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Feasibility and Barriers for Anaerobic Digestion in Mexico City

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Abstract: Due to the high organic fraction in municipal solid waste (MSW) composition in Mexico City, anaerobic digestion (AD) is considered as a viable treatment method for organics in this study. The most feasible way refers to the waste from the wholesale market Central de Abasto, which is predominantly organics. This work aims to perform a business plan and discuss the barriers for AD technology in Mexico. In this case study, the cost-benefit analysis (CBA) approach is applied to estimate the profitability of the project. The net present value of this project is positive, and the model resulted in a payback period of 7 years. Identified barriers to feasibility of energy generation through biogas of MSW in Mexico include the need for large investment, low profitability through sales of electricity, and no use for generated heat. An attractive panorama for clean energy in Mexico was not evidenced, even though the Energy Reform took place in 2013. However, the environmental analysis also demonstrates a positive environmental impact of 730 kg CO_2 per 1 Mg of MSW. Therefore, support incentives are needed to promote the use of other by-products of the AD process, such as heat and digestate.

Keywords: waste management; anaerobic digestion; emerging countries; biogas; digestate; Easewaste

1. Introduction

An increasing number of developing countries are showing interest in recovering energy from municipal solid waste (MSW). While some European Union states have been successful in this regard, many developing countries are investigating waste-to-energy (WtE) technologies to adopt [1]. So far, only a few have recorded successes. Undoubtedly, the investment and technical demands for advanced waste treatment systems are the major reasons for the slow adoption of WtE in emerging countries [2]. Additionally, recent data on characteristics of the MSW is missing in most developing countries. This also hinders the feasibility of WtE projects [3].

The functionality of waste management nowadays has shifted from the disposal of wastes towards energy and resource recovery [4]. Even though the primary objective of WtE is waste management, it is also a renewable energy source that can complement traditional power supplies [5]. To support a rapid transition in this direction, energy from waste technology should be promoted using political instruments.

In this research, Mexico City, the capital of Mexico, was selected as a case study. In 2013, the Energy Reform created favorable conditions for the renewable energy generators throughout the country.

This paper examines the economic feasibility of an Anaerobic Digestion (AD) plant fed with MSW under the new circumstances. After the change of the government at the end of 2018, the plan to construct an incineration plant in the city was abandoned, therefore, there is a need to search for alternative waste management solutions [6]. The prevailing percentage of MSW in Mexico is presented by organics [7]; thus, anaerobic digestion technology was selected as the suitable treatment solution. The suggested substrate is the waste stemming from the wholesale market Central de Abasto, located in the borough Iztapalapa, east of the city. The MSW was sampled and examined to report data on its properties and estimate if it is suitable for the AD process.

This study analyzes the barriers and feasibility of a biogas plant in Mexico City fed with the organic fraction of MSW produced at Central de Abasto. The aim of this work is to use accurate business planning to discuss the barriers to AD technology in Mexico City. At the local level, the primary objective of this assessment is to support efforts of the authorities to incorporate an AD plant into the integrated waste management system. Overall, it is expected that the study will assist in stimulating further growth of waste generation technologies in emerging countries, especially in Latin America.

Previous works have analyzed other technologies, such as Escamilla García et al. [8] focusing on landfill gas collection for Mexico City, and Rios and Kaltschmitt [9] comparing electricity generation in Mexico from landfill gas with use of biogas from wastewater and livestock manure. De Medina Salas et al. [10] have discussed several treatment options for the organic fraction of MSW (OFMSW) in Sierra Madre Orienta, in northeastern Mexico. However, to the best of author's knowledge, there is no detailed economic feasibility study of large-scale biogas projects for electricity generation in Mexican urban areas available currently.

2. Background Information

2.1. Sustainabilty Development Goals

The Sustainable Development Goals (SDGs) address the global challenges, including poverty, inequality, climate, environmental degradation, prosperity, peace, and justice. They are interconnected and are set for the year 2030. SDG 7 is focused on energy. This goal is especially important as it interlinks with all other Sustainable Development Goals. Universal access to energy, energy efficiency, and the wider spread of renewable energy are crucial for creating sustainable and inclusive communities and resilience to environmental issues such as climate change. Access to electricity is closely linked with improvements in human development, including productivity (SDG 8), health and safety (SDG 3), gender equality (SDG 5), and education (SDG 4) [11]. The correlation between human development and electricity consumption per capita was proved by Goldemberg et al. [12].

Mexico has undertaken many initiatives towards sustainable development and the SDG 7. The country has a high potential for development of renewable energies, solar, and wind power, with potential for bioenergy, hydropower, and geothermal power as well [13,14]. Nevertheless, the Mexican electric power sector is characterized for the prevalence of fossil fuels (82%) in the energy mix [15]. Mexico is a country with a high degree of electricity coverage, but challenges still remain in isolated rural areas. In this context, the utilization of renewable energy sources for electric power generation becomes an important factor in achieving the SDGs. Nonetheless, technologies face significant barriers in their wide usage, such as establishing appropriate financial sources and mechanisms to allow widespread use of the renewable energy in the national power mix [16].

AD technology can contribute significantly to the implementation of SDGs, not only through generating low carbon energy and fertilizers, but also through the reduction of methane emissions from food and farming wastes, providing energy security, reducing poverty, and improving waste management and sanitation. AD offers decentralization of energy generation. Rural and remote communities that are not connected to the electricity grids are able to produce their own from the waste and the agricultural residues and become energy self-sufficient. Also, AD is a reliable energy source compared to other renewables. Once started and stabilized, the plant produces biogas on a continuous basis independently of external factors, such as the sun or wind [17].

2.2. Energy Reform in Mexico

The government of Mexico under the president Enrique Peña Nieto, who served from December 2012 until November 2018, aimed to transition the country to cleaner and more diversified sources of energy. The Energy Reform, which took place in 2014, was implemented to increase energy security, minimize the negative effects of fossil fuel dependence, and minimize environmental impacts [18]. Mexican Energy Reform consists of the introduction of the Electricity Industry Law and the Federal Commission of Electricity Law, along with other regulations arising from the amendments to articles 25, 27, and 28 of the Constitution. This legal framework created better conditions for renewable energy sources. The government also set the clear clean energy goals: to generate 35% of its electricity from clean energy by 2024 and to reduce greenhouse gas emissions by 22% by 2030.

Before the reform, most of the functions of the electricity market were concentrated at Comisión Federal de Electricidad (CFE), the state-owned electric utility of Mexico. In a nutshell, the goal of the reform is to open parts of energy sector to private investors, while retaining control over transmission and distribution channels [19].

The reform introduced new stakeholders to the market and gave more freedom to the energy generators. The Energy Reform allows private firms to compete against the state companies for the production, distribution, and retail of energy [20]. Power stations received the right to participate in the electricity system under three schemes: sell electricity on the wholesale market, through contracts directly to the Suppliers or Qualified Users, and through auctions organized by CENACE, Centro Nacional de Control de Energía (National Center of Energy Control) [21].

Mexico's new president starting from January 2019, Andres Manuel Lopez Obrador (AMLO), made energy sovereignty the center of political agenda. However, to achieve this goal AMLO emphasizes existing hydroelectric, diesel, fuel oil, and coal fired power plants, while eliminating market mechanisms that had allowed for investment in wind and solar capacity at record low prices [22]. For instance, the fourth clean power auction was postponed indefinitely [23].

Energy from biomass can play a central role in achieving ambitious CO_2 reduction, sustainability, and energy sovereignty targets in Mexico. Biogas is particularly important because it can be used flexibly to generate heat, gas, electricity, or liquid fuels, and it can readily be stored and transported if upgraded to biomethane [24]. However, use of biomass for biogas production for energy purposes may compete with food production for the available area. In light of this competition for space, it is desirable to include previously unused biomass fractions, such as the organic fraction of MSW into new sources for energy production [25]. The advantage here is no competition with food and no land use competition due to the fact that the input into the biogas fermenter is considered as waste, although the AD technology has to cope with non-technological barriers, such as public acceptance, availability of incentives, distribution infrastructure, and shortage of institutional and regulatory support [26].

2.3. Anaerobic Digestion Technology

Anaerobic digestion (AD) is a microbiological process of decomposition of organic matter in the absence of oxygen. The key process phases of AD are hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the course of these stages, complex organic molecules are broken down into simpler ones and intermediate products are converted to methane, carbon dioxide, and water. The main components of biogas are methane (48–65%), carbon dioxide (36–41%), nitrogen (up to 17%), and traces of other gases, such as hydrogen sulphide (H_2S) and siloxanes. Anaerobic digestion and biogas production are influenced by parameters such as the total solids content (TS), the volatile solids content (VS), the carbon and nitrogen ratio (C/N), the particle size, the temperature, the pH, and the inoculum type [27].

The digestion process takes place at mesophilic (35–42 °C) or thermophilic (45–60 °C) temperature conditions. Two process types are mainly adopted, namely wet or dry fermentation. In the first case, the input has a solid concentration below 12%, whereas, in dry digestion plants, solid concentration is higher than 20%. Concerning the continuity, AD technologies can be classified into batch and continuous systems. In a batch system, the reactor is filled with the feedstock and left for a pre-defined period, during which digestion and biogas production take place. At the end of the period, the reactor is emptied, and the process restarts. In a continuous system, the biomass is regularly fed into the reactor, and, at the same time, effluent is discharged. All wet digestion processes are operated continuously, whereas, for dry fermentation, both batch and continuous processes are applied [27]. Moreover, one-stage or two-stage processes can be differentiated. In a one-stage system, all biochemical reactions take place in one reactor, while a two-stage system consists of two reactors [28].

Worldwide, the biodegradable fraction of the MSW (i.e., food and biomass residues, paper, and cardboard) varies between 30% and 65% [7]. In this respect, several studies [29–32] show that MSW is a potential primary energy source, especially the organic fraction of the municipal solid waste (OFMSW), thanks to the amount of biogas that can be produced through anaerobic digestion (AD). Therefore, AD is seen as a proper waste management solution in terms of solving the problem of waste generation and renewable energy production [33,34].

In practice, biogas is used onsite, for heating, local energy production and, in larger facilities, for district heating. Since biogas is a low-value fuel, it is not economically feasible to transport it for long distances beyond the site where it is generated. Also, biogas cannot be easily shipped, considering its corrosive potential. In contrast, upgraded biomethane could be more economically distributed to its point of use [26].

A by-product of AD, digestate, can be used as a fertilizer, which can help to avoid the negative impact of the production and use of chemical fertilizers. Most food waste plants have a pasteurization unit for deactivating the pathogens present in the waste, which allows the use of the digestate in gardening operations [35]. The most important minerals in fertilizers are nitrogen (N), phosphorus (P), and potassium (K) [36]. Industrial nitrogen production relies on the Haber-Bosch manufacturing process, an energy-intensive nitrogen-fixation process that accounts for 1.2% of global energy consumption [37]. Phosphorus and potassium, on the other hand, are obtained through mining. The phosphorous production chain is fragile because 77% of the world’s phosphate reserves are concentrated in just one country—Morocco. That is not the case with potassium fertilizers, which are mined and produced in many parts of the world. However, though potassium itself does not pose environmental risks, the mining activities may cause long-lasting ecological damage [38].

2.4. Case Study: Mexico City

Mexico City, the capital and the most populated city in the country, is an increasingly globalized and spatially growing city in which MSW is a critical issue in terms of urban and environmental governance. The city consists of 16 boroughs and is spread over an area of 1485 km^2. The estimated population of 9 Million [39] generates 12,998 Mg of MSW per day, from which only 10,678 Mg are collected through public services [40], while 48% of the generated waste stem from households, 39% from services and commercial establishments, 5% from Central de Abasto (the biggest wholesale market), and the remaining 8% from medical units and laboratories, green areas, and other sources (see Figure 1). Lack of proper solid waste management infrastructure is a striking problem due to the rapidly growing population. Further pressure is caused because people in urban areas consume 2–3 times more natural resources than rural inhabitants [41].

The MSW management system of the city consists of twelve transfer stations, three separation and eight composting plants, and 5 landfills located outside of the city. As in the case with more than two-thirds of waste generated in Latin America and the Caribbean, the majority of MSW in Mexico-City is disposed of at the landfills [7]. Since 2011, when the only local landfill Bordo Poniente was closed, the city has had to send its waste for final disposal to nearby states. The landfills for final disposal are the following: Milagro, Cañada, Cuautitlán, Chicoloapan, and Cuautla [40]. Transportation costs are high, and moreover, the access to the landfills has become an instrument of pressure in the conflicts between different political parties governing in neighboring Mexico State and Mexico City. To reduce the amount of waste sent to the landfill, in 2011, the city reinforced the source separation system, which was first introduced in 2003. According to this, household waste needed to be separated into two fractions: organics and inorganics. Unfortunately, the separation does not work properly, and the average separation efficiency for organics is 46% [40]. This system was designed to improve the treatment of organic fraction with the help of several composting plants. In July 2017, the new environmental regulation for Mexico City NADF-024-AMBT-2013 came into force [42]. This norm aims to increase the amount of separately collected recyclable materials, and thereby decrease the quantity of landfilled material. Non-recyclables were supposed to be treated in the incineration plant. The regulation introduces separation into four fractions: recyclables, non-recyclables, organic, and special waste, including Waste Electrical and Electronic Equipment (WEEE) and bulky waste. However, this type of segregation has not been implemented at full scale, and the separation efficiency is still low. The tender opened by the city was won the company from France Veolia [43]. However, the plan to construct a thermovalorization plant was paused after the change of the City's government [6]. The possible reasons for that are the high capital and operating costs, ash generated, and gaseous pollutants to the atmosphere in case of inadequate air pollution control [29]. There is a belief in Mexico that due the poor government control, the emission standards would not be respected during operation of the plant.

Since the incineration project is now paused in Mexico City, other alternatives should be discussed. Due to the high organic fraction and the lower set-up time, anaerobic digestion as a treatment method for organics should be considered. Interest in AD in Mexico has grown significantly in the last years, especially in the agricultural sector to treat cattle manure. The agricultural biogas plants represent covered lagoons with no mechanical agitation [44]. In 2012, there were 966 biodigesters treating animal slurries in Mexico [45].

The most feasible MSW feedstock are the residues from the wholesale market Central de Abasto (Supply Centre of Mexico City) (CEDA), which comprises 5% of total MSW generated in the city. Based on the composition study from 2017, these residues are mostly organics with low levels of contaminants. It needs to be mentioned that the main prerequisite for the AD is source-separated organics. In the case of waste from Central de Abasto, this condition could be fulfilled.

CEDA is a significant point of food distribution in Mexico City. It was founded in 1982. This 327-hectare terminal is the largest of its kind in the world, with 5000 businesses and over 300,000 visitors per day. The Central de Abasto buys and distributes 30% of national fruit and vegetable production, with a value of around USD 9 billion per year, provides approximately 70,000 jobs and represents a central hub in the extensive network of formal and informal food-related activities in Mexico City [46]. The production of residues is seasonal, associated with the harvest times of different products [47].

For the purpose of this study, the AD plant is to be constructed in the borough of Tláhuac, which is still rural in character. It is located on the south east edge of the district and has the area available for the plant and agricultural fields to accept the produced digestate. Also, Tláhuac is the neighbor municipality to Iztapalapa, where the CEDA market is located. The distance from CEDA to the center of Tláhuac is 20 km. Therefore, the implementation of the project would reduce the emission of pollutants to the atmosphere through the reduced transportation distance.

2.5. Anaerobic Plant Design

Continuous wet anaerobic digestion technology is chosen for this project because it is a proven technology for treatment of OFMSW [27,48]. The AD plant consists of eight digesters with a total volume of 51,472 m^3. An average retention time of 63 days was achieved through the number of digesters. The gas storage capacity has a maximum of 21,900 m^3. The combined heat and power (CHP) units generates approximately 6 MW electrical and 6 MW thermal energy. The heat produced from the engine is recovered to provide heat to the reactors and evaporator for the digestate.

The pretreatment system consists of a hammer mill with contaminant separation and a grit separation tank. Process water is also added to make the input pumpable. The biogas cleaning system consists of water removal and a reduction of the sulfur content by the addition of iron chloride in the digesters and carbon filters before the engines. Before the digestates are used as a fertilizer, they pass through a heat treatment in the pasteurizers followed by a separator to remove the remaining contamination, after which it is sent to an evaporation unit to decrease the water content and increase nutrient concentrations in the fertilizer. Process water is also generated in this step. The CHP system consists of two engines of 3 MW each. The plant has a control and monitoring system achieving a high degree of automation.

The mass flow diagram of the AD project discussed in this study is presented in Figure 2. The organic waste is delivered to the plant, where the contamination is sorted out. The part of the digestate is sent to the evaporator to reduce the water quantity, and then to the agricultural fields as a fertilizer. Sulphur acid is added to the digestate to fix the nitrogen in the evaporation process and convert it to a valuable plant fertilizer. The thermal power applied in the evaporator is the waste heat from the CHP unit, which is not used for self-supply of the plant. It is not enough to process the whole amount of output product; 70,498 Mg of digestate is sent directly to the fields.

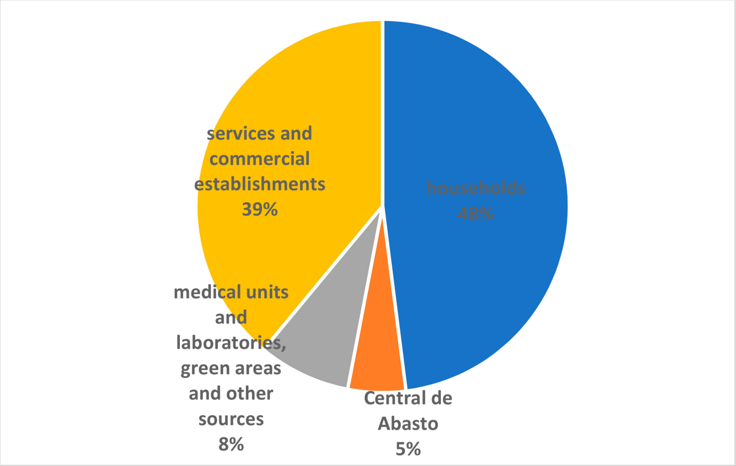

Figure 1. MSW generators in Mexico City [40].

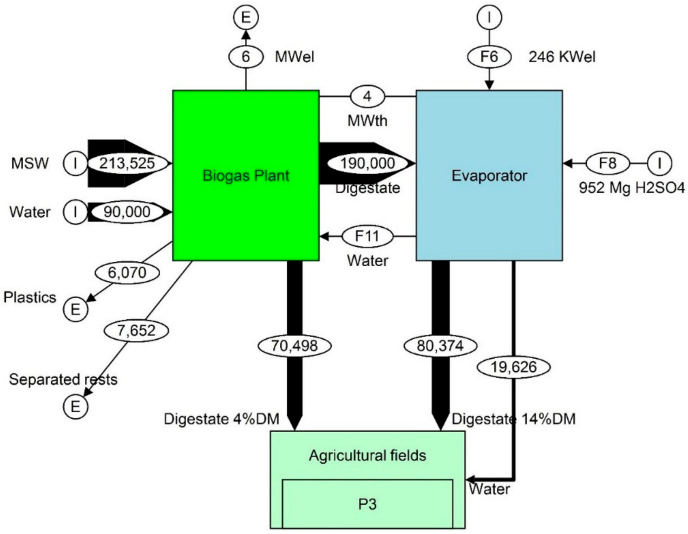

Figure 2. Flow diagram of the AD plant (Mg/a).

3. Materials and Methods

3.1. Economic Assessment

The methodology presented in this paper is based on the following steps: identification of main waste categories (i.e., grass, nopal, corn shells, etc.) contained in residues from the central wholesale market in Mexico and characterization of the waste (in terms of water and ash content, organic matter, pH, N, P, C/N); estimation of energy generation of the anaerobic digestion plant based on the GIZ study [49]; and economic feasibility.

The economic assessment is based on the analytical framework of Cost and Benefit Analysis (CBA) applied in Boardman et al. [50] and Berber [51]. In a CBA, the criterion for decision-making is based on the Net Present Value (NPV) and Internal Rate of Return (IRR). As a last step, a sensitivity analysis is performed in order to examine the robustness.

3.1.1. Net Present Value (NPV)

This study uses the cash flow model with NPV and IRR. Cash inflows arise from the following activities: financing operations, and investing while the outflows occur because of expenses, investments, and losses. Cash flow is often used for estimation of a company's financial strength [52], the present case study is focused on the operating cash flow based on the International Accounting Standards (IAS). The IAS distinguish three types of cash flows for operating, investing, and financing activities. The operating cash flow is normally used to identify which revenues generate cash inflows to repay loans, cover the operating costs, pay dividends, and make new investments. In this model, interests to be paid and dividends received are classified as financing cash flows and investing cash flows, respectively, because they are costs of obtaining financial resources or returns on investments [53]. Therefore, they are not included in the calculations here.

Although the unitary prices were only available in Mexican pesos ($), all the analyses were carried out with economic values in euros (€). The exchange rate used was 21.54 Mexican pesos to 1 euro. The data was provided by the Central Bank of Mexico—BANXICO on 26 March 2019.

In this case study, the net present value (NPV) approach is applied to estimate if the project is profitable or not. The NPV of an income stream is the sum of the present values of the individual amounts in the income stream. Each future income amount in the stream is discounted, meaning that it is divided by a number representing the opportunity cost of holding capital. The formula used to determine the NPV is described as follows:

$$NPV = -P\frac{NCF_1}{(1+i)^1} + \frac{NCF_2}{(1+i)^2} + \ldots + \frac{NCF_n}{(1+i)^n} \tag{1}$$

where NCF_n is net cash flow in the year n, P is Initial investment in the year 0, and i is reference rate corresponding to the minimal acceptable rate of return (MARR) [8].

The NPV of an investment shows if the particular project is profitable for an investor or not, in comparison with the alternative one. When NPV is positive, the investment can be undertaken. A negative NPV means that the alternative project is more profitable [54]. The NPV estimation model has some shortcomings concerning the uncertainty and management's flexibility to respond to uncertainty during the whole life of the project [55]. Nevertheless, the NPV approach is widely used to make investment decisions. The applied NPV is a before-interest benchmark. The debt in this case is disregarded due to the uncertainty about the conditions and the amount of credit the potential investor is going to get.

The net present value (NPV) implies the difference between the present value of cash inflows and the present value of cash outflows over a period of time. It does not represent the profit or loss that can be generated during the project. The NPV simply indicates whether, within the investment, the desired MARR is achieved or not [56]. A negative NPV does not imply that there is a loss in the investment throughout the period of analysis. It indicates that the investment project is not generating the expected profit. Therefore, the acceptance criteria for the NPV in investment projects are based on the following: (1) NPV > 0 accepted; (2) NPV < 0 rejected.

3.1.2. Minimal Acceptable Rate of Return (MARR)

In order to carry out the financial analysis, the determination of a minimum acceptable rate of return (MARR) is required to provide a reference rate about the profitability of the investment. The MARR serves as a comparative base for the calculation of economic evaluations; if this rate of return is not obtained, the investment should be rejected and shall be defined as economically unviable. The MARR is defined by the investor and should consider the levels of inflation plus a risk premium [57].

The risk premium was defined considering the following assumptions: the electricity demand in Mexico is stable; it shows few fluctuations and will increase in the following years. In addition, the renewable energy market in Mexico is new; therefore, there is no strong competition among power plants. Based on the aforementioned, it is supposed that the investment risk is relatively low, and the risk premium can fluctuate between 2% and 5%. MARR is determined by the following formula:

$$\text{MARR} = \text{Three times the inflation rate} + \text{Risk Premium} \tag{2}$$

The inflation rate is assumed to be 4.28%. Therefore, the MARR in this study makes up 14% [8].

3.1.3. Internal Rate of Return (IRR)

The annual profit in the project can be expressed as IRR. The IRR is the interest rate, which equates the future value of the investment [58]. The IRR is the discount rate, which makes the NPV equals to zero. The acceptance criteria are the following: IRR > MARR = accepted, IRR < MARR = rejected.

3.1.4. Payback Period

The payback period refers to the exact time when the initial investment is recovered. The method for the calculation of the payback period may vary according to the type of project.

However, a recurrent formula includes the following aspects:

$$PP = n + \frac{(I - CFA)}{CFI} \tag{3}$$

where n is the immediate previous period in which the investment is recovered, I is the initial investment, CFA is the cash flow accumulated from the immediately previous period in which the investment is recovered, and CFI is the cash flow for the period in which the investment is recovered.

3.1.5. Input Categories

The calculation of project costs was based on literature sources [59,60]. The average capital costs and the operation and maintenance (O&M) costs are estimated based on typical project designs of AD plants with similar characteristics operating in Europe, therefore, there may be variations when applying the analysis of a real case. The capital costs are estimated to be €31.2 million. Capital costs include civil works, electrical and mechanical installations, but do not include the following elements: taxes, planning, and design fees. No pasteurization stage for disinfection of the waste is applied in the project due to the low percentage of the waste of animal origin, such as bones. It is assumed that the biogas plant needs 2 ha of land for its construction. However, the price of land is not considered in the economic model due to the lack of data. For the calculation of personnel costs, a salary of €14,000 per year [8] is considered. The lifetime of the project is expected to be 20 years, as in other studies [8,61]. The economic assumptions have also been checked with the data provided by bwe Energiesysteme GmbH, a German company with partners in Mexico. The input data for economic analysis is presented in Table 1.

Table 1. Input data for economic analysis.

Costs Values	
Investment Costs	€31,200,000
Technology (Electrical Equipment, Gas equipment and Heating equipment, Feeding technology and pre-treatment)	€12,900,000
Evaporator	€5,500,000
CHP units	€4,200,000
Civil Engineering Works	€4,900,000
Reception building and air treatment	€1,200,000
Electrical connection	€1,400,000
Planning	€400,000
Legal, Insurance, and Consultants costs	€200,000
Other costs	€500,000
Revenues	
Price of electricity	€0.06/kwh
Price of N2 in digestate	€1.38/kg of N2
Gate fee	€10/Mg MSW
Savings through shorter transportation distance	€1,579,316.31/a
Price of transport	€0.44/Mg/km
Other Parameters	
Tax	25%
Discount rate	14%
CHP efficiency (electrical)	38%

The revenue budget refers to the estimation of the expected economic profits through the sales of the product or service. The income generated by the project included electricity generation, sale of digestate, and gate fee for waste treatment. Electricity generation from biogas is assumed to be realized exclusively with CHP technology, proven to be an efficient option with huge market potential. Due to lack of heat demand, only the conversion of biogas to electricity is considered within this potential assessment. However, the heat provided in CHP is used to a certain extend to heat up the organic matter within the fermenter and for the evaporator.

The savings through shorter transport distance are considered to be the income source. The price of the transport is supposed to be €0.44/Mg of MSW per km [62]. The average distance of the current scenario where the waste from CEDA is delivered to a composting plant in Bordo Poniento and landfills in Mexico State is 36.81 km, while the length between the CEDA and AD plant is 20 km.

The price for electricity considered in this research is €0.06/kwh, which is based on the local commercial tariff High Demand in Medium Tension (GDMTH), as was done by Rios and Kaltschmitt [9]. This study applies the average price from the period starting from January 2018 until June 2019. Also, the result of the official 3d CENACE public electricity auction which took place in 2017 could be considered. The price established at the end of the auction was €11.2 per MWh, however, it cannot be applied for this study, given this price is only satisfactory for the big technology providers of photovoltaic parks and wind power plants, such as Enel Engie Solar, which participated in the 3d auction. Therefore, a higher price of €0.06/kwh is applied in this study. The price is stable during the lifetime of the AD plant; however, it is expected that it will increase.

The production of digestate is a source of income. The price of the bio-fertilizer was estimated by relating the N content to the average selling price per Mg of N-fertilizer in the urea and ammonium sulphate in Mexico; these prices were obtained from the Ministry of the Economy, at $1.55 USD/kg N (€1.38/kg) [63]. The gate fee is considered to be equal to the amount paid to the landfills, at €10/Mg MSW [64].

To collect the required data of the waste management system, available official reports, legal documents, and scientific literature related to the MSW trends in Mexico City were studied.

3.2. Environmental Assessment

For the purpose of the analysis, the calculation of environmental impact was conducted with the life cycle assessment (LCA) software EASEWASTE [65]. EASEWASTE is designed for LCA of waste management systems and facilitates a comprehensive environmental impact assessment by calculating waste flows, resource consumption, and environmental emissions from individual waste processes within the system. The model allows flexible definition of individual scenarios and includes default data needed for the LCA calculation. The model calculates emissions into water, air, and soil, along with the consumption of resources, and applies life-cycle impact assessment (LCIA) methods for conversion of these exchanges into environmental impacts [65]. Also, EASEWASTE considers the biggest number of indicators compared to similar programmes [66].

The LCA model calculates the emissions from "cradle to grave", from the point at which a material is discarded into the waste stream to its final disposal. The system boundaries of LCA analysis are presented in Figures 3 and 4. The functional unit of the study is 1 Mg of waste generated at CEDA. Scenario 1 involves direct landfilling of the residues (74%) and composting (26%). This represents a baseline option for waste management in Mexico City. The scenario includes construction and operation of a landfill, leaching to water and soil, and leaking of landfill gas during the 100-year time horizon. Scenario 2 represents an AD treatment of the waste. The scenario includes fugitive emissions, emissions from stationary engines, substitution of mineral fertilizer, and electricity. The data for both scenarios is based on the EASETECH database.

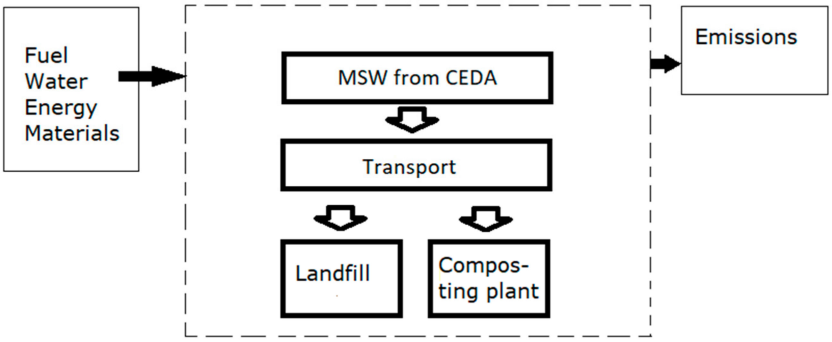

Figure 3. System boundary of LCA of baseline scenario.

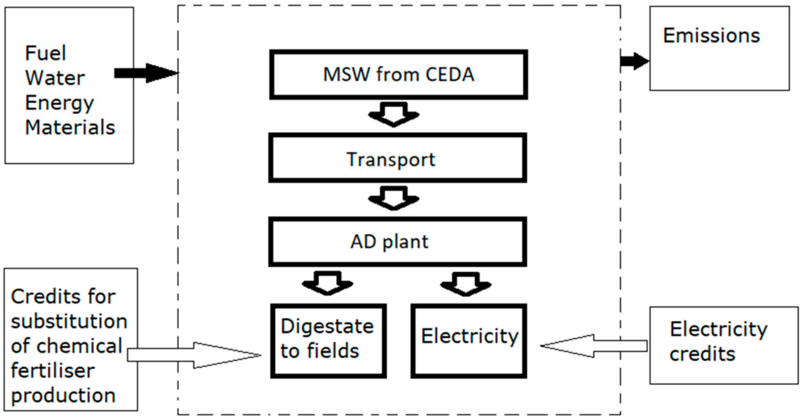

Figure 4. System boundary of LCA of AD scenario.

Energy derived from the AD system is regarded as a substitute for fossil fuel energy. Emissions into and alongside resource consumption, which would be avoided as a result of using a digester, are subtracted from the other emissions and resource consumptions in the waste system. The characterized environmental impacts assessed in this paper followed the IPCC 2007 methodology. The calculations were made using the database of EASETECH from July 2017. All the processes were based on the pre-modelled technologies existing in the database. The system boundaries are presented in Figures 1 and 2.

The program also evaluates emissions associated with the fuel consumption for collection and transportation of waste. The distance for waste transportation was calculated using the free geographic information systems (GIS) software QGIS. Location of the landfills and the biggest composting facility in Mexico City is presented in Figure 5. For the purpose of this analysis the following distances were considered: from CEDA to landfills (36.81 km), and from CEDA to the AD plant (20 km). The emissions from the transport of by-products of the compost (Baseline scenario) and of the digestate (AD scenario) are not considered. It is to be mentioned that the digestate is to be spread at the fields in Tláhuac, in the same borough where the AD plant is to be constructed. The exact destination of the compost is not defined.

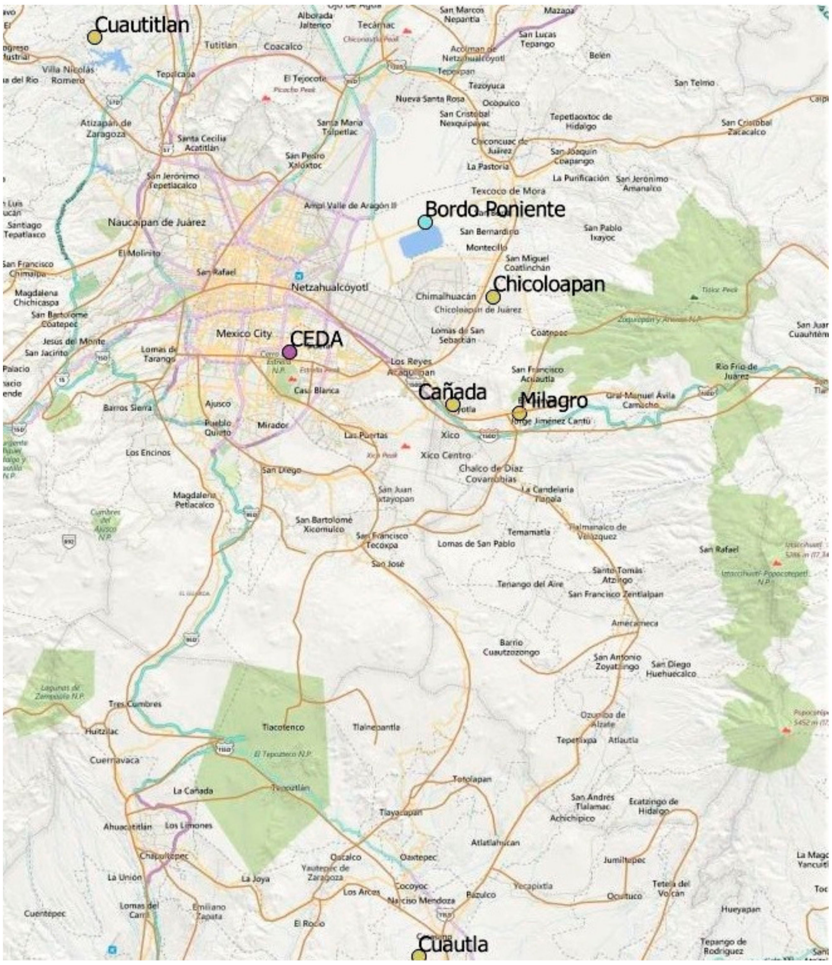

Figure 5. Location of the landfills and the composting facility Bordo Poniente and CEDA in Mexico City.

3.3. Composition Analysis

The analysis of waste composition was performed at the CEDA transfer station where the waste from the market is sent to. The samples were taken twice, in November 2017 and in February 2018. Five waste dump trucks were selected randomly. For the sample, five containers with a capacity of 200 L were collected. The composition analysis was performed according to the Mexican norm NMX-AA-15-1985 [67]. The results of the composition analysis are presented in the next section.

3.4. Physicochemical Analysis

For the physicochemical analysis, the samples were ground to homogenize the components. Every experiment was performed 10 times to define mean values and standard deviations. The analysis included the following procedures: pH definition according to NMX-AA-25-1984 [68], water content (NMX-AA-016-1984) [69], organic matter (NOM-AA-21-1985) [70], ashes (NMX-AA-18-1984) [71], C/N ratio (NOM-AA-67-1985) [72], phosphorous (NMX-AA-32-1976) [73], and nitrogen (Micro-Kjeldahl method) [74].

3.5. Sensitivity Analysis

The Sensitivity Analysis procedure is based on previous work [61]. The analysis consists of a series of tables that show the effect of varying the most important input parameters (electricity price, gate fee, digestate price, investment costs, biogas yield, and efficiency degree of CHP) on the financial feasibility indicators. The variation range for the parameters is 10%.

4. Results

4.1. Waste Composition

Table 2 presents the composition of the sample of the waste generated at Central de Abasto. The sample is almost purely organic and contamination does not exceed more than 1%. Therefore, this fraction is suitable for the AD process and does not need a pasteurization stage due to the low percentage of animal products.

Table 2. Waste composition of MSW from Central de Abasto.

	Mean Value		Standard Deviation	
Waste Category	**Kg**	**%**	**Kg**	**%**
Broccoli and Radish	0.13	0.23%	0.1	0.001%
Lettuce	0.77	0.01%	0.8	0.015%
Peas, Beans	1.11	0.02%	0.9	0.014%
Nopal	0.11	0.002%	0.1	0.002%
Spinach	2.18	0.04%	1.8	0.027%
Onion and Garlic	0.07	0.001%	0.05	0.001%
Tomato	10.09	0.18%	9.6	0.150%
Carrot	0.13	0.002%	0.1	0.001%
Herb	0.90	0.02%	0.9	0.017%
Cane	0.13	0.002%	0.1	0.002%
Tangerine	1.10	0.02%	1.1	0.017%
Mandarin	2.19	0.04%	0.3	0.002%
Orange	3.01	0.05%	0.2	0.001%
Exotic Fruits: Avocado, Papaya, Pineapple, Banana	1.05	0.02%	0.4	0.008%
Sweet Fruits: Apple, Grape	0.25	0.004%	0.1	0.002%
Chili	0.11	0.002%	0.1	0.002%
Jicama	0.59	0.01%	0.6	0.011%
Watermelon	2.96	0.05%	3.0	0.047%
Flowers in Good Condition	0.28	0.005%	0.3	0.005%
Bones, Stems, Shells, Leaves	11.02	0.19%	2.7	0.027%
Residues of Edible Grass (Stems, Leaves, and Roots)	5.20	0.09%	5.2	0.101%
Residues of Nopal	7.46	0.13%	1.2	0.035%
Residues of Corn	5.50	0.10%	4.7	0.093%
Wood, Plastics, Styrofoam, Paper	0.28	0.005%	0.0	0.001%
Rest	0.78	0.01%	0.8	0.012%
Total	57.36	100.00%		

Table 3 shows the results of the physical-chemical characterization of the sample. In order to obtain representative results, ten replicates were analyzed for each type of waste and the mean values were calculated. These values correspond to the parameters needed for a stable AD process, as mentioned in other studies [75,76].

Table 3. Characteristics of MSW from Central de Abasto.

Parameter	Mean Value	Standard Deviation
pH	4.03	0.06
Water content (%)	80.9	1.34
Dry matter (DM) (%)	19.1	Calculated, based on water content
Organic DM (%)	17.34	Calculated, based on previous work [44]
Ash (%)	7.96	0.25
Nitrogen (%) of DM	1.39	0.22
C/N ratio	39.01	5.55
Phosphorous (ppm)	120.94	22.33

4.2. *Economic Analysis*

4.2.1. Quantification of Energy Generation

The economic analysis of the project is based on the estimation of the biogas generation from the substrate presented in Table 2. According to the study of German Corporation for International Cooperation (GIZ) in Mexico, the values of the theoretical potential biogas generated in cubic meters per Mg of MSW from the studied wholesale markets is 634 m^3/Mg DM of MSW. This varies depending on factors such as climate conditions, type of waste, microbial activity, dry matter content, and the composition of the waste. For the purpose of the present analysis, the model relates to information from the GIZ. These results match the outcomes of the previous research in Mexico City [76,77]. Therefore, these values were used to calculate the energy generation in this case study. Considering the amount of waste generated in CEDA, the modeling resulted in an estimation of biogas, including expected generation, as shown in Table 4.

Table 4. Energy generation of the project.

Origin of MSW	Biogas Yield (m^3/Mg of OFMSW)	Electricity Generation (kWh_{el}/Mg)	MSW Generation (Mg/a)	Electricity Generation (kWh/a)	Installed Capacity (kW_{el})
CEDA	111.34	253.86	213,525	54,205,309.57	6776

4.2.2. Quantification of Costs and Revenues

The cost structure is described in order to provide detailed information related to the expected expenses. The investment costs include construction works, all equipment required, and a spare parts package in case of necessary repairs. The equipment is specified according to the project size and expected energy generation. Running costs include O&M.

The revenues and expenditures are presented in Table 5. The total installed capital cost is €34,200,000. The cash flow output considers total estimations of O&M costs during the operating years and the cashflow input shows the revenues. Finally, the estimated net incomes and cash flows of the project are shown. The total installed capital cost is high; therefore, the project starts to generate profits only after 7 years of operation. The cash flow can be found in the Supplementary Materials.

Table 5. Annual revenues and expenditures.

Revenues (Figures in 1000 of €)	**€/a (Figures in 1000 of €)**
Sale of Electricity	3088
Sale of compost	782
Gate fee	2135
Savings from transport costs	1579
Expenditures	
Maintenance cost (without engines)	312
Maintenance cost (engines)	170
Engine (major overhaul)	400 every 7th year
Self-consumption of electricity	434
Insurance	156
Disposal of contamination at landfill	137
Sulfur acid consumption	95
Personnel costs	84
Transport from digestate	75
Analysis of substrate	6
Other expenses	312

The cash flow is based on the lifetime of 20 years. For the purpose of this analysis, the NPV = €1 436.64, which is positive value, and therefore, investment in this case should be pursued. The model resulted in IRR = 11%. The payback period is 6.34 years. The cumulated cash flow is presented in Figure 6.

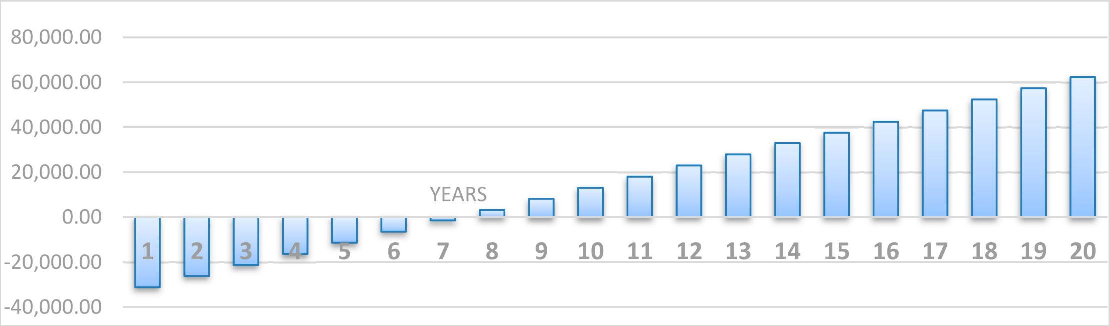

Figure 6. Cumulated cash flow of the project.

4.3. Environmental Impact

The project is based on an AD plant with an average daily capacity of 585 Mg of MSW. The alternative scenario represents the present disposal structure as a baseline, where the waste is disposed at the landfills and composting plants. Therefore, the main environmental benefits are represented by the amount of methane avoided, which is not released into atmosphere, but captured and utilized for electricity production. In addition, as disposal sites are located far from Mexico City, the use of fossil fuels for the transport of the waste to the final disposal site contributes to the environmental impact. For the purpose of this study, the construction of the biogas plant takes place in the borough Tláhuac. It is located on the south east edge of the district, and while much is still rural, it has land available for the AD plant and agricultural fields to accept the produced digestate. Also, Tláhuac is the neighboring municipality to Iztapalapa, where the CEDA market is located. Therefore, the implementation of the project can help to reduce the emission of pollutants to the atmosphere through the reduced transportation distance.

The project is expected to collect 63,722 m^3 of biogas daily (assuming 57% of methane), and that approximately 36,321 m^3 of methane are expected to be avoided through the capture and burning of the biogas. Also, this project evidences important environmental benefits through shorter transportation distance of 0.527 kg CO_2 eq per Mg of MSW based on the calculations of Easetech database. The emissions (kg CO_2 per Mg) per process are presented in Table 6. The major impact in the baseline scenario is made by degradation of organic waste in landfills. The low emission level of the AD scenario is explained through the shorter distance for transportation of MSW, avoidance of decay of organics in landfills, and emission offset through substitution of grid electricity. Overall, the construction and operation of the AD plant can help to reduce the environmental impact by 730 kg CO_2 per Mg of MSW.

Table 6. LCA Results.

Baseline Scenario	kg CO2-Eq/Mg MSW	AD	kg CO2-Eq/Mg MSW
Composting	16.26	AD	2.91
Landfill	716.03	Transport of MSW	1.10
Transport of MSW	2.12		
Sum	734.42	Sum	4.01

4.4. Employment

The project is expected to generate six job positions for staff responsible for operating and supervising the plant [62].

4.5. Sensitivity Analysis

The sensitivity analysis was performed considering the following parameters: electricity price, gate fee, digestate price, investment costs, biogas yield, and efficiency degree of CHP with a variation range of 10%. According to the results, the project is sensitive to the change of electricity price. With the decrease of electricity price and CHP efficiency, as well as with the rise of investment costs, the NPV becomes negative (Table 7). The files can be found in the Supplementary Materials.

Table 7. Parameters for Sensitivity Analysis.

Parameter	Variation	NPV
Electricity Price	+10% −10%	2689.21 −295.73
Gate Fee	+10% −10%	2451.69 330.39
Digestate Price	+10% −10%	1779.64 1002.44
Investment Costs	+10% −10%	−1657.53 4530.81
Biogas Yield	+10% −10%	2797.08 67.82
Efficiency Degree of CHP	+10% −10%	2801.69 −1045.26

5. Discussion

Based on the results of the feasibility study, the barriers for the application of anaerobic digestion for MSW in Mexico can be summarized and divided into administrative, economic, and market-related [78]. Among administrative barriers in Mexico are the following: bureaucracy (including difficulty in obtaining permission), instability of policies, discontinuity of support measures, and lack of public acceptance of the technology. The process of application and authorization is complicated and may need years to complete. This may lead investors to lose interest, in view of the significant upfront expenses and faraway returns, slowing down the development of the entire sector. Also, a change of government may affect the implementation of infrastructure projects, as happened with the incineration plant which got delayed for an undefined time. Another issue concerns the failure of the government to perform the efficient source-separation and separate collection of MSW. Therefore, organic substrates with low contamination suitable for the AD process would be missing.

The second category includes the need for large investment, lack of long-term perspective, low profitability through sales of electricity, no use for generated heat, limited investment resources due to possible economic recession, and costs of transportation. Financing is frequently mentioned as a problem for the implementation of biogas projects in many countries [26]. Even in Germany, which has a well-developed internal biogas market, some biogas facilities suffer from lack of long-term perspective [79]. Financing is also the biggest barrier for the development of AD technology for waste treatment, as can be observed in the previous section due to the negative NPV value.

Market-related barriers are presented for the use of biogas, since biogas is part of a regulatory system for renewable energies (together with solar, hydro, and geothermal); this results in a functional orientation toward maximizing electricity production within biogas facilities. Heat-only production and injection into the gas grid have been largely ignored by incentive schemes. Biogas can be used for other purposes than the production of electricity alone, such as district heating and transportation, in which its use is more efficient and sustainable in terms of energy and environment. In addition, biogas has the ability to be stored for later use. Since producers have no incentive to use the heat produced, aside from self-consumption, no infrastructure for its exploitation is created and heat excess is released into the atmosphere. The upgrade to biomethane to be injected into the natural gas network should also be considered. This praxis has grown in European countries in the last years. Biomethane can be also applied in the transportation sector. In Mexico, transportation is the sector with the highest energy consumption—2362 PJ per annum and 46% of the total energy consumption in 2017 [80]. In light of these considerations, an overall reorganization of incentives is generally needed regarding the overall recovery of energy and of all other by-products from each project, as well as diversification of final uses for the biogas [81].

Another market-related barrier refers to the absence of the high demand for the substrate as organic fertilizer. Most farmers display a “more-is-better” preference [82], in which over-fertilization leads to eutrophication of water bodies [83]. An educational concept could help gardeners and farmers develop practices which are both more ecologically sound and personally more satisfying. Positioning digestate-based fertilizers as environmentally friendly may create a market and prevent the negative environmental impact of overfertilization.

6. Study Limitations

The composition analysis was performed twice, which explains high standard deviation. For further research it is recommended to take more samples for the analysis.

Calculations of the economic modelling are based on the current prices and future fluctuations, for example, for maintenance costs and the increase of electricity, price was not considered. This approach was also used in previous work [84]. Also, no capital and property costs were considered due to the lack of data.

In LCA the emissions from transportation of digestate and compost to final disposal is not considered. Due to the lack of field data, LCA is performed based on the database of EASETECH.

7. Conclusions

In Mexico City there is available stock for anaerobic digestion—the residues from the Central de Abasto, which are predominantly organic. Energy generation by biogas from this fraction has be proven, in the terms of this study, to be a financially feasible option. However, an attractive panorama for clean energy was not evidenced. The project has to cope with several barriers, such as administrative, market-related, and economic, given low production of energy through biogas in Mexico. The financial indicators, including NPV, IRR, and payback period, prove the profitability of the investment, therefore, the project was evidenced as economically feasible. However, the results are not stable and change with the decrease of electricity price and CHP efficiency or increase of investment costs.

The analysis also evidenced positive environmental impacts due to the decrease of methane released in the atmosphere. Therefore, incentives from the government are needed to promote the AD technology. The development of new alternatives for waste treatments, such as biogas plants, can lead to an integrated waste management system in Mexico, where waste is incorporated in a virtuous circle.

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