"N	74°04'00.0"W
	Asoproagroandes – Los rosales	9°17'36"N	74°7'7.0"W
	Asomupropan -	9°10'15.2"N	74°14'58.0"W
San Sebastián	Renacer – Bellavista	9°15'56.5"N	74°21'11.8"W
	Asodegans – Dios me vea	9°18'30.0"N	74°18'59.4"W
	Camsebas	9°22'0.5"N	74°13'10.17"W
Santa Ana	Asolafé – Santa fe	9º35'23.4"N	74º24'38.8"W
	Agropar del Paraiso – Burro viejo	9º19'45.7"N	74º18'59.4"W
	Asopgab – El Redil	9°23'43.7"N	74°38'12.6"W
Ariguaní	Asopepamo – Ecoparque Emmanuelle	9º51'22.35301"N	74º14'10.28465"W
	Asoagrobril – Villa Adriana	9º52'22.90087"N	74º7'32.7841"W
	Asociación campesina agropecuaria de Ariguaní	9°55'4.81"N	74°11'11.9"W
Plato	Asociación Agropecuaria Esperanza Verde – Nueva Unión	9º51'43.89088"N	74º37'22.9057"W
	Asoveltorito – El Encanto	10º0'3.42511"N	74º31'12.66179"W
	Aafrigamag – Dios me vea	9°48'22.5"N	74°44'56.3"W
El Piñón	Coopsabanas – Finca el Espejo	10°27'14.4"N	74°42'23.1"W
	Asosalado – Finca el Salao	10°18'21.9"N	74°42'52.4"W
	Asoproagromon – Finca Montería	10°18'44.0"N	74°40'56.2"W
Pivijay	Hernagro – Jerusalen	10°26'35.8"N	74°27'05.0"W
	Asodecampi – La Estelita	10°26'53.9"N	74°32'09.4"W
	Asodoagropi - IED Agropecuaria José María Herrera	10°27'52.7"N	74°36'18.6"W
Sitionuevo	Asosclarin – Macondo 1	10°57'30.2"N	74°44'30.3"W
	Asopihorsit – Agua viva	10°47'30.8"N	74°42'09.4"W
	Agesye de la Vipis – La bendición de Dios	10°59'14"N	74°42'26"W
Ciénaga	La Helena – La bendición del milagroso	10.970028° N	74.219367° W
	Asocher – La María	11°0.793' N	74°13.898' W
	Asomcor – Villa Goez	11°1.687' N	74°12.800' W
Santa Marta	Asoprosierra – Villa del Mar	11°05'37.9"N	74°04'57.5"W
	Aprogaira frutal – La Manguera	11°11'13.4"N	74°12'41.9"W
	Aecopaz – Cacahualito	11°8'18"N	74°6'12"W
Zona Bananera	Ascexamag – El Carmen	10.80253° N	74.107863° W
	Fundapad – Negrini (Villa Miriam)	10°45'53.3"N	74°17'50.4"W
	Camtuzb – La Carmencita	10°38'24.4"N	74°08'21.4"W

After selecting the 33 plots, we proceeded with the sizing of the 33 PV systems to power a pump of up to 3 hp, single-phase 220V, for the irrigation system. Thus, a 1740 Wp off-grid PV system was dimensioned, with a 200 Ah battery bank operating at 48V for an autonomous operation of 2 h/day. Table 3 shows the specifications of the devices used for the PV system, while Figure 3 shows the block diagram with the implemented connections.

The manufacturer guarantees an annual degradation of 0.55% over a 25-year period, with an efficiency under standard test conditions of 20.01%. This data will be particularly useful for calculating the reduction in the CO_2 footprint over the lifetime of the PV system, considering the degradation and declaring confidence intervals in the tests.

With the site locations defined and the peak power of each PV system, Global Solar Atlas was used to estimate the annual energy production for an installed power of 1kWp. These values were scaled by a factor of 1.74, considering that each system sized in this project is 1740Wp. Based on the characteristics of the implemented PV systems, the Global Atlas was configured with the following data, which correspond to those used in the installations: PV System: Small Residential, PV Panel Tilt: 14°, System size: 1kWp. For the rest of the parameters such as Global Horizontal Irradiance, Air Temperature, among others, the default values defined in the Atlas database were left (Solargis, 2023).

Information on annual energy generation was obtained for each of the properties and the GHG emission factors in Colombia and some of the harmonization values defined in section 2 were used to proceed with the actual calculation of the reduction of CO_2 emissions with the implementation of the 33 PV systems in the Department of Magdalena. What makes this type of system so striking is the verification of its efficiency over time, considering the parameters offered in this area by the manufacturer of each of the panels.

Annual degradation: 0.55% for 25 years.

Regular efficiency: 20.01%.

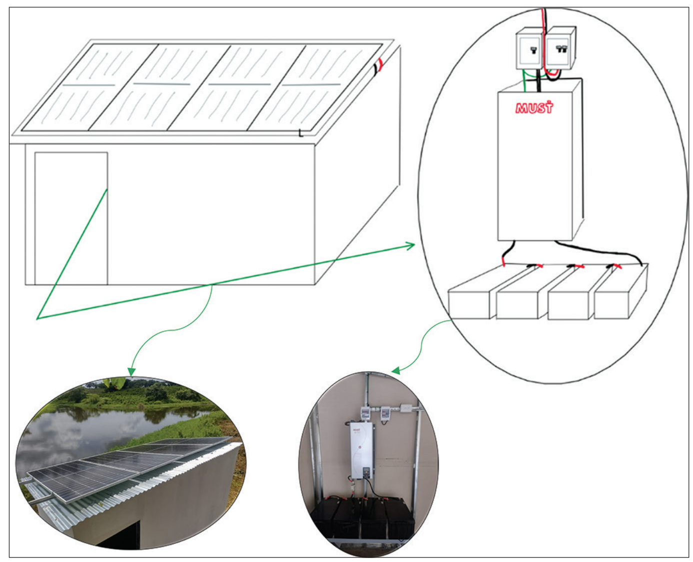
4.2. Weather Station Data and Mathematical Modeling

In order to compare the results of the non-emitted CO_2 emissions with the implementation of the 33 PV systems, based on calculations using data from the Global Solar Atlas, temperature and irradiance data were obtained from 10 meteorological stations located in the same study area. These data served as a reference for obtaining the generated energy and non-emitted CO_2 emissions. In this way, a comparison could be made between the theoretically calculated CO_2 emissions with the implementation of the 33 PV installations from our research and the emissions calculated based on local meteorological data and mathematical modeling. Table 4 shows the locations of the 10 properties and the quantity of temperature and irradiance data obtained from the installed meteorological stations.

Table 3: Devices used in the PV system

Item	Quantity per system
Monocrystalline photovoltaic module 435 Wp ZXM6-NH144.	4
12V-200Ah sealed dry lead-acid battery.	4
PV3300 TLV 4KW multifunctional inverter-charger PV3300 TLV. Includes: 24V/48VDC to 60A/30A MPPT charge controller.	1
Metal rails and accessories in anodized aluminum AL 6005-T5	1 kit

Figure 3: Photovoltaic systems implemented



The power, generated energy, and non-emitted CO_2 data were calculated by modeling the PV system described in Table 3 and using temperature and irradiance data from Table 4 for the years 2019 and 2020. To obtain a projection of the performance of the systems over the years, with manufacturer data, the total annual power dependent on the decrease in efficiency is calculated from the following relation.

$$Projected\ \ annual\ \ power = \frac{PFY * RE - n * ED}{RE} \tag{3}$$

PFY: Total real power generated 1st year.
RE: Regular efficiency.
n: Current year number since system installation.
ED: Annual efficiency degradation.

4.2.1. PV module modeling

In order to simulate the photovoltaic module, the mathematical model described in Eq. 4 was used. The choice of the model to be used largely depends on the characteristics specified in the datasheet obtained from the manufacturer of the panel (Viloria-Porto et al., 2018).

$$I(V) = \frac{I_x}{1 - e^{\left(\frac{-1}{b}\right)}}\left[1 - e^{\left(\frac{V}{bV_x} - \frac{1}{b}\right)}\right] \tag{4}$$

Table 4: Location of meteorological stations and amount of irradiance and temperature data used

Municipality	Associations - properties	Latitude	Longitude	Amount of data	Start date	End date
Santa Bárbara de Pinto	El Tesoro	09°31'16"N	74°38'57"W	11933	March 01, 2020	September 30, 2020
Guamal	La Carpa	09°08'40"N	74°13'34"W	19276	November 01, 2019	October 31, 2020
Zona Bananera	La Cecilia	10°47'34"N	74°10'40"W	14934	December 01, 2019	September 30, 2020
Zona Bananera	Padelma	10°47'34"N	74°10'40"W	17363	December 01, 2019	September 30, 2020
Chibolo	La Sonrisa	10°01'37"N	74°37'15"W	19944	November 01, 2019	October 31, 2020
Sabanas de San Ángel	Monterrubio	10°14'08"N	74°16'30"W	7726	July 01, 2020	October 31, 2020
Sabanas de San Ángel	No Te Canses	10°07'56"N	74°15'12"W	7044	July 01, 2020	October 31, 2020
Nueva Granada	La Mina	09°48'07"N	74°23'33"W	19042	December 01, 2019	October 31, 2020
Isla de Salamanca (VIPIS)	Isla Salamanca	10°58'00"N	74°30'00"W	19390	December 01, 2019	September 30, 2020
Sitionuevo	San José	10°46'37"N	74°43'14"W	15416	March 01, 2020	August 31, 2020

In this equation, I_x and V_x represent the open circuit voltage and short circuit current for time-varying operating temperature and irradiation. b is the curve fitting parameter and is the only value that must be calculated for this model, using the parameters from the PV module datasheet.

$$V_x = s\frac{E_i}{E_{iN}}TC_V\left(T-T_N\right)+sV_{max}-s\left(V_{max}-V_{min}\right) e^{\left(\frac{E_i}{E_{iN}}\ln\left|\frac{V_{max}-V_{oc}}{V_{max}-V_{min}}\right|\right)} \quad (5)$$

$$I_x = p\frac{E_i}{E_{iN}}\left[I_{sc}+TC_i\left(T-T_N\right)\right] \quad (6)$$

E_i is the solar irradiance, E_{iN} is an irradiance constant of 1000 W/m^2, I_{sc} is the short circuit current, p is the number of PV modules in parallel, s is the number of PV modules in series, T is the operating temperature, TC_i and TC_v are the current and voltage temperature coefficients, T_N is the temperature constant of 25°C, V_{oc} is the open circuit voltage, V_{max} is 103% of V_{oc} and V_{min} is the 85% of V_{oc}.

To find the value of b, Robles Algarín et al., (2017) shows that it is in the range of 0.01 to 0.18, so it is valid to perform the following approximation:

$$1-e^{\left(\frac{-1}{b}\right)} \approx 1, \quad I\left(V\right) = I_x\left[1-e^{\left(\frac{V}{bV_x}-\frac{1}{b}\right)}\right] \quad (7)$$

From Eq. 7 the expression to find b can be obtained.

$$b = \frac{V-V_x}{V_x \ln\left|1-\frac{I\left(V\right)}{I_x}\right|} \quad (8)$$

Table 5 shows the parameters of the 435 W PV module used in this work, which were implemented to find the parameter b and the mathematical model. In this way, it was possible to model the PV system and calculate CO_2 emissions.

Table 5: Parameters of photovoltaic module

Item	Value	Unit
Module Type	ZXM6- NH144-435/M 1/2	-
Output power (P_{max})	435	W
Voltage at *Pmax* (V_{mp})	42.80	V
Current in *Pmax* (I_{mp})	10.17	A
Open circuit voltage (V_{oc})	51.2	V
Short-circuit current (I_{sc})	10.60	A
Module efficiency (ηm)	20.01	%
Temperature coefficient of V_{oc}	−0.29	%/°C
Temperature coefficient of I_{sc}	0.05|	%/°C

For V_x=V_{OC}=51.2, V=42.80, I=10.17, I_x=I_{SC}=10.60; the value of b=0.05119 is obtained.

This model provides an accurate estimate of the energy produced by a photovoltaic system at a specific location and climatic conditions, which is essential for the proper design and sizing of photovoltaic systems, as well as for the planning of solar energy generation at long term.

5. RESULTS

5.1. Energy Generated and Emissions Saved Estimated with the 33 PV Systems

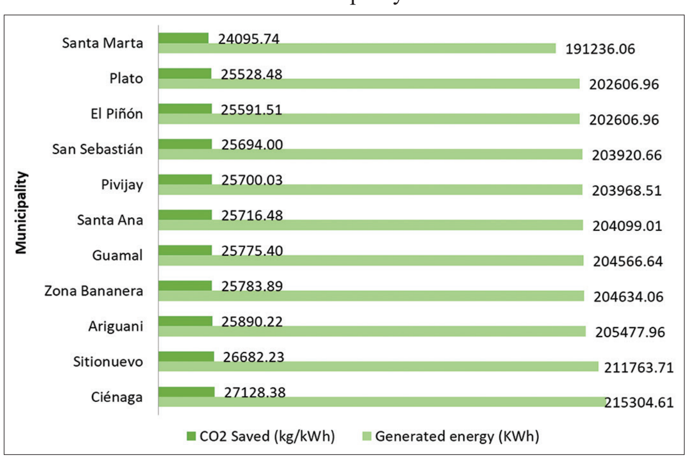
Table 6 summarizes the production of kWh for 25 years, time in which it works with considerable efficiency according to the manufacturer's data previously exposed, a minimum of 6% efficiency is reached for each panel after 25 years of continuous operation, therefore, it is an ideal estimate of the deterioration of the panels and the result of a good installation and proper maintenance of the complete system that is expected to correspond to the disposed amounts of kWh generated and kgCO_2 saved for each farm. Briefly, the results of the total projection of energy produced and CO_2 not emitted for 25 years per farm, which includes the decrease in the efficiency of the system transducer until it drops to an approximate efficiency of 6%.

It is important to highlight that for the calculations of the CO_2 emissions saved, the calculation provided by the UPME was used, with a model that has been in force since 2020 (UPME, 2016). Figure 4 shows the results of total CO_2 emissions saved

Table 6: Total energy produced, and CO_2 not emitted per location in 25 years of PV system use (estimate) including fabrication CO_2 emissions

Municipality	Associations-properties	Total per locality in 25 years	
		Energy Generated (kWh)	Saved Emissions kgCO_2
Guamal	Asoproagro – Dios da para todos	68101.88	8580.77
	Asoproagroandes – Los rosales	68025.75	8571.25
	Asomupropan -	68439.00	8623.31
San Sebastián	Renacer – Bellavista	68456.40	8625.51
	Asodegans – Dios me vea	67864.80	8550.97
	Camsebas	67599.45	8517.53
Santa Ana	Asolafé – Santa fe	67599.45	8517.53
	Agropar del Paraiso – Burro viejo	67621.20	8520.27
	Asopgab – El Redil	68747.85	8678.67
Ariguaní	Asopepamo – Ecoparque Emmanuelle	68395.50	8617.83
	Asoagrobril – Villa Adriana	68869.65	8677.58
	Asociación campesina agropecuaria de Ariguaní	68212.80	8594.81
Plato	Asociación Agropecuaria Esperanza Verde – Nueva Unión	66672.90	8400.79
	Asoveltorito – El Encanto	67081.80	8452.31
	Aafrigamag – Dios me vea	68852.25	8675.38
El Piñón	Coopsabanas – Finca el Espejo	68443.35	8623.86
	Asosalado – Finca el Salao	67147.05	8460.53
	Asoproagromon – Finca Montería	67516.80	8507.12
Pivijay	Hernagro – Jerusalen	67708.20	8531.23
	Asodecampi – La Estelita	67877.85	8552.61
	Asodoagropi - IED Agropecuaria José María Herrera	68382.45	8616.19
Sitionuevo	Asosclarin – Macondo 1	71031.60	8949.98
	Asopihorsit – Agua viva	69409.05	8745.54
	Agesye de la Vipis – La bendición de Dios	71323.05	8986.70
Ciénaga	La Helena – La bendición del milagroso	71418.75	8998.76
	Asocher – La María	72232.20	9101.26
	Asomcor – Villa Goez	71653.65	9028.36
Santa Marta	Asoprosierra – Villa del Mar	60678.60	7645.50
	Aprogaira frutal – La Manguera	72019.05	9074.40
	Aecopaz – Cacahualito	58538.40	7375.84
Zona Bananera	Ascexamag – El Carmen	65755.05	8285.14
	Fundapad – Negrini (Villa Miriam)	70879.35	8930.80
	Camtuzb – La Carmencita	67999.65	8567.96

Figure 4: Total continuous CO_2 emissions saved in 25 years by municipality



in each of the 11 municipalities involved in the research, for a projection of 25 years according to the lifetime of the PV modules established by the manufacturer. It can be seen that the greatest savings in emissions are obtained in the municipality of Ciénaga, due to the greater energy production obtained in this municipality.

5.2. Energy Generated and Emissions Saved in the 10 Reference Properties with Weather Stations

In order to have reference data to compare the estimated results of CO_2 emissions saved, which were detailed in Table 6 and Figure 4, calculations of energy generated were performed for 10 farms (distributed in 8 municipalities) located in sectors surrounding the 33 PV installations, from which the temperature and irradiation data were obtained. With these data, the calculations of energy generated from the model were performed. Figure 5 shows the data on energy generated and emissions saved for the 8 municipalities for the 25-year lifetime of the PV modules. It is important to note that these emissions are estimated, as the temperature and irradiation field data have missing information for some months due to issues with the acquisition mechanism of the weather stations. For this reason, these estimations may differ from the calculations made to obtain the reported saved CO_2 emissions presented in Table 6.

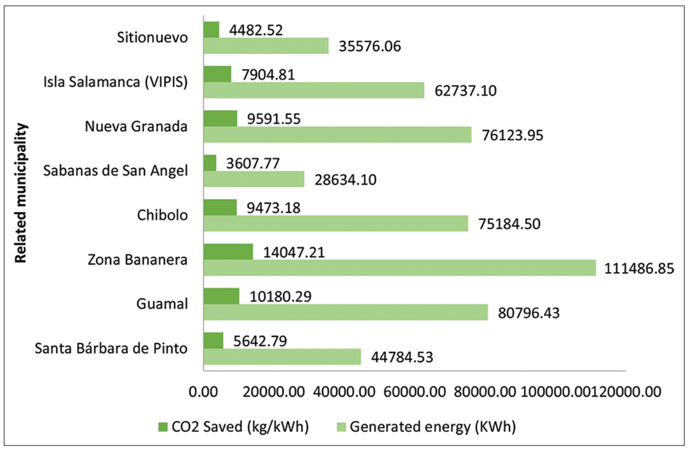
5.3. Comparison of the Data Obtained with the Project and the Reference Municipalities

Of the 8 reference municipalities, only Sitionuevo, Zona Bananera and Guamal were intervened with this research project, allowing for a direct comparison. For the remaining municipalities, we established associations between locations based on their geographical proximity to enable comparisons of CO_2 emissions as can be seen in the map in Figure 6.

Initially, the results are shown for the three mentioned municipalities (Sitionuevo, Zona Bananera and Guamal). The months presented are for which data exists in both data groups (Reference farms vs. farms intervened with the project).

Figure 7 shows the CO_2 emissions not emitted for the case of the municipality of Sitionuevo. The first farm (San José) corresponds

Figure 5: Total continuous CO_2 emissions saved in 25 years by related municipality



to a reference property, while the farms Macondo 1, Agua viva and La Bendición de Dios are part of the 33 properties intervened in the investigation. It can be seen that the data obtained are very similar, which initially corroborates the estimates made. An analogous situation occurs with the municipality of Zona Bananera, in which the calculations of saved emissions are similar for the reference farms (La Cecilia and Padelma) and the farms intervened with the project (El Carmen, Negrini and La Carmencita), which can be seen in Figure 8. Finally, for Guamal (Figure 9), the calculations for the reference farm (La Carpa) and the 3 farms intervened in the research project show greater differences in emissions calculations, but they still fall within an acceptable percentage of difference, never exceeding 10%.

In Figures 10-12, the saved emissions calculations are presented for 3 cases where comparisons were performed based on geographical location: (1) Santa Bárbara de Pinto – Santa Ana, (2) Chibolo – Plato, and (3) Isla de Salamanca – Ciénaga. In these cases, the trend of obtaining similar results for saved emissions persists, confirming the proposed methodology and the estimated long-term emission reductions achieved with the implementation of the 33 PV systems in this project.

The estimation of the energy generated and the CO_2 saved in an installation of a solar photovoltaic (PV) system on agricultural farms involves considering confidence intervals to ensure an accurate and reliable evaluation. This robust approach provides estimates with a degree of statistical certainty, facilitating informed decision-making

Figure 6: Map of municipalities related by geographic location

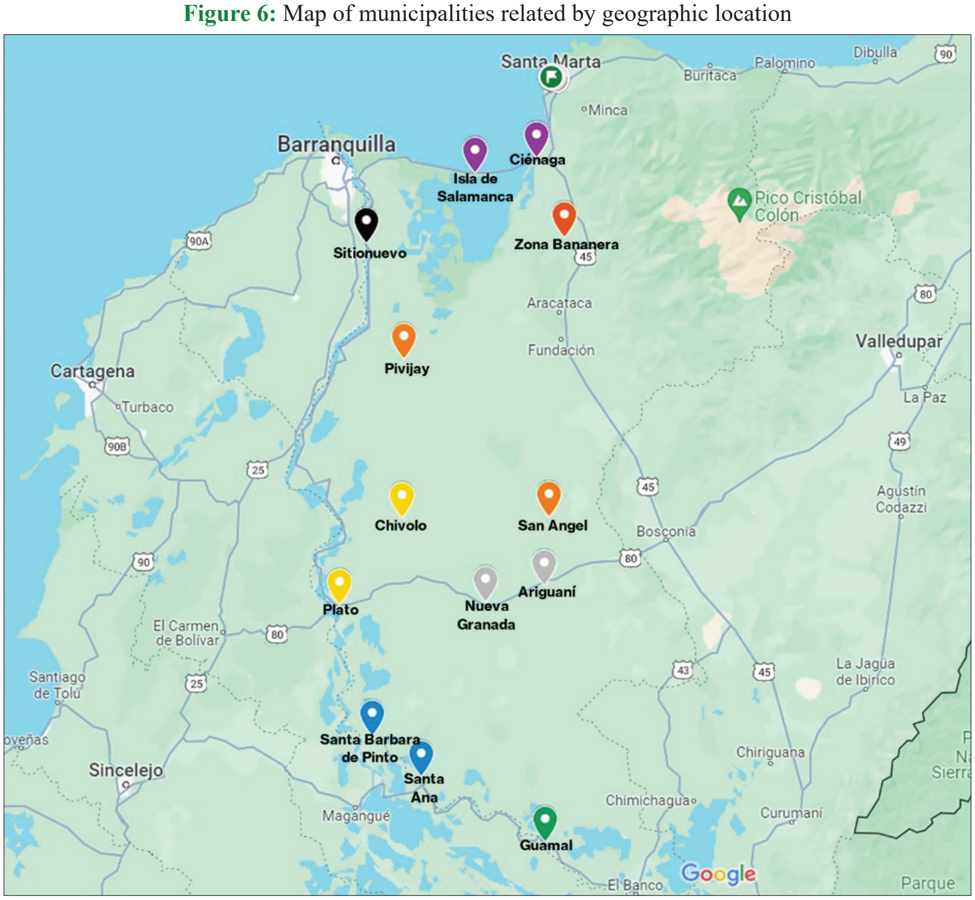


Figure 7: Total continuous CO_2 emissions saved of each farm in the unified municipality Sitionuevo

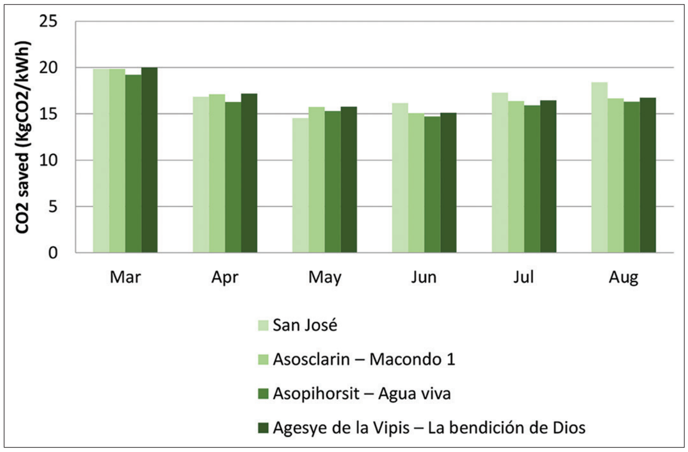


Figure 8: Total continuous CO_2 emissions saved of each farm in the unified municipality Zona Bananera

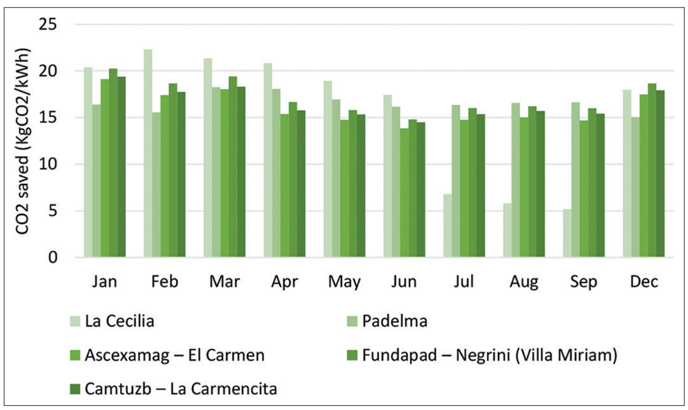
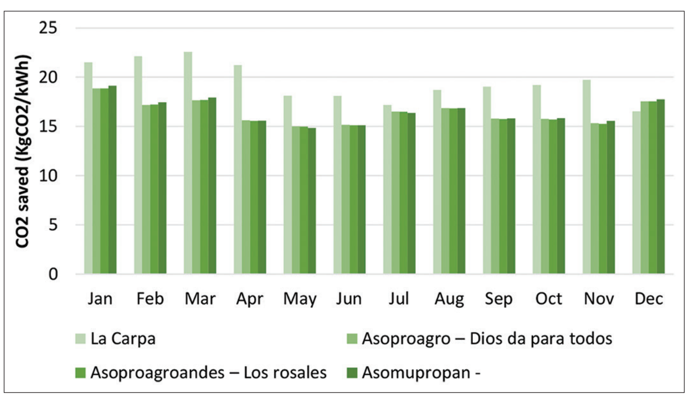


Figure 9: Total continuous CO_2 emissions saved of each farm in the unified municipality Guamal



supported by reliable data in the area of the transition towards renewable energy sources in the agricultural sector.

Normally, confidence intervals are defined based on the projected time frame of the data under study. Considering that the projection in this estimate spans 25 years, during which the system is expected to reach an efficiency of 6% under favorable conditions as specified by the manufacturer, it is advisable to set a confidence level of 70%. The upper limit would be 85%, while the lower limit stands

Figure 10: Total continuous CO_2 emissions saved of each farm in the unified municipality Santa Bárbara de Pinto - Santa Ana

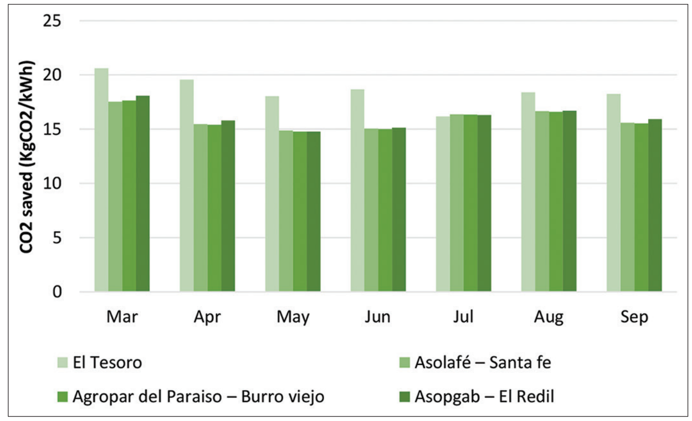


Figure 11: Total continuous CO2 emissions saved of each farm in the unified municipality Chibolo – Plato

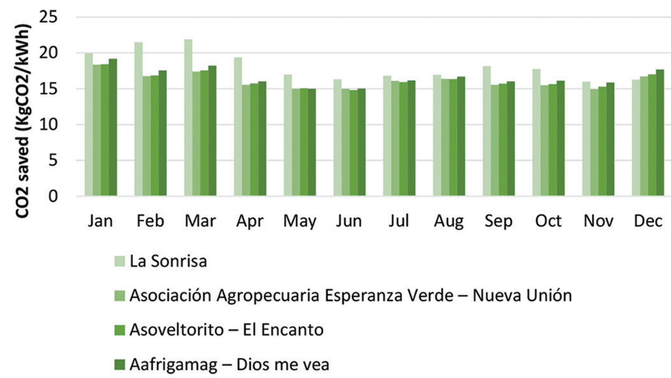
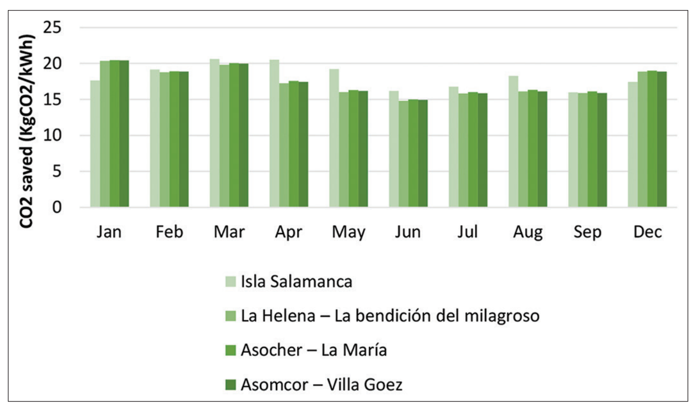


Figure 12: Total continuous CO_2 emissions saved of each farm in the unified municipality Isla de Salamanca – Ciénaga

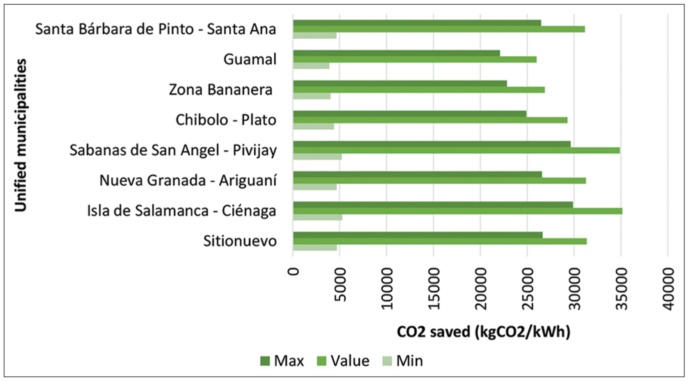


at 15%, aiming to align the distribution tails in the projection with the variable climatic conditions observed in recent years. Figure 13 shows the results of CO_2 emissions saved for the unified municipalities, considering the confidence intervals.

6. CONCLUSIONS

With the completion of this work it can be concluded that the non-emitted CO_2 emissions that were calculated with the data from the Global Solar Atlas are similar to the calculations obtained from

Figure 13: CO_2 saved continuously over 25 years by unified municipality with confidence intervals



local temperature and irradiation data and mathematical modeling. In this way, the positive impact on the reduction of CO_2 emissions in the long term (25 years) was evident, with the implementation of 33 PV systems in the rural areas of the Departamento del Magdalena. The importance of the implementation of PV systems in agricultural environments could be demonstrated, because they contribute to sustainability, efficiency, energy quality and competitiveness in local production by reducing the dependence on fossil fuels.

This paper is the initial part of a complete study of data related to agricultural production, with the implementation of more precise technologies for data processing, which seeks to obtain the impact of the reduction of greenhouse gases in daily activities and production tasks in the context of agricultural farms, due to the need for convergence to sustainable energy in the sectors that require it most depending on their current subsistence conditions, extremely important in the rural context.

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