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Economic Feasibility of Biogas Microgeneration from Food Waste: Potential for Sustainable Energy in Northeastern Brazil

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Abstract: This study evaluates three scenarios' technical and economic viability for implementing a microgeneration power plant using biogas derived from the anaerobic digestion of food waste. The case study focuses on the Federal University of Pernambuco (UFPE) campus in Recife, northeastern (NE) Brazil, targeting the organic fraction of solid waste from food units (restaurants, canteens, and kiosks). The analysis was based on field data, the chemical composition of the waste, and the electric energy consumption. Biogas production of 166 m^3/day from 1 ton/day of food waste was estimated using an anaerobic reactor of 126 m^3. This amount of biogas could generate about 360 kWh/day of electricity if the plant operates at peak hours using a generator set with an alternative internal combustion engine of 120 kW, with a consumption of 66 m^3/h and fuel efficiency of 30%. The system could generate 390 kWh/day of electrical energy using a microturbine, with a consumption of 78 m^3/h and 30% efficiency. The scenario utilizing a tubular reactor and an internal combustion engine demonstrated the best economic viability. While this study focuses on financial aspects, the findings suggest significant potential contributions to sustainability, including reducing greenhouse gas (GHG) emissions and advancing renewable energy solutions. This model can be adapted for small NE Brazil municipalities, offering economic and environmental benefits.

Keywords: biogas microgeneration; economic feasibility; anaerobic digestion; internal combustion engine; sustainable cities; food waste management

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1. Introduction

Waste management has become one of the main problems of modern society due to a growing urban population and changing household consumption patterns. The total municipal solid waste (MSW) generated worldwide is around 2 billion tons annually [1]. Much of this waste has an inadequate destination, contributing to environmental degradation and the emission of greenhouse gasses. It is estimated that 1 ton of urban solid waste with 60% organic matter and 40% humidity, disposed of in landfills, can theoretically generate 200 Nm^3 of methane [2]. According to the National Solid Waste Survey in Brazil, in 2017, the generation of MSW was approximately 78.4 million tons, a growth of 1.0% compared to 2016. Of this total, 71.6 million tons were collected, but only 59.1% was allocated adequately in landfills. The remaining 40.9% was disposed of inadequately on non-controlled sites [3].

Similarly, Brazil faces significant challenges in this area. There are still substantial challenges regarding waste management in Brazil, ranging from environmental education, generation reduction, segregation, and transportation logistics to developing technologies adapted to each location's scales and socioeconomic conditions. The National Solid Waste Policy (PNRS) (Law 12.305/2010) outlines the guidelines for the proper management of MSW in Brazil. Among other things, the law stipulates the energy recovery requirement of organic waste.

In this context, public educational institutions, such as the Federal University of Pernambuco (UFPE), decided to implement a waste management system on the campus in Recife, where more than 30 thousand people circulate daily. The idea is to create a "Model City" in the theme, which will serve as a focal point to demonstrate and stimulate the adequate management of MSW in the cities of the northeastern region of Brazil. The main types of waste produced on the campus of the UFPE (as in most municipalities in Brazil) are the residual biomass from sweeping, weeding, and pruning services of parks and gardens, as well as the organic fraction of solid waste (OFMSW) from buildings, mainly food waste from the restaurants, which is the focus of the present paper. Other types of waste, such as recyclable (paper, cardboard, plastic, metal, glass, and various other materials) and non-organic waste (construction waste, electro-electronic waste, and unserviceable furniture), will not be discussed in the present paper.

One of the most feasible technologies to process food waste is anaerobic digestion (AD), where the organic matter is decomposed by the action of microorganisms in the absence of oxygen, generating biogas. This mixture includes CH_4 and CO_2 and traces of other gasses such as hydrogen, hydrogen sulfide, and water vapor. The liquid effluent generated during the digestion process is rich in nutrients, such as N, P, K, and Ca, and serves as high-quality organic fertilizer [4].

Biogas has been used for a long time in many parts of the world for thermal and electrical energy generation. The most widely used systems for generating electricity from biogas are based on primary switches with electrical efficiency between 22 and 33%, such as microturbines and internal combustion engines [5]. Also noteworthy are combined electric power generation and thermal energy systems for small and medium installed capacities [6]. However, technical and economic feasibility studies still need to be made available for electricity generation from food waste in the context of residual biomass management in Brazil and other developing countries.

Su et al. [7] conducted a techno-economic analysis of an industrial composting plant for food waste, which did not include biogas production. Oliveira et al. [8] analyzed energy generation from a biogas plant, carrying out stochastic economic analyses for a single technology and for organic waste from cassava processing.

Focusing on biogas generation and food waste, Nketiah et al. [9] analyzed the potential for energy generation and greenhouse gas (GHG) mitigation using data from a Chinese province. Still, only one biodigester model was observed, and the economic analysis was simplified. Hossain et al. [10] focused on generating heat and electricity with a more robust financial analysis, but only one biodigestion technology was considered. In turn, the study by Cudjoe et al. [11], carried out using data from Ghana, was similar to the proposal in this study, as it looked at the economic viability of producing electricity from biogas. The authors used classic financial evaluation metrics and presented a sensitivity analysis but did not consider different technologies in the biodigestion process, which should be explored.

As noted, several factors may affect the feasibility of a system for the microgeneration of electricity from food waste. For instance, there are different types of reactors, other conditions for operation (e.g., the volume of solids, organic loading rate, hydraulic retention time, temperature, pH, etc.), and other technologies for electricity generation (e.g., microturbine, internal combustion engine) [1]. The success in adopting a combination of these variables will change by location and period. So, a detailed study is needed to guide these decisions. Furthermore, it is important to highlight that less than

1.0% of Brazil's electricity demand is currently met with biogas production technology from urban solid waste [12], demonstrating immense growth potential.

Thus, the present study aims to evaluate the feasibility of implementing a microgeneration plant using biogas from food waste by addressing the technical and economic aspects of a case study on the campus of the UFPE in Recife, northeast Brazil. Three scenarios were chosen based on the different technologies of anaerobic digesters and the power generation equipment available on a small scale. The scenarios evaluated were: (1) a Chinese-type digester (fiberglass tank) and a generator set with an internal combustion engine, (2) a tubular digester and a generator with an internal combustion engine, and (3) a tubular digester and a gas microturbine. Finally, the economic analysis of the project was developed to determine the most appropriate setting.

In addition to presenting unpublished data for the Brazilian scenario, this article includes economic analysis for more than one biogas production and electricity generation technology. A sensitivity analysis was also used to consider different tariffs, operation during peak and off-peak hours, and operation only during off-peak hours.

Implementing biogas-based microgeneration systems aligns with global efforts to achieve sustainability by addressing critical challenges such as waste management, energy security, and climate change mitigation. By converting organic waste into renewable energy, such systems reduce reliance on fossil fuels, decrease greenhouse gas (GHG) emissions, and promote circular economy principles. Furthermore, they contribute to the United Nations' Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy), Goal 11 (Sustainable Cities and Communities), and Goal 13 (Climate Action). This study highlights the economic feasibility of these technologies and their potential to foster sustainable development in resource-constrained regions like northeastern Brazil.

2. Materials and Method

2.1. Waste Generation and Energy Use Characteristics at the UFPE Campus

This study focused on the organic fraction of solid waste from buildings, specifically those from the food units (restaurants, canteens, and kiosks) installed in the Federal University of Pernambuco-Recife campus. The university is located in northeastern Brazil, 8°04′03″ S, 34°55′0″ W, and at an average altitude of four meters above sea level. The campus serves about 30,000 people, including students, faculty, and staff.

On campus, 13 food service units with contracts managed by the University Environmental Management Unit were identified. These units vary significantly regarding the type and quantity of food products sold daily. The main food waste generator is the University Restaurant, which serves over 3000 meals per day. In each of the food units, a waste separation system was established, dividing it into "recyclables", "waste", and "organic". All residues were weighed daily during the study period, and the University Environmental Management Unit collected and analyzed the data. The food waste, the object of this study, had an average of nearly 1 ton/day over the four months evaluated. Currently, the waste is being deposited in landfills at an average cost of transportation and final disposal of USD 54.62 per ton [13]. When extrapolated to one year, there is an annual cost of transportation and final disposal of USD 17,042.86 (considering 312 working days per year).

The proposed biogas digester will be installed at the Nuclear Energy Department (DEN), and the electricity generated will be provided to the university's facilities. The energy consumption of the whole area of the campus of UFPE averaged about 27,000 MWh/year during the five years previous to the date of the current research [13]. Moreover, the average annual consumption of DEN was about 481 MWh in the same period.

To better understand the proposed system's potential financial impact, the DEN energy costs were analyzed in detail. The university's Budget and Finance Department provided the university's energy bill data for nine months. In more detail, the energy consumption is divided into peak consumption (17:30 h to 20:30 h) and off-peak consumption (20:30 h to 17:30 h). On average, the cost of energy at peak hours is USD 0.64, while in the off-peak hours, it is USD 0.13. Like many regions in the world, this pricing system was established to discourage consumption at peak hours because it increases the complexity and cost of the operation of the electrical system. Based on the above, we observed that the average monthly consumption of DEN at peak hours, between 17:30 h and 20:30 h, was 2753 kWh, implying an average annual cost of USD 13,888.85. In the off-peak hours, the Department had an average of 35,840 kWh, corresponding to an average yearly cost of USD 29,955.76.

2.2. Design and Technical Criteria of the Electrical Energy Microgeneration System

Within the design process of the electrical energy microgeneration system, the following essential criteria were defined: characteristics and conditions of the region, operating parameters of the digester, and operating parameters of the equipment for power generation.

2.2.1. Operating Parameters of the Anaerobic Digester

The first step was to estimate the hydraulic retention time (HRT). Based on the information in the literature, the stable anaerobic digestion (AD) of food waste (FW) was usually attained for HRT ranging between 16 and 40 days [1]. Fiore et al. [14] and Wang et al. [15] carried out studies with food-processing industrial wastes and vegetable and kitchen wastes using 20 and 30 days as HRT and organic loading rates between 0.5 and 4.0 kg of volatile solid amount (VS)/m^3.d. Therefore, an HRT of 30 days was chosen in this work.

To estimate the digester volume, the HRT can be defined (HRT = $V_R/\dot{F}_S$) according to Equation (1):

$$V_R=\dot{F}_S\times \mathrm{HRT} \tag{1}$$

where V_R is the working volume of the digester (m^3); $\dot{F}_S$ is the volume of daily load (waste + water) (m^3/day); and HRT is hydraulic retention time (day).

To define the dilution ratio of the organic material to water, different findings have been observed in the literature. Evaluating organic waste digestion studies [16–18], a 40 m^3 stirred tubular digester with a 1:1 dilution ratio was adopted for this study.

Furthermore, it is essential to note that during the start-up of the digester, there is a need to add a certain amount of inoculum to accelerate the stabilization time of the organic material and to improve biogas production [19,20]. According to the literature, an ideal proportion of inoculum to substrate is a widely studied variable, and there is no concern about it. The ratio chosen in the present study was 15% of inoculum in total dry matter. Among the main types of inoculum that could be used are manure, sewage sludge, and gray water. In the present study, we chose cattle manure as the inoculum since it was easier to obtain at the study site.

The next step was the estimation of the methane production potential. The procedure was based on the methodology of Diaz et al. [21]. First, it requires a known volatile solid amount (VS) in the food waste that is charged daily. Subsequently, the average value of the potential methane yield (MET_{VS}) from food waste is estimated. Then, a production potential (P) from all the food waste generated on the campus of the UFPE is obtained according to Equation (2).

Numerous studies measure the methane yield from food waste. Differences in the chemical composition of the feedstock, particle size, temperature, type of mixing tool, and reactor configuration can explain such large ranges [22].

$$\mathrm{P} = MASS_{VS}\times MET_{VS} \tag{2}$$

where P is methane production daily (m^3/day); $MASS_{VS}$ is volatile solids mass of substrate (kgVS/day); and MET_{VS} is methane yield (m^3/kgVS).

2.2.2. Operating Parameters of the Power Generation Equipment

The power value of the electric power generation equipment can be estimated from the maximum load power consumption connected to it. For this, the maximum consumption presented at the DEN was observed according to the period the equipment will operate. Thus, according to the biogas potential, it was decided that the engine would run during peak hours (17:30 h to 20:30 h). Although the Department determines the maximum power consumption, it is essential to note that the engine generator must be sized with a 10% higher capacity of its power due to voltage fluctuations.

It is essential to know the fuel consumption to determine the efficiency with which the engine turns chemical energy into practical work [23]. Thus, with data on fuel consumption and engine power, the specific fuel consumption (SFC) can be calculated with the following equation:

$$\mathrm{SFC} = \frac{\mathrm{CR}_B}{P} \tag{3}$$

where SFC is specific fuel consumption (m^3/kWh); CR_B is the biogas consumption rate (m^3/h); P is active power (kW).

To estimate the biogas conversion efficiency in electrical energy, the following equation was used [23]:

$$\eta = \frac{P}{\mathrm{CR}_B * \mathrm{LCV}_R} \tag{4}$$

where η is engine–generator efficiency; P is active power (kW); CR_B is biogas consumption rate (m^3/h); and LCV_R is biogas lower calorific value (kWh/m^3).

2.3. Financial Analysis of the Project

For the financial evaluation of the project, some scenarios had previously been defined, mainly based on different types of reactors and different choices of electric generation equipment. The proposed scenarios were as follows:

- Scenario 1: Chinese-type digester (fiberglass tank) and a generator set with an internal combustion engine;
- Scenario 2: tubular digester and a generator with an internal combustion engine;
- Scenario 3: tubular digester and a gas microturbine.

To determine the general monetary values and the electricity tariffs over time, as well as the estimation of the profitability ratios, the time horizon, and three constant parameters were defined: the consumer price index (CPI), a growth rate for the electricity tariff, and a specific discount rate for the type of project that will be developed.

To estimate the cash flow, the values related to expenses and revenue of the project had been raised previously, transforming those values to future value as the determined horizon and according to the value of the CPI and the growth rate set for the electricity rates, as appropriate. A time horizon of 15 years was adopted. The following constant parameters were established (Table 1) to estimate the monetary values over time and the estimation of profitability ratios: the current CPI value for Brazil of 6.5%, a growth rate for electricity tariff of 13%, according to the average value of the annual electricity bill adjustments of the Energy Company of Pernambuco (CELPE), which occurred between 2001 and 2008 [24]. We also considered a discount rate of 12%, based on the current rate of the SELIC (Special System of Clearance and Custody), plus an additional 2% for the risks inherent in the project. Usually, in the Brazilian energy sector, this is the required return rate for the capital investment in new small-scale projects [24].

Regarding the base costs, the monthly average tariffs adopted for the electricity cost calculations were USD 0.64/kWh for peak hours and USD 0.13/kWh for off-peak hours, including an increase in the electricity tariff of 30%, according to the predictions of experts [25]; this value was adopted for year zero, and in the subsequent years, it was considered the average increase defined previously for the electricity tariff (13%).

It was confirmed that the current electricity consumption of the UFPE during the January–September period had an average monthly value of will have an average annual value of USD 21,247.51. Likewise, at off-peak hours, the monthly average value was 35,840.92 kWh, and the average annual value was USD 55,959.80. With these values, the average yearly costs of peak and off-peak hours could be determined, and finally, the total base energy cost was calculated, with a resulting value of USD 77,207.31. On the other hand, the annual cost for the transportation of food waste to landfill, according to the cost per ton and the potential daily waste, was USD 17,042.86. Thus, the total value of the base costs was USD 94,250.17, as detailed in Table 1.

Table 1. Base costs associated with the implementation of an anaerobic digestion unit to process food waste and generate electrical energy.

Base Costs	
Electricity Tariff (Average)—Peak Hours	USD 0.64
Electrical Energy Consumption (Average)	2753.17 kWh
Electricity tariff (Average)—Off-Peak Hours	USD 0.13
Electrical Energy Consumption (Average)—kWh	35,840.92 kWh
Total Base Costs—Energy	USD 77,207.31
Total Base Costs—Food Waste Transportation to Landfill	USD 17,042.86
Total Base Costs	USD 94,250.17

Regarding expenses, the initial investment was defined by checking the market cost of equipment that could be integrated into the system, either in published studies or directly with manufacturers and suppliers. These values included costs, fees, and transportation. The labor and civil work costs were also estimated for the initial implementation.

Besides that, other base costs that the UFPE assumes were also included, such as those current costs related to electricity consumption in buildings of DEN and the cost of transporting the food waste and disposing of it in landfills.

After that, the costs after the project implementation and commissioning were defined and included. Amongst them are electricity costs because of the discount on the electrical energy consumption costs of the plant's equipment and the monetary values of the energy generated by the plant compared to the energy base costs. Other remaining expenses, such as the costs of operation and maintenance, were also estimated, including operators' wages, inputs, equipment maintenance, and depreciation costs. Equipment depreciation was calculated based on the useful life of the assets [26,27] and the cost of each, using Equation (5) as the straight-line depreciation method.

$$\text{Depreciation} = \frac{\text{active cost}}{\text{useful life}} \tag{5}$$

The operating revenue was interpreted as the savings on the electricity rates after the project implementation, especially at peak hours when the cost is higher. In addition, the savings relative to the transportation costs of food waste to the landfill were considered, since these will be used as feedstock for the system. Likewise, the biofertilizer, the liquid effluent produced could be used in the parks and gardens of the UFPE campus, and the UFPE saves the money needed to purchase fertilizers. The cost of storing the biofertilizer was considered, disregarding other treatment costs and sales revenue. In the context of

UFPE, where there is a biorefinery (for more, see [28]), biofertilizers are used without pretreatment to optimize the composting process carried out in the same space.

It is important to note that the electrical energy microgeneration system proposed and developed in this work is not intended to have an acquisition of financial assets. It was designed to find an environmentally sound and viable economic solution to food waste management at the university restaurants, serving as a tangible example to small cities in Brazil.

When using a deterministic method, the calculations of the net present value (NPV), internal rate of return (IRR), capital recovery factor (discounted payback period—DPBP), and benefit–cost ratio (B/C) were conducted with the annual values obtained in the cash flow, according to the discount rate of 14%, and applying the formulas using a Microsoft Excel spreadsheet.

NPV uses the cash flows, composed of investment costs, operating costs and possible revenues linked to a given investment. These flows are discounted in time using a discount rate [29,30]. The NPV metric was calculated using Equation (6) [31]:

$$NPV = \sum_{t=1}^{n} \frac{FC_t}{(1+i)^t} - FC_o \tag{6}$$

where FC_t is the expected cash inflow or outflow value for each time interval *t*; FC_0 is the cash flow verified at the initial moment; *n* is the total number of periods–project horizon; *t* is the period in which the value occurs; and *i* is the discount rate [32].

The IRR metric, which is the discount rate that makes the revenue and expense amounts of a cash flow equivalent in present value (i.e., makes the NPV equal to 0), was calculated using Equation (7) [31,33]:

$$NPV = \sum\nolimits_{t=1}^{n} \frac{FC_t}{(1+IRR)^t} - FC_o = 0 \tag{7}$$

where FC_t is the expected cash inflow or outflow value for each time interval *t*; FC_0 is the cash flow verified at the initial moment; *n* is the total number of periods–project horizon; *t* is the period in which the value occurs; and *IRR* is the discount rate that equals outflows with inflows.

The DPBP was calculated using Equations (8) and (9). The first step in this method is to calculate all the present values of the cash inflows using the following equation [31,34]:

$$PV = \sum_{t=0}^{n} \frac{FC_t}{(1+i)^t} \tag{8}$$

where FC_t is expected cash inflow or outflow value for each time interval *t*; *n* is the total number of periods–project horizon; *t* the period in which the value occurs; and *i* the discount rate.

Subsequently, the sum of the project's future cash flows is observed until it ceases to be negative. Thus, the DPBP can finally be calculated using the following equation [31]:

$$DPBP = t^* + \frac{|PV_{t^*}|}{\left[\frac{FC_{t^*+1}}{(1+i)^{t^*+1}}\right]} \tag{9}$$

where t^* is the last period with a negative discounted cumulative cash flow (an integer in years); PV_{t^*} is the value of discounted cumulative cash flow at the end of the period t^*; FC_{t^*+1} is the cash flow during the period after t^*; and *i* is the discount rate.

The B/C indicator can be calculated using Equation (10) [33,35]:

$$B/C = \frac{PV_B}{PV_C} \tag{10}$$

where PV_B is the present value of benefits and PV_C is the present value of costs.

Finally, when using a non-deterministic method, the sensitivity analysis was carried out by changing the plant operating hours since this variable affects the system's profitability most because of the different electricity costs between peak and non-peak hours.

3. Results and Discussion

3.1. Design and Technical Criteria of the Electric Power Microgeneration System

The digester size was calculated based on the daily substrate amount added and the previously defined HRT (Table 2).

Table 2. Operating parameters of the anaerobic reactor to be implemented for the biodigestion of food waste.

Operating Parameters	
Volume of digester	126 m^3
Feed rate	2 ton/day
Hydraulic retention time	42 days
Operating temperature	30 °C
pH	6.8

Thus, the following data were obtained: (1) the daily potential of food waste, as established by the daily weighing on the campus of the UFPE, reaches nearly 1000 kg/day, and (2) the daily amount of water needed for the process, assuming the food waste is already crushed. It will be diluted in water in a ratio of 1:1 (*w*/*w*), with the density of water considered to be equal to 995.65 kg/m^3 [36] and a density of food waste considered to be equal to 897 kg/m^3 [37,38], and the daily loading will be 1004 m^3 of water and a 1115 m^3 of food waste. Therefore, with a loading volume ($\dot{F}_s$) of 2.119 m^3/day and an HRT of 30 days [14], according to Equation (1), the minimum working volume required for the digester will be 63.6 m^3.

Moreover, as already mentioned, during the startup of the digester, an amount of inoculum equivalent to 15% of the dry mass of the substrate will be added. Therefore, the initial amount of inoculum will be 300 kg. It is important to note that, in the case of food waste, it was not necessary to add chemical reagents in the pre-treatment stage [39], and only a physical treatment process was used. During the operation, there was also no acidification of the process, so no addition of reagents was necessary.

The estimation of the biogas production potential was determined based on a previous study run at a university, where the fresh food waste was characterized. An average food waste moisture content of 70.8% and a ratio between total and volatile solids (VS/TS) of 92.5% were found [40,41]. Thus, an average daily production of 1000 kg of waste has a TS amount of 292.0 kg and 270.1 kg of vs. per ton of fresh food waste.

Moreover, Kuczman et al. [42] studied the anaerobic digestion of food waste from a restaurant in Brazil, performed in a semi-continuous feeding system. According to these results, we chose the 0.44 m^3/kg VS value as the methane yield (MET_{VS}) from food waste in this study. Thus, the potential of the methane production (P) considered in this study, according to Equation (2), reaches 118.8 m^3/day. It is worth noting that Zhang et al. [43] confirmed that the methane content corresponds to 50–60% of the total content of biogas.

The power of the generation equipment was calculated based on data from DEN's electricity bill. It has been observed that DEN has two electricity meters, and with the data from each of their bills, we followed the total consumption and energy cost. The highest consumption at peak hours occurred in August, with a value of 3057.35 kWh. Thus, it was determined that the average amount of power consumed during peak hours that month was 139 kWh, assuming 21 working days.

According to the ANEEL Normative Resolution 482/2012 [44], focused on micro- and mini-distributed generation in Brazil, "when the generation is greater than consumption, the surplus of energy can be used to decrease the consumption rate elsewhere" in the UFPE or the subsequent monthly bill.

According to the above, equipment with higher power and fuel consumption must be chosen to take advantage of the full potential of power generation at peak hours. Thus, the selected engine generator set was a Fockink SG-150B model, with a rated power of 120 kW and consumption of 66 m^3/h. Regarding the gas microturbine, the manufacturer catalog has two units of the C65 model device with a power of 65 kW and a total consumption of 78 m^3/h. Still, this amount exceeds the threshold value of the contracted demand (165 kW) by the UFPE, so it could not be selected. Even so, it was considered in the following estimations and the economic analysis since it may be helpful in scenarios in small cities in Brazil.

Equation (4) calculated the specific fuel consumption, obtaining a 0.55 $m^3 \cdot kWh^{-1}$ value. In the case of the microturbine, the specific fuel consumption was 0.6 $m^3 \cdot kWh^{-1}$. The conversion efficiency of biogas into electrical energy was calculated with Equation (5), obtaining a value of 30% for the engine generator and 30% for the microturbine.

3.2. Economic Analysis of the Project

The economic analysis of the project was conducted according to each scenario selected, which considers the costs associated with each type of technology adopted and the time of operation. For each scenario, cash flows and profitability ratios were estimated to determine the viability of the proposed options.

To determine the value of the expenses, we defined the initial investment, the current base costs that assume the UFPE, and the remaining costs after the system implementation. Equipment costs were estimated according to the prices submitted by suppliers (Tables 3 and 4). The temperature control and agitation systems were not included in the estimation of the initial investment since they are not offered in the quote prices of the suppliers.

Table 3. Maintenance costs of the engine–generator set of an anaerobic digestion unit to process food waste and generate electrical energy.

Components	Interval	Quantity	Unit Cost	Total Cost	Annual Cost
Spark plug	300 h	6	USD 7.43	USD 44.61	USD 112.42
Spark plug cords	1000 h	6	USS 11.15	USD 66.91	USD 50.59
Lubricant oil	400 h	18	USD 6.69	USD 120.45	USD 227.64
Oil filter	400 h	1	USD 26.02	USD 26.02	USD 49.18
Engine overhaul	5000 h	1	USD 1858.74	USD 1858.74	USD 281.04
Total cost					USD 720.87

Table 4. Costs of preventive maintenance of the microturbine of an anaerobic digestion unit to process food waste and generate electrical energy.

Components	Interval	Total Cost	Annual Cost
Air filter	8000 h	USD 202.30	USD 19.12
Fuel inlet filter (internal gas system)	20,000 h	USD 1927.30	USD 72.85
Fuel inlet filter (external)	8000 h	USD 1963.46	USD 185.55

Igniter (gas system)	20,000 h	USD 623.08	USD 23.55
Set of injectors (gas system)	20,000 h	USD 1921.15	USD 72.62
TET thermocouple (gas system)	20,000 h	USD 470.38	USD 17.78
Total cost			USD 391.45

Regarding the generator set, the Fockink supplier offers the power generation system and other devices included in the quoted prices, such as the compressor, interconnection hoses, washing and decanting filter, and biogas reservoir. Furthermore, the labor costs for installation and the cost of using a backhoe were supplied by the administration of UFPE.

Then, the remaining costs after the implementation and commissioning of the project were defined, including the remaining costs of energy, the costs of O&M, and the costs of equipment depreciation. The remaining electrical energy costs were estimated by discounting the energy consumption costs by the equipment and the price of energy generated by the plant from the previously defined energy base costs.

The annual electricity consumption by the food waste crusher and the pump for extraction and agitation equipment were added to the calculation, assuming that the crusher would operate at peak hours and the compressor in the off-peak hours. Thus, the consumption in scenarios 1 and 2 was 2828.75 kW. However, in the case of scenario 3, the consumption was 7690.55 kW because the compressor for the microturbine will have a higher power. Therefore, the energy consumption costs of the plant were USD 348.38 for scenarios 1 and 2 and USD 3872.73 for scenario 3.

Concerning the energy generated by the project, in the case of the internal combustion engine, 124,830 kW per year could be generated, which implies a monetary value of USD 90,490.15. Moreover, 135,780 kW could be generated using the microturbine with an economic value of USD 98,427.88. Finally, the remaining energy costs for scenarios 1 and 2 were estimated to be USD 14,229.59 and USD 18,642.97 for scenario 3. It may be noted that the Department of Nuclear Energy's energy costs would be covered entirely by the energy generated by biogas.

Moreover, we also estimated the operating costs, the costs of staff salaries, and the cost of water and inoculum acquisition. The system operation would need the presence of two operators. The first is a handyman, responsible for the reception of food waste, mixing and preparing the substrate, loading the digester, and the overall cleanliness of the facility. The second is a technician, responsible for operating the generators (engine or microturbine) and monitoring the optimal conditions of the digester and other equipment. With the help of the UFPE administration, it was possible to obtain the monthly salaries of the staff responsible for system operation.

The daily volume of water to be used will be 1 m^3, and, considering the cost of a cubic meter at USD 3.72, the annual cost was calculated to be USD 1356.88. It is worth noting that using rainwater caught from rooftops could reduce this cost significantly. According to the quotes, the manure acquisition cost in farms near UFPE would be about USD 18.59 per 250 kg. Thus, the value of the annual operational costs would be USD 14,988.85. Maintenance costs were obtained from some published studies, and their values were adjusted to the present value according to the inflation rate set (6.5%).

For scenarios 1 and 2, the maintenance costs were defined according to the periodic maintenance of the engine–generator set, which is the most valuable piece of equipment and the most expensive system, and it will operate three hours daily as defined. The maintenance costs of the engine–generator set are presented in Table 4. The maintenance costs for scenario 3 were explicitly described according to the preventive maintenance of the microturbine with a daily operation of 3 h. The microturbine maintenance costs are shown in Table 4.

Annual depreciation costs of equipment for the three scenarios are presented in detail in Table 5, and the values of the remaining costs for the three scenarios obtained are shown in Table 6.

Table 5. Depreciation costs of equipment of an anaerobic digestion unit to process food waste and generate electrical energy.

Description	Total	Useful Life (years)	Depreciation
Digestion system and accessories			
Geomembrane liner	USD 9386.21	15	USD 625.75
Geomembrane cover	USD 9386.21	15	USD 625.75
Pipe, valves	USD 185.87	25	USD 7.73
Digestion system and accessories			
Fiberglass water tank (x2)	USD 39,515.95	25	USD 1580.64
Pipe, valves	USD 185.87	25	USD 7.73
Electrical equipment and accessories			
Crusher with engine	USD 5204.46	15	USD 346.96
Pump	USD 557.62	10	USD 55.76
Pipe, valves, cables	USD 557.62	25	USD 7.73
Engine–generator set Fockink (SG-150B Model)	USD 80,297.40	20	USD 4014.87
Capstone microturbine (CR-65 Model), two units	USD 182,000.00	30	USD 6066.67
Compression system	USD 1301.12	10	USD 130.11
Auxiliary systems and accessories			
Tank for the mixture of the substrate	USD 1301.12	25	USD 52.04
Pipe, valves (filter)	USD 557.62	25	USD 22.30
Tank for the biofertilizer	USD 2602.23	20	USD 130.11
Pressure meter	USD 111.52	1	USD 111.52
Flow meter	USD 185.87	1	USD 185.87
Shed for the generator set	USD 2788.10	30	USD 92.94
Total Depreciation Costs—Scenario 1			USD 8116.00
Total Depreciation Costs—Scenario 2			USD 8087.19
Total Depreciation Costs—Scenario 3			USD 10,213.33

Table 6. Remaining costs of an anaerobic digestion unit to process food waste and generate electrical energy.

Remaining Costs	Scenario 1 [1]	Scenario 2 [2]	Scenario 3 [3]
Electricity tariff (average)—peak hours	USD 0.64	USD 0.64	USD 0.64
Electricity tariff (average)—off-peak hours	USD 0.13	USD 0.13	USD 0.13
Energy consumption of the equipment of the plant (average)—kW	2828.75	2828.75	7690.55

Total Energy Consumption Costs of The Plant	USD 311.32	USD 311.32	USD 2267.70
Electricity tariff (average)—peak hours	USD 0.64	USD 0.64	USD 0.64
Electrical energy generated by the plant—kW	124.830	124.830	135.780
Total Price of the Electricity Generated	USD 58,344.09	USD 58,344.09	USD 63,206.10
Total Remaining Costs of Energy	USD −21,033.28	USD −21,033.28	USD −16,268.92
Operating Costs	USD 14,988.85	USD 14,988.85	USD 14,988.85
Maintenance Costs	USD 720.87	USD 720.87	USD 391.47
Total O&M Costs	USD 15,709.72	USD 15,709.72	USD 15,380.62
Total Depreciation Costs	USD 8116.00	USD 8087.19	USD 10,213.33
Total Remaining Costs	USD 43,000.27	USD 42,971.45	USD 41,862.57

[1] Chinese-type digester (fiberglass tank) and a generator set with an internal combustion engine; [2] tubular digesters and a generator set with an internal combustion engine; [3] tubular digesters and a gas microturbine.

Revenues were set into two groups: those related to the savings in energy and the savings in the transportation of food waste to landfills.

Revenue from electricity can be understood as the value achieved with the savings and the reduction in expenses in the energy bill of the UFPE due to system installation. Thus, it was possible to obtain an annual savings of 100% (USD 67,153.08) in DEN’s energy bill at peak hours for the three scenarios proposed. It is important to note that when the system is also operated during off-peak hours, the savings will decrease since the tariff during peak hours is lower, and O&M costs would significantly increase, so profitability and economic viability would be affected.

Regarding the transportation costs of food waste to landfills, they would be saved entirely and included as project revenue. Therefore, UFPE would have savings of USD 17,042.86, as defined above. Moreover, the resulting biofertilizer will depend on the percentage of volatile solids degradation of the substrate during digestion. According to Zhang et al. [45], the process achieves an approximate degradation of 80% of volatile solids. Thus, for an annual vs. amount of 101,835 kg, an estimation of 20,367 kg will be produced, which could be used in the parks and gardens of the UFPE. Finally, after defining the revenues and expenses of the project, the cash flow was estimated.

3.3. Calculation of Profitability Indicators

3.3.1. Deterministic Methods

The deterministic economic metrics of each proposed scenario were calculated based on the previously estimated cash flow. Table 7 shows the resulting profitability indicators.

Table 7. Economic metrics for the proposed scenarios of an anaerobic digestion unit to process food waste and generate electrical energy.

Scenarios	**NPV**	**B/C (Unitless)**	**IRR**	**DPBP (Years)**
Scenario 1 [1]	USD 588,138.00	3.76	49.07%	4.17
Scenario 2 [2]	USD 609,172.14	4.16	54.60%	3.76
Scenario 3 [3]	USD 540,339.93	2.88	37.87%	5.47

[1] Chinese-type digester (fiberglass tank) and a generator set with an internal combustion engine; [2] tubular digester and a generator set with an internal combustion engine; [3] tubular digester and a gas microturbine.

Based on the economic analysis and profitability ratios obtained, it can be concluded that the proposed three scenarios are economically viable. For scenarios 1 and 2, the investment would be recovered in the fourth year of operation, and for scenario 3, the return would happen at the beginning of the sixth year. The values of the NPVs were positive in the three scenarios with very high values, confirming economic solvency.

Regarding the IRR, the values are well above the discount rate used for the first two scenarios, and scenario 1 presents greater attractiveness. Thus, the project with both digestion technologies (Chinese or tubular digesters) and an internal combustion engine will be very economically attractive. Likewise, the IRR in scenario 3 continues above the discount rate established, which is also viable.

The B/C ratio of the first two scenarios also confirmed the viability since their values were much higher than 1. In the case of scenario 3, the value of B/C was close to 1, so this option remains viable even with lower attractiveness.

Overall, the project demonstrates high viability for scenarios that include either of the two technologies proposed for digestion and power generation with an internal combustion engine. Moreover, the choice of the microturbine as a power generation equipment can also be considered; even through this option presented lower viability than the other options, it remains attractive. Figure 1 illustrates scenario 2, which has the greatest economic viability according to the NPV criterion.

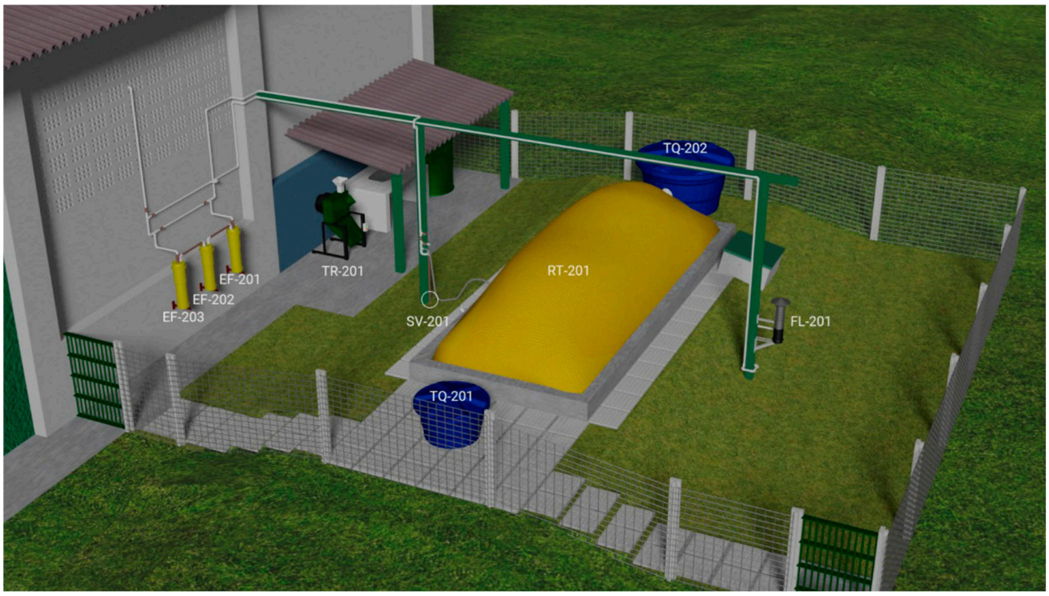

Figure 1. Low-cost pilot plant developed for biogas and biofertilizer production from food waste on experimental biorefinery of organic solid waste. TR-201: food grinding machine; TQ-201: feeding tank; RT-201: pilot biodigester; TQ-202: storing biofertilizer tank; SV-210: safety valve; FL-201: flare; EF-201: filter 1; EF-202: filter 2; EF-203: filter 3. Source: [28].

The conditions of the present study are very favorable when compared to scenarios in other countries. For example, in a study conducted to assess the economic feasibility of electricity generation from biogas in small pig farms with and without H_2S removal using an electric generator [46] under the reference scenario (i.e., 45% subsidy on digester installation and fixed electricity price at 0.06 Euro/kWh) and based on the assumption that the biogas was fully utilized for electricity generation in the system, the payback period for the system without H_2S removal was about four years. With H_2S removal, the payback period was within the economic life of the digester but almost twice that of the case without H_2S removal.

3.3.2. Sensibility Analysis

After having conducted the scenarios and the economic analysis, it was essential to evaluate the effect of modifying a vital variable, such as the operating hours of the plant, which could cause significant changes affecting the economic viability of the project.

As for the first proposed case, the continuous operating time of the plant was assumed to be 3 h for peak hours and 4 h for off-peak hours. These assumptions were made based on the potential of biomass available and the consumption of the engine and microturbine selected (60 kW and 65 kW, respectively).

Similarly, a second case was proposed for the operation of the plant only at off-peak hours (3 h continuously), also by the potential of biomass and the consumption of the engine and the microturbine selected. Thus, the profitability ratios for the sensibility analysis were obtained, as shown in Table 8.

Table 8. Economic metrics for sensitivity analysis of an anaerobic digestion unit to process food waste and generate electrical energy.

Scenarios	NPV	B/C (unitless)	IRR	DPBP (years)
	Operation During Peak and Off-Peak Hours			
Scenario 1 [1]	USD 237,018.96	3.37	41.06%	5.17
Scenario 2 [2]	USD 226,992.57	2.90	36.31%	5.88
Scenario 3 [3]	−USD 30,302.97	0.89	12.48%	-
	Operation Only During Off-Peak Hours			
Scenario 1 [1]	USD 108,528.62	2.04	27.98%	7.63
Scenario 2 [2]	USD 86,337.92	1.70	23.64%	9.23
Scenario 3 [3]	−USD 356,838.66	0.25	−0.94%	-

[1] Chinese-type digester (fiberglass tank) and a generator set with an internal combustion engine; [2] tubular digester and a generator set with an internal combustion engine; [3] tubular digester and a gas microturbine.

The sensitivity analysis confirmed that operating the plant over seven continuous hours at peak and off-peak times would still be economically viable in scenarios 1 and 2. However, under these conditions, the system is not feasible for scenario 3, since a return on investment in the projected horizon will not happen. Moreover, if operating the plant during off-peak hours, it was verified that the viability of scenarios 1 and 2 would be within the limit, with a return on investment at the end of the projected horizon.

The economic analysis of this case study also aimed to confirm the viability of installing similar systems in small municipalities. In this case, economic viability will be an essential criterion for accepting proposals. Since the potential of food waste in these communities is much higher, as well as energy consumption at peak hours, the proposal to use a power microgeneration system will probably have greater economic viability. The analyses of such systems would be critical in the northeast region of Brazil, where the need for more government capital for investment and job opportunities could be facilitated by implementing these microgeneration systems. In addition, it would lead to less greenhouse gas house emissions associated with food waste disposal and an increase in renewable energy generation.

4. Conclusions

Based on the conditions of the case study, the most economically viable scenario for energy recovery from food waste through anaerobic digestion includes using a tubular digester with the plant operating at peak hours with a generator set with an internal combustion engine. Under these conditions, the investment in the system is recovered in over four years, which is very attractive. It may also be concluded that the operation of the plant during off-peak hours strongly reduces the system's economic viability and makes it unviable when using a microturbine for electricity generation. This case study establishes a model to be adapted for implementing microgeneration units in small municipalities in the northeast region of Brazil, potentially benefiting over 30 million people. These benefits could include decentralized opportunities for job and income generation and positive environmental impacts, such as a more sustainable destination for food waste, increased renewable energy generation, and decreased greenhouse gas emissions from landfills.

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References

1. Braguglia, C.M.; Gallipoli, A.; Gianico, A.; Pagliaccia, P. Anaerobic bioconversion of food waste into energy: A critical review. *Bioresour. Technol.* **2018**, *248*, 37–56. https://doi.org/10.1016/j.biortech.2017.06.145.
2. Scarlat, N.; Motola, V.; Dallemand, J.F.; Monforti-Ferrario, F.; Mofor, L. Evaluation of energy potential of Municipal Solid Waste from African urban areas. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1269–1286. https://doi.org/10.1016/j.rser.2015.05.067.
3. ABRELPE—Associaço Brasileira de Empresas de Limpeza Pública e Resíduos Epeciais. *Panorama dos Resíduos Sólidos no Brasi*; ABRELPE: Avenida Paulista, Brazil, 2017.
4. Xu, F.; Li, Y.; Ge, X.; Yang, L.; Li, Y. Anaerobic digestion of food waste—Challenges and opportunities. *Bioresour. Technol.* **2018**, *247*, 1047–1058. https://doi.org/10.1016/j.biortech.2017.09.020.
5. Aguilar-Virgen, Q.; Taboada-González, P.; Ojeda-Benítez, S.; Cruz-Sotelo, S. Power generation with biogas from municipal solid waste: Prediction of gas generation with in situ parameters. *Renew. Sustain. Energy Rev.* **2014**, *30*, 412–419. https://doi.org/10.1016/j.rser.2013.10.014.
6. Lantz, M. The economic performance of combined heat and power from biogas produced from manure in Sweden—A comparison of different CHP technologies. *Appl. Energy* **2012**, *98*, 502–511. https://doi.org/10.1016/j.apenergy.2012.04.015.
7. Su, Y.; Zhou, S.; Tian, P.; Qi, C.; Xu, Z.; Zhang, Y.; Huh, S.-Y.; Luo, W.; Li, G.; Li, Y. Techno-economic assessment of industrial food waste composting facility: Evaluating bulking agents, processing strategies, and market dynamics. *Bioresour. Technol.* **2024**, *408*, 131210. https://doi.org/10.1016/j.biortech.2024.131210.
8. Oliveira, D.d.S.; Gomes, G.C.; Rocha, L.C.S.; Junior, P.R.; Aquila, G.; Bernardes, P.A.; Janda, K. Energy and stochastic economic assessment for distributed power generation from Manipueira biogas. *Environ. Technol.* **2024**, *45*, 1608–1621. https://doi.org/10.1080/09593330.2022.2148569.
9. Nketiah, E.; Song, H.; Adjei, M.; Adu-Gyamfi, G.; Obuobi, B.; Cudjoe, D. Assessment of energy generation potential and mitigating greenhouse gas emissions from biogas from food waste: Insights from Jiangsu Province. *Appl. Energy* **2024**, *371*, 123717. https://doi.org/10.1016/j.apenergy.2024.123717.

10. Hossain, M.S.; Das, B.K.; Das, A.; Roy, T.K. Investigating the techno-economic and environmental feasibility of biogas-based power generation potential using food waste in Bangladesh. *Renew. Energy* **2024**, *232*, 121017. https://doi.org/10.1016/j.renene.2024.121017.
11. Cudjoe, D.; Nketiah, E.; Obuobi, B.; Adu-Gyamfi, G.; Adjei, M.; Zhu, B. Forecasting the potential and economic feasibility of power generation using biogas from food waste in Ghana: Evidence from Accra and Kumasi. *Energy* **2021**, *226*, 120342. https://doi.org/10.1016/j.energy.2021.120342.
12. Freitas, F.; Ferreira, L.; Otto, R.; Alessio, F.; De Souza, S.; Venturini, O.; Junior, O.A. The Brazilian market of distributed biogas generation: Overview, technological development and case study. *Renew. Sustain. Energy Rev.* **2019**, *101*, 146–157. https://doi.org/10.1016/j.rser.2018.11.007.
13. Ferreira, J. Quantificação e Caracterização Química e Energética da Biomassa Residual Gerada no Campus Recife da UFPE. Bachelor's Thesis, Federal University of Pernambuco UFPE, Recife, Brazil, 2014.
14. Fiore, S.; Ruffino, B.; Campo, G.; Roati, C.; Zanetti, M.C. Scale-up evaluation of the anaerobic digestion of food-processing industrial wastes. *Renew. Energy* **2016**, *96*, 949–959. https://doi.org/10.1016/j.renene.2016.05.049.
15. Wang, L.; Shen, F.; Yuan, H.; Zou, D.; Liu, Y.; Zhu, B.; Li, X. Anaerobic co-digestion of kitchen waste and fruit/vegetable waste: Lab-scale and pilot-scale studies. *Waste Manag.* **2014**, *34*, 2627–2633. https://doi.org/10.1016/j.wasman.2014.08.005.
16. Neuner, T.; Meister, M.; Pillei, M.; Rauch, W. Optimizing mixing efficiency of anaerobic digesters with high total solids concentrations using validated CFD simulations. *Biochem. Eng. J.* **2024**, *208*, 109320. https://doi.org/10.1016/j.bej.2024.109320.
17. Ramos-Suárez, J.L.; Álvarez-Méndez, S.J.; Padrón Tejera, E.; Ritter, A.; Mata González, J. Temperature Control Effect on Cheese Whey Anaerobic Digestion with Low-Cost Tubular Digesters. *Processes* **2024**, *12*, 1452. https://doi.org/10.3390/pr12071452.
18. Shah, S.V.; Yadav Lamba, B.; Tiwari, A.K.; Chen, W.-H. Sustainable biogas production via anaerobic digestion with focus on CSTR technology: A review. *J. Taiwan Inst. Chem. Eng.* **2024**, *162*, 105575. https://doi.org/10.1016/j.jtice.2024.105575.
19. Boulanger, A.; Pinet, E.; Bouix, M.; Bouchez, T.; Mansour, A.A. Effect of inoculum to substrate ratio (I/S) on municipal solid waste anaerobic degradation kinetics and potential. *Waste Manag.* **2012**, *32*, 2258–2265. https://doi.org/10.1016/j.wasman.2012.07.024.
20. Takeda, P.Y.; Paula, C.T.; Giglio, G.L.; Borges, A.d.V.; Pereira, T.D.S.; Damianovic, M.H.R.Z. Efficient reactivation of anammox sludge after prolonged storage using a combination of batch and continuous reactors. *Environ. Sci. Pollut. Res.* **2023**, *31*, 2408–2418. https://doi.org/10.1007/s11356-023-31355-1.
21. Díaz Valencia, A.B.; Toledo Méndez, C.D.R.; Magaña Villegas, E. Propuesta De Un Sistema Digestor Anaerobio Y Generación Eléctrica Para Abastecer El Herbario De La Dacbiol. *Kuxulkab'* **2014**, *15*, 28. https://doi.org/10.19136/kuxulkab.a15n28.436.
22. Lopez, V.M.; De la Cruz, F.B.; Barlaz, M.A. Chemical composition and methane potential of commercial food wastes. *Waste Manag.* **2016**, *56*, 477–490. https://doi.org/10.1016/j.wasman.2016.07.024.
23. Marques, C. Microgeração de energia elétrica em uma propriedade rural utilizando biogás como fonte primaria de energia elétrica. Master's thesis, Universidade Estadual do Oeste do Paraná—UNIOESTE, Cascavel, Brazil, 2012.
24. Pecora, V. Implantação de uma unidade demonstrativa de geração de energia elétrica a partir do biogás de tratamento do esgoto residencial da USP—Estudo de caso. Master's thesis, São Paulo University, São Paulo, Brazil 2006.
25. Jornal do Comércio. Estimativa aponta um aumento de 30% na conta de luz até março 2015. Available online: http://jconline.ne10.uol.com.br/canal/economia/pernambuco/noticia/2015/02/05/estimativa-aponta-um-aumento-de-30_porcento-na-conta-de-luz-ate-marco-166992.php (accessed on 3 May 2023).
26. Duque, N.; Scholten, L.; Maurer, M. Exploring transitions of sewer wastewater infrastructure towards decentralisation using the modular model TURN-Sewers. *Water Res.* **2024**, *257*, 121640. https://doi.org/10.1016/j.watres.2024.121640.
27. Uhlemann, J.-P.R.; Oude Lansink, A.; Leahy, J.J.; Dalhaus, T. Do investments in phosphorus recovery from dairy processing wastewater pay off? *J. Environ. Manage* **2024**, *357*, 120606. https://doi.org/10.1016/j.jenvman.2024.120606.
28. de Sousa, M.H.; da Silva, A.S.F.; Correia, R.C.; Leite, N.P.; Bueno, C.E.G.; Pinheiro, R.L.d.S.; de Santana, J.S.; da Silva, J.L.; Sales, A.T.; de Souza, C.C.; et al. Valorizing municipal organic waste to produce biodiesel, biogas, organic fertilizer, and value-added chemicals: An integrated biorefinery approach. *Biomass. Convers. Biorefinery* **2022**, *12*, 827–841. https://doi.org/10.1007/s13399-020-01252-5.
29. Pires, A.L.G.; Rotella Junior, P.; Rocha, L.C.S.; Peruchi, R.S.; Janda, K.; Miranda, R.d.C. Environmental and financial multi-objective optimization: Hybrid wind-photovoltaic generation with battery energy storage systems. *J. Energy Storage* **2023**, *66*, 107425. https://doi.org/10.1016/j.est.2023.107425.
30. Chen, X.; Chen, Y.; Fu, L.; Zhang, Z.; Tang, M.; Feng, J.; Jiang, S.; Lei, Y.; Zhang, D.; Shen, B. Photovoltaic-driven liquid air energy storage system for combined cooling, heating and power towards zero-energy buildings. *Energy Convers. Manag.* **2024**, *300*, 117959. https://doi.org/10.1016/j.enconman.2023.117959.
31. Aquila, G.; Rotella Junior, P.; Rocha, L.C.S.; Balestrassi, P.P.; Pamplona, E.D.O.; Nakamura, W.T. Net metering rolling credits vs. net billing buyback: An economic analysis of a policy option proposal for photovoltaic prosumers. *Renew. Energy* **2024**, *232*, 121154. https://doi.org/10.1016/j.renene.2024.121154.
32. Aquila, G.; Souza Rocha, L.C.; Rotela Junior, P.; Saab Junior, J.Y.; de Sá Brasil Lima, J.; Balestrassi, P.P. Economic planning of wind farms from a NBI-RSM-DEA multiobjective programming. *Renew. Energy* **2020**, *158*, 628–641. https://doi.org/10.1016/j.renene.2020.05.179.

33. Coelho, E.d.O.P.; Aquila, G.; Bonatto, B.D.; Nakamura, W.T.; Rotella Junior, P.; Rocha, L.C.S. Stochastic financial analysis of diesel generation extension vs investment in hybrid photovoltaic-diesel-battery in a microgrid in the Amazon indigenous community. *Energy Sustain. Dev.* **2023**, *77*, 101344. https://doi.org/10.1016/j.esd.2023.101344.
34. Rodrigues, S.; Chen, X.; Morgado-Dias, F. Economic analysis of photovoltaic systems for the residential market under China's new regulation. *Energy Policy* **2017**, *101*, 467–472. https://doi.org/10.1016/j.enpol.2016.10.039.
35. Bakhshi-Jafarabadi, R.; Sadeh, J.; Dehghan, M. Economic evaluation of commercial grid-connected photovoltaic systems in the Middle East based on experimental data: A case study in Iran. *Sustain. Energy Technol. Assess.* **2020**, *37*, 100581. https://doi.org/10.1016/j.seta.2019.100581.
36. Farber, P.; Gräbel, J.; Kroppen, N.; Pötschke, L.; Roos, D.; Rosenbaum, M.; Stegschuster, G.; Ueberholz, P. Electricity generation in a microbial fuel cell with textile carbon fibre anodes. *Comput. Math. Appl.* **2021**, *83*, 4–23. https://doi.org/10.1016/j.camwa.2019.11.019.
37. Singh, D.; Sharma, D.; Soni, S.L.; Sharma, S.; Kumar Sharma, P.; Jhalani, A. A review on feedstocks, production processes, and yield for different generations of biodiesel. *Fuel* **2020**, *262*, 116553. https://doi.org/10.1016/j.fuel.2019.116553.
38. Papargyriou, D.; Broumidis, E.; de Vere-Tucker, M.; Gavrielides, S.; Hilditch, P.; Irvine, J.T.; Bonaccorso, A.D. Investigation of solid base catalysts for biodiesel production from fish oil. *Renew. Energy* **2019**, *139*, 661–669. https://doi.org/10.1016/j.renene.2019.02.124.
39. Lee, J.; Chen, W.-H.; Park, Y.-K. Recent achievements in platform chemical production from food waste. *Bioresour. Technol.* **2022**, *366*, 128204. https://doi.org/10.1016/j.biortech.2022.128204.
40. Keche, D.D.; Fetanu, Z.M.; Babiso, W.Z.; Wachemo, A.C. Anaerobic digestion of urea pretreated water hyacinth removed from Lake Abaya; bio-methane potential, system stability, and substance conversion. *RSC Adv.* **2022**, *12*, 8548–8558. https://doi.org/10.1039/D2RA00303A.
41. Dell'Orto, A.; Trois, C. Double-Stage Anaerobic Digestion for Biohydrogen Production: A Strategy for Organic Waste Diversion and Emission Reduction in a South African Municipality. *Sustainability* **2024**, *16*, 7200. https://doi.org/10.3390/su16167200.
42. Kuczman, O.; Gueri, M.V.D.; De Souza, S.N.M.; Schirmer, W.N.; Alves, H.J.; Secco, D.; Buratto, W.G.; Ribeiro, C.B.; Hernandes, F.B. Food waste anaerobic digestion of a popular restaurant in Southern Brazil. *J. Clean Prod.* **2018**, *196*, 382–389. https://doi.org/10.1016/j.jclepro.2018.05.282.
43. Zhang, Y.; Banks, C.J.; Heaven, S. Co-digestion of source segregated domestic food waste to improve process stability. *Bioresour. Technol.* **2012**, *114*, 168–178. https://doi.org/10.1016/j.biortech.2012.03.040.
44. ANEEL—National Electricity Agency. Normative Resolution No. 482 of 17 July 2012. Available online: http://www2.aneel.gov.br/cedoc/ren2012482.pdf (accessed on 6 November 2024).
45. Zhang, R.; El-Mashad, H.M.; Hartman, K.; Wang, F.; Liu, G.; Choate, C.; Gamble, P. Characterization of food waste as feedstock for anaerobic digestion. *Bioresour. Technol.* **2007**, *98*, 929–935. https://doi.org/10.1016/j.biortech.2006.02.039.
46. Pipatmanomai, S.; Kaewluan, S.; Vitidsant, T. Economic assessment of biogas-to-electricity generation system with H2S removal by activated carbon in small pig farm. *Appl. Energy* **2009**, *86*, 669–674. https://doi.org/10.1016/j.apenergy.2008.07.007.