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Energy and economic analysis of waste-to-energy plants with government incentives in Colombia

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Abstract

Globally, the excessive generation of Municipal Solid Waste (MSW) has become a challenge for mankind, which requires different management models and policies, the objective of this study, is to carry out an energy and economic assessment that values the MSW flows generated by medium-sized cities with less than 1.5 million inhabitants, through incineration technology with electrical production, using an analytical approach, was evaluated at the energy level, a conventional plant configuration, estimating steam parameters at 40 bar and 380°C and the lower heating value (LHV) of MSW at 8,786 kJ/kg, calculated thermodynamic properties in each process stream, plant energy yields were determined, such as energy efficiency at 22.6% and electrical energy delivered to the grid at 87.4 GWh per year, yields used in the economic evaluation, which was conducted in two scenarios, taking into account the state benefits of law 1715 of 2014. The first scenario, which did not include the benefits of the law, yielded economically unfeasible results, with a net present value (NPV) of $ 6,634,332 USD, an internal rate of return (IRR) of 9.18% and a levelized cost of electricity (LCOE) of $189. 33 USD/MWh, however, the scenario that evaluated the state incentives, presents an economic viability with a payback period of 11 years, a NPV of $40,232,650 USD, IRR of 15.78% and a LCOE of $175,197 USD/MWh. Sensitivity analyses were carried out to obtain the NPV and IRR limits for each scenario, showing that the most significant variables to be taken into account in the economic viability of this type of project are: the sale price of electricity, the MSW disposal fee and the percentage of the loan for initial investment.

Keywords: Energy evaluation, Economic evaluation, Direct incineration, Municipal solid waste MSW, Levelized cost of electricity (LCOE)

1. Introduction

The proper generation and disposal of municipal solid waste (MSW) is a fundamental concern for any society aspiring to industrial prosperity. Poor management of these wastes could cause significant environmental impacts, in turn triggering social problems. Globally, waste generation has increased considerably in recent decades. In 1999, 680 million tons of MSW were produced, a figure that tripled to reach 1.3 billion tons in 2012, representing a 91% increase in less than 15 years. According to World Bank projections, it is estimated that by 2025 MSW generation could amount to approximately 2.2 billion tons. 2.200 [1], this requires an alternative for municipal solid waste management, which opens the door to technologies such as direct incineration (WtE), which reduces the volume of waste by 90% and its specific weight by 75%. This technology not only reduces greenhouse gas emissions, but also contributes to reducing soil and water pollution compared to traditional landfills [2][3] and generating partially renewable electrical energy. and generating partially renewable electrical energy (MSW biomass fuel), thus strengthening energy security and diversifying primary fuel sources [4][5][6].

Currently, there are more than 800 thermal waste-to-energy plants distributed in 40 countries around the world. These facilities handle approximately 11% of the municipal solid waste (MSW) generated globally and have a combined capacity to produce 429 TWh of energy per year [7], incineration involves the direct and controlled combustion of waste in the presence of oxygen, generating ash, flue gases and heat that are used for electricity production, during this process, the flue gases reach minimum temperatures of 850°C for at least 2 seconds to ensure adequate decomposition of toxic organic substances [8]. However, the amount of energy recovered from waste combustion varies considerably depending on MSW characteristics (composition, mass flow, frequency and lower heating value), combustion technology employed, specific configurations and steam cycle parameters. Corrosion in MSW boilers remains a significant challenge due to its complex and evolving nature, influenced by changing MSW composition and steam parameters. Limited pressure and temperature at 380°C and 40 bar in steam generators play a crucial role in corrosion generation, which restricts the cycle efficiency to a range between 20% and 25%. These values are significantly lower than the efficiencies achieved by thermal cycles using fossil fuels such as coal, which can exceed 35-40% [9][10][11][12].

The feasibility of implementing this technology has been evaluated by the scientific community, which indicates through life cycle analysis that incineration offers superior economic benefits when combined with energy recovery and technical conditions that promote the environmental sustainability of the project are ensured [13][14]. In terms of energy and economics, Tan et al. conducted an analysis of waste management in Malaysia, comparing incineration and gasification technologies. Their findings highlighted better energy and economic performances for incineration. However, it is important to consider that these results may vary depending on the type of waste, the scale and efficiency of the system, as well as the region studied. Lino and Ismail concluded that the electricity generated through this practice could supply up to 135,680 households and generate monthly revenues of approximately US$5.8 million. According to Dalmo et al. the implementation of MSW incineration plants in the state of São Paulo could generate up to 5.7 TWh, which represents a potential capable of meeting 79% of the state's energy demand. Furthermore, waste incineration in only 16 large Brazilian cities could substitute 1.8% of the total residential electricity consumption in Brazil [16].

In addition to the above, incineration plants face social resistance and require costly systems for the control and treatment of exhaust gases. The reduction of hazardous emissions from incineration is a topic continuously investigated in the literature. For example, Silva et al. [17] proposed a reactor model combining pyrolysis and incineration, using a mixture of MSW and wood chips with high calorific value. This approach allowed minimizing emissions of compounds such as HCl, dioxins and furans, keeping them below Brazilian legal standards and other international environmental indicators. These innovations are crucial for the future of incineration and energy generation from MSW. A comprehensive review on the evolution and improvement of gaseous effluent treatment methods in incineration plants during the last decades can be found in [18]. Due to these high costs, this technology is not widely deployed worldwide and is mainly concentrated in three regions: Europe, Asia and North America. Despite this, the potential for incineration in regions where this technology is not yet widespread is considerably high. The objective of this study is to perform an energetic and economic evaluation that values the MSW flows generated by medium-sized cities with less than 1.5 million inhabitants, through incineration technology with electrical production. For this case study, the MSW flows generated in

Bucaramanga were taken, using an analytical approach the plant yields were calculated, which are the input to build a methodology to evaluate economic feasibility indicators taking into account the benefits of the state, serving as a starting point for new researchers and decision makers who intend to implement this technology in their cities.

2. Methodology

This study aims to energetically and economically evaluate an urban solid waste incineration plant taking into account the application of state incentives for electricity generation from non-conventional energy sources in Colombia. the research was divided into three phases, in the first phase the definition of the technical scope was performed, followed by the development of the energy evaluation and finally, the evaluation of the economic analysis, it was divided into two scenarios, taking into account state benefits of Law 1715 of 2014. For the numerical exercise, a medium-sized conventional plant was characterized, with its respective technical parameters, among them, the thermal plant capacity of 66 MWt, according to the MSW energy characteristics offered by the city of Bucaramanga and its metropolitan area (Colombia).

2.1. Case studies

In the present study, the reference case was the flow of MSW entering the El Carrasco landfill, located in the city of Bucaramanga (Colombia). The physical composition of MSW was determined by averaging three studies carried out at the landfill, as shown in Figure 1. The energy value of MSW varies from one country to another and even between cities of the same nation, mainly influenced by socioeconomic aspects. It depends on the moisture content and composition of the waste, and the energy recovery per ton will depend on the lower heating value (LHV), the efficiency of the boiler and the final destination of the product, either in the form of steam or electricity [19][20].

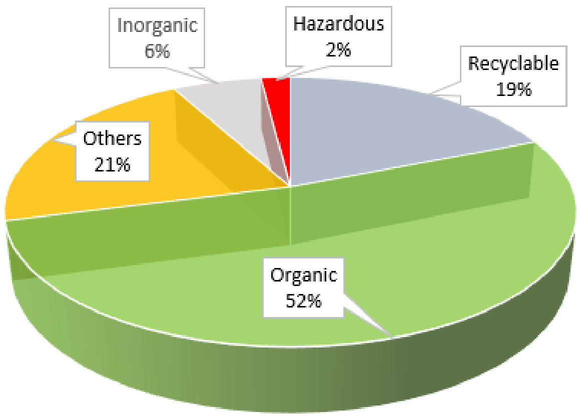

Figure 1. Physical composition of MSW

The plant, whose arrangement is shown in Figure 2, operates as follows; water is pumped from pump 2 as compressed liquid, passes through the economizer to become saturated steam, and then through the superheater where it reaches superheated steam state in the boiler. This superheated steam enters the turbine (stream 5), where it expands to condensing pressure (stream 7). During this process, an extraction is performed in the turbine to provide the necessary steam to the deaerator (stream 6). The working fluid then enters pump 1, increasing the water pressure to the operating pressure required by the deaerator (stream 2). Finally, the water returns to pump 2 through stream 3, completing the cycle.

2.2. Energy calculations

The methodology used for the energy evaluation is shown in Figure 3. After defining the initial plant parameters (see Table 1), the main thermodynamic properties are calculated for each steam flow stream (Table 2), using CoolProp software (open access, free of charge) [21].

Through an energy review of the steam cycle, the mass flow produced by the boiler and the waste flow (plant capacity) entering the furnace are determined using Equation 1.

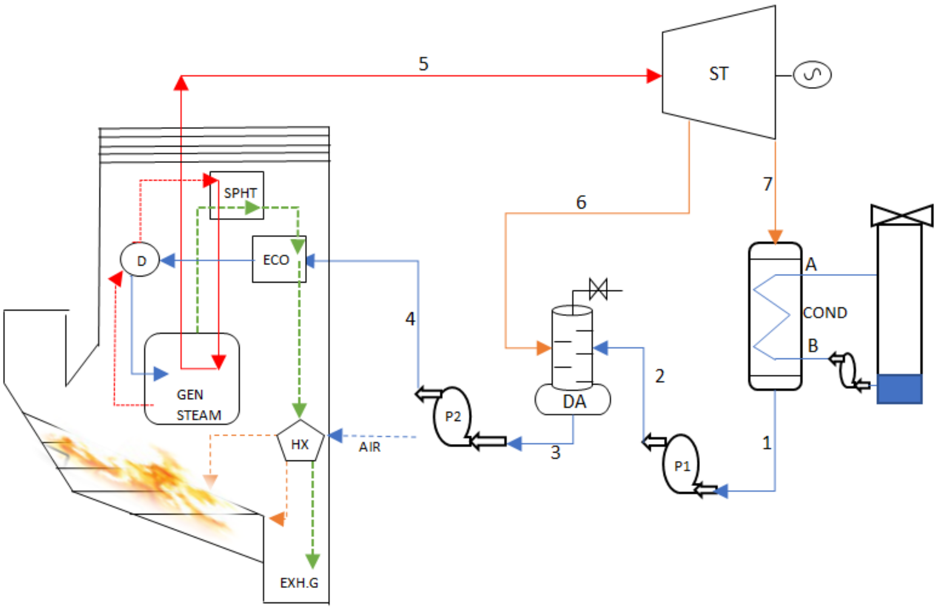

Figure 2. Plant layout

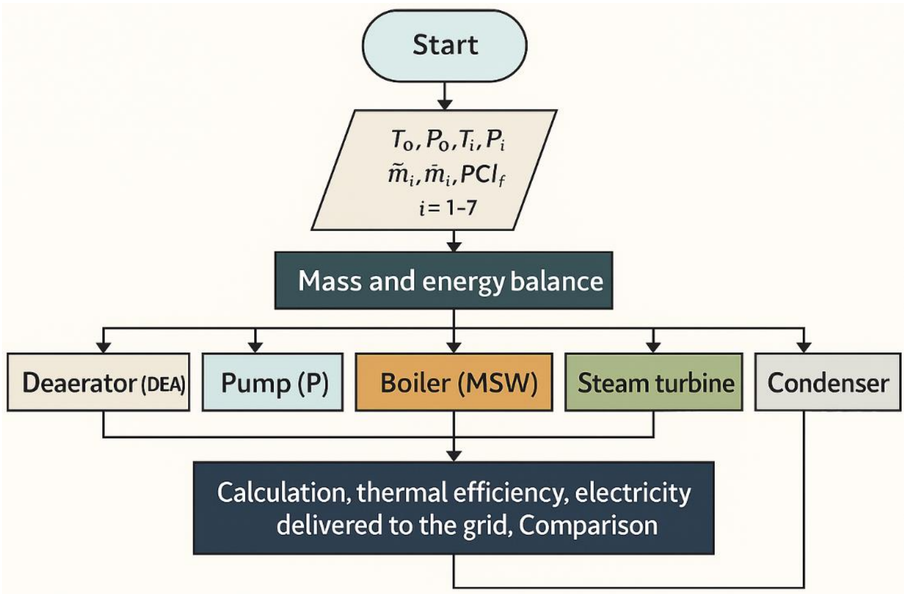

Figure 3. Methodology energy analysis

Through an energy review of the steam cycle, the mass flow produced by the boiler and the waste flow (plant capacity) entering the furnace are determined using Equation 1.

$$\dot{m}_{S,OUT,BOIL} = \frac{\dot{m}_{RSU} . \eta_{BOIL} . PCI_{RSU}}{(h_{OUT,BOIL} - h_{IN,BOIL})} \quad (1)$$

The electrical and mechanical power of the steam turbine are calculated with equations (2) and (3), if the electrical energy consumed in the EECP plant is subtracted from the electrical power, the liquid electrical power generated by the cycle is obtained

$$\dot{W}_{ST,el} = \dot{W}_{ST,mec} \cdot \eta_{Gen} \quad (2)$$

$$\dot{W}_{ST,mec} = w_{ST,termico} \cdot \dot{m}_{IN,ST} \quad (3)$$

The thermal and liquid efficiency of the cycle are calculated using Equations 4 and 5

$$\dot{W}_{ST,el} = \dot{W}_{ST,mec} \cdot \eta_{Gen} \quad (4)$$

$$\dot{W}_{ST,mec} = w_{ST,termico} \cdot \dot{m}_{IN,ST} \quad (5)$$

The electrical energy delivered to the grid, the specific MSW consumption and the surplus liquid electricity rate are calculated with Equations 6, 7, and 8 respectively:

$$\dot{W}_{Electrica\ Red} = \dot{W}_{ST,el,liq} \cdot Hrs_{Operation\ per\ year} \quad (6)$$

$$CER = \dot{m}_{RSU}/\dot{W}_{ST,el} \quad (7)$$

$$IELE = \dot{W}_{ST,el,liq}\ /\dot{m}_{msw} \quad (8)$$

Table 1. Initial plant parameters

Parameter		Value	Ref
Furnace temperature	$(\mathbf{T_{Furnace}})$ °C	1,150	[22]
MSW fuel LHV	$(\mathbf{LHV_{MSW}})$ $\mathbf{kJ/kg}$	8,786	[19]
Steam temperature	$(\mathbf{T_{ST}})$ °C	380	[23]
Boiler pressure	$(\mathbf{P_{ST}})$ $\mathbf{kPa}$	4,000	[23]
Boiler efficiency	$(\eta_{\mathbf{BOIL}})$ %	75	[5]
Generator efficiency	$(\eta_{\mathbf{Gen}})$ %	96	[24]
Pump isentropic efficiency	$(\eta_{\mathbf{Isent-PUMP}})$ %	85	[25]
Steam turbine isentropic efficiency	$(\eta_{\mathbf{Isent-ST}})$ %	85	[26]
Condensing pressure	$(\mathbf{P_{COND}})$ $\mathbf{kPa}$	15	[27]
Deareador pressure	$(\mathbf{P_{DEA}})$ $\mathbf{kPa}$	350	[28]
Installed power	$(\mathbf{\dot{W}_{ST,el}})$ $\mathbf{MW}$	15	[29]
Hours of operation	$(\mathbf{Hrs/year})$	8,000	[30]
Electric energy consumed plant	(EECP) $\mathbf{kWh/t_{RSU}}$	150	[29]

Table 2. Thermodynamic properties

Stream	Flow $\dot{\mathbf{m}}$ (kg/seg)	Pressure P (kPa)	Temperature T (°C)	Enthalpy h (kJ/kg)
1	16.497	15	53.969	225.944
2	16.497	350	53.997	226.344
3	19.270	350	138.857	584.261
4	19.270	4,000	139.384	588.893
5	19.270	4,000	380.000	3166.766
6	2.774	350	138.857	2712.874
7	16.497	15	53.969	2319.956
A	826.414	101.325	298.150	104.920
B	826.414	101.325	308.150	146.720

2.3. Economic calculations

In order to determine the economic viability of the plant, two scenarios were evaluated, the first without taking into account the benefits offered by Law 1715 of 2014 and the second scenario, applying the incentives offered by this law (See Table 3). For this purpose, the methodology shown in Figure 9 was used. This methodology is based on four main axes depending on the MSW treated in the plant per year (plant capacity), the first axis is to calculate the plant investment, the second is to calculate the operating costs, variable and fixed maintenance of the plant, the third axis is based on selecting the financing model and the last axis is to determine the income generated by the plant, These calculations were adjusted to the methodology used by [31], with the above results, the levelized cost of electricity LCOE is calculated using equation (9), indicating how much it costs to produce one kWh of electricity.

$$\mathrm{LCOE} = \frac{\mathrm{CIA} + \mathrm{O\&M}_{Year}}{\dot{\mathrm{W}}_{\mathrm{ST,el}} . \mathrm{Hrs}_{Operation\ per\ year}} \tag{9}$$

Where CIA is the annualized investment cost and is defined as; the product of the capital recovery factor FRC times the plant investment.

$$\mathrm{FRC} = \frac{\mathrm{i}\, .\, (1+\mathrm{i})^{\mathrm{t}}}{(1+\mathrm{i})^{\mathrm{t}} - 1} \tag{10}$$

where t is the useful life of the plant in years e (i) is the interest rate.

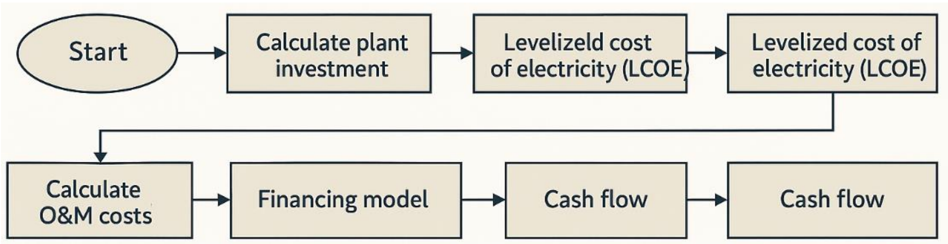

Figure 4. Economic analysis methodology

Having the knowledge of the production and investment costs, a cash flow is elaborated, which aims to calculate the net present value NPV and the internal rate of return IRR which indicated financial closures and economic viability of the plant.

Table 3. Incentives under Law 1715 of 2014

Article	Concept	Detail
Article 11	Income tax	They will have the right to deduct from their income, in a period of no more than 15 years, counted as of the taxable year following the year in which the investment started operations, 50% of the total investment made.
Article 12	Sales Tax	Exclusion of sales tax - VAT on the acquisition of goods and services, equipment, elements, machinery and national or imported services used for pre-investment and investment.
Article 13	Tariff Incentive	Exemption from payment of import duties on machinery, equipment, materials and inputs destined exclusively for reinvestment and investment in such projects.
Article 14	Incentive accounting	The accelerated depreciation regime will be applicable to machinery, equipment and civil works necessary for the reinvestment, investment and operation of the projects.

3. Results

3.1. Energy evaluation

The main results, derived from the different mass and energy balances, are shown in Table 4. The plant under consideration delivers about 87,433 GWh of electrical energy per year to the grid, with a thermal efficiency of 22.6%, capable of generating 1.81 kg of MSW per kg of MSW per kWh of electrical energy and 402.7 kWh per ton of waste.

3.2. Economic assessment

For the definition of investment, production costs and plant maintenance, the work of Schneider (2010) [31], was used as a reference, the values were estimated based on plant capacity, i.e. MSW processed in the plant per year. It is evident that the incentives of law reduce the investment cost in scenario 2 by about 11% ($ 15,396,672.06). The costs for each capital investment scenario are shown in Table 5.

Table 4. Plant energy yields

Parameter		C0
Steam production	TON_{Steam}/hr	5.352
Plant capacity	TON_{MSW}/day	651.346
Thermal efficiency	%	22.6
Liquid electrical power	MW	10.929
Electricity to grid	GWh/year	87.433
Specific MSW consumtion	kg/kWh	1.810
Net electricity generation	kWh/t_{MSW}	402.701

Table 5. Capital investment costs

Concept plant investment	Cost $\$/t_{MSW-year}$	% Capital investment	Cost $ Scenario 1	Cost $ Scenario 2
MSW plant infrastructure	51.05	8%	$ 10,903,248.18	$ 10,903,248.18
Steam generator system	216.42	33%	$ 46,222,937.72	$ 37,902,808.93
Water and steam system	88.78	13%	$ 20,379,569.79	$ 16,588,097.25
Electromechanical Install	55.5	8%	$ 11,853,678.23	$ 11,853,678.23
Gas cleaning system	85.45	13%	$ 18,250,392.88	$ 14,965,322.16
Other investment costs	65.5	10%	$ 13,989,476.11	$ 13,989,476.11
Construction	79	12%	$ 16,872,803.25	$ 16,872,803.25
Design	22.2	3%	$ 4,741,471.29	$ 4,741,471.29
		Total	$ 143,213,577.47	$ 127,816,905.41

According to reference [32], the operation and maintenance costs of an MSW plant are estimated at $392.82/kW-year, for fixed and variable costs at $8.75/MWh-year. The LCOE for each scenario with an interest rate of 10% and a plant life of 25 years was calculated at $189.33 per MWh for scenario 1 and $175.19 per MWh in scenario 2. Regarding the costs of electric power production in MSW WtE plants, the US Department of Energy and the Office of Energy Efficiency and Renewable Energy in 2019 published LCOE values for WtE plants in the US, being between 120 and 170 US$/MWh [33], which are close to the values of this study.

Table 6. Variables for the calculation of LCOE

	Investment cost (USD)	CRF	O&M (Fixed) (USD)	O&M (Variables) (USD)	Hours Year	Power Plant (KW)	LCOE (US$/MWh)
Scenario 1	143,213,577	0.11	5,892,300	1,050,000	8,000	15,000	189.33
Scenario 2	127,816,905	0.11	5,892,300	1,050,000	8,000	15,000	175.19

The financing model represents a financial burden due to the fiscal rules of each nation and loan interest, for this study the loan conditions, type of financing (long term) and amortizations (PRICE) were defined. it can be observed in Scenario 1, that the interest added during the 25-year life of the project is US$83.5 million, approximately 58% of the project investment. For Scenario 2, although the interest payment with respect to the plant investment remains at 58%, in absolute terms, since the amount of the investment financed is lower, there is a saving in interest payments of US$8.98 million during the project versus Scenario 1.

Analyzing the costs represented by income tax, there is a considerable reduction in the payment of this tax in Scenario 2, around 49% with respect to Scenario 1. This is due to the application of the income tax benefit granted by Law 1715, which exempts the payment of this tax for 15 years, as long as 50% of the project investment is not exceeded. In Scenario 2, year 15 is reached with an income tax payment value of $ 63,752,515, being half of the investment for this scenario of $ 63,908,452.70, for this reason, the benefit is reached during the 15 years.

Table 7. Costs on loan and tax conditions

Financial and tax concept	Value	Value to be paid during the project	
Financial and tax concept	25 years	Scenario 1	Scenario 2
Financed portion of the investment	60%		
Minimum Acceptable Rate MAT	10%		
Financing term	15 years		
Loan interest	10%	$ 83,531,322.90	$ 74,550,998.49
Income tax	35%	$ 123,513,795.86	$ 62,904,395.63

To elaborate the cash flow, income related to; prices for energy sales, metal sales and MSW disposal fees were taken into account and are described in the following table. The annual depreciation of equipment and assets was calculated, calculating the annual depreciation at 4,905,101 USD and redefining the costs distributed in plant, being 60% for equipment [34].

Table 8. Income generated by annual plant

Item Revenue	Estimate	Ref.	Income $ (Annual)	Income $ (25 years)
Sale Electricity	147,4 US$ / MWh	[35]	10,063,500	324,209,744
MSW disposal fee	42,1 US$ / t MSW	[36]	15,348,250	383,706,250
Sale of separated metals	665,610 US$/year	[31]	665,610	16,640,250
Total			28,982,250	724,556,244

Once the cash flow calculations for each scenario have been made, the economic returns of the plant can be observed, for Scenario 1, with the conditions proposed, the project is not viable, since it does not achieve a return on investment, with a Net Present Value NPV of minus -6.6 million dollars in losses and an internal rate of return (9.18%) below the minimum attractive rate (10%). However, in Scenario 2, positive results are achieved at an economic level, the NPV of the calculated project is around 40 million dollars, an IRR of 15.7% and a recovery of the investment at the end of year ten, evidencing the need for this type of projects to comply with the state requirements to enjoy the sustainable development policies offered at governmental level.

Table 9. Economic performance of the plant

Economic indicator	Scenario 1	Scenario 2
Net Present Value $ (NPV)	-6,634,332	40,232,650
Internal rate of return % (IRR)	9.18%	15.78%
Return on Investment in years (RI)	No return	10.7

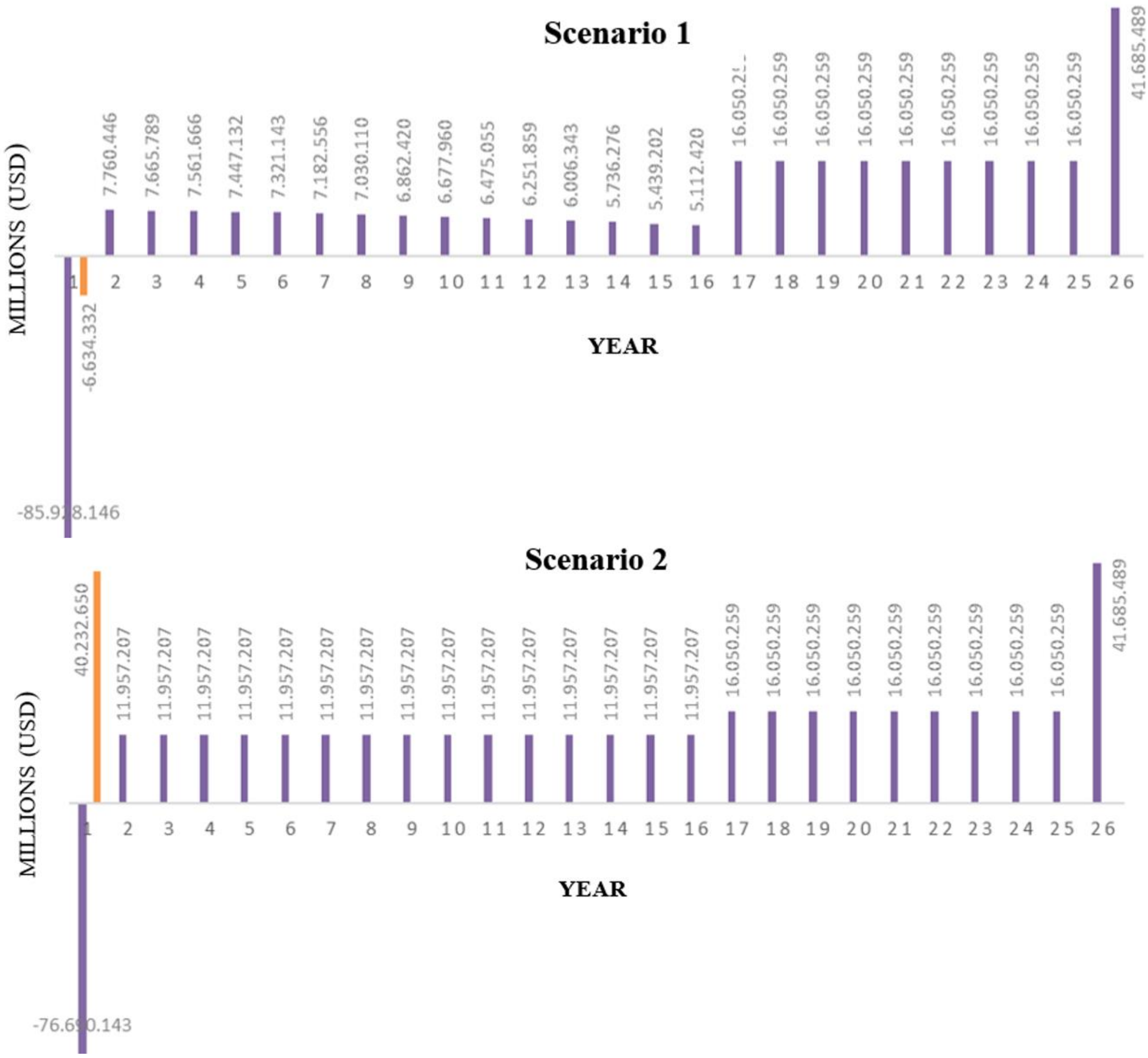

Figure 5. Cash flows of each scenario

Economic analyses tend to present certain subjectivity, due to the multiple variables with which the calculations are made, as it could be observed in the previous sections, there is a chain of results, from the energy evaluation to the assumptions of the loan conditions, including plant income and state benefits. For this reason, this study applied a sensitivity, choosing three variables, which, according to the results seen above, generate the greatest impact on the viability of the project. The variables to be considered in the sensitivity are; electricity sales, MSW management price and financed percentage of the investment. By considering these variables and evaluating them in the model, it is expected to attenuate the bias produced by the initial values with which the base case was evaluated, observing, up to what point of the sensitivity of each variable, the project is feasible or economically viable.

It can be observed that by increasing the selling price of electricity in scenario 1 by 10%, the project enters into zones of economic viability, the minimum that electricity can be sold is 160 dollars for each megawatt hour, and if electricity is sold at 40% more, the NPV reaches around 24 million dollars in profitability.

For the variation of the MSW management price, it is observed in Scenario 1, that by increasing the price by 10%, the project begins to be economically viable, the minimum that could be charged for MSW management is $45 per ton of MSW. In Scenario 2, the minimum that could be charged for the MSW management fee is US$25 per ton of waste managed to reach financial closure. To have a reference of this value in both scenarios, in Europe, fees associated with waste disposal are around 120 USD/TMSW [37].

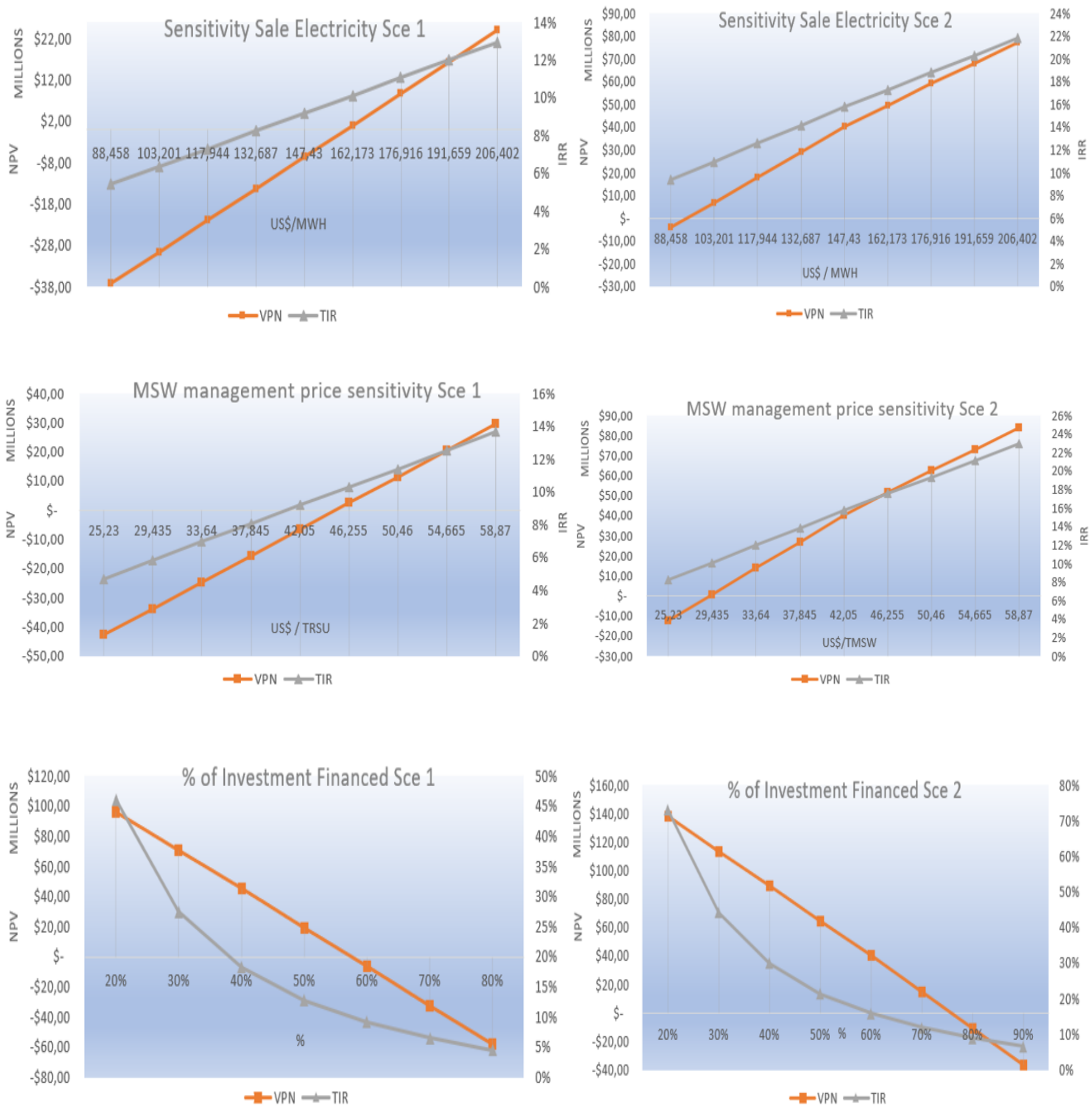

Figure 6. Sensitivity of variables for each scenario

Finally, in the sensitivity analysis, the percentage of the investment that would be financed was considered. This variable is significant, due to the associated financial costs. In this aspect, other implicit variables are involved, such as the interest rate of the loan and the financing term. In Scenario 1, US$83.5 million in interest was paid during the 15 years of financing, starting from a base capital of US$57.3 million (40% initial capital). Under the conditions of Scenario 1, an initial capital of 57.5% of the investment cost, i.e., US$82.2 million, would be required to make the project economically viable. Due to the state benefits enjoyed by Scenario 2, the plant investment cost is US$127.8 million, thus making it possible to implement the plant with 24.3% of the total plant investment, i.e. US$31.1 million of capital investment, without generating losses.

4. Conclusions

WtE technologies present an alternative for sustainable MSW management. Direct incineration processes with energy production (electricity / district heating and in some cases, district cooling) dominate the waste market, reaching a proven technological maturity in more than 2000 plants installed around the world, however, a management model that combines biological, thermal, WtE technologies, together with reuse and recycling policies at plant and source respectively, would increase sustainability in a waste management project.

From the energy analysis, it was determined that the plant processing 640.7 tons of MSW per day, with a thermal efficiency of 22.6%, would produce 87 GWh per year, an estimated monthly electricity coverage of 46,000 homes in Colombia. However, energy yields could be improved by increasing the energy characteristics of MSW (increasing the LHV) before it enters the furnace through mechanical and biological treatments.

Evaluating the results of the economic analysis, loaded with subjectivity due to estimates linked to financial variables, two relevant aspects on which the profitability of a WtE plant depends are evident, being of the technical and financial order, technical aspects such as plant capacity, i.e. how many MSW are processed in the year and the PCI of the MSW, susceptible to increase, if mechanical biological treatments MTB are carried out in the plant. On the financial side, government benefits in terms of taxation have a significant influence on the economic viability of this type of technology, other economic factors such as loan conditions (to promote public-private partnerships), income from the sale of electricity and a predominant factor in this analysis, the MSW disposal fee, which for this study was estimated at US$42 per ton; in Europe values of around US$120 per ton of MSW processed are used.

MSW incineration plants face significant challenges due to social resistance and uncertainty related to the exhaust gases generated during combustion. These gases contain polychlorinated dibenzodioxins and dibenzofurans, which are hazardous substances for human health. However, thanks to the development of advanced flue gas cleaning technologies, it is possible to operate modern WtE plants in strict compliance with established regulations and emission limits. This implies continuous monitoring by the environmental authorities and obliges the managers of these facilities to invest in appropriate technologies for the treatment of combustion products.

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