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Proposals for Energy Efficiency Solutions in the RÍO NUEVO Agroindustry through Biogas, Solar Energy and Thermal Preheating

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Abstract

The energy efficiency project developed at the RÍO NUEVO company in Jacona, Michoacán, whose main objective was to propose sustainable solutions using available resources to reduce the high energy costs of its broccoli and fruit processing, focused on three proposals after a plant visit. The first was the use of organic broccoli waste to produce biogas (with a minimum of 55% methane) to power a 70 kW motor-generator that would operate 10.48 hours a day using 440 m^3 of gas. The second was the sizing of a photovoltaic system that, with 962 modules, could generate 30.48% of the total annual consumption, achieving savings of 143616.40 USD ($2872328.00 MXN). The third is the implementation of a solar water preheating system for the boiler, which, by heating from 22˚C to 90˚C, would save 48.3% in LP gas costs. While the study is valuable for integrating solar resources and agro-industrial waste to generate economic benefits and reduce fossil fuel consumption, its implications point out that biogas production is interrupted four months a year due to the seasonality of waste, and that photovoltaic generation is limited by available land.

Keywords

Agribusiness, Organic Waste, Energy Efficiency, Biogas, Solar Energy

1. Introduction

The company RÍO NUEVO, located in Jacona, Michoacán 19˚58'09"N 102˚17'34"W (Figure 1), is dedicated to food processing, mainly cooked broccoli and seasonal fruits such as mango and berries. Broccoli is mainly processed during the months of March, April, September and October, coinciding with the peak production seasons in the region. On the other hand, mangoes are received and transformed between February and July, when the local harvest takes place. The process includes stages such as receiving, selecting, washing, cooking, cooling, packaging and cold storage, as can be seen in Figure 2, which requires significant amounts of thermal and electrical energy. Currently, the company operates under the GDMTH (Great Demand in Hourly Medium Voltage) tariff scheme [1], which reflects a significant electricity consumption profile throughout the day. Furthermore, it has a high consumption of LP gas, used primarily for the operation of the steam boiler, which is essential in thermal processes such as cooking broccoli. In this context, energy consumption represents a considerable portion of operating costs and environmental impact, due to the intensive use of fossil fuels and grid-connected electricity. This presents an opportunity and a need to implement energy efficiency measures that reduce costs and improve the sustainability of the production process.



Figure 1. Area and location. Google Earth 2025.

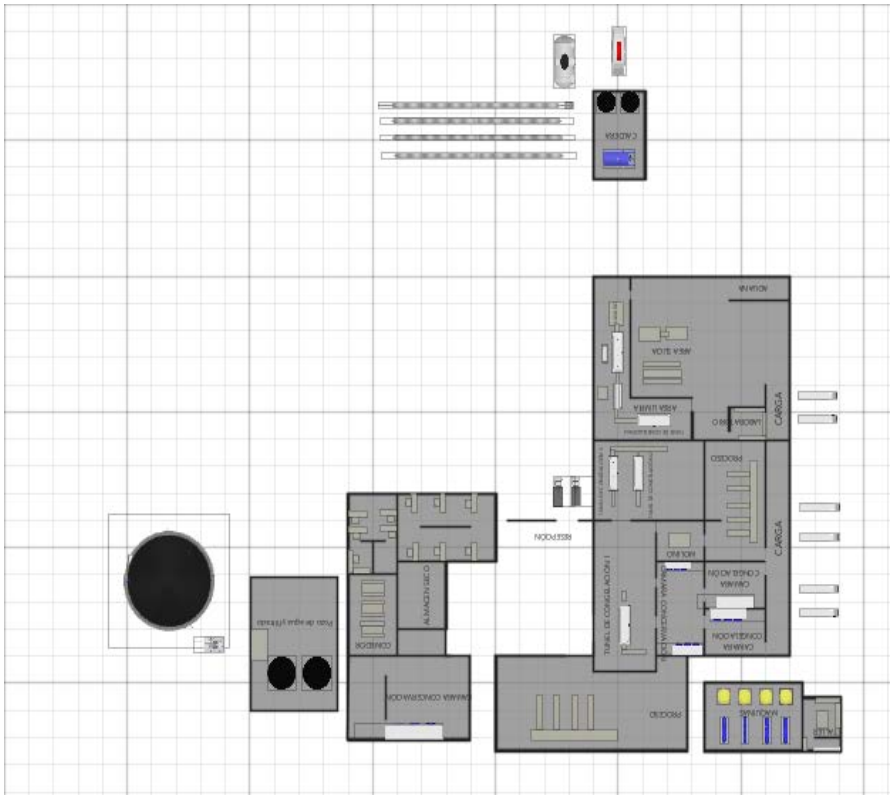


Figure 2. Path sketch. Sweet Home 3D software, open source 2025.

In the case of broccoli, anaerobic digestion can produce 22 L per kg of plant material with a retention time of 18 to 20 days, using a 2:1 ratio, *i.e.*, two parts of broccoli to one part of water at room temperature with a minimum methane quality of 55% in the biogas and a PC = 15,350 kJ/kg [2].

For mango waste, anaerobic digestion produces 7.5 ml of biogas per gram of substrate with a retention time of 29 days using a 1:1 ratio at room temperature, with an elemental analysis of 43% = C, 6% = H, and 0.6% = N. Using a stoichiometric ratio, this yields a methane quality of 26.6% and a PC = 6300 kJ/kg [3].

Solar irradiation data were obtained from the NASA Prediction of Worldwide Energy Resources (POWER) Data Access Viewer using the geographic coordinates of the RÍO NUEVO processing plant (19˚58'09"N, 102˚17'34"W) [4]. The analyzed period extended from November 2024 to June 2025, corresponding to the operating period considered in this study. Monthly solar irradiation values provided by NASA POWER were used to calculate the average irradiation for the analyzed period, resulting in an average value of 5.76 kWh/m^2·day.

2. Methodology

A plant visit was conducted at the RIO NUEVO food processing plant to learn about the processes and collect relevant data on electrical (**Table 1**) and thermal (**Table 2**) energy consumption. Historical consumption data from the last year will be obtained to identify energy demand and costs.

During the plant visit, operational information was obtained through meetings with personnel responsible for the plant's maintenance and production areas. Electricity consumption data for the period from April 2024 to April 2025 were obtained from the historical billing records available through the Federal Electricity Commission (CFE) website, using a CFE electricity bill provided by the Industry, Head of Maintenance at RÍO NUEVO, as the reference for accessing the account information. The electricity consumption values reported in this study correspond to actual billing records rather than estimates.

Table 1. Consumption of the Rio Nuevo processor, May 2024 - April 2025. CFE.

Month	Demand kW	Total consumption kWh	Power factor %	Load factor %	MXN/kWh	MXN (Energy)	USD/kWh	USD (Energy)
May	858	320,055	94.92	50.14	$2.68	$857683.39	$0.13	$42884.17
Jun	1205	406,332	93.65	46.83	$2.54	$1031717.58	$0.13	$51585.88
Jul	1224	488,983	93.02	53.7	$2.49	$1219034.62	$0.12	$60951.73
Aug	1244	438,422	93.71	47.37	$2.54	$1115038.67	$0.13	$55751.93
Sep	668	228,279	95.8	47.46	$2.74	$625712.74	$0.14	$31285.64
Oct	403	141,847	98.54	47.84	$2.35	$333765.99	$0.12	$16688.30
Nov	617	134,140	97.67	30.2	$3.11	$417014.43	$0.16	$20850.72
Dec	561	175,254	96.76	41.99	$2.85	$499211.02	$0.14	$24960.55
Jan	826	239,475	93.62	38.97	$2.89	$692418.02	$0.14	$34620.90
Feb	741	220,923	91.57	44.37	$3.05	$674632.57	$0.15	$33731.63
Mar	1183	312,880	93.96	35.55	$2.69	$841647.20	$0.13	$42082.36
April	1196	389,957	92.5	36	$2.59	$1008038.85	$0.13	$50401.94
Min.	403	134,140	91.57	30.2	$2.35	$333765.99	$0.12	$16688.30
Ave.	894	291,379	94.64	43.37	$2.71	$776326.26	$0.14	$38816.31
Max	1244	488,983	98.54	53.7	$3.11	$1219034.62	$0.16	$60951.73
Total		3,496,547				$9315915.08		$465795.75

Table 2. Gas historical consumption per ton of broccoli (annual).

Months	t/day	t/month	L gas LP/T	MXN	USD
Nov	20	300	25	$82950.00	$4147.50
Dec	20	500	25	$138250.00	$6912.50
Jan	20	520	25	$143780.00	$7189.00
Febr	20	480	25	$132720.00	$6636.00
Mar	20	520	25	$143780.00	$7189.00
April	20	520	25	$143780.00	$7189.00
May	20	500	25	$138250.00	$6912.50
Jun	20	300	25	$82950.00	$4147.50
		Total cost		$1006460.00	$50323.00

Based on knowledge of consumption and costs, sustainable strategies will be proposed to increase the plant's energy efficiency by implementing power generation technologies, leveraging available resources to reduce energy bills over time. Process analysis revealed that broccoli and mango processing generates a large amount of organic waste, which can be used to produce biogas and harness it to supply part of the plant's consumption, generating electricity through the use of a motor-generator. Due to the plant's location, solar resources are available; therefore, photovoltaic generation and water preheating for steam generation are also feasible.

2.1. Biogas Production for Engine-Generator

Broccoli processing generates a large amount of organic waste; around 50% of the product is discarded in the form of stems, leaves, and vegetable grits. The 50% fraction of broccoli residues was established based on an operational relationship reported by Eng. Ramón Romero Campos, Head of the Plant, during the field data collection. According to the plant's operating conditions, approximately 40 t of broccoli is processed per day. Of this amount, approximately 20 t corresponds to the usable finished product (florets), while the remaining 20 t consists mainly of stems and leaves, which are considered residual biomass. Therefore, a 50% residue fraction was used to estimate the available feedstock for biogas production. Since broccoli processing depends on seasonal raw material availability, the estimated 20 t/day of residual biomass represents the availability during peak production periods and was not assumed to be continuously available throughout the year.

Similarly, mango processing generates 46% of waste in the form of stems and pits. It should be noted that the processing of these foods is seasonal, so the waste is not constant throughout the year. To estimate biogas generation, literature on the production potential of the respective waste will be reviewed to understand technical aspects such as organic matter processing, retention days, volume of biogas obtained per kg of waste, and percentage of methane in the biogas [5]. In the case of broccoli, anaerobically digested, 22 L can be produced per kg of plant material with a retention time of 18 to 20 days using a 2:1 ratio, *i.e.*, two parts broccoli to one-part water at room temperature with a minimum methane quality of 55% in the biogas and a PC = 15,350 kJ/kg [2]. For mango waste, anaerobically digested, 7.5 ml of biogas per gram of substrate are obtained with a retention time of 29 days using a 1:1 ratio at room temperature, with an elemental analysis of 43% = C, 6% = H, and 0.6% = N. Using a stoichiometric ratio, this yields a methane quality of 26.6% and a PC = 6300 kJ/kg [3]. Using the information obtained, biogas production will be estimated in each case, taking into account the amount of waste generated. Using the volume of biogas obtained, the biodigester and the engine-generator suitable for utilizing the fuel supply will be sized, and the energy generated will be calculated to meet the energy demand. Once the energy produced is obtained, the savings will be graphed and quantified using the average kWh cost in the tariff schedule during the hours the power will be on, as well as the investment cost and return on investment.

Operational Assumptions of the Biogas System

The biodigester start-up is considered using cattle manure from an operating biodigester as inoculum, occupying 20% of the useful working volume, while the remaining volume is initially completed with water [6]. Subsequently, the biodigester is fed daily with broccoli waste and water at a 2:1. From the first day of broccoli feeding, a retention time of 20 days is considered before biogas production is available for use.

The reference used for broccoli digestion does not report an additional biogas filtration process; therefore, no specific gas-cleaning stage was included in the present proposal. The selected motor-generator is sized to consume the volume of biogas produced daily, so no long-term gas storage is considered under normal operation.

The digestate resulting from anaerobic digestion is considered suitable for subsequent use as an organic soil amendment in agricultural land. Electricity generation is planned to complement the plant's electricity consumption during the hours with the highest electricity cost. Since the plant does not operate on Sundays, this day is considered suitable for preventive maintenance of the motor-generator. In addition, during periods in which the biodigester is not producing biogas due to the absence of broccoli waste, general maintenance of the biodigester can be performed.

2.2. Power Generation Using a Photovoltaic System

To calculate the photovoltaic sizing, the average daily energy consumption (kWh/day), the power of the selected panel, the system efficiency, and the available peak solar hours in the region will be considered to quantify the number of photovoltaic modules required [7]. Various factors will be considered, such as the available area (5000 m^2), coordinates and orientation (19˚58'09"N 102˚17'34"W). The module selected for the system is a 660 W "Vertex monocrystalline" module with an efficiency of 21.6%, a height of 2.38 m, and a width of 1.30 m. Considering the module dimensions, the appropriate quantity for the available area will be proposed, and the ideal distribution will be simulated to prevent the modules from being shaded and the system's efficiency from decreasing. Using the number of modules and HSPs available throughout the year, the daily, monthly, and annual power generated will be calculated, and the inverter(s) for the system will be selected. Knowing all this data, the investment cost of the system will be estimated, considering modules, panel structure, wiring, and labor. Savings will be calculated based on the energy generated and graphed by comparing annual consumption and annual generation. The return on investment will be determined based on the investment cost and savings.

2.3. Preheating Water

LP gas fuel consumption is 500 L on an ideal work day, processing 20 tons of broccoli in a 16-hour workday. The boiler operates at 1205 HP = 898 kW with water supply at 22˚C and steam output at 134˚C for 17 hours. The daily water volume requirement can be calculated using data obtained from the boiler, where the volumetric flow rate can be easily obtained, and the total daily water volume can be estimated using the operating hours.

The fuel cost per ton of production per day, month, and year will be estimated. In this case, energy will be analyzed in terms of heat Q = kJ, where the energy supplied by the LP gas to heat the water from 22˚C to 134˚C will be calculated. The energy input for preheating using solar collectors, where the water temperature reaches 90˚C, will also be determined. Knowing the volume of water and the region's irradiation = 5.76 kWh/m^2 [4], the preheating system can be sized, therefore suitable equipment will be selected and the investment cost will be determined. Knowing the heat supplied by the solar heater, the equivalence in liters of LP Gas will be calculated. With these equivalent liters and considering the cost of LP Gas, the savings generated by preheating can be calculated. Finally, the return on investment will be estimated and the heat supply in both cases will be graphed.

3. Calculations and Results

3.1. Biogas Production for Engine-Generator

Biogas production from mango waste is ruled out due to the low methane content. For biodigester dimensions, the volume is calculated using the kilograms of broccoli waste and its water ratio (2:1) over the retention days.

$$kg_{substratum} = kg_{waste} + \left(L_{Water} * \rho_{Water}\right)$$

$$kg_{Total} = kg_{mix} * 20 \text{ days}$$

$$L_{Total} = kg_{Total} * 1\,\text{L}/1\,\text{kg}$$

According to the literature, the amount of Biogas per day and per month is calculated depending on the amount of waste after the first 20 days of retention.

$$L_{Biogas/day} = kg_{waste} * \left(22\,\text{L}/1\,\text{kg}\right)$$

$$L_{biogas/month} = kg_{waste} * \left(22\,\text{L}\right)/1\,\text{kg} * Days_{month}$$

$$m^3_{biogas} = 1000\,\text{L}$$

For the selection of the biodigester, the total volume of the mixture during the 20 days of retention is considered, as can be seen in Table 3.

Table 3. Mixing volume to Biodigestor sizing (20 days of retention).

Days	Month	kg_{waste} waste kg/day	kg water	kg_{Total} kg Total	$L_{Biogas/day}$ m³ day	$L_{biogas/month}$ m³ Total
15	Nov	20,000	10,000	30000	30	600
25	Dec	20,000	10,000	30000	30	600
26	Jan	20,000	10,000	30000	30	600
24	Feb	20,000	10,000	30000	30	600
26	Mar	20,000	10,000	30000	30	600
26	Apr	20,000	10,000	30000	30	600
25	May	20,000	10,000	30000	30	600
15	Jun	20,000	10,000	30000	30	600

A continuous flow biodigester from JINGCHENG WEIYE company with a capacity of 650 m^3 was selected.

With the available volume of biogas, its Heat Value (HV) = 15,350 kJ/kg, its density = 1.57 kg/m^3, working hours, and 25% efficiency of a biogas engine, the potential for electrical generation will be obtained to then choose the engine-generator that adapts to the fuel supply.

$$HV_{m^3} = HV * \rho = 24{,}099.5\ \mathrm{kJ/m^3}$$

$$Power_{electric} = HV * \dot{m} * \eta_{engine}$$

$$\dot{m} = \left(24099.5\frac{\mathrm{kJ}}{\mathrm{m^3}}\right)(0.25)\left(70\frac{\mathrm{kJ}}{\mathrm{s}}\right) = 0.01166\frac{\mathrm{m^3}}{\mathrm{s}}$$

$$Supply = Power_{electric} * \frac{h}{day} * \frac{day}{month}$$

Knowing the generation potential, a motor-generator is proposed that meets the daily fuel supply capacity, thus determining the engine's operating hours and the energy generated at rated power. Motor-generator selection. Model TG7.IDG 70 kW, 15-year life. All this is done with the help of the engine's technical data.

The generator motor requires a supply of 0.6 m^3/kWh, so that it works at its nominal power of 70 kW (Figure 3), considering the volume of biogas produced per day to know how long it is able to keep the motor running and how much energy it generates (Table 4).

$$h_{supply} = \frac{m^3_{day}}{0.6\ \mathrm{m^3} * 70\ \mathrm{kWh}}$$

$$Energy_{generated} = h_{supply} * 70\ \mathrm{kW}$$

To calculate the savings, the average cost of kWh is calculated in the GDMTH tariff scheme (Table 5) and the schedule that the engine-generator is intended to be kept on, which is from 11:30 am to 10:00 pm.

Parameters and Supply Details for 70kW Biogas Generator

Parameters	3 Phase 50Hz 220/380V or 60Hz 110/220V
Engine Basic Parameters	
Model	TG7.1GD
Continuous Power/Speed	85kW/1500rpm
Method	Turbocharged and Intercooled of Aspiration/Cooling
Gas Consumption	0.6 m^3/kWh
Starting Method	24V Electric Start
Alternator Basic Parameters	
Brand	Stamford
Type	Brushless, 100% Copper Wiring Stator and Rotor
Varnished Copper Wires (Times/Layers)	3 Times/Layers
Nominal Output Power	70kW
Voltage Regulation Method	Automatic Adjustment by AVR
Protection Class/Insulation Class	IP21 / H

Figure 3. Parameters and supply details for 70 kW Biogas Generator.

Table 4. Electric generation with biogas.

Month	Consumption (kWh)	Generation (kWh)	Saving (MXN)	(USD)
May-2024	320,055	18333.33	$38357.00	$1917.85
Jun-2024	406,332	11000.00	$23014.20	$1150.71
Jul-2024	488,983	0.00	0.00	0.00
Aug-2024	438,422	0.00	0.00	0.00
Sep-2024	228,279	0.00	0.00	0.00
Oct-2024	141,847	0.00	0.00	0.00
Nov-2024	134,140	11000.00	$23014.20	$1150.71
Dec-2024	175,254	18333.33	$38357.00	$1917.85
Jan-2025	239,475	19066.67	$39891.28	$1994.56
Feb-2025	220,923	17600.00	$36822.72	$1841.14
Mar-2025	312,880	19066.67	$39891.28	$1994.56
Apr-2025	389,957	19066.67	$39891.28	$1994.56
Annual		133466.67	$279238.96	$13961.94

The economic savings from biogas electricity generation were calculated according to the GDMTH tariff periods corresponding to the proposed operating schedule of the motor-generator. From Monday to Friday, 6.48 h/day of generation corresponds to the intermediate period at a cost of $2.006 MXN/kWh and 4 h/day to the peak period at $2.253 MXN/kWh, considering 155 operating days. On Saturdays, 8.48 h/day corresponds to the intermediate period and 2 h/day to the peak period, considering 32 operating days. Based on the 70 kW generator capacity, the weighted calculation results in an equivalent electricity cost of approximately $2.0922 MXN/kWh. Therefore, this value represents the weighted cost of the electricity displaced during the actual generation periods rather than a general average electricity tariff.

Table 5. Average cost per kWh during electricity generation hours.

$ Cost per kWh (GDMTH)											
	Monday - Friday 113708 kWh/day					Saturday 23475.2 kWh/day					
Fee	Hours	Cost (MXN/USD)	kW	Days	Cost (MXN/USD)	Hours	Cost (MXN/USD)	kW	Days	Cost (MXN/USD)	
Intermediate	6.48	$2.006/$0.100	70	155	$141037.85/$7051.89	8.48	$2.006/$0.1003	70	32	$38104.37/$1905.22	
Tip	4	$2.253/$0.113	70	155	$97780.2/$4889.01	2	$2.253/$0.1127	70	32	$10093.44/$504.67	
				Total	238818.048/$11940.902				Total	$48197.81/$2409.89	
	Generation Total (kWh)				Total Cost (MXN/USD)					Average $/kW h (MXN/USD)	
	113708				$238818.048/$11940.902					$2.0922/$0.1046	
	23475.20				$48197.8112/$2409.891						
Addition	137183.20				$287015.8592/$14350.793						

Figure 4 shows the energy that can be generated by the biogas engine generator compared to the total energy consumption during the year. Knowing the savings and investment cost (Table 6) allows to estimate the return on investment and the economic benefit over time.

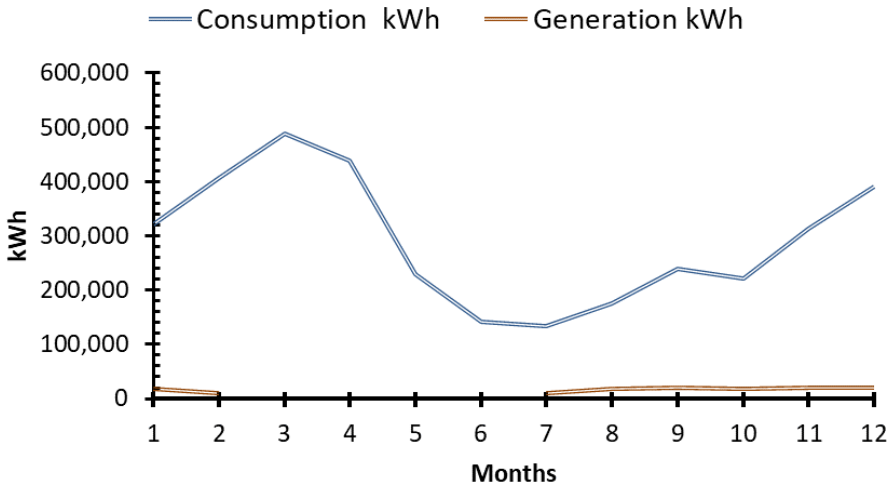


Figure 4. Consumption vs. electricity generation with biogas.

Table 6. Biogas engine generator investment costs.

Component	Unit Cost (MXN/USD)	Quantity	Subtotal (MXN/USD)
Biodigester 650 m^3	\$620,000/\$31,000	1	\$620,000/\$31,000
Motor-generator 70 kW	\$150,000/\$7500	1	\$150,000/\$7500
Engineering and Installation	\$500,000/\$25,000	1	\$500,000/\$25,000
Shipment	\$130,000/\$6500	1	\$130,000/\$6500
Accessories	\$100,000/\$5000	1	\$100,000/\$5000
TOTAL			\$1,500,000/\$75,000

$$Payback = \frac{Inverment}{Anual\ savings} = \frac{\$1500000(\$75000.00)}{\$279238.96(\$13961.95)} = 5.3 \text{ years}$$

Sensitivity Analysis

The biogas production proposal was evaluated considering the main parameters involved in the calculation. The available data establish a biogas yield of 22 L/kg of broccoli waste, with a minimum methane content of 55% and a retention time of 18 - 20 days. For the design calculations, a retention time of 20 days was adopted.

The system considers 20,000 kg/day of broccoli waste mixed with 10,000 kg/day of water, resulting in a daily mixture volume of approximately 30 m^3. With a 20-day retention time, the required volume is 600 m^3, for which a 650 m^3 continuous-flow biodigester was selected.

For electricity generation, 25% generator efficiency was considered. The proposed 70 kW motor-generator requires approximately 0.6 m^3 of biogas per kWh generated.

The number of operating days varies according to broccoli availability, with the available records considering 15 days in November, 25 in December, 26 in January, 24 in February, 26 in March, 26 in April, 25 in May, and 15 in June. Therefore, annual biogas and electricity production are directly conditioned by the seasonal availability of broccoli waste and the actual operating days of the plant.

3.2. Photovoltaic Sizing

The sizing was based on the average daily energy consumption, Peak Sun Hours (PSH), power of the selected panel, and system efficiency. According to the guidance, the efficiency drops to 85%. Various estimates were made using minimum, average, and maximum consumption to determine the number of modules needed (Table 7) to cover the energy supply in each case (Table 8), and these were graphed along with the annual consumption (Figure 5).

$$Paneles = \frac{Consumo\ \text{kWh/dia}}{\eta_{sistema} * Pot._{panel} * HSP}$$

Table 7. Number of panel.

	660 W			
	PSH	**kWh month**	**kWh day**	**# Panels**
Min	4.71	134,140	4471.33	1692.21
Intermediate	5.692	291,379	9712.63	3041.65
Max	7.42	488,983	16299.43	3915.67

$$Generation_{panels} = \eta_{sistem} * Pawer._{panel} * Num._{panels} * PSH$$

Table 8. Simulated photovoltaic generation for a typical local year.

Month	Min kWh/month	Intermediate kWh/month	Max kWh/month
Jan	168,344	302,483	389,290
Feb	188,267	338,281	435,361
Mar	237,276	426,339	548,691
Apr	248,729	446,918	575,176
May	242,125	435,053	559,905
Jun	195,430	351,150	451,924
Jul	187,049	336,092	432,545
Aug	186,357	334,848	430,943
Sep	166,266	298,749	384,484
Oct	186,357	334,848	430,943
Nov	170,959	307,181	395,337
Dec	163,149	293,147	377,275

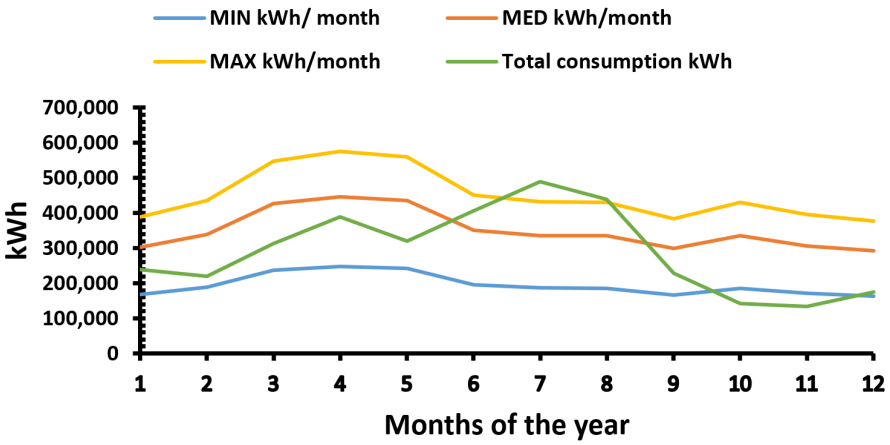


Figure 5. Total consumption vs. photovoltaic generation: minimum, average, maximum.

For a real sizing, important factors were taken into account such as the available and optimal area for the installation of the system, in this case 100 m × 50 m, the dimensions of the photovoltaic module with a height of 2.38 m and 1.30 m wide and the optimal distance between panel sheets to avoid shadows and guarantee the efficiency of the system. The sizing for the optimal distribution of the panels was carried out with the help of the PVsyst software [8] that simulates the solar path as can be seen in Figure 6 and Figure 7, while the resulting monthly percentage values are compiled in Table 9.

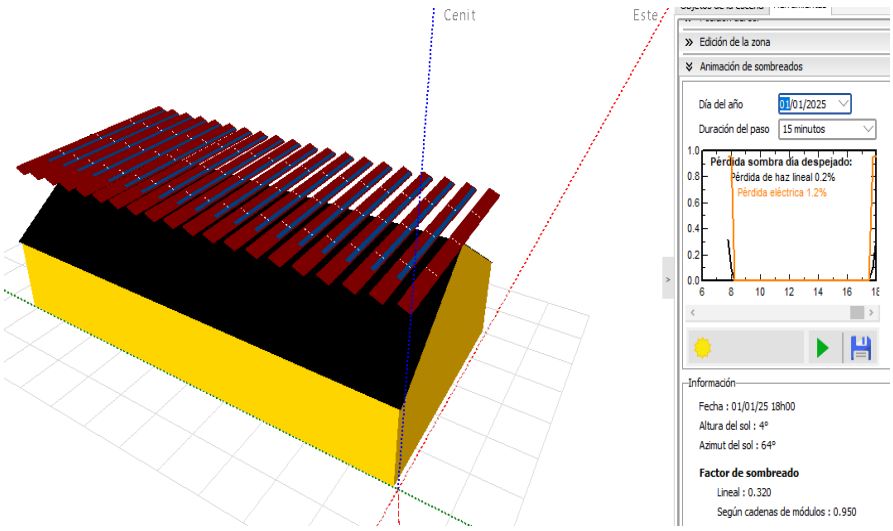


Figure 6. Dimension and simulation (software PVsyst) [8].

The electricity generated from biogas is intended for on-site consumption during plant operation. As shown in Figure 6, the monthly electricity generation from biogas remains below the plant's electricity consumption; therefore, no electricity export to the grid or generation curtailment is considered in the proposed operating scheme, integrated with the complete monthly photovoltaic yield performance detailed in Table 10.

Table 9. Efficiency losses due to shadows (Software PVsyst) [8].

Month	% losses
Jan	1.2
Feb	0.4
Mar	0
Apr	0
May	0
Jun	0
Jul	0
Aug	0
Sep	0
Oct	0
Nov	0.1
Dec	0.9

Table 10. Photovoltaic generation (PVsyst) [8].

962 modules						
Days		PSH	Generation (kWh)	Consumption total (kWh)	Cost $/kWh	Saving (MXN/USD)
31	Jan	4.86	76,525	239,475	$2.8914/$0.145	$221,266/$11,063
29	Feb	5.81	85,582	220,923	$3.0537/$0.153	$261,342/$13,067
31	Mar	6.85	107,860	312,880	$2.69/$0.135	$290,143/$14,507
30	Apr	7.42	113,066	389,957	$2.585/$0.129	$292,277/$14,614
31	May	6.99	110,064	320,055	$2.6798/$0.134	$294,951/$14,748
30	Jun	5.83	88,838	406,332	$2.5391/$0.127	$225,568/$11,278
31	Jul	5.4	85,028	488,983	$2.493/$0.125	$211,976/$10,599
31	Aug	5.38	84,713	438,422	$2.5433/$0.127	$215,452/$10,773
30	Sep	4.96	75,580	228,279	$2.741/$0.137	$207,167/$10,358
31	Oct	5.38	84,713	141,847	$2.353/$0.118	$199,331/$9967
30	Nov	5.1	77,714	134,140	$3.1088/$0.155	$241,597/$12,080
31	Dec	4.71	74,163	175,254	$2.8485/$0.142	$211,255/$10,563
Total Generation			**1,063,851**	**Saving per year**		**$2,872,329/$143,616**

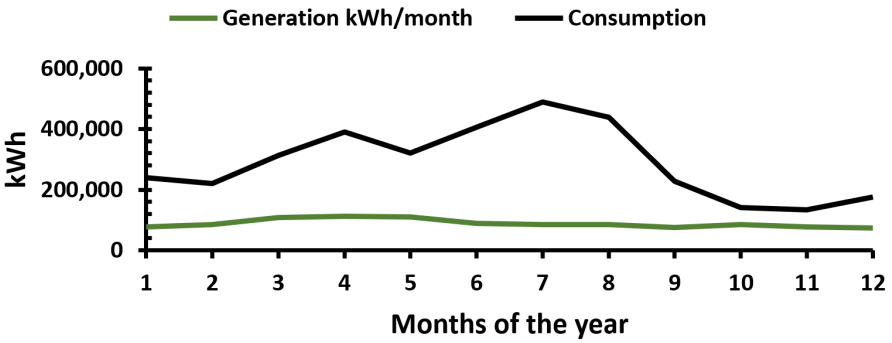


Figure 7. Photovoltaic generation (PVsyst) [8] vs. consumption.

For the investment cost of the photovoltaic system, 962 Vertex modules, model TSM-DE21 660 W, will be taken into account. The height is 2.50 m at the highest point and 0.3 m at the lowest point, therefore a manufactured aluminum structure is considered. To select the inverters, the installed power is taken into account, in this case 508 kW. Three inverters of 125 - 150 kW Mod. MAX 124 - 150KTL3 and one inverter of 50 - 70 kW Mod. MAC 50 - 70KTL3-X LV/MV; of the Growatt brand were selected. Another important part of the investment is the wiring used, cabinets, trays and/or pipes, accessories, connectors, switches, electrical protections and finally the cost of labor, which accounts for 30% of the total investment cost (Table 11). The lifespan of a high-efficiency photovoltaic system is approximately 25 years.

Table 11. Photovoltaic system investment costs.

Component	Quantity	Unit cost (MXN/USD)	Subtotal (MXN/USD)
Module	962	$4500/$225	$4,329,000/$216,450
Structure	962	$1300/$65	$1,250,600/$625,30
Inversor 150	3	$92,000/$4600	$276,000/$13,800
Inversor 50	1	$55,000/$2750	$55,000/$2750
Accessories		$600,000/$30,000	$600,000/$30,000
Labour		$1,953,180/$97,659	$1,953,180/$97,659
Total Investment			$8,463,780/$406,594

$$Payback = \frac{Investment}{Annual\ savings} = \frac{\$8463780}{\$2872329} = 2.95 \text{ years}$$

3.3. Water Preheating

The boiler operates at 1200 HP with a feedwater temperature of 22˚C and generates steam at 134˚C, which is supplied directly to a water vat to maintain it at 95˚C and be used in the broccoli precooking process. To determine the heat supplied, the volume of water required during the day must be determined, considering that the boiler is fired for 17 hours, *i.e.*, 1 hour for the vat water to reach the ideal process temperature and 16 hours to maintain the water temperature (Table 12). The fuel consumption log records a consumption of 500 L of LP gas for a daily production of 20 tons of broccoli. Figure 8 shows the heat input of the preheating system compared to the current LP gas input. This calculation methodology was obtained from the book Solar Engineering of Thermal Processes [9] and standard solar thermal design fundamentals [10].

$$\dot{V}_{LPGas} = \frac{500\ \text{L}}{17\ \text{h}} = 29.41\ \text{L/h}$$

$$\dot{m}\ Production = \frac{20\ \text{t}}{16\ \text{h}} = 1.25 \frac{\text{t}}{\text{h}}$$

$$Consumtion_{Gas\ LP} = \frac{500\ \text{L}}{20\ \text{t}} = 25\ \text{L/t}$$

To know the volume of water needed during the day.

$$\dot{m}\ water_{Boiler} = \frac{\dot{Q}}{\Delta h} = \frac{1200HP\left(898\ \text{kW}\right)}{2735\frac{\text{kJ}}{\text{kg}} - 92\frac{\text{kJ}}{\text{kg}}} = 0.340\frac{\text{kg}}{\text{s}}$$

$$\dot{m}\ water_{day} = 0.340\frac{\text{kg}}{\text{s}} * \left(\frac{3600\ \text{s}}{1\ \text{h}}\right) * 17\frac{\text{h}}{\text{day}} = 20879.6\frac{\text{kg}}{\text{day}}$$

$$\dot{V}\ water_{day} = \frac{\dot{m}\ water_{day}}{\rho} = \left[20879.6\frac{\text{kg}}{\text{day}} \Big/ 997.8\frac{\text{kg}}{\text{m}^3}\right] * \frac{1000\ \text{L}}{1\ \text{m}^3} = 20925.6\frac{\text{L}}{\text{day}}$$

$$Consumtion_{water} = \frac{20925.6\ \text{L}}{20\ \text{t}} = 1046.28\ \text{L/t}$$

Thermal efficiency of the boiler is 85%, calorific value (HV) of LP gas equal to 46,000 kJ/kg and a liquid state density of 500 kg/m^3.

$$\dot{m}_{LPGas} = \left(29.41\frac{\text{L}}{\text{h}}\right) * \left(\frac{\text{m}^3}{1000\ \text{L}}\right) * \left(\frac{1\ \text{h}}{3600\ \text{s}}\right) * \left(\frac{500\ \text{kg}}{1\ \text{m}^3}\right) = 4.08\times10^{-3}\frac{\text{kg}}{\text{s}}$$

$$\dot{Q}fuel = \dot{m}_{LPGas} * HV_{LPGas} = \left(4.08\times10^{-3}\frac{\text{kg}}{\text{s}}\right) * \left(46000\frac{\text{kJ}}{\text{kg}}\right) = 354.58\ \text{kJ/s}$$

$$46000\frac{\text{kJ}}{\text{kg}} * \left(\frac{500\ \text{kg}}{1\ \text{m}^3}\right) * \left(\frac{\text{m}^3}{1000\ \text{L}}\right) = 23000\frac{\text{kJ}}{\text{L}}$$

$$\dot{V}_{LPGas} = \left(4.08\times10^{-3}\frac{\text{kg}}{\text{s}}\right) * \left(\frac{1\ \text{m}^3}{500\ \text{kg}}\right) * \left(\frac{1000\ \text{L}}{1\ \text{m}^3}\right) = 0.00816\ \text{L/s}$$

$$Qsupplied_{LPGas} = HV * L = \left(23000\frac{\text{kJ}}{\text{L}}\right) * \left(500\ \text{L}\right) = 11.5\times10^6\ \text{kJ}$$

Knowing the volume of water per day, it is possible to size the number of solar collectors to heat the water up to 90°C (Table 12).

$$\dot{Q}_{sun} = \dot{m} * Cp * \Delta T = \left(20879.6\frac{\text{kg}}{\text{day}}\right)\left(4.186\frac{\text{kJ}}{\text{kg}\cdot^{\circ}\text{C}}\right) * \left[\left(90-22\right)^{\circ}\text{C}\right] = 5943450.2\frac{\text{kJ}}{\text{day}}$$

To select the preheating system, the volume of water required for steam generation is taken into account; in this case, the volume is 20,925.6 L/day. A parabolic solar collector system was chosen. This calculation methodology was obtained from the book Solar Engineering of Thermal Processes [9]. The economic savings are shown in Table 12 and Figure 8.

$$\dot{Q} = 5943450.2\frac{\text{kJ}}{\text{day}}\left(\frac{1\ \text{kWh}}{3600\ \text{kJ}}\right) = 1651\frac{\text{kWh}}{\text{day}}$$

$$Area = \frac{\dot{Q}}{\eta * Irradiation} = \frac{1651\frac{\text{kWh}}{\text{day}}}{0.7 * 5.7\frac{\text{kWh}}{\frac{\text{m}^2}{\text{day}}}} = 413.78\ \text{m}^2$$

$$No.\ Solar\ Collectors = \frac{413.78\ \mathrm{m}^2}{15.3\ \mathrm{m}^2} = 27.04$$

$$\dot{Q}_{saved} = \dot{Q}_{LPGas} - \dot{Q}_{sun}$$

$$Economic\ Saving = \left(\frac{Q_{saved}}{HV\left[\frac{\mathrm{kJ}}{\mathrm{L}}\right]} \right) * \left(\frac{\$}{\mathrm{L}} \right)$$

Table 12. Heat supplied by solar preheating and LP gas.

Month	MJ gas LP	MJ solar collectors	MJ saving LP gas	Saving (MXN/USD)
Nov	172,500	89,152	83,348	$40079.52/$2003.68
Dec	287,500	148,586	138,914	$66799.51/$3339.47
Jan	299,000	154,530	144,470	$69471.23/$3473.04
Feb	276,000	142,643	133,357	$64127.32/$3205.89
Mar	299,000	154,530	144,470	$69471.23/$3473.04
Apr	299,000	154,530	144,470	$69471.23/$3473.04
May	287,500	148,586	138,914	$66799.51/$3339.47
Jun	172,500	89,152	83,348	$40079.52/$2003.68
Total	**2,093,000**	**1,081,708**	**1,011,291**	**$486299.06/$24311.31**

$$Savings = (486299.06/1006460) \times 100 = 48.32\%$$

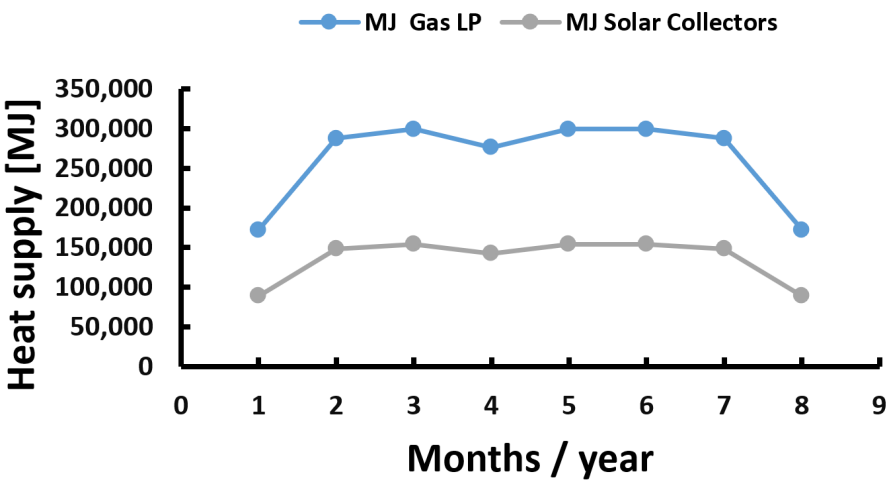


Figure 8. Heat supplied LP Gas vs. solar preheating heat.

Collectors of the brand "Shandong Gaia PT-30" with a useful life of 15 years and a 15,000 liters' storage tank with thermal insulation coating, were selected since the production day is 16 hours a day and water has to be stored for the hours when there is no solar radiation. With the savings generated by the preheating system and the investment cost (Table 13) the return on investment is estimated.

Table 13. Investment cost.

Component	Unit cost (MXN/USD)	Amount	Subtotal (MXN/USD)
Collector	$40,000/$2,000	27	$1,080,000/$54,000
Installation	$10,000/$500	27	$270,000/$13,500
Accessories	$15,000/$750	1	$15,000/$750
Tariffs	$200,000/$10,000	1	$200,000/$10,000
Shiping	$100,000/$5,000	1	$100,000/$5,000
Water tank	$200,000/$10,000	1	$200,000/$10,000
	Total Investment		**$1,865,000/$93,250**

$$Payback = \frac{Inversment}{Anual\ Savings} = \frac{1865000}{486299.06} = 3.84 \text{ years}$$

Considering the sum of the two proposals for electricity generation (Table 14), a significant part of the energy consumption can be satisfied, as we can see in Figure 9.

Table 14. Total generation with biogas and photovoltaic panels.

Month	Total consumption (kWh)	Biogas generation (kWh)	Ph generation (kWh)	Generation Ph + Biogas (kWh)
May	320,055	18,333	110,064	128,397
Jun	406,332	11,000	88,838	99,838
Jul	488,983	0.00	85,028	85,028
Aug	438,422	0.00	84,713	84,713
Sep	228,279	0.00	75,580	75,580
Oct	141,847	0.00	84,713	84,713
Nov	134,140	11,000	77,714	88,714
Dec	175,254	18,333	74,163	92,496
Jan	239,475	19,066	76,525	95,591
Feb	220,923	17,600	85,582	103,182
Mar	312,880	19,066	107,860	126,926
April	389,957	19,066	113,066	132,132
Total	**3,496,547**	**133,464**	**1,063,846**	**1,197,310**

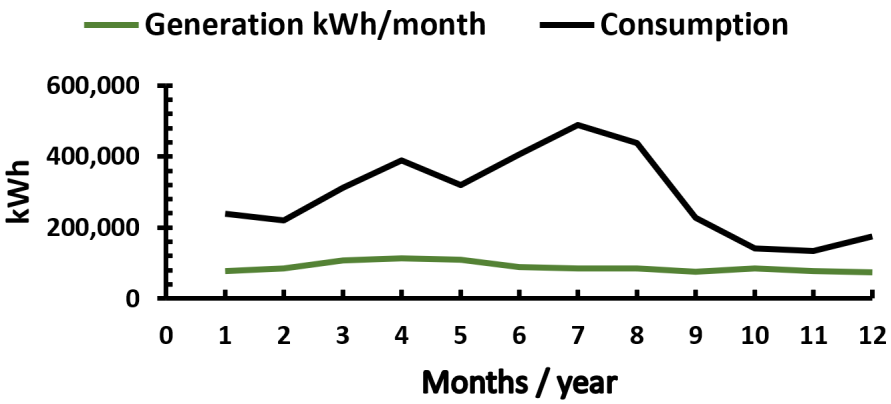


Figure 9. Consumption *vs.* total generation.

4. Conclusion

Biogas production from broccoli waste is viable and represents an alternative source of electricity, with the potential to reduce grid electricity consumption. The use of mango waste was ruled out due to its low methane content. The proposed photovoltaic system, with 962 modules, covers a significant portion of the plant's annual electricity consumption. Its installation represents a high investment, but with a reasonable payback period and a lifespan of up to 25 years. Solar water preheating using parabolic trough collectors reduces LP gas consumption by raising the temperature of the boiler feedwater, thus decreasing thermal costs and improving the overall efficiency of the system. The integration of these technologies makes RÍO NUEVO a more competitive and environmentally responsible company by leveraging local resources and reducing its carbon footprint.

Author Contributions

Julio César Zarate Vega and Iván Vera-Romero: All sections of the article. José Martínez Reyes and Beatriz Martínez Pérez: Sections 2.1, 2.3 and 3.1 and 3.3. Agustina Ortiz Soriano and Ignacio Moreno Nava: Sections 1. and 2. Víctor Manuel Méndez Ábrego: Sections 2.2 and 3.2.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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