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Financial and Technical Evaluation of Energy Production by Biological and Thermal Treatments of MSW in Mexico City

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Abstract: This research aims to compare, from a technical and financial perspective, the application of biological (methane-capture) and thermal (incineration) treatments of waste in Mexico City in order to generate clean energy. For each alternative, pessimist (50%), realistic (80%), and optimistic (100%) scenarios were considered in terms of the efficiency collection rates of methane and the efficiency of the capacity conversion factor for incineration. For the methane project, the LandGEM model was used to evaluate the potential generation of methane. In order to calculate the electricity output that could be generated through incineration, we relied on two key factors: the total amount of heat that could be generated by burning the waste and the average level of moisture in the waste material. The evaluation resulted in an annual energy generation of 206.09 GWh for methane and 4183.39 GWh for incineration, both in the realistic scenario. Both projects reported positive financial indicators with a discount rate of 12%. Incineration resulted in a net present value of USD 706,377,303 and an internal rate of return of 23% versus USD 4,975,369 and 24% for the methane project. However, the incineration project only became feasible by omitting financing. Incineration resulted in a payback period that was lower by a ratio of 2:1 compared to methane, but the levelized cost of energy resulted in higher figures (USD 216.92). The aim of these findings is to support the decision-making process for the creation and implementation of sustainable energy strategies based on circular economy principles in Mexico and other similar regions across the globe.

Keywords: incineration; methane; Mexico City; waste-to-energy; sustainable energy

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1. Introduction

Excessive growth in urban sprawl can lead to the emergence of several problems which impact society and the environment. The higher the population and population density, the higher the demand for public services such as water, electricity, transportation, waste management, and communications, as well as the higher the increment of pollution [1]. In this regard, Mexico City is the largest city in Mexico and one of the largest in the world. With a population of over 21 million people (also considering the metropolitan area) [2], the city generates a huge amount of municipal solid waste (MSW) every day. The problem of MSW in Mexico City is complex, and it is characterized by an inadequate waste-management infrastructure and a lack of public awareness about waste reduction, reuse, and recycling [3–5]. According to the government's official figures, the city generates about 13,400 tons of MSW every day [6]. However, only about 85% of this waste is collected, and the rest ends up in streets, rivers, and landfills [7,8]. The city utilizes external landfills, but most of them are already full, and they do not comply with environmental standards nor counter their impact with biogas capture systems [9].

Another problem is that a significant amount of the waste is dumped illegally in open spaces, creating environmental and health hazards [10]. Furthermore, the informal sector of waste pickers known as "pepenadores" plays a crucial role in recycling, but they work in hazardous conditions and their work is often not recognized [11]. In 2023, the waste-management infrastructure of the city comprises 13 transfer stations and 3 sorting plants; nevertheless, the high number of unregulated actors within the recycling chain results in a low recycling level of 10% [6].

The government has implemented several initiatives to tackle the problem of MSW in Mexico City. For example, the city has introduced a program to separate organic waste, and some areas have implemented a pay-as-you-throw system to encourage waste reduction [12]. The government has also created a program to support the formalization and professionalization of waste pickers. However, these initiatives face several challenges, including a lack of funding, inadequate waste-management infrastructure, and low public awareness about waste reduction and recycling [13,14]. Therefore, there is a need for a comprehensive approach that involves all stakeholders, including the government, the private sector, and the public to address the problem of MSW in Mexico City. Particularly, projects and initiatives focused on energy exploitation with a sustainable approach are required not only to mitigate the environmental impacts associated with MSW but also to increase the generation of clean energy that can gradually substitute for fossil-fuel dependency. In the field of waste treatment, thermal and biological approaches have been extensively developed; nevertheless, these types of technologies are non-existent in Mexico. Thermal treatment for MSW refers to a process that uses heat to treat and dispose of MSW [15]. There are several types of thermal treatment for MSW, including incineration and gasification. Incineration involves burning MSW at high temperatures (usually between 800 and 1200 degrees Celsius) to convert the waste into ash, gases, and heat [16]. The heat generated by incineration can be used to generate electricity or to heat buildings [17]. Incineration can help reduce the volume of MSW and generate energy; however, it also has potential environmental impacts. Incinerators emit pollutants such as nitrogen oxides, sulfur dioxide, and particulate matter, which can contribute to air pollution and respiratory problems; furthermore, waste incineration can release greenhouse gases such as carbon dioxide and methane, as well as ash that contains heavy metals and other toxic substances, which can pose risks to human health and the environment if not properly disposed of. In addition, incineration facilities can discharge pollutants into water sources, such as wastewater from scrubbers used to remove pollutants from flue gases [18]. Therefore, it is important to use advanced pollution-control technologies to minimize these impacts. Thermal treatment can also be used in combination with other waste-management methods such as recycling and landfilling. For example, incineration can be used to treat the non-recyclable fraction of MSW, while the recyclable materials can be separated and processed for reuse [19,20]. This can help reduce the amount of waste sent to landfills and minimize the environmental impacts of waste management. On the other hand, there are also several biological treatment methods for MSW that can help to reduce the volume and environmental impact of waste. These methods may include composting, anaerobic digestion, and methane-capture systems in landfills [21]. From these, methane capture in landfills is a process of capturing and utilizing methane gas that is produced during the decomposition of organic waste in landfills [22]. As organic waste decomposes in landfills, it produces a mixture of gases, including methane, carbon dioxide, and other trace gases [23]. In order to capture methane gas in landfills, a system of pipes and collection wells is installed in the landfill; the pipes and wells are used to collect the methane gas that is produced during the decomposition process [24,25]. The collected methane gas can then be used as a renewable energy source.

From these technologies, controlled incineration and methane capture can arise as a potential project to be implemented in developing countries with a high rate of MSW generation such as Mexico. Nevertheless, as mentioned before, this type of infrastructure is non-existent in Mexico City. Therefore, feasibility studies should be conducted in order to generate key technical, environmental, and economic indicators to assist the decision-making process regarding investment and the implementation of this infrastructure. Although several research works have focused on the evaluation of viability of waste-to-energy projects in developing countries, none of these have used Mexico City as a study location. Several recent studies have evaluated the feasibility of these technologies in cities with similar demographic conditions such as Sao Paulo, Brazil [26], Lagos, Nigeria [27], and New Delhi, India [28]; however, although such results can be taken as a reference, due to the fact that particular parameters such as climatic conditions, the characterization of waste, and the distance of waste-management facilities from urban settlements are defining aspects to determine feasibility, there is gap in the research regarding Mexico. Under this approach, the aim of the research is to conduct a financial and technical evaluation of energy production by methane capture and waste incineration in Mexico City by comparing key performance indicators which enable the identification of the best suitable alternative in the context of Mexico City. With this, we expect to answer the research question: Which energy alternative is more profitable for the specific case of Mexico City: methane-capture systems in landfills or the construction of a controlled waste-incineration plant?

2. Materials and Methods

Since the research question and the general aim focus on the determination of the technical and economic feasibility of methane-capture systems and controlled incineration plants, the methodology applied aims to address the lack of key indicators regarding the performance of both alternatives. Therefore, firstly, the methodology is based on obtaining technical parameters such as methane flow rates for the capture system and calorific potential values for incineration. Hence, first-order equation models are the most suitable approach. Secondly, as the economic reliability is also required, valuation methods that take into account the change in money over time are also suitable for this research. The overall methodology approach followed in this research allow readers to replicate our estimations and projections with scientific rigor given that all equation models have been validated in several research works.

2.1. Energy Recovery from Biogas

The recovery of energy from landfill-CH_4 has been identified as a feasible process since biogas is composed mainly of carbon dioxide and methane. However, measuring landfill-CH_4 emissions is difficult, so first-order decay gas-generation models are recommended to estimate gas production over the lifespan of the landfill. This research used the LandGEM model developed by the US-EPA [29] to measure CH_4 emissions, which is known to provide reliable estimates in temperate climate regions of North America [30]. The LandGEM model includes several variables, such as the potential CH_4-generation capacity and the CH_4-generation rate, to estimate the landfill gas-generation flow rate based on the mass of solid waste disposed of each year and its age. Equation (1) describes the LandGEM Model:

$$Q_{LFG} = \sum_{t=1}^{n} \sum_{j=0.1}^{1} kLo \left[\frac{Mi}{10} \right] \left(e^{-kt_{ij}} \right) \tag{1}$$

For CH_4-yeilds, an L_0 value of 3204 ft^3/tonne was used, considering organic waste with an average moisture of 64.3% in a summer scenario as suggested by Ozcan et al. [31]. The generation rate k was 0.040 k/yr, considering a value of 663.5 mm/yr of precipitation in the region [32]. The methane content in the landfill gas was fixed at 50%, and the collection efficiency considered three scenarios: 50%, 80%, and 100%. Taking into account the aforementioned parameters, the evaluation involved the operation of an 800-acre landfill on the outskirts of Mexico City with a reception rate of 13,149 tons of MSW. The waste characterization followed the percentages reported in the last available yearbook from the Ministry of Environment in Mexico City (see Table 1).

Table 1. Waste characterization utilized in LandGEM [33].

Waste Type	Tons	%	Waste Type	Tons	%
Organic waste	5404.24	41.10%	Textiles	276.13	2.10%
Aluminium	78.89	0.60%	Coloured glass	144.64	1.10%
Paperboard	407.62	3.10%	Clear glass	394.47	3.00%
Leather	131.49	1.00%	Cotton	223.53	1.70%
Tetra Brik	670.60	5.10%	Fine residue	131.49	1.00%
Cans	512.81	3.90%	Vegetable fibber	131.49	1.00%
Ferrous metal	131.49	1.00%	Synthetic fibber	394.47	3.00%
Paper	775.79	5.90%	Rubber	223.53	1.70%
Plastic film	618.00	4.70%	Ceramic	144.64	1.10%
Rigid plastic	539.11	4.10%	Diapers	394.47	3.00%
PET	1104.52	8.40%	Other	315.58	2.40%
Total: 13,149 tons					

The study also took into account an average depth of 19.81 m, which is typically used for landfill cells in the region, in order to estimate the costs of installing vertical gas wells for a new landfill gas-collection and flaring system (not expanding the existing system). The methane exploitation was assumed to start from the fifth year of the landfill's operation. Additionally, the study calculated the carbon-dioxide emission savings using Equation (2) for the methane scenario [34].

$$CH_4MT = (AGU)(\%CH_4)(GWPCH_4)\left(\frac{0.0423lbCH_4}{ft^3CH_4}\right)\left(\frac{0.9072MT}{2.000lb)}\right)\left(\frac{MMT}{10^6MT}\right) \quad (2)$$

It must be noted that for the purposes of this research, the LandGEM model is a reliable tool to estimate methane yields as proven in other research works [22,30]; however, we recognize that the model assumes several factors according to preloaded data and this might cause a simplified approach to estimations. The model's accuracy depends on the quality and availability of input data, and it may not reflect site-specific conditions or the variability in landfill operations for other geographic conditions. It must also be noted that the model provides estimates of methane emissions with a degree of uncertainty and has the potential to underestimate methane emissions from landfills, especially in cases where gas collection and control systems are not fully operational or where landfill operators do not provide accurate data.

2.2. Energy Recovery from Incineration

The estimation of the energy from incineration first considered the per capita generation index fixed at 1.48 kg per person each day. The volumetric fraction assumed equal values to those reported by SEMARNAT [33]. The study utilized information on calorific values (wet basis) gathered from technical studies conducted by the Japan International Cooperation Agency in Mexico City [35], in order to determine the potential energy yield of MSW. The focus was on mobile grate incineration technology, which is currently the recommended approach [36]. This technology slowly moves the waste through the combustion process [37]. The incineration process includes two key stages: in-bed moving-grate combustion and over-bed gas-turbulent combustion [38]. In order to facilitate the combustion process and avoid incomplete combustion, oil was used as an auxiliary fuel. The study assumed that the residual ash yield would remain steady at 2.5–3% under consistent conditions [39]. To calculate the MSW energy potential, the study employed the Bernal et al. method [40], which involves determining the lower calorific value of each waste type and multiplying it by the total mass of waste and calorific values reported in other studies [41–43]. The total calorific value was determined by applying a conversion constant based on the density and moisture content of each waste type, using values reported by Gawande et al. [44]. The results of this analysis could be useful in the development of sustainable energy strategies based on circular economy principles in Mexico and similar regions around the world. The parameters described were calculated using Equations (3) and (4).

$$LCV_{\mathrm{i}} = (LCV)(W_{\mathrm{i}})(k_1) \tag{3}$$

$$CV_{\mathrm{Total}} = \sum\nolimits_{i=1}^{m} LCV_{\mathrm{i}} \tag{4}$$

After calculating the total calorific values, we used Equations (5) and (6), developed by Santos et al. [45], to determine the power and energy generated in the incineration process. Equation (5) considers the achievable electrical power from the thermal process (20%), a unit setting constant (k_2 = 0.01157), the electrical power in kW (P), the number of hours per year (8760), and a capacity factor (C_{f}) which we evaluated in three different scenarios: pessimistic (0.5), realistic (0.8), and optimistic (1). Equation (5) shows that the total calorific value is related to the achievable electrical power in incineration processes, which ranges from 28 to 32% for mixed MSW with less than 10% moisture content according to Leme et al. [46]. Equation (6) relates the electrical energy resulting from the incineration process to the efficiency rates considering an operating schedule of 8760 h per year.

$$P = (CV_{\mathrm{Total}})(\eta)(W)(k_2) \tag{5}$$

$$E = \frac{(P)(C_{\mathrm{f}})(8760)}{1000} \tag{6}$$

2.3. Economic Estimations

The economic study for the methane project considered the evaluation of a set of turbines with a CHP system (combined heat and power), since it is the recommended technology for large-scale projects [33]. The project infrastructure also considered the pipeline and the burning system, as well as the interconnection equipment with the nearest power substation (5 km). The financial parameters can be observed in Table 2. The selling price of the energy (USD/kWh) was based on the intermediate usage rate (over 75 KW/h) according to official rates authorized by the Federal Commission of Energy of Mexico [47]. The interest rate took as a reference TIIE published by BANXICO in April 2022. The inflation rate was fixed considering the average value during the second quarter of 2021. Finally, the marginal tax rate took as a reference the income tax (ISR) in Mexico.

Table 2. Economic inputs for financial estimations of the biogas project.

Parameter	**Value**
Electricity generation (USD/KWh)	0.094
CHP hot water/steam production (USD/million BTU)	2.5
Annual electricity purchase price escalation rate (%)	2
General inflation rate (%, applied to O&M costs)	3.5
Equipment inflation rate (%)	3.5
Marginal tax rate (%)	35

On the other hand, the economic study for the incineration project considered the evaluation of moving-grate boilers. The technical features of the technology are shown in Table 3. The capital cost of the project involved the total investment of fixed and current assets; we used Equation (7) which considers the total cost according to Xin-Gang et al. [37], the total investment in US millions, and the expected power in kWh/yr. The estimated values also consider the expenses associated with technical equipment to mitigate environmental impacts related to ash and leachate control. Finally, construction and installation, land use, loan interest, and administrative expenses were also considered

$$I = (15{,}797)\left(P^{0.82}\right) \tag{7}$$

Table 3. General characteristics of moving-grate technologies employed in the economic assessments [48].

Item	Characteristic
Requirement of calorific material	>1200 kcal per kg
Auxiliary fuel	Oil
Application conditions	Higher heat value, plenty of financial resources, state-owned operator
Technical maturity	Long history, mature technology
Operating cost	4% of total capital cost (investment)
Flue gas	3500–4800 m^3 per ton of waste
Flying ash	2.5–3% of the waste disposal amount
Leachate treatment	Separate treatment, cannot be sprayed back into the furnace for combustion

In addition, the O&M cost estimation considered 8% of preliminary capital [49]. Finally, the price of energy for each MWh was fixed at 69 USD according to official rates applicable in Mexico [47].

In both biogas and incineration, the financial profitability was measured by evaluating net cash flows with a discount rate of 12% to obtain the net present value (Equation (8)) and the internal rate of return (Equation (9)), where the net cash flows were evaluated with a discount rate of 12%.

$$NPV = \sum\nolimits_{t=1}^{n} \frac{(E \cdot t) - C_{o\&m}}{(1+i)^{n}} - I \tag{8}$$

$$0 = NPV = \sum\nolimits_{t=1}^{T} \frac{C_t}{(1+IRR)^{t}} - I \tag{9}$$

In the end, we calculated the levelized cost of energy by comparing the total energy generated with the overall capital investment needed.

$$LCOE = \frac{\sum_{n=0}^{T} (I_{\mathrm{n}} + O_{\mathrm{n}} + M_{\mathrm{n}}) - (1+i)^{n}}{\sum_{n=0}^{T} E_{\mathrm{n}} - (1+i)^{n}} \tag{10}$$

3. Results and Discussion

3.1. Biogas Generation Performance at Different Efficiencies Rates

The generation of MSW reaches 4,799,385 tons/year (see Table 1). This value would result in a peak methane generation of 26,400 (ft^3/min) with an annual average of 15,387 (ft^3/min) for the optimistic scenario (100% collection efficiency). At 80%, the CH_4 obtained would reach 12,309 (ft^3/min), whereas 7693 (ft^3/min) would be obtained with a 50% collection efficiency rate (see Table 4).

The data presented in Table 4 illustrate that yields vary significantly based on collection efficiency rates. While methane projects have been proven feasible with collection efficiencies of up to 33% [50], it is recommended that collection-efficiency rates ranging from 50 to 80% are used for MSW management in landfills with advanced equipment, given the project size and operating schedule, as noted by Calabro [51]. This is because lower collection-efficiency rates result in a significant decrease in energy production and a rise in total CO_2 and CH_4 emissions. It should be noted that the primary methane generation is based on the temperature, rainfall, and moisture content of the waste. An accumulated rain precipitation of 663.5 mm/yr in the region with an average temperature of 26 °C was considered for the analysis to fix the methane generation rate (k). Therefore, these results are based on reliable parameters suitable for measuring energy-generation levels, and they are in agreement with comparable results reported in the literature [52,53].

Table 4. Methane yields at different collection efficiencies.

	Pessimist (50%)	**Realistic (80%)**	**Optimistic (100%)**
Average annual amount of methane generated during the project lifetime (ft^3/min LFG)	7693	12,309	15,387
Total lifetime amount of methane collected and destroyed (million ft^3)	30,327	48,523	60,654
Average annual amount of methane collected and destroyed (million ft^3/yr)	2022	3235	4044
GHG value of total lifetime amount of methane utilized in energy project (MMTCO2E)	13.529	21.646	27.058
GHG value of average annual amount of methane utilized in energy project (MMTCO2E/yr)	0.902	1.443	1.804
Total lifetime carbon dioxide from avoided energy generation (MMTCO2E)	1.376	2.202	2.753
Average annual carbon dioxide from avoided energy generation (MMTCO2E/yr)	0.092	0.147	0.184

3.2. Calorific Potential for the Incineration Scenario

After analyzing the waste samples, the total calorific value (TCVi) was determined to be 13,951.56 kJ/kg by combining the lower calorific potential of each type of waste and using a conversion constant of 4.184 as suggested by Silva et al. [49]. Table 5 shows the volumetric weight and estimated calorific potential in kcal/kg for each waste type as reported by JICA [35]. The obtained TCV of 13.95 MJ/kg falls within the acceptable range reported in various cities around the world, such as Istanbul, Turkey, with 14.8; Lahore, Pakistan, with 25.9; and São Paulo, Brazil, with 21.6 [54–56]. The values obtained are suitable for energy estimations, as the World Bank [57] recommends incineration projects if the TCV is greater than 7 MJ/kg.

Table 5. Total caloric value of selected waste.

Type of Waste	**Volumetric Weight (%)**	**Calorific Values (kcal/kg)**	**Lower Caloric Value (kJ/kg)**
Organic waste	0.411	1673	2876.93
Paperboard	0.031	3910	507.14
Leather	0.01	3400	142.26
Tetra Brik	0.051	2729	582.32
Paper	0.059	4400	1086.17
Plastic film	0.047	9970	1960.58
Rigid plastic	0.041	8500	1458.12
PET	0.084	11,030	3876.56
Textiles	0.021	4000	351.46
Cotton	0.017	3300	234.72
Rubber	0.017	5600	398.32
Diapers	0.03	3800	476.98
	Total		13,951.64

3.3. Energy Recovery

The methane project evaluated three scenarios with variable collection efficiencies; the flow rates observed in Table 4 allowed us to measure different feeding values in the CHP turbine generation set. The realistic scenario (80%) resulted in 49,324.08 kW of total capacity and an average energy production of 206 GWh/yr. As reported in Table 6, the variation among the pessimistic and realistic scenario differs by 29.75 GWh/yr. It must be noted that for the case of methane, the generation gradually increases year by year. In the first three years, the energy generation remains lower than 100 GWh, whereas in the three final years, the generation surpasses 300 GWh. These significant variations are due to the amount of CH_4 captured. As the volume of waste increases every year, so does the methane flow rate. After the 20th year, the generation and capture of methane gas start to decrease because the landfill cells begin to close. As the amount of methane gas decreases, the energy generation also decreases, making it less viable to use methane for energy purposes. Therefore, it is recommended to utilize methane for energy purposes only for a period of 15 years.

Table 6. Energy generation (GWh/yr).

	Pessimistic	**Realistic**	**Optimistic**
Methane	176.34	206.09	244.11
Incineration	3558.51	4183.39	4862.35

By contrast, the energy recovery in thermal processes resulted in 4183.39 GWh/yr in a realistic scenario. In order to obtain the variation, we also calculated the power generation by adjusting the capacity factor in the energy-transformation process at 50%, 80%, and 100% to match the scenarios of methane. As observed in Table 6, the incineration project reports significantly higher values than methane. Nevertheless, the energy generation in both alternatives can provide important contributions towards increasing the electricity generation from sustainable sources. The average per capita energy consumption in Mexico reaches 2220.52 kWh [58], which involves a total energy consumption of 19,662.70 GWh for Mexico City. The domestic sector utilizes 2556.15 GWh (13%), transportation 11,797.62 (60%), industry 4719.04 (24%), and service/commerce 589.88 (3%) [59]. Taking into perspective such parameters, methane exploitation could supplement 8.06% of the domestic consumption with a complementary total residual heat of 13,601,988.95 million BTUs at 76.6 °C that could satisfy the heating requirements of 2210 households, given that 12,000 Btu/h can heat 24 m^3 of space [60] as reported in successful applications of heat resulting from methane burning [48,61].

With respect to the incineration project, the total energy generation in the realistic scenario could cover the totality of the domestic demand of 3.96 million households, since the energy consumption per household in Mexico is reported to be 1504.90 kWh [59]. The incineration project could provide 21.28% of the total energy demand in the city. Nonetheless, although the values obtained demonstrate attractive yields, our results must be taken with caution since several assumptions were considered during calculations. The incineration project assumes the combustion of the entire flow of MSW generated, which in practice is hard to replicate since, as some studies suggest [21,62], the implementation of thermal treatments must follow the waste hierarchy where reuse and recycling come first before recovery and disposal. In addition, our study does not consider the high presence of unregulated rubbish scavengers that might reduce the amount of high-energy-content materials that arrive at the incineration plant.

However, despite such limitations, our results offer a reliable scenario for developing WTE projects in Mexico City and similar regions. The estimated energy capacity in both projects is consistent with values reported in evaluations of similar technologies; for instance, Yin et al. [63] and Coskuner et al. [64] reported energy yields ranging between 120 and 190 GWh with collection efficiencies of methane of 60–70%, whereas capacities up to 2500 GWh/yr have been recorded for combustion of 8000–10,000 tons of MSW [65].

3.4. Financial and Economic Results

In order to compare the two projects, only realistic scenarios were considered for estimating their economic benefits and financial-profitability indicators. The cost of the methane project was USD 105.18 million, with USD 87,211,402 for turbines with a CHP system and USD 17,965,848 for the collection and flaring system. The average operating and maintenance cost was USD 8.1 million, and the net cash flow became positive after 5 years, generating USD 12.75 million.

In contrast, the incineration project had a mobile grate system with ash retention and a filter for polluting gases. The total installed capital cost was USD 907.45 million, and the average operating and maintenance cost was USD 72.59 million. The incineration project took 5 years longer to evaluate due to its significantly higher initial investment. The financial analysis applied a discount rate of 12%, which was three times the inflation rate in Mexico.

As shown in Table 7, both projects were profitable. The methane project had a net present value (NPV) of USD 4.97 million and an internal rate of return (IRR) of 24%. In comparison, the incineration project had an NPV of USD 706.37 million and an IRR of 23%. Nevertheless, it must be noted that the incineration project becomes feasible only if the financing of the capital cost is not added. If we include a financial loan (10-years financing with 8% interest) to cover the total capital cost, the cash flow is discounted by a fixed annuity of USD 146.05 million. With these variations, the NPV would result in a negative value of USD 118.87 million and an IRR of 10% (lower than the discount rate). Therefore, the economic evaluation, particularly in incineration projects, should follow the analysis of different parameters including financing and the percentage of the total cost to be financed; this would provide a clearer scenario of profitability. Additionally, the implementation of cost-reduction strategies can be explored to make the project feasible even with a financial loan.

Table 7. Economic comparation of projects in USD.

	Methane	**Incineration**
Total cost of capital (USD)	105,177,251	907,453,363
Average annual O&M expense (USD)	5,150,780	72,596,269
Evaluation period (yrs)	15	20
Annual average cash flow (USD)	7,338,526	216,057,680
Net present value (NPV) (USD)	4,975,369	706,377,303
Internal rate of return (IRR) (%)	24	23
Payback period (yrs)	8	4.2
Levelized cost of energy (LCOE) (USD)	0.1145	216.92

According to Gradus et al. [66], investment and operating costs can be significantly reduced by up to 50% by implementing measures such as government subsidies to finance projects, using different auxiliary fuels [67], and limiting infrastructure to necessary equipment based on waste characteristics and installed capacity [68]. Our estimations are reliable because similar projects with comparable power capacity have reported similar values. For example, a 25% return on waste-to-energy (WTE) projects in Saudi Arabia was reported by managing similar amounts of waste with calorific values between 4000 and 6000 kcal/kg [69], and Xin-Gang et al. [36] obtained an 18% return on incineration projects in China with a lower plastic content. In addition, our analysis shows that both projects present a more attractive investment alternative than other waste-management projects, with gasification and anaerobic digestion of waste reporting IRRs of 10% and 15%, respectively [70,71]; composting projects of 20% [72], and pyrolysis systems of 15% [73]. Finally, the payback period also indicates feasible scenarios, with incineration recovering the total capital cost in 4.2 years and the methane project in 8 years. It should be noted that while both projects report a positive levelized cost of electricity (LCOE), incineration would be significantly more expensive than methane for producing energy.

3.5. Sensibility Analysis

Since the real performance of energy projects might vary according to the characteristics of the waste and technology used, we conducted a sensibility analysis to estimate variations in yields that can influence profitability (See Table 8). For the case of the methane project, we evaluated the technical performance of an engine-based system instead of the initial CHP turbine system. The technical parameters described in Section 2.1 were kept constant for the realistic scenario and financial profitability conditions.

Table 8. Sensibility analysis for methane technologies.

	Standard Engine	**Small Engine**	**CHP Engine**
Total generation capacity (kW)	56,967	35,500	56,997
Average generation (million kWh/yr)	252	154	252
Total installed capital cost for year of construction (USD million)	86.01	104.69	134.85
Annual O&M costs for initial year of operation (USD million)	2.96	2.68	2.91
Internal rate of return (%)	N/V	N/V	8%
Net present value (USD million)	−14.43	−20.42	3.82

Scenarios with standard engines and CHP engines would report equal levels of energy capacity; however, the CHP system requires a higher installed capital cost. Although a CHP engine system resulted in a positive VPN and IRR considering a discount rate of 12%, the alternative cannot be considered viable, and a CHP turbine option should be selected instead. It must be noted that implementing engine-based systems increases installation and O&M costs; as a result, a higher gas supply is needed to make their operation profitable [74]. Based on our analysis, single-cycle systems are not efficient and would not result in profitable outcomes due to the current municipal solid waste (MSW) reception rate. The efficiency of methane systems (engine/turbine) depends on various factors such as the ambient air temperature of the project site [75], the altitude of the site [76], and the project lifespan [77].

For the case of incineration, variations in profitability were measured by adjusting the lower calorific value of the waste. As stated previously, this is due to the main risk in thermal processes which lies in the decrease in materials with a high calorific potential such as plastic and complementary cardboard and paper.

As observed in Table 9, if plastic and paper materials reduce in availability, the LCV total is also reduced, impacting the energy recovery potential. With current parameters, the project permits a 25% reduction in the flow of such materials to remain viable; at 50% and 75%, the project become unfeasible as the energy generation drops whilst costs show no significant variations. The viability of the incineration project is highly dependent on the calorific potential of the waste. Even though our estimations are based on values from official sources, actual values could differ due to a decrease in the amount of high-energy-content materials in landfills resulting from an unregulated recycling market, as indicated in some studies [78,79]. Thus, sensitivity analysis was conducted to comprehend the variations in calorific potential and prevent unrealistic energy-generation expectations.

Table 9. Variation in key indicators of the incineration project.

	25%	**50%**	**75%**
LCV total (kJ/kg)	11,729.41	9507.27	7285.15
Energy generation (GWh/yr)	3517.08	2850.76	1184.45
Total installed capital (USD)	783,718,548	662,581,802	594,854,981
Annual O&M costs (USD)	57,210,864	53,006,544	52,587,841
Internal rate of return (%)	18.5%	10.68%	N/V
Net present value (USD)	410,749,686.43	174,930,352	−86,397,575

4. Conclusions

Mexico City is a large and modern city, but its waste management service is outdated and heavily reliant on fossil fuels. This study examines two waste-to-energy (WTE) options: capturing and using methane and incinerating waste. The results show that incineration has a significantly higher investment, capital, and energy cost compared to the methane project, but its energy generation capacity is much greater. However, incineration projects in Mexico City may face risks such as a decreased flow of plastic materials due to unregulated recycling intermediaries and difficulty in verifying financial profitability with loans. Therefore, unless there is a direct investment or cost-reduction strategies are implemented, incineration is a financial risk. On the other hand, the methane alternative has a lower installed capital cost and lower operational expenditures, making it a more profitable option. The downside of the methane project is the need for sanitary landfills, which have associated environmental impacts and must be eradicated in the medium-to-long term. Such environmental impacts include groundwater pollution due to pollutants seeping into the groundwater and contaminating drinking water sources, air pollution by the release of methane and other gases and volatile organic compounds (VOCs), and soil contamination due to harmful chemicals released into the soil, which can make it difficult or impossible to grow crops or other vegetation in the area. Then, these projects must only be considered in existing facilities in order to discourage the opening of new landfills; for new waste-management infrastructure, thermal processes must be favored. In any case, both projects represent feasible options to offset the fossil-fuel dependency (incineration only with a direct investment). Our results aim to assist the decision-making process regarding sustainable energy generation; responding the research question, the methane-capture system in landfills is the feasible alternative with a positive NPV and an IRR higher than the discount rate of 12%. We must clarify that our results should be taken with caution since there are certain limitations such as the assumption of several parameters including calorific values and the moisture content of waste which can vary, affecting the performance of both projects. Therefore, we strongly suggest the conduction of complementary analysis, such as environmental-impact assessment and multicriteria decision analysis, that considers social and economic aspects to provide a wider panorama in this matter. In addition, further research can be conducted on life-cycle assessments of both alternatives to identify deeper environmental impacts and thus obtain a broader compendium of information for decision making.

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