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Reduction of the carbon footprint in the biomass pelletization process by incorporating photovoltaic solar energy

Reducción de la huella de carbono en el proceso de peletización de biomasa mediante la incorporación de energía solar fotovoltaica

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Abstract

This study analyzes the environmental impact of installing a photovoltaic solar system in a company that produces sorghum stubble pellets. The goal is to reduce emissions associated with the production process. The implementation of 100 solar panels of 160 W each to cover parking spaces is analyzed. The results show that this measure could reduce CO_2 equivalent emissions associated with electricity consumption by 56 %, without including the biomass transport to the company. Beyond transportation logistics, the integration of renewable energy significantly reduces conventional electricity consumption, helping to mitigate the environmental impact of the production process. Therefore, integrating photovoltaic energy would be an effective strategy to reduce greenhouse gas emissions from this pellet production process. Promoting the production of these pellets is of importance for this region, where dry biomass is widely available but has a limited use.

Keywords: bioenergy, biomass energy, pellet production, energy quantification, photovoltaic solar energy

Resumen

Este trabajo analiza el impacto ambiental de la instalación de un sistema solar fotovoltaico en una empresa productora de pélets de rastrojo de sorgo, para reducir emisiones asociadas al proceso productivo. Se propone implementar 100 paneles solares de 160 W para cubrir plazas de estacionamiento. Los resultados muestran que esto podría reducir las emisiones de CO_2 equivalente vinculadas al consumo eléctrico en aproximadamente un 56 %, sin considerar el transporte de biomasa. La integración de energía renovable reduce notablemente el consumo de electricidad convencional, lo que contribuye a mitigar el impacto ambiental del proceso productivo. Por tanto, incorporar energía fotovoltaica sería una estrategia efectiva para disminuir las emisiones de gases de efecto invernadero de este proceso de producción de pélets. Promover la producción de estos pélets resulta de importancia para esta región, donde la biomasa seca está ampliamente disponible pero tiene un uso reducido.

Palabras claves: bioenergía, energía de la biomasa, producción de pélets, cuantificación energética, energía solar fotovoltaica.

Introduction

Projections regarding the use of dry biomass pellets show their high growth potential in applications for the global decarbonization of energy production (Bajwa et al., 2018). Among ongoing discussions including land use, crop varieties, and required technical innovations, the offset of the CO_2 eq. emitted in the pellet production process still appears to be pending (Wiloso et al., 2020), (Wang and Wu, 2023). Although the life cycle analysis has been widely applied to evaluate the environmental performance of biomass pellet production, most studies focus on woody feedstocks in European or North American contexts, leaving agricultural residues in Latin American scenarios largely underrepresented (Martín-Gamboa et al., 2020, Silva et al., 2022). While the synergistic use of solar energy and biomass has been explored in the context of thermochemical conversion processes such as pyrolysis and gasification (Naveen et al., 2023), the literature review conducted for this study found no evidence of such integration being examined specifically for pelletization processes. This is a relevant gap, given that electricity is consistently identified as the dominant contributor to environmental impacts within pellet production systems (Laschi et al., 2016), and that Argentina's grid relies predominantly on fossil fuels (CAMMESA, 2024). The present study addresses this by quantifying, in a real-scale Argentine case, the carbon footprint reduction achievable through photovoltaic (PV) solar integration in an agricultural residue pelletization process.

In order to provide a study on this aspect, a real-scale pellet production example is detailed in this work, where a company that produces sorghum stubble pellets is required to reduce the environmental impact of the process by incorporating renewable energy. Due to the scale of the venture, relatively small-capacity equipment is being used, as this is barely larger than a pilot project to validate the technical and commercial viability of dry biomass pellets in the region. It has been found that electricity consumption is one of the critical factors influencing environmental impact, as all equipment requires electricity to operate (Laschi et al., 2016). Within the pellet production system analyzed by Gallardo Figueroa (2021), electricity consumption is the dominant contributor to the global warming potential impact category, accounting for 84.20% of the total CO_2 eq. emitted throughout the process, that is, for every kg of CO_2 eq. generated in the pellet production process, 0.842 kg corresponds to electricity consumption. It should be noted that the reference study was conducted for Chile's energy matrix, which, compared to Argentina's, has a higher share of renewable energy and coal in comparison to natural gas (Generadoras de Chile, 2025).

In the Argentine context, it should be noted that the main source of energy supplying the electricity grid is fossil fuels, mainly gas (CAMMESA, 2024). However, in 2017, National Law 27424 “Regime for the promotion of distributed generation of renewable energy integrated into the electricity grid” was passed, which establishes the possibility for all users of the distribution network to install energy generation equipment using renewable sources for self-consumption, with the eventual injection of energy into the distribution network. In this context, the figure of the user-generator is created, defined as someone who not only consumes energy from the electricity grid but can also feed in the energy generated and not consumed (Ley 27424, 2017). Subsequently, in 2018, the province of Córdoba adhered to this national law through Provincial Law 10604 “Provincial Adherence to National Law 27424” (Ley 10604, 2019).

This study aims to determine how favorable the use of PV solar panels is for self-supplying a portion of the energy demand of the production process in question, with a focus on reducing emissions that cause global warming. It is confirmed that the emissions caused by the production, transport, and installation of the PV system are offset by its own generation, and a calculation is made for the consumption of energy from the grid that is avoided through PV plant generation. Therefore, the avoided emissions are calculated based on the level of pollution associated with the mix of energy sources of the grid to which it is connected. The study is proposed for San Francisco, a town in the province of Córdoba, Argentina, so that the aforementioned regulations on distributed generation are applicable. As per the literature research performed for this study, only a few indirect references can be found regarding such emission offset efforts by means of PV systems specifically for dry biomass pelletizing processes.

First, the production process and the characteristics of the equipment involved in each of the stages are briefly described. Then, the electricity consumption of each piece of equipment is calculated to quantify the total energy involved in the process. Finally, a study is carried out on the environmental impact of the manufacture, transport, and installation of the solar panels. In order to limit the scope of the study, this analysis omits the environmental impact related to the manufacture of the machinery used in the production process, its installation, or the implementation of auxiliary facilities, which are considered a necessary basis to produce the pellets in question.

Development

Description of the production process

The raw material proposed for pellet production is sweet sorghum stubble (*Sorghum saccharatum*, variety M81), supplied by the Manfredi Agricultural Experiment Station (EEA Manfredi, Estación Experimental Agropecuaria Manfredi) of the National Institute of Agricultural Technology (INTA, Instituto Nacional de Tecnología Agropecuaria). This type of biomass requires prior conditioning before entering the pelletizing stage (Ortmann et al., 2023).

- Once the company receives the raw material, a drying stage is carried out with the aim of reducing the initial moisture content of the material from 60 % to 10 % (Puig-Arnavat et al., 2016), using an industrial flash dryer. This consists of a fluidized bed pilot dryer that can process up to 200 kg/h of material, operates at a temperature of 120 °C, and requires 7.50 kg/h of fuel, which, in this case, will be the same pellets generated in the production process. The drying stage uses sorghum pellets as fuel, consuming 7.50 kg/h over 78 operating hours per month, totaling approximately 585 kg of pellets per month — equivalent to 4.20 % of total monthly production. In accordance with Intergovernmental Panel on Climate Change (IPCC, 2006) guidelines, CO_2 emissions from the combustion of biomass fuels, including agricultural crop residues, are not included in national totals or reported in the sector, as they are considered to be offset by the carbon previously absorbed during the crop's growth cycle. This treatment is consistent with standard Life Cycle Assessment (LCA) practice for annual lignocellulosic crops such as Sorghum saccharatum, which exhibit high CO_2 fixation capacity through their C_4 photosynthetic pathway (Ameen et al., 2024). Given the relatively small share of thermal energy involved and the biogenic nature of the fuel used, its contribution to the global warming potential of the system is expected to be minimal, and its simplification in the carbon footprint analysis is considered a reasonable and justified assumption. However, it is useful to clarify that the equipment has a centrifugal fan and other auxiliary components attached to it that require electrical power to operate, with an electric motor that has a rated power of 5.50 kW.
- The sorghum is then ground using a high-capacity hammer mill operating at 2000 rpm to obtain material with a smaller particle size than the original. The mill motor has a rated power of 10 hp, which is equivalent to approximately 7.36 kW, and a processing capacity of 170 kg/h.
- From there, the processed sorghum is transported to the pelletizer by a screw conveyor whose electric motor has a rated power of 2.20 kW. The pelletizer operates at ambient temperature and humidity to obtain sorghum pellets in different particle sizes without the addition of additives, and its motor has a nominal power of 7.50 kW. The machine can generate an average of up to 100 kg/h of pellets; given this capacity, the pelletizer is considered the bottleneck of the process. In this case, mass losses due to evaporation during the pelletizing process are in the range of 2 % to 4 % and depend on the batch and the type of biomass being processed. As these percentages are small, they do not influence the calculation of total electricity consumption. Once the product is ready, it is transported by a conveyor belt with a 2.20 kW electric motor to the packaging and storage stage.

Since the maximum flow rate of raw material that can be processed is limited by the pelletizer, this equipment is used as a reference to determine the amount of sorghum stubble that can be processed monthly. This is 100 kg/h of pellets for 176 hours per month with a load factor (LF) of 0.80, which considers downtime for setup, maintenance, and cleaning, resulting in a mass flow of 14 080 kg of pellets per month. Considering a 10 % overall loss in the initial conditioning process, the amount of material to be supplied monthly is 15 645 kg.

Fig. 1 shows the pilot-scale flow diagram with the main stages of the process including drying and pelletizing, with the energies involved in accordance with DIN 1304 (Deutsches Institut für Normung, 1994).

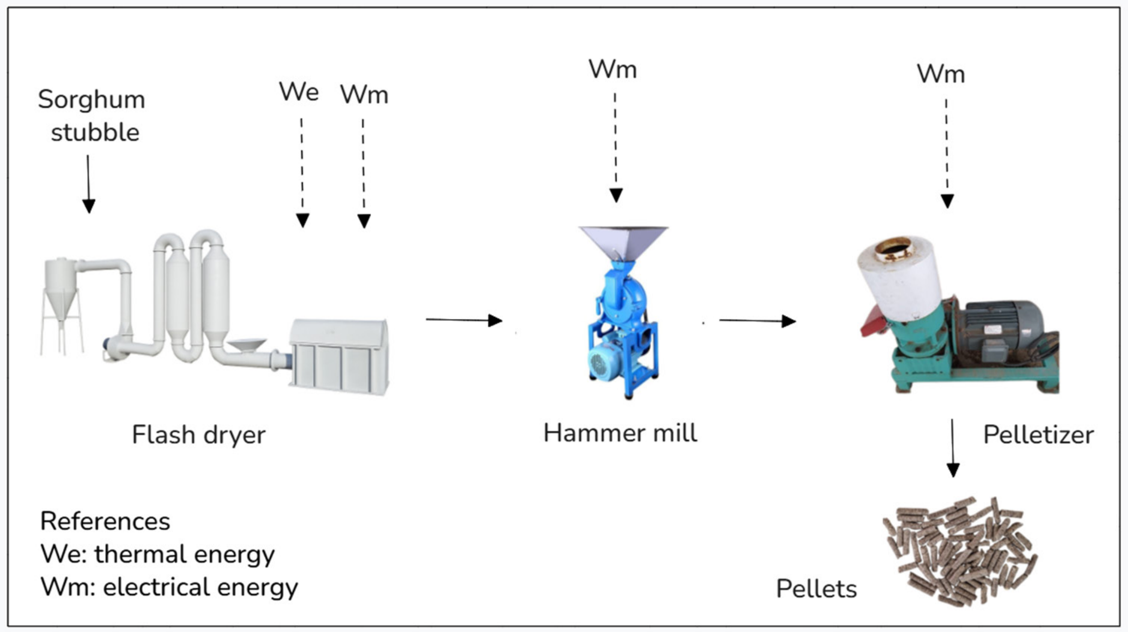

Fig. 1: Flow chart of the pellet production process - Source: https://secadoras.meelko.com/ and images by the authors

Table 1 details the electricity consumption of each piece of equipment and the LF adopted for each one; an average efficiency of 85 % is used as a reference for all electric motors, considering partial loads. In the case of the dryer and hammer mill, because they have greater processing capacity, they operate fewer hours per month at full load, and adjustment, maintenance, and cleaning tasks can be performed during idle times. Equation (1) is applied to the equipment to obtain the monthly electricity consumption in kWh (WEG, 2021).

$$Electrical\ consumption = \left(LF\ x\ Nominal\ power\ x\ 176h\right) / Efficiency \qquad (1)$$

Pilot scale - sorghum stubble pellets (based on 176 working hours per month)								
Stage	Equipment	LF	Nominal power (kW)	Efficiency	Total flow (kg/month)	Max. feed rate (kg/h)	Operating time (h/month)	Electrical consumption (kWh/month)
Drying	Flash dryer	0.52	5.50	0.85	15 645	200	78.23	506.16
Size reduction	Hammer mill	0.44	7.36	0.85	15 645	170	92.03	796.87
Raw material transport	Screw conveyor	0.80	2.20	0.85	14 080	100	140.80	364.42
Pelletizing	Pelletizer	0.80	7.50	0.85	14 080	100	140.80	1242.35
Final product transport	Belt Conveyor	0.80	2.20	0.85	14 080	100	140.80	364.42
TOTAL:								3274.23

Table 1: Electrical consumption of the equipment

Therefore, the pelletizing process requires a total electricity consumption of approximately 3274 kWh per month, considering an average of 176 working hours per month. Conventionally, 11 months of work are adopted to account for holidays, non-working days, and leave. This corresponds to an annual demand of about 36 014 kWh. Production is mainly concentrated during daytime hours (from 8:00 a.m. to 4:00 p.m.), which is an advantage because, by implementing a PV plant, self-consumption would be maximized, thus minimizing the energy injected into the electrical grid, given that energy demand occurs during generation hours. It should be noted that the number of hours of operation of the solar plant will vary according to the time of year.

Carbon emissions analysis

Definition of the objective and scope of the study

The carbon emissions of the solar PV installation is analyzed, without considering the equipment used in pellet production that is already installed and will continue to operate regardless of the existence of the PV plant. The main objective is to reduce the environmental impact of electricity consumption in the pellet production process by installing solar PV panels.

First, the objective, functional unit, scope of the system, and type of impact being analyzed are defined. The functional unit is defined as 1 kWh since it can be used directly to quantify both the energy generated by the PV system and the electricity consumed in the pellet production process. This is based on a monthly operation of 176 hours, which corresponds to the actual operating schedule of the production plant. The use of 1 kWh of electricity generated as functional unit is the standard approach in LCA studies of photovoltaic systems, as it enables straightforward comparison of impacts across different technologies and sites (Ihoume et al., 2026). The carbon footprint of the PV installation is assessed as the means by which the study quantifies the net emission reduction achievable in the pelletization process, since the pellet production equipment is already installed and operates independently of the PV system. In this way, the analysis of the PV installation serves the broader goal of reducing the carbon footprint of biomass pellet production.

In terms of system boundaries, the scope of this study is from cradle-to-gate, as the analysis involves everything from the construction of the solar panels to their installation and the generation of electricity at the company, considering each of the materials and their transport. In addition, a regional scope is established as the geographical boundary, considering the company's location in the urban area of the city of San Francisco, Córdoba, Argentina.

Finally, regarding the type of impact, this study focuses exclusively on the global warming potential (GWP) impact category, quantified in kg of CO_2 eq. This corresponds to a carbon footprint analysis, consistent with ISO 14067, rather than a full multi-category LCA as defined by ISO 14040 and 14044 (Ilari et al., 2022). This scope was deliberately chosen given the study's primary objective, quantifying greenhouse gas (GHG) emission reductions through PV integration, and the limited scale of the production system under analysis. While restricting the assessment to GWP reduces interpretive breadth compared to a full LCA, it provides a focused and transparent evaluation of the environmental benefit most directly associated with renewable energy integration, which is the central contribution of this work.

Inventory analysis

According to what was established in the general project for this factory, the area available in the company for the installation of solar panels is on the roofs of the parking lot, with capacity for 8 vehicles distributed in 4 double spaces, which is approximately 70 m away from the general energy connection point. The proposal is to install 25 panels of approximately 1 m^2 each in each space to provide shade for the vehicles. To meet the requirements, different elements are needed, not all of which are nationally produced.

In this case, 100 PV panels of 1 m^2 each are required, as well as two power inverters to transform direct current into alternating current, synchronize with the grid, and provide anti-islanding protection; electrical protections (automatic circuit breakers, differential protections, and relays); cables and conductors sized for the transport of the energy from the PV modules to the inverters, and from the inverters to the connection point; metal structures (profiles, anchors, and pipes) for the mechanical assembly; and conduits for the protection and channeling of electrical conductors.

It should be clarified that solar panels of 1 m^2 of surface area and 160 W of nominal power are specifically adopted because there are clear references in the literature on the environmental impact associated with the manufacturing of this size of panels. The present analysis could eventually be extended to a smaller number of larger panels, according to the nominal powers that are more frequent in current distributed generation installations. This would imply a recalculation and adjustment of the results obtained in this work: it would be expected that a smaller number of panels with a larger unit surface area would result in a lower environmental impact, so the result of the present work can be considered conservative.

Environmental impact assessment

To study the environmental impact of the solar PV installation, the CO_2 eq. emissions produced by the different elements in its manufacture are first considered. In some cases, specific values are used for each element; in other cases, only global values are used due to the complexity of the systems, such as the inverters, which contain multiple electronic components whose impact is difficult to quantify.

CO_2 eq. emitted in the manufacture of solar panels

Regarding the manufacturing of solar PV panels, the production of the cells can be divided into different stages, with their respective inputs and outputs (Guzmán Niño, 2017), as listed in Table 2. In addition to the materials and the consumption of electrical energy and fossil fuel, the estimated emission of CO_2 eq. for each component is included. For the electricity consumption associated with panel manufacturing, a CO_2 emission factor of 0.6835 t CO_2/MWh was adopted, corresponding to the average Chinese energy mix (Zhang et al., 2024). This choice is justified by the fact that the most energy-intensive stages of solar panel manufacturing are predominantly carried out in China, regardless of where the final assembly takes place. It is important to clarify that the emissions depend on various production factors that are specific to each company and difficult to access as public information. Therefore, global values are taken, and in some cases, a range with a minimum and a maximum is considered.

The final result in the analysis is for a 1 m^2 panel as detailed in the reference (Guzmán Niño, 2017), although limited characteristics are given. For this case, it is then assumed that it is a panel of 160 W nominal power, like the SOLARTEC® KS160T-24V, whose collection area is 1 m^2 (SOLARTEC, 2024a).

Stage	Inputs		kg CO_2 eq. maximum	kg CO_2 eq. minimum	Outputs
Production of metallurgical-grade silicon	Electricity	11.00 kWh	7.52		1 kg of metallurgical grade silicon
	Diesel fuel	0.87 L	2.07		
	Silica sand	2.70 kg	0.03		
	Petroleum coke	0.50 kg	0.17		
	Wood chips	2.35 kg	0.94[1]		
	Coal	0.17 kg	0.41		
	Graphite electrodes	0.10 kg	1.10	1.50	
Production of electronic-grade silicon	Metallurgical grade silicon	1.00 kg			0.676 kg of electronic grade silicon
	Electricity	23.90 kWh	16.34		
	Hydrochloric acid	3.60 kg	3.20		
	Deionized water	43.50 kg	34.80		
	Sodium hydroxide	0.79 kg	0.88		
	Hydrogen	0.10 kg	0.16		
Molded polycrystalline silicon production	Silicon production mixture	1.14 kg			1 kg of polycrystalline silicon
	Electricity	19.31 kWh	13.20		
	Argon	0.27 kg	0.03	0.05	
	Nitrogen	0.05 kg	0.005		
Waffle production	Melted polycrystalline silicon	1.14 kg			Wafers (1 m²)
	Electricity	8.00 kWh	5.47		
	Diesel	0.15 L	0.36		
	Deionized softened water	0.49 kg	0.39		
	Drawn steel	1.48 kg	2.62		
	Dipropylene glycol monomethyl ether	0.30 kg	0.93		
Cell doping	Wafer	1.06 m2			Cells (1 m²)
	Electricity	30.22 kWh	20.66		
	Diesel	0.22 L	0.52		
	Deionized water	1.00 m3	0.80		
	Liquid nitrogen	1.85 kg	0.79		
	Sodium hydroxide	0.16 kg	0.18		
Panel production	Electricity	47.22 kWh	32.27		Panel (1m²)
	Diesel	0.22 L	0.52		
	Flat tempered glass	10.10 kg	8.58		
	Solar glass, low iron content	10.10 kg	44.44		
	Aluminum alloy	2.63 kg	21.41		
	Ethyl vinyl acetate	1.00 kg	2.50	3.00	
Total			223.30	224.22	

[1] CO_2 emissions from wood chips include biogenic and process-related fractions. Following IPCC (2006) and Pastor-Vallés et al., (2025), biogenic emissions are considered carbon neutral and reported separately.

Table 2: CO2 eq. emissions in the manufacture of a polycrystalline solar panel 1 m²

By summing the total emissions, it can be seen that they are in the range between 223.30 kg of CO_2 eq. and 224.22 kg of CO_2 eq. for each 1 m^2 panel. It can be interpreted that this range is applicable to a panel of about 160 W nominal power. According to the IEA (International Energy Agency), the average CO_2 eq. emissions produced in the manufacturing of solar panels is 780 kg of CO_2 eq. per kW of nominal power (Kester et al., 2024).

To compare these values, the range of emission values from Table 2 is extrapolated to 1 kW, obtaining values of approximately 1008 and 1014 kg of CO_2 eq. per kW. Although this range is considerably higher than that reported by the IEA, it should be considered that a power of 1000 W is electrically equivalent to 6.25 panels of 160 W like the one considered. If the same collection area were covered using panels of a larger unit surface area, the incidence of some elements would decrease, such as the aluminum of the frames, the material of the electrical conductors, and part of the production waste, naturally reducing the total CO_2 eq. emissions.

Another important point is that, over time, the panels lose part of their efficiency. Although the datasheet of the adopted model does not establish a specific value, a decay of up to 20 % in 25 years is normally taken as a reference, as is the case with the SOLARTEC® Sol-6P-60-260-4BB module (SOLARTEC, 2024b). As a conservative measure, a useful life of 20 years is adopted for the installation. Once this period is over, the replacement of the solar panels should be evaluated; however, under normal conditions, they could continue to operate at reduced power.

CO_2 eq. emitted in the manufacture of inverter equipment and protections

The inverter is an electronic system that transforms the direct current energy generated by the panels into alternating current energy, adapted to the voltage and frequency values of the grid to which it is connected. This equipment contains a large number of electronic components, which makes it impractical to calculate the individual pollution of each element to obtain the exact value of CO_2 eq. emitted in the manufacture of the assembly. Therefore, the value assigned to the inverter by the IEA report is used, which is 71.80 kg of CO_2 eq. per kW of nominal power (Kester et al., 2024).

In this case, based on the power to be installed (160 W x 25 panels per space x 4 spaces = 16 000 W), two SolaX Power® X3-MIC-4K-G2 inverters (ADN SOLAR, 2024) are selected, each with a power of 8 kW, resulting in a total of 1148.80 kg of CO2 eq.

As for electrical protections and weatherproofing panels, there is limited specific information available on their CO2 eq. emissions, but their composition is considerably simpler and they use fewer materials than the inverter equipment. The main elements they are made of are copper, steel, and plastic: a detailed estimate based on the main commercial component manufacturer data allowed for their impact to be estimated at 3 % of the total for the inverters, that is, 34.46 kg of CO2 eq. (Fthenakis and Kim, 2011).

The useful life of an inverter is normally estimated at 10 years due to the expected obsolescence of electronic equipment. However, this does not necessarily mean that the equipment must be discarded once this period has elapsed, but rather that the possibility of replacement should be evaluated. In this case, such action is not considered, as it will depend on the condition of the equipment at the time and the financial possibility of purchasing a new one.

CO_2 eq. emitted in the cable manufacturing

To reduce Joule effect losses in the installation conductors, the inverter should be located as close as possible to the PV panels (Szwarc, 2018). Therefore, for this case, the distance from the panels to the inverter is considered negligible, while the distance from the inverter to the connection point is maximum. Initially, it was specified that the linear distance from the parking lot to the connection point is 70 m; however, the conductors must be routed for about 100 m, which includes both horizontal and vertical distances.

For the alternating current wiring, Payton PVC Superflex conductors from the Argentine brand IMSA® are selected. In the alternating current section, four 4-conductor cables must be used, since each inverter is three-phase (3 phases + 1 neutral) with two outputs each. The cross-sectional area of the active conductor is 4 mm^2. According to the manufacturer's declaration, this conductor has a total weight of 316 kg/km; with this data, it is possible to determine the total weight of the conducting element (copper) and the insulating and protective material (PVC) (IMSA, 2024).

Table 3 determines the CO_2 eq. emitted by each element of the conductor in its manufacturing; the column of kg CO_2 eq. per kg of product shows the maximum and minimum values of the emissions corresponding to the manufacture of each material.

Material	kg/km	Number of sections	Length (m)	Density (kg/m3)	kg CO2 eq. per kg of product	kg CO2 eq. emitted
Copper (4 mm^2)	**35.84**	**16**	**100**	**8960**	**4.60** (1)	**263.78**
PVC (insulation + sheath)	**172.64**	**4**	**100**	**1420**	**1.40** (2)	**96.68**
					2.45 (2)	**169.19**
Total						**360.46**
						432.97

(1) International Copper Association (2023)
(2) Rubio-Domingo and Halevi (2022)

Table 3: Calculation of emissions in the manufacture of conductors

In addition, it has been verified that the voltage drop in the conductors does not exceed the permissible level for this type of installation (3 % of the nominal output voltage of the inverter), taking as a reference the voltage drop (VD) value declared by the conductor manufacturer (8.61 V/A·km); the nominal current (In) and nominal output voltage of the inverter (Vn) (6.1 A and 380 V); and the conductor length (L) of 100 m. Using Equation (2), the total voltage drop percentage (ΔV) can be obtained, which in this case is 2.40 % (Schneider Electric, 2006).

$$\Delta V\% = \sqrt{3} * VD * In * L / 380V \tag{2}$$

CO_2 eq. emitted in the manufacture of structural elements

Table 4 lists the materials that must be included to implement the structure. As a summary, it shows the total lengths of the materials required, as well as the corresponding maximum and minimum CO_2 eq. emissions. It is important to mention that all pipes and profiles are made of steel.

Structure	Width (mm)	Height (mm)	Total length (m)	Thickness (mm)	Density (kg/m³)	Emissions (kg CO_2 eq. per kg of product)	kg CO_2 eq. emitted
6 circular pipes	Ø 100		21.00	3.20	7840	1.50 (3)	240.33
						3.00 (3)	480.65
6 circular pipes	Ø 25		27.00	2.50	7840	1.50	56.11
						3.00	112.22
6 circular pipes	Ø 25		12.00	2.50	7840	1.50	24.94
						3.00	49.88
6 circular pipes	Ø 75		7.20	2.50	7840	1.50	48.21
						3.00	96.43
16 rectangular pipes	100	40	80.00	1.60	7840	1.50	23.17
						3.00	46.33
40 rail guide profiles	50	40	200.00	1.80	7840	1.50	731.47
						3.00	1463.13
Circular concrete footing	Ø 500		9.00	Solid	244	2.46 (*)	1060.29
Paint	40 L			Liquid	1.09	0.037 (4)	1.63
Minimum total							2186.23
Maximum total							3310.56

(3) Ghoneim et al. (2022)
(*) 600,00 (kg CO_2 eq. /m³). Brunatti et al. (2014)
(4) MITECO. (2024)

Table 4: Calculation of emissions from the construction of the eight parking spaces

CO_2 eq. emitted during transport of the elements

An important factor to consider in the environmental impact study is the transportation of the different components of the PV system. Some of them, although purchased from domestic suppliers, are manufactured in other cities or even other countries, and must be transported by different means to the city of San Francisco, Córdoba, where this installation is proposed.

The panels are purchased in Argentina under the SOLARTEC® brand (https://solartec.com.ar/modulos-fotovoltaicos/), but are imported from Castelfidardo, Italy. From there, they are transported together with other components by heavy goods vehicle to the port of Barcelona in Spain, and then by ship to the port of Buenos Aires.

The inverter is manufactured in Hangzhou, China, by SolaX Power® (https://solax.com.ar/), from where it is shipped to the port of Buenos Aires. Both products are transported by heavy-duty trucks to the city of Córdoba, capital of the province of the same name, where the distributors of these items are located. The supplier then dispatches them by light trucks to their final destination in the city of San Francisco, Córdoba.

The iron for the structure is purchased locally, but the supplier acquires it from the Acindar® plant (https://www.acindar.com.ar/) located in the city of Rosario, province of Santa Fe, from where it is shipped by heavy-duty trucks.

The cables needed for the electrical connections are transported by heavy trucks from the IMSA® (https://imsa.com.ar/), a factory located in the town of Merlo, province of Buenos Aires, to the same company's warehouse in the city of Córdoba; from there, they are shipped to the city of San Francisco by light trucks.

The plastic boards, conduits, and supports for the various electrical components are transported from Burzaco, in the province of Buenos Aires, to the city of San Francisco by light transport trucks. The materials proposed in the project estimate are from the Zoloda® brand (https://www.zoloda.com.ar/).

All electrical circuit protection components are purchased from one of the local distributors of WEG Equipamentos Eléctricos SA (https://www.weg.net/institutional/BR/es/). This company, the Argentine subsidiary of the multinational WEG is in the city of San Francisco, but the required products are manufactured in Jaraguá do Sul, Brazil, and transported by heavy-duty trucks.

For this study, a heavy truck is defined as one that can transport more than 16 tons and travels long distances, and a light truck as one that transports less than 16 tons, in accordance with the literature used to determine their emissions (Mulholland et al., 2023).

Table 5 shows a summary of the route taken by each of the items and the means of transport used, thus enabling the CO_2 eq. emissions from the transport of each item to be calculated.

Element	Type of transport	Starting point	Arrival point	Weight (kg)	Distance traveled (km)	g CO_2 eq. per kg per km	Total (kg CO_2 eq.)
Solar panels	Heavy truck	Castelfidardo, Italy	Barcelona, Spain	2000	1361	0.06 (5)	174.21
	Ship	Barcelona, Spain	Buenos Aires, Argentina		10 000	0.05 (6)	972.00
	Heavy truck	Buenos Aires Argentina	Córdoba, Argentina		696	0.06 (5)	89.09
	Light truck	Córdoba, Argentina	San Francisco, Argentina		223	0.10 (5)	45.63
Inverter	Ship	Hangzhou, China	Buenos Aires Argentina	31	22 124	0.05 (6)	33.33
	Heavy truck	Buenos Aires Argentina	Córdoba, Argentina		696	0.06 (5)	1.38
	Light truck	Córdoba, Argentina	San Francisco, Argentina		223	0.10 (5)	0.71
Iron	Heavy truck	Rosario, Argentina	San Francisco, Argentina	750	266	0.06 (5)	12.76
Cables	Heavy truck	Buenos Aires Argentina	Córdoba, Argentina	126	696	0.06 (5)	5.63
	Light truck	Córdoba, Argentina	San Francisco, Argentina		223	0.10 (5)	2.88
Electrical accessories	Light truck	Buenos Aires Argentina	San Francisco, Argentina	40	561	0.10 (5)	2.30
Electrical protections	Heavy truck	Jaraguá do Sul, Brazil	San Francisco, Argentina	10	1674	0.06 (5)	1.07
Total							1338.87

(5) Mulholland et. al. (2023)
(6) Sustainable Business Network (BSR). (2018)

Table 5: CO_2 eq. emissions in transport

Calculation of total CO_2 eq. emitted by the PV installation

Table 6 summarizes the different elements comprising the installation and the emissions involved in the manufacture and transport of each of them. At the end, the sum of the minimum and maximum values is shown.

Element	Features	Quantity	kg CO_2 eq. min.	kg CO_2 eq. max.
Solar panels	**1 m2, 160 W**	**100**	**22 330**	**22 422**
PV inverters + protections	**8 kW**	**2**	**1183.26**	
Cables	**4 Payton PVC® 4 mm²**	**100 m**	**360.46**	**432.97**
Structure	**Pipes, profiles, and concrete**	**8**	**2186.23**	**3310.56**
Transportation	**Light trucks, heavy trucks, and boats**	**-**	**1338.87**	
Total			**27 398.82**	**28 687.66**

Table 6: Total calculation of kg of CO_2 eq. released by the installation of solar equipment

Calculation of the energy generated by the PV installation

The annual energy generated can be estimated using the procedure established in Equation (3) (Rocchia et al., 2016).

$$E = PI \ x \ EP \ x \ EI \ x \ EG \ x \ SP \ x \ NP \ x \ 365 \ days \tag{3}$$

- PI = Annual average daily irradiation (4.25 kWh/m²)
- EP = Panel efficiency (14 %)
- EI = Inverter efficiency (97.80 %)
- EG = Overall efficiency of the installation (95 %)
- SP = Surface area of each panel (1 m²)
- NP = Number of panels (100)

Thus, it is estimated that, for the first year, the annual energy generated by the installation is 20 178 kWh. Taking into account the energy to be generated, the aging of the panels (which, in this case, was considered to be 1 % per year on a linear basis) and the emissions recorded in Table 6, the approximate amount of CO_2 eq. per kWh generated can be obtained. The following is considered for this calculation:

- Total energy generated in 20 years: 365 217 kWh
- Total emissions at the facility: minimum of 27 399 kg of CO_2 eq. and maximum of 28 688 kg of CO_2 eq.
- CO2 eq. emissions per kWh generated: minimum of 58 g of CO_2 eq. per kWh and maximum of 62 g of CO_2 eq. per kWh.

The values for this emission are relatively high compared to the ones found in the literature, which places it between 25 g of CO_2 eq. per kWh and 32 g of CO_2 eq. per kWh (Resch, 2007). The high value obtained is mainly due to the structure supporting the panels, which also serves as a shade for a parking lot; this requires a considerable amount of steel for its construction, as well as the associated transport. In addition, only 20 years of use for the installation have been considered; if this time were extended to the more typical 25 years, this value would decrease.

Calculation of avoided emissions from the use of solar panels

According to the 2024 Climate Action Strategy report prepared by the Empresa Provincial de Energía de Córdoba (EPEC), the emission intensity indicator for electricity generation in the province of Córdoba is 0.38 t CO_2 /MWh (EPEC, 2024). This value was selected as it is more representative of the local energy context than the national grid average, given that the production plant is located in the city of San Francisco, Córdoba, and is supplied by EPEC's distribution network. Based on this value, it can be determined that it takes between 3.60 and 3.80 years to recover the emissions from the manufacture and transport of the elements necessary for the PV installation. From that point on, the installation can be considered carbon neutral. The emission intensity indicator of 0.38 t CO_2/MWh reported by EPEC (2024) reflects the carbon intensity of electricity generation within the provincial energy system, making it more representative of the local context than national average factors. While transmission and distribution losses are accounted for separately in EPEC's carbon footprint methodology, their inclusion would result in a slightly higher effective emission factor at the point of consumption, which would further increase the avoided emissions calculated in this study. This simplification is therefore conservative and does not affect the conclusions of the work.

Considering that the target production plant consumes 36 014 kWh per year (13 685 kg of CO_2 eq. released), and that the solar installation generates an average of 20 178 kWh per year (7668 kg of CO_2 eq.), it can be estimated that, after achieving carbon neutrality, approximately 56 % of the CO_2 eq. released by electricity consumption is offset, without considering the influence of sorghum stalk transportation.

Considerations regarding raw material logistics

As a complementary analysis, carried out outside the scope of the assessment defined in this study, an estimation of the CO_2 eq. emissions associated with the transport of raw material is presented below. Although this analysis falls beyond the declared system boundaries, it is included as supplementary information to provide a broader picture of the overall carbon footprint of the pelletization process and to identify opportunities for future emission reduction strategies. According to the values summarized in Table 1, approximately 15 645 kg of sorghum stubble must be transported per month. To do this, it is necessary to use a truck that transports the biomass from INTA's EEA Manfredi to the city of San Francisco. Therefore, taking into account the weight of the raw material, the transport distance (200 km), and the emissions corresponding to the type of truck (0.06 g of CO_2 eq. per kg and km) (Mulholland et al., 2023), 187.74 kg of CO_2 eq. are emitted per month, corresponding to 2065 kg of CO_2 eq. per year, considering 11 months. Previously, when considering only the emissions attributable to electricity consumption, a reduction of 56 % was obtained by incorporating the PV solar installation; if the transport of sorghum stubble is now included, this percentage decreases to 49 %.

A priori, taking these values into account, it would seem important to work on reducing these additional emissions, given that transport has a direct impact on the percentage of compensation achieved with the installation of solar panels. A reasonable solution could be to transport the raw material from locations closer to the company, establishing, for example, a maximum radius of 100 km (equivalent to 1033 kg of CO_2 eq. per year). With this parameter, a 52 % reduction in emissions would be achieved instead of the estimated 49 %. Given this result, it is clear that a more in-depth technical-economic analysis is needed, including the possible variation in sorghum stover prices due to a reduction in the number of suppliers in the region from which the raw material would be obtained.

Discussion and conclusions

The results presented in this study show how photovoltaics can help reduce the environmental impact of a biomass production process. In this particular case, it is clear that the system analyzed offsets the CO_2 eq. emissions generated during the construction, transport, and installation of the solar panels in less than a quarter of its useful life. From that point on, approximately 56 % of the CO_2 eq. emissions resulting from electricity consumption are offset, without considering the transport of sorghum stubble to the company.

Regarding operational continuity, the PV system is not intended to replace grid electricity entirely, but rather to offset a portion of it. The conventional electricity grid remains the primary energy source, ensuring uninterrupted operation of the plant, while the PV installation reduces the share of grid-sourced electricity consumed and, consequently, the associated greenhouse gas emissions. The energy generated by the panels is fully directed to supply the production process, prioritizing self-consumption and minimizing dependence on the conventional grid.

These findings are consistent with broader evidence on the environmental performance of PV systems, which confirms that PV generation represents a substantially lower-emission alternative compared to fossil fuel-based electricity (Sobczuk et al., 2025). This effect is particularly significant in carbon-intensive energy regions such as Argentina, where renewable integration yields greater net GHG mitigation benefits (Chen et al., 2023). In the specific domain of biomass pellet production, electricity consumption has been identified as the dominant contributor to environmental impacts, suggesting that renewable energy integration is the most effective lever for emission reduction in this type of process (Gallardo Figueroa, 2021).

From a policy perspective, Argentina's distributed generation framework — established by National Law 27424 and Provincial Law 10604 — provides the regulatory conditions to replicate this model in other pelletization facilities. However, financial feasibility will depend on access to public financing instruments and electricity tariff evolution. A full techno-economic assessment, including investment recovery periods, is identified as a priority area for future work.

For future work, in accordance with what has been presented on the logistics for the raw material, this study should be expanded with an analysis including the optimization of transport, considering the possibility of obtaining sorghum straw from more adjacent suppliers, including a technical-economic scheme that analyzes the emissions associated with transport and the price variations of the raw material.

At the same time, the possibility of increasing the number of solar panels installed on the property could also be evaluated. This would allow more electricity to be generated from the same renewable source, which could be used both to supply the pellet production process and for other company needs. By increasing energy self-consumption, dependence on the conventional electricity grid, which is still heavily influenced by fossil fuels, would be reduced, thus contributing to a further decrease in greenhouse gas emissions in the context of distributed generation.

It should be noted that, even if the proportion of surplus energy fed into the electricity grid increases due to an increase in installed PV power, this energy is still more environmentally sustainable than the energy currently provided by the grid.

On the other hand, in the domestic market, it is now possible to obtain solar panels of higher nominal power, surface area, and efficiency; this would make it possible to reduce the amount of certain components used in their manufacture, such as the aluminum frames that support the panels or the frames of the general metal structure, which could further reduce the associated carbon footprint.

Additionally, the shading effect provided by the PV panels over the parking area represents a secondary benefit not accounted for in this study. Quantifying this dual function through a consequential LCA approach could result in a further reduction of net emissions and is identified as a complementary area for future research.

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Contribución de los Autores

	Colaboración Académica													
Nombres y Apellidos del autor	1	2	3	4	5	6	7	8	9	10	11	12	13	14
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Jorge Vega				x		x							x	
Diego Ferreyra		x		x		x			x			x	x	
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1-Administración del proyecto, **2-**Adquisición de fondos, **3-**Análisis formal, **4-**Conceptualización, **5-**Curaduría de datos, **6-**Escritura - revisión y edición, **7-**Investigación, **8-**Metodología, **9-**Recursos, **10-**Redacción - borrador original, **11-**Software, **12-**Supervisión, **13-**Validación, **14-**Visualización.

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