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Technical and economic analysis of energy generation from waste incineration in Mexico

Pablo Emilio Escamilla-García [a,*], Raúl Horacio Camarillo-López [b], R. Carrasco-Hernández [c], Emmanuel Fernández-Rodríguez [d], Jesús Michel Legal-Hernández [e]

[a] CECYT 13, Instituto Politécnico Nacional, 1620 Taxqueña Ave., Coyoacán, 04250, Mexico City, Mexico
[b] ESM, Instituto Politécnico Nacional. Salvador Díaz Mirón, Miguel Hidalgo, 11340, Mexico City, Mexico
[c] ENCB, Instituto Politécnico Nacional, Luis Enrique Erro Ave., Gustavo A. Madero, 07738, Mexico City, Mexico
[d] Technological Institute of Merida, Technological Ave., Merida, 97118, Yucatan, Mexico
[e] UPIICSA, Instituto Politécnico Nacional, 950 Te Ave., Iztacalco, 08400, Mexico City, Mexico

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ABSTRACT

In this paper we evaluated the feasibility of energy generation by incineration of waste in Mexico. The population of Mexico was split into six population-size classes, each one associated to a waste generation index. The total amount of waste and the lower calorific values were used to estimate the power and energy resulting from each size class. The economic feasibility was evaluated using the Levelized Cost of Energy (LCOE), Net Present Value (NPV) and Internal Rate of Return (IRR). For populations up to 3 million inhabitants the incineration of waste resulted in 58.9 MW. The total energy generation resulted in 11,681.64 GWh contributing to 4.3% of the national demand. The NPV and IRR showed negative values per lower sizes of population and the LCOE resulted in higher values than other energy sources. A sensitivity analysis was conducted, addressing specific elements of the analysis to show how the project can become economically feasible when adjusting investment, O&M and sales tariff. This research provides evidence on how the Waste-To-Energy (WTE) incineration industry is feasible in Mexico and provides significant benefits, not only by strengthening the renewable energy sector but also by significantly improving the waste management system.

1. Introduction

Waste generation is an arising problem generated by the increase of the global population and the development of economic and industrial activities [1]. An aggregation of human settlements has the potential to produce a large amount of municipal solid waste (MSW). This waste can pose significant risks, especially those associated to public health [2]. The presence of toxic compounds in the MSW stream demands controlled handling procedures to ensure minimum environmental contamination and human exposure [3]. As population increases, the amount of MSW generated increases. This aspect has become a major concern for many under-developed nations as local governments have generally assumed the collection, transfer and disposal of waste [4,5]. As many developing countries, Mexico continues to urbanize. Mexico is ranked as the 11th most populated country in the world with 126,191, 000 million inhabitants [6]. Among its 32 states, the most populated include the State of Mexico, Mexico City, Veracruz and Jalisco (each one has more than 7.5 million inhabitants) contrasting with the least populated, Campeche, Baja California Sur and Colima (states that do not reach to 1 million inhabitants) and 18 states with a population ranging from 1 to 3 million [7]. With its increasing population, Mexico is encountering extreme waste management issues. The structural public policies designed to provide waste management services have been exceeded by high rates of population growth and intensive business activities. Mexico generates 109,145.75 tonnes of waste every day with a generation rate of 0.87 kg per capita, which is higher than the world average of 0.74 kg/person [8]. The annual waste generation worldwide is expected to increase by 70% from 2016 levels to 3.40 billion tonnes in 2050 given the population growth and urbanization. Thus, Mexico will also experience a significant increase in waste generation. This increase has led the government of Mexico to base public services on rudimentary techniques using obsolete equipment and adopting the use of landfills as

* Corresponding author.
E-mail addresses: peescamilla@ipn.mx (P.E. Escamilla-García), rulojadfarij@gmail.com (R.H. Camarillo-López), rcarrash@yahoo.com.mx (R. Carrasco-Hernández), fratellosole22@hotmail.com (E. Fernández-Rodríguez), jlegalh@ipn.mx (J.M. Legal-Hernández).

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the predominant waste management strategy.

Landfills are a potential threat to environmental quality due to air and soil contamination [9]. In addition, landfills are sources for public health issues due to exposure to landfill gas and to ground and surface water contaminated with landfill leachates [10]. Therefore, different technologies and methods have been developed to treat MSW, including mechanical, biological and thermal treatments. Among the thermal treatments, incineration is identified as the main Waste-To-Energy (WTE) strategy, with a worldwide rate of 255 million tonnes of incinerated waste per year [11].

Incineration involves a direct controlled burning of waste in the presence of oxygen to generate ash, flue gas and heat used to produce electricity [12]. During the process the flue gases reach a temperature of at least 850 °C for 2 s in order to ensure proper breakdown of toxic organic substances [13]. Incineration can reduce solid volume by up to 90%, effectively recover energy, avoid CH_4 release and mitigate soil and water contamination [14]. Additionally, the solid residues from the incinerator may be considered as inert and hygienically faultless and can be deposited in aboveground landfills or blended with building material [15]. It can be noted that incineration not only reports better reduction performances when compared to other MSW treatment technologies [16], but it also is an efficient option to address the problem of shortage of energy sources. In this regard, incineration provides an approach to cope with energy demand and has attracted great attention for its higher energy recovery rate and less land occupation [17]. Therefore, waste can play a crucial role in offsetting fossil fuel consumption and increasing the renewable energy share [18]. The amount of energy generated by incineration varies depending on the type of waste and its calorific value; however, several studies have obtained higher production of energy over other waste treatment methods [16,19–21].

Mexico is a country highly dependent on fossil fuels with an increasing demand of energy. Nonetheless, the decline in oil production and the gradual depletion of oil reserves have led to a renewed interest in developing renewable energy systems for electricity and heat production, while simultaneously, promoting the energy diversification and leading to a cleaner and more sustainable economy [22]. To contribute to these goals, Mexico created the National Program for the Sustainable Use of Energy, which requires companies to generate clean energy with specific national goals of 30% of clean energy production by 2021 and 35% by 2024 [23].

In Mexico, the main renewable technologies used to generate electricity are hydropower, onshore wind farms, and geothermal [24]. Hydropower has the highest installed capacity with 11,603 MW while geothermal power has the lowest with 958 MW [25]. However, WTE technologies have not yet been developed efficiently. Thermal treatment processes including waste incineration have not been considered as a strategy to strengthen the waste management system in the country. Yet, WTE is a potential source of electricity generation to contribute to the national energy demand. Given the trends of population growth and the consequential growth of waste generation, it is important to evaluate the feasibility of incineration processes according to different population sizes associated with the corresponding MSW generation rate.

2. Methods

The potential energy recovery was estimated from the incineration of waste according to different sizes of population. Each estimation considers a population size associated to average amounts of waste generated in order to determine the total potential of economically viable energy derived from the incineration process. This approach is consistent with the methods reported by Silva et al. [21] and Santos et al. [26]. Details are described in the following section.

2.1. Estimation of waste generation

The basis for the estimation considers the waste generation index

Table 1
Index of waste generation per capita in Mexico [27].

Population size	Waste generation index (kg/person)
30,000	0.605
100,000	0.755
250,000	0.855
1,000,000	0.955
3,000,000	1.205
National average in 2018	0.875

Table 2
Fraction of each type of residue in Mexico [28].

Type of waste	Percentage (%)
Textiles	1.4
Paper, cardboard and other paper products	13.8
Plastics (includes rigid and film)	10.9
Glass	5.9
Aluminium	1.7
Ferrous metal	1.2
Other non-ferrous metals	0.6
Other	12.1
Food waste, Garden waste and similar organic materials	52.4
Total	**100**

(Table 1) per each population size according to data reported by the Secretariat of Environment and Natural Resources of Mexico (SEMARNAT) [27]. This per capita generation index measures the relationship between the level of waste generated and the population. It is obtained by dividing the total amount of MSW reported in transfer stations, by the number of inhabitants in each population. For research purposes, the analysis focuses on populations with a maximum of 3,000,000 inhabitants, therefore estimations were performed considering six sets of population: 30,000; 100,000; 250,000; 500,000; 1,000,000 and 3,000,000 inhabitants. Additional estimations considered the total population of México of 124,738,000 [7]. With these population size classes; the waste generation was estimated applying Eq. (1).

$$W = \frac{(P_{op})(I_g)}{1000} \tag{1}$$

Where:

W = waste generated (ton/day)
P_{op} = population size
I_g = per capita waste generation index (kg/person day)

Additionally, the production of each type of waste per each population size was estimated with data from Table 2 and applying Eq. (2).

$$W_i = (W)(F_i) \tag{2}$$

Where:

W_i = production of each type of waste (ton/day)
W = waste generated (ton/day)
F_i = fraction of each type of residue removed from the gravimetric composition

2.2. Estimation of energy outputs

The basis for the generation of energy through incineration is the use of the calorific value of the waste by taking advantage of the amount of energy per unit of mass or unit of volume of matter that can be released when a chemical oxidation reaction occurs. Since the analysis evaluates only moving grate incineration processes, our estimation of energy considered the heat-generating values according to three main

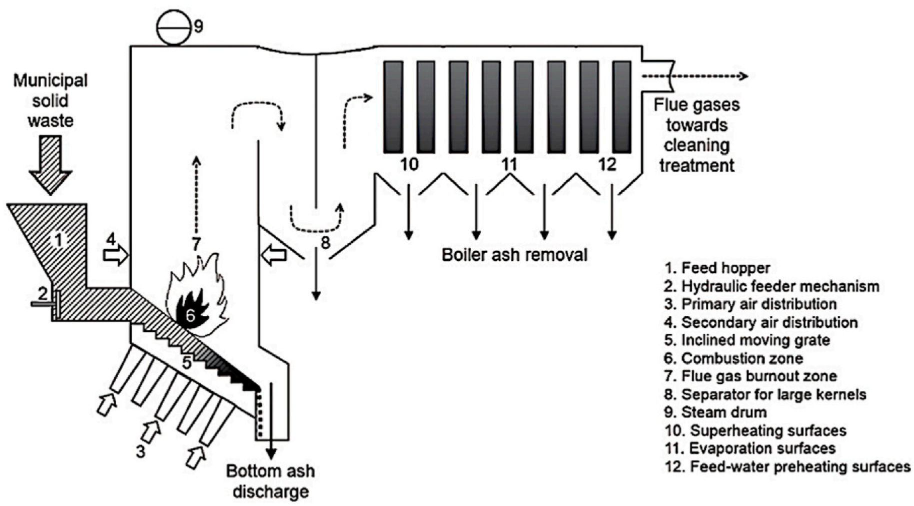

Fig. 1. Flow diagram of moving grate technologies [35].

categories: organic waste, plastic waste and paper waste. The calorific potential used in the estimations considered a calorific value (wet basis) of 758 kcal/kg for organic waste [29], 3192 kcal/kg for plastic waste [30] and 2729 kcal/kg for paper and cardboard [21]. These calorific values were used to estimate the total heat value applying Eqs. (3) and (4) developed by Bernal et al. [31] and the energy produced by incineration technologies with Eqs. (5) and (6) developed by Silva et al. [21].

$$LCV_i = (LCV)(W_i)(k_1) \tag{3}$$

$$LCV_{total} = \sum_{i=1}^{m} LCV_i \tag{4}$$

$$P = (LCV_{total})(\eta)(W)(k_2) \tag{5}$$

$$E = \frac{(P)(C_f)(8760)}{1000} \tag{6}$$

Where:

LCV = Lower calorific value kcal/kg
LCV_i = Calorific value contained in each RSU fraction in kJ/kg
LCV_{Total} = Total calorific value of the residue in kJ/kg
k_1 = Conversion constant from kcal/kg to kJ/kg (4.184)
η = Electric recovery considering a thermal replacement achievable
k_2 = Unit adjustment constant
P = Electric power in kW
8760 = Number of hours per year
C_f = Capacity factor
E = Electric energy produced in MWh/year.

2.3. Estimation of economic parameters

Economic parameters were estimated in order to determine the financial feasibility of waste incineration. Estimations consider moving grate incineration technologies. Although fluidized bed boilers are also used to combust waste, this research evaluates moving grate boilers since this technology is typically used for combustion of municipal wastes in 87% of plants in Europe [32]. Moving grate technology involves a slow movement of the processed waste in the layer in order to be subject of different processes (Fig. 1), including drying, pyrolysis/gasification, combustion and burnout [33]. The incineration process involves two main phases: the in-bed moving grate combustion and the over-bed gas turbulent combustion [34]. During the process the flue gases reach a temperature of at least 850 °C for 2 s in order to ensure proper breakdown of toxic organic substances [13].

Table 3
Average parameters of moving grate technologies used in economic estimations [26].

Item	Characteristic
Calorific value requirement	More than 1200 kcal/kg (5040 kJ/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, can not be sprayed back into the furnace for combustion

The data used for the estimations is presented in Table 3.

Given the actual investment cost for a waste incineration plant depends on multiple factors, the investment was calculated using Eq. (7) developed by Xin-Gang et al. [36].

$$I = (15797)\left(P^{0.82}\right) \tag{7}$$

Where:

I = Investment in US millions
P= Estimated power in kWh/yr

The investment cost includes estimations of equipment and devices, construction costs, land use and other costs, preparation funds, loan interest and risk management. Whereas the O&C cost includes estimations of: raw materials, plant power consumption, staff salaries, depreciation loss, maintenance charge, environmental expenses (Fly ash handling, bottom ash processing, leachate treatment and environmental monitoring), financial expenses and additional expenditure.

Considering the parameters described previously, the Net Present Value was estimated with equation (8), and the Internal Rate of Return with Eq. (9).

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

Where:

NPV = Net Present Value

Table 4
Total waste generation per type of waste in Mexico per population size (ton/day).

Type of waste	Population size					
	30,000	100,000	250,000	1,000,000	3,000,000	124,738,000
Textiles	0.2541	1.057	2.9925	13.37	50.61	1528.04
Paper, cardboard and other paper products	2.5047	10.419	29.4975	131.79	498.87	15062.11
Plastics (includes rigid and film)	1.97835	8.2295	23.29875	104.095	394.035	11896.89
Glass	1.07085	4.4545	12.61125	56.345	213.285	6439.60
Aluminium	0.30855	1.2835	3.63375	16.235	61.455	1855.48
Ferrous metal	0.2178	0.906	2.565	11.46	43.38	1309.75
Other non-ferrous metals	0.1089	0.453	1.2825	5.73	21.69	654.87
Other	2.19615	9.1355	25.86375	115.555	437.415	13206.63
Food waste, Garden waste and similar organic materials	9.5106	39.562	112.005	500.42	1894.26	57192.37
Total	**18.15**	**75.5**	**213.75**	**955**	**3615**	**109145.75**

t = Energy sales tariff in USD/MWh
$C_{o\&m}$ = Average cost of operation and maintenance
i = Discount rate
n = Lifetime of the project in years
I = Investment

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

Where:

IRR = The internal rate of return
C_t = Net cash inflow during the period t
I = Investment
n = Lifetime of the project in years (20 years)

Additionally, the economic estimations also considered a parameter that measures the minimum rate of energy sale that makes the investment economically viable. Eq. (9) developed by Gómez et al. [37] states that if the energy sales tariff is higher than the LCOE, then the proposal is economically viable.

$$LCOE = \frac{\sum_{n=0}^{T} (I_n + O_n + M_n)/(1+i)^n}{\sum_{n=0}^{T} E_n/(1+i)^n} \quad (10)$$

Where:

LCOE = Levelized cost of electricity
n = Project lifetime in years
E_n = Energy produced in MWh
I_n = Initial investment (Capital cost) in USD
M_n = Maintenance costs in USD
O_n = Operation costs in USD
i = Discount rate (%)

For the purpose of this analysis, the value adopted for the discount rate considers the inflation levels reported by the Central Bank of Mexico. The discount rate was fixed in 10%. The average cost levels including installation, operation and maintenance considered 4% of initial investment as suggested by Branker et al. [38] for similar projects. Finally the estimation of revenues considered a fixed price of energy of 42.53 USD/MWh.

3. Results and discussion

3.1. Waste generation per population size

Through Eqs. (1) and (2) and using the per capita waste generation index, the fraction of each type of residue in Mexico was estimated for the different classes of population size (Table 4).

As seen in Table 4 the total amount of waste shows that a population of 30,000 inhabitants produces 18.15 tonnes per day, whereas 3,000,000 inhabitants produce 3615 tonnes daily. Additionally, the total amount of waste in Mexico was estimated as 104,946.16 tonnes per day. Even though these estimations show the normal tendency of parallel growing of population and waste generation, stationary forms of the unemployment rate and population as independent variables can significantly improve modelling of waste management generation to be used in WTE projects [36].

3.2. Calorific values

With the total amount of waste generated per each size class, Eqs. (3) and (4) were applied considering the data mentioned in section 2.2. The estimations for lower calorific value resulted in 1575.70 kJ/kg for paper, cardboard and other paper products, 1455.73 kJ/kg for all plastics (including rigid and film) and 1661.85 for food waste, garden waste and similar organic materials. The total lower calorific value was estimated as 4693.28 kJ/kg. Although these values are low compared to those reported in similar studies [39], they are still located within the average parameters regarding minimum levels recommended for incineration processes [40,41].

3.3. Power and energy generation

The calculations of power and energy generation resulting from the incineration of waste were obtained with Eqs. (5) and (6). The estimations of power applied a unit adjustment constant of 0.01157 so that the resulting power is in kW [42]. The electric recovery considered a thermal replacement achievable of 30% and a capacity factor of 75% based on parameters reported by Silva et al. [21].

The values of the electricity per each size of population can be observed in Table 5. The installed capacity of waste incineration varies to one set of population to another. These variations are given by the amount of waste incinerated, the higher amount of waste, the higher

Table 5
Electric power and energy produced by incineration of waste.

	Population size					
	30,000	100,000	250,000	1,000,000	3,000,000	124,738,000
Electric power in kW	295.67	1229.92	3482.07	15557.32	58889.76	1778027.02
Electric energy in MWh/year	1942.55	8080.604	22877.20	102211.61	386905.76	11681637.50

Table 6
Economic and financial results (thousands USD).

Population	Investment	O&M	Cash flows	NPV	IRR	LCOE
30,000	1677.40	67.10	25.56	−1436.41	−4.45%	898.04
100,000	5398.52	215.94	169.50	−3800.62	−0.38%	694.81
250,000	12673.06	506.92	584.32	−7164.72	2.24%	576.12
1,000,000	43247.52	1729.90	3145.59	−13594.28	6.01%	440.04
3,000,000	128827.11	5153.08	13302.32	−3427.28	9.68%	346.29
124,738,000	2106318.64	84252.75	472961.36	2352247.69	22.40%	187.52

production of energy. However, it can be observed that with a population of 3 million inhabitants the electric power in the incineration processes reaches 58,889.7 kW (58.9 MW). When this value is compared to other sources of sustainable energy, the value surpasses values reported by small hydroelectric power stations in Mexico. Mexico operates 64 hydroelectric power stations from which 33 stations report power capacity of less than 50 MW [43]. In terms of biomass, a city with 3,000, 000 inhabitants in Mexico, generates 3615 tonnes of MSW (Table 4). According to CFE [44] a reception rate of waste ranging 2500–3000 tonnes per day can produce 3 MW. Regarding wind energy Escamilla--García et al. [22] reported that in Tabasco (state with 2.4 million inhabitants) wind turbines at a 125-m height could generate 2 MW each. Therefore, in terms power and energy generation, the incineration process in Mexico proves more efficient than other sources of sustainable energy. Regarding to the contribution that incineration can have in the mexican energy system, in 2018 Mexico reported an electricity consumption per capita of 2228.10 kWh which equals 267,234.91 GWh. As can be observed in Table 5, if the analysis considers the total amount of waste produced in Mexico, electricity could reach 11,681.64 GWh contributing to 4.3% of the national demand. For particular cases, the north region of Mexico (States of Chihuahua and Durango) has 2,519, 000 inhabitants with an average consumption of 23.734 GWh [45]. Results showed that populations up to 3,000,000 inhabitants could produce 386.91 GW, which would cover the entire demand of the region. In regard to a comparison on the estimation data with other studies from the government, the only study for the incineration of MSW in Mexico was conducted by the SEMARNAT in collaboration with the German Society for International Cooperation (GIZ) in 2016 [43]. It is important to point out that such study exclusively analyzes the potential of waste incineration in cement kilns. Therefore, as the characteristics of infrastructure, as well as the amounts of capital investment and O&M differ significantly from those analyzed in this article, the comparison of results is not possible. However, in spite of different approaches, our results align with the SEMARNAT-GIZ study to the extent that incineration is identified as a highly efficient model for the treatment of MSW by reporting optimal levels of co-processing and control of polluting emissions. It must be pointed out that our result aim to provide average levels and further studies should be conducted in order to determine specific values considering accurate data for each region, nevertheless, results show that incineration of waste can be an efficient option for contributing to a greater portion of the national energy matrix.

3.4. Economic and financial indicators

Economic and financial results are shown in Table 6. The calculations considered data presented in Table 3 for moving grate incineration technologies. The investment for each project was estimated using Eq. (7). The Operation and Maintenance cost was calculated by considering 4% of the total investment as suggested by SENER [46]. The revenues considered a sale tariff of 45.27 USD per MW [36]. All projects considered a lifetime of 30 years with a discount rate of 10% integrated by three times the inflation rate in Mexico (2.83%) plus 1.51% of risk factor.

From Table 6 it can be observed that cash flows per each size population are positive, nevertheless, except for the whole population of Mexico, Net Present Values are negative with Internal Rates of Return less than the discount rate. This implies that projects are proven economically infeasible. These results are consistent with economic results reported in similar studies conducted in developing economies like China and Brazil [47]. These negative values are due to several aspects. Incineration projects require high levels of investment and capital costs given that the collection and treatment costs of plastic waste are high. According to Xin-Gang et al. [36] the collection costs for plastic waste are almost seven times the collection costs of mixed waste. All projects consider an infrastructure with systems of a typical incineration plant. However, investment and O&M costs can decrease significantly up to 50% by applying measures such as the integration of government subsidies that help in the financing of projects [48], the modification of auxiliary fuels used in the process [49], the limitation of infrastructure only to the necessary equipment depending on the installed capacity and the characteristics of the waste [50]. According to Xin-Gang et al. [36] the determination of O&M costs can be lower if estimated as a function of the number of metric tons per year.

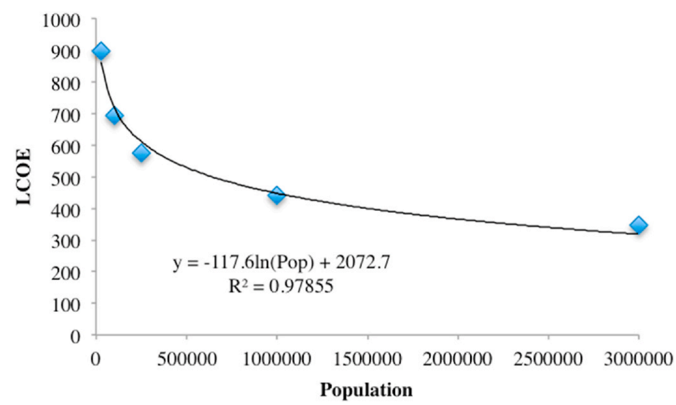

Fig. 2. Correlation between population sizes and LCOE.

In addition, the sale tariff per MW is low compared to fossil fuels of 58 USD/MWh [51]. Also, the calorific value of plastic waste used in the estimations is low. The problem with low calorific values in plastic waste is mainly due to the fact that the LCV reported in the literature considers only the plastics that reach the landfills and not all the plastics generated [46]. The discrepancy between the LCV values is caused by the existence of a significant number of intermediaries that separate the plastic for sale in other markets which in turn causes the amount of incinerated plastic to be lower than the actual levels of plastic generated. The calorific values can increase not only when considering the missing plastic fraction, but also when modifying part of the incineration process. There is evidence showing that the calorific value in the incineration of waste can be significantly increased by modifying the method of determination [30], by including a prior storage process of the waste [52] and by adding by-products in the incineration [53].

Regarding the levelized cost of electricity, results showed that LCOE decreases as the amount of population increases. This refers to an inverse correlation validated with a coefficient of determination of 0.97855 (Fig. 2).

The LCOE values estimated also proved the projects economically

Table 7
Comparison of financial indicators: Moving Grate Combustion (MGC) vs Circulating Fluidized Bed Combustion (CFBC) for populations of 3 million (thousands USD).

Indicator	MGC	CFBC
Capital investment	128,827.11	147,764.7
O&M cost	5153.08	5910.58
Cash flows	13302.32	12,544.81
NPV	−3427.28	−29,505.784
IRR	9.68%	7.52%
LCOE	346.29	397.19

infeasible, given that the LCOE for wind and solar energy is estimated in 1700 USD/kW [54] and hydroelectric plants report a LCOE of 1670 USD/kW [45]. The LCOE obtained increased not only due to the high capital cost but also to the current levels of energy generation. The LCOE can be reduced either by adjusting the capital cost or by increasing the calorific value especially in the organic fraction [47]. Although the economic feasibility of the project cannot be proved with the parameters used in the calculation, these initial estimations of NPV, IRR and LCOE provide preliminary data in a general scope to base further studies considering specific parameters according to accurate levels of population, waste generation and capital cost so that incineration processes could be economically viable.

As mentioned, the analysis focuses only on moving grate combustion technologies (MGC), nevertheless as circulating fluidized bed combustion technologies (CFBC) have been highly used in emerging economies such as China and India, we briefly compared these two alternatives in terms of investment and O&M cost (Table 7). Considering the parameters reported in existing literature, CFBC power generation plants involves a capital investment of approximately $40,000 per daily tonne of capacity [55] with a total plant cost of 3990 US$/kW and a fixed O&M of 116.9 US$/kW-yr [56]. As observed in Table 7, the average investment and O&M cost of CFBC is approximately 14.7% higher than that from MGC, which results in lower profitability values. This variation in costs is due to the low moisture content in the waste, which requires the integration of auxiliary fuels to facilitate combustion. As reported by Wheeldon and Thimsen [56], CFBC is ideal for burning high moisture fuels such as sewage and industrial sludge, however as MSW are mainly composed by waste with high heating value and low moisture content, CFBC is not a suitable alternative.

3.5. Sensitivity analysis

The analysis resulted in economic values that cannot verify the financial feasibility of the project. Therefore, a sensitivity analysis was conducted. Since 21 out of 32 states in Mexico have population ranging 1 to 4 million inhabitants, the sensitivity analysis considered only the population sizes of 1 and 3 million. The adjustment focused on the reduction of the capital cost and the variation of the energy sales tariff in 4 different levels. With these adjustments the sensitivity analysis was carried out by reducing the investment and the O&M cost in 10% which alongside with the increase of the sale tariff resulted in higher cash flows for the project considering a life span of 30 years.

The impact of both capital cost reduction and the increased energy sales tariff over the economic potential of the incineration projects is significant. As can be observed in Table 8, not only the NPV shows positive values when projects for 1 and 3 million inhabitants reduces the capital cost in 10% but also the IRR is higher than the original discount rate. It is worth mentioning that such reductions are achievable given the possible adjustments in equipment and supplies as explained in section 3.4. Even with the adjustment of the original tariff of 45.27 USD to the smallest increase of 60USD, the projects could be economically feasible. It must be noted that variations on the energy tariffs have to be based on specific values from the energy auctions conducted by SENER. The values adopted in the variations aim to show the behavior of financial indicators to achieve feasibility. It was shown that reductions of the capital cost are viable and could provide attractiveness to investors in the incineration projects. For the LCOE, the lower calorific values were adjusted considering a higher value of 8000 kcal/kg for plastic waste, which would increase the power and electricity generated. It must be noted that this increment is also feasible as long as the plastic collection is improved. The LCOE for a population of 3 million inhabitants resulted in a reduction of 31.84%. Although, the value is lower, the feasibility cannot be verified yet. Nevertheless, it shows that addressing the current issues related to low calorific values, the LCOE can reach levels less than LCOE reported by other energy sources making the project feasible.

4. Conclusions

The study focused on demonstrating the feasibility of waste incineration in Mexico. Current data shows that the population growth will lead to an increasing amount of MSW generation in years ahead. Therefore, thermal treatment techniques should be explored to contribute to waste management and energy generation. The analysis carried out resulted in evidence that demonstrates the technical feasibility of generating energy through incineration. The results showed a greater generation capacity with the incineration of waste than the current capacity of other renewable sources such as hydroelectric and wind power. For populations up to 3 million inhabitants incineration processes reaches 58.9 MW. However, given the current amounts of investment and O&M costs, the economic feasibility of the processes was not verified. Conversely, the sensitivity analysis showed that when reducing capital costs by 10% the project becomes viable. This lays the groundwork in which public and private investors could address limitations and flaws in projects focused on different population sizes in order to create mechanisms to increase revenues and facilitating their financial viability. It must be noted that our results are intended to provide a general overview of the potential that waste incineration has on energy generation in Mexico. The development of projects focused on specific populations must consider the characterization of waste as well as the associated calorific potential, in the same way, capital costs can vary significantly due to the characteristics of the equipment for interconnection with the local electrical grid. Nevertheless, with the strengthening of governmental programs aimed to support the development of WTE projects, the incineration of waste in Mexico can enter into an industry that will grow more rapidly with expanding market scales, thus boosting the whole waste management sector and the generation of energy from renewable sources.

CRediT authorship contribution statement

Pablo Emilio Escamilla-García: Conceptualization, Methodology,

Table 8
Effect of the reduction of capital cost and energy sales tariff on NPV and IRR.

		60 USD/MWh	80 USD/MWh	100 USD/MWh	120 USD/MWh
1,000,000	NPV	4212775.99	23483579.83	42754383.67	62025187.5
	IRR	11%	17%	22%	27%
3,000,000	NPV	59175330.7	132121881.3	205,068,432	278014982.6
	IRR	16%	23%	29%	36%

Writing - original draft, Project administration. **Raúl Horacio Camarillo-López:** Writing - review & editing, Formal analysis. **R. Carrasco-Hernández:** Validation, Investigation. **Emmanuel Fernández-Rodríguez:** Resources, Writing - review & editing. **Jesús Michel Legal-Hernández:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2020.100542.

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