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Article

Comprehensive Analysis of Solid Waste for Energy Projects in Colombia

Diego Alejandro Ossa[1,a], **Andrés Julián Aristizábal**[2,b,*], **and Daniel Ospina**[3,c]

1 Superintendencia de Servicios Públicos Domiciliarios, Bogotá 110231, Colombia
2 Engineering Department, Universidad de Bogotá Jorge Tadeo Lozano, Bogotá 110311, Colombia
3 Mewbourne College of Earth and Energy, The University of Oklahoma, OK 73019, United States
E-mail: [a]daossa@superservicios.gov.co, [b]andresj.aristizabalc@utadeo.edu.co (Corresponding author), [c]danycol@ou.edu

Abstract. The purpose of this study is to determine the financial feasibility of electricity production projects in Colombia using thermal treatment technologies for Municipal Solid Waste (MSW), by assessing the generation potential, the costs associated with investment, operation and maintenance of infrastructure, and the environmental impacts in terms of CO_2 emissions. The study is developed for three capital cities that reflect different conditions of production and characteristics of the MSW, which are: Bogotá D.C., Cartagena and Manizales. MSW production volumes were determined from information reported by public sanitation service providers, while their lower calorific value was estimated from a predictive model referenced in the literature. The results of the study indicate that the development of these technologies, in the three cities mentioned, would allow to contribute 2.309 GWh/year, corresponding to approximately 3,3% of the electricity demand in Colombia; likewise, they would reduce CO_2 emissions by more than 3 million tons per year, compared to the emissions generated by the final disposal of waste in sanitary landfills. The plant located in the city of Bogota would have the best financial performance, with an internal rate of return of 7,1%, while the infrastructure located in the cities of Cartagena and Manizales would not have an interesting financial performance; under the assumptions raised in the study.

Keywords: Solid waste, thermal treatment, feasibility analysis, CO_2 emissions, energy generation, incineration systems.

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1. Introduction

The generation of solid waste at urban and rural scale in Colombia was estimated for 2014 at 13,8 million tons per year [1]. Notwithstanding the foregoing, according to official information, only 26.528 daily tons of solid waste were presented for final disposal in 2014, corresponding to 9,7 million tons [2]. 96,9% of the total waste presented for final disposal during 2017 was adequately disposed in sanitary landfills, recovery plants and contingency cells, while the remaining 3,1% was inadequately set in transitional cells, open-air dumps, bodies of water, burnt or buried [3].

By 2035, it is estimated that Colombia will have 64 cities with a population greater than 100.000 inhabitants that will concentrate 83% of the population. Similarly, the generation of solid waste estimated for 2030 is 18,74 million tons per year, of which 14,2 million tons should be disposed in landfills that currently do not have enough capacity [1]. In fact, out of the total number of disposal sites in the country, about 13% have no remaining useful life, 15,3% have remaining useful life between 0 and 3 years, 15,7% between 3 and 10 years, and only 22,2% have a useful life of more than 10 years. There is no information on the remaining percentage [3].

Particularly in Colombia, since the issuance of Law 1715 of 2014, by means of which the integration of unconventional renewable energies into the national energy system was regulated, the energy content of waste that is not susceptible to reuse or recycling is considered as unconventional source of renewable energy [1,4].

At the end of 2016, the National Council for Economic and Social Policy (CONPES in Spanish), the highest national planning authority and advisory body of the Colombian government on aspects related to the country's economic and social development [5], issued the National Policy for Integrated Management of Solid Waste, whose action plan considers the promotion of the circular economy as one of its main axes, seeking to develop instruments that promote the prevention, minimization, reuse, recycling and treatment of solid waste for the purpose of valorization (generation of fuel or electrical energy).

In recent years, several authors have similarly analyzed the benefits of using the MSW that reach the final disposal sites for the generation of electrical energy. For example, Islam [6] evaluated the potential of electrical energy generation and the reduction of carbon emissions associated with the management of MSW in Bangladesh using different energy exploitation strategies. Likewise, Tan et al. [7] evaluated the energy, economic and environmental impact of different MSW energy exploitation technologies in Malaysia. Leme et al. [8] evaluated different alternatives of exploiting energy from MSW generated in Brazilian cities, finding that landfills are the worst waste management option from the environmental point of view and the direct combustion of MSW for energy recovery turned out to be the best identified option, despite its low financial performance. Also, Ouda et al. [9] examined different MSW energy exploitation technologies in Saudi Arabia, identifying their costs and benefits. Scarlat et al. [10] evaluated the energy potential of the MSW in Africa, performing a spatial analysis of the energy available from the concentration of the population. Likewise, Safar et al. [11] evaluated the feasibility of generating electricity from MSW in Pakistan, identifying the power generation potential both from biological and thermal treatments. Xin-Gang et al. [12] analyzed political, economic, social and technological factors of the MSW incineration industry in China, finding that plants of this type have good profitability and environmental benefits. In the same sense, Teixeira et al. [13] analyzed the evolution of MSW management in Portugal and the policies implemented for different thermal treatment technologies.

In Colombia, there have not been many studies aimed at analyzing the exploitation of MSW to produce electrical and thermal energy. Among the studies identified are, first, the one carried out by Morales [14] in 1984, in which the feasibility of generating electricity by incinerating solid waste from the city of Bogotá was evaluated, limited to perform a brief technical analysis based on the MSW calorific value of that time. Second, Pérez et al. [15] conducted a technical economic study in 2010 to establish the possibilities of using MSW in the municipality of Facatativá (Cundinamarca) as a source of thermal energy, estimating its calorific value and comparing it with other fossil fuels. Likewise, the work carried out by Sánchez [16] was identified, in which the recovery of energy through incineration process of the MSW disposed in Doña Juana landfill in the city of Bogotá D.C. was analyzed, using system dynamics as a modeling technique for different proposed scenarios. Finally, Alzate et al. [17] evaluated the feasibility of energy recovery projects in Colombia from different technologies applying the tax benefits established in current legislation.

2. Methodology

Five main components were analyzed to carry out the feasibility assessment: i) the volumes and characteristics of MSW, ii) the efficiency and capacity of the MSW thermal treatment technologies available in the market, iii) the investment and operation costs of the selected reference technology, iv) the environmental impacts of said reference technology, and v) the market conditions for the generation of electrical energy in Colombia. Once these components were analyzed, the financial analysis was carried out based on the results obtained. Figure 1 describes the process performed to obtain the main elements of the analysis, as well as the relations used.

The analysis was carried out on particular cases in three cities of the country, which had different climatic, population and MSW production conditions, in order to better visualize the effects of economies of scale and characteristics of waste in the performance of the technologies evaluated. The cities of Bogotá D.C., Cartagena and Manizales were selected due to their representativeness with respect to the mentioned factors.

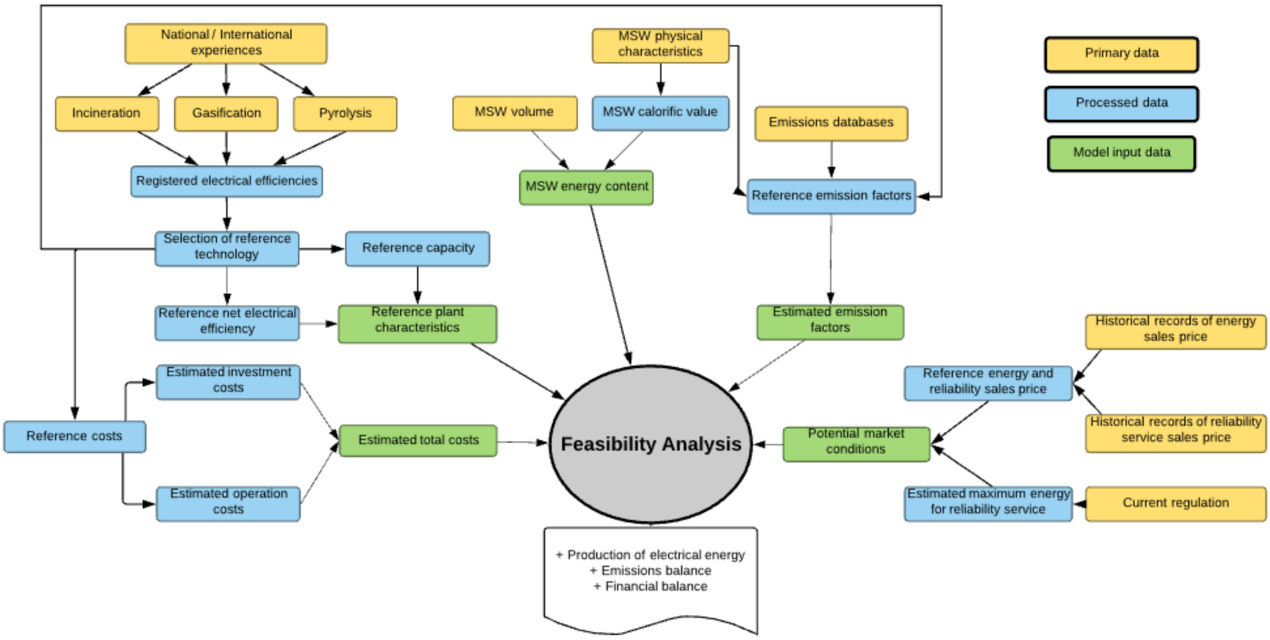

Fig. 1. Relationship diagram of the analysis carried out. Source: Authors.

2.1. MSW Volumes and Characteristics

The characteristics of production and composition of the MSW in the country were obtained from information available in the Single System of Information of Public Domestic Services (SUI in Spanish) [18] and other databases managed by the Superintendence of Public Services (SSPD in Spanish), entity in charge of surveillance and control of public services in Colombia.

Likewise, there was information provided by the Special Administrative Unit for Public Services (UAESP in Spanish) [19], a decentralized entity of the district administration of Bogotá D.C. responsible for guarantee, among others, the provision, coordination, supervision and control of the collection, transport, final disposal, recycling and exploitation services of the MSW in the city [20].

Based on physical composition of MSW, several mathematical models designed to estimate its lower calorific value (LCV) were identified [21]. The model used for the present study was developed in [22] based on information on the composition of MSW from 35 countries, including Colombia. Equation (1) corresponds to the representation of the referenced estimation model.

$$\mathrm{LCV}\left(\frac{\mathrm{btu}}{\mathrm{lb}}\right)=\{23*[\mathrm{OW}+3{,}6(\mathrm{C}+\mathrm{P})]\}+[160*(\mathrm{Pl}+\mathrm{Ru})] \quad (1)$$

where the variables OW, C, P, Pl and Ru correspond to the content (% by weight) of organic waste, cardboard, paper, plastic and rubber, respectively, in the MSW. In order to standardize the units to MJ/kg, a factor of 0,002326 was used.

2.2. Efficiency and Capacity of MSW Thermal Treatment Technologies Available in the Market

Based on compilation of different international experiences in the field of implementation of MSW thermal treatment technologies [23-41], it was determined that the mass incineration technology is the one that has recorded more and better information in relation to its probable performance during the operation, especially in terms of net electrical efficiency and treatment capacity. Due to the above, said technology was used as a reference technology for the present study.

However, the efficiency of a MSW incineration plant dedicated to the generation of electrical energy is highly dependent on the size of the installation. Although there was not access to a sufficient amount of data on the performance and efficiency of MSW incineration plants dedicated to the generation of electrical energy with different capacities, in order to build an estimation model; it was identified that Bogale et al. [42] modeled and analyzed high-efficiency plants from the thermodynamic and technological point of view to investigate, among other aspects, the effects of installation size on net electrical efficiency. Figure 2 shows the results of this work, in which the capacity of the plant was expressed in terms of input thermal energy, in MW.

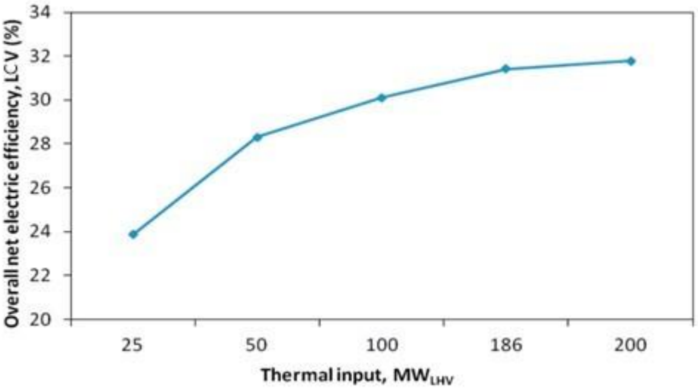

Fig. 2. Net electric efficiency vs plant capacity. Source: own elaboration with data from [42].

The estimated values of net electric efficiency for each of the projects in the selected cities were obtained from the calculation of the average available input thermal energy and the model defined in Fig. 2.

2.3. Investment and Operation Costs of Selected Reference Technology

For the estimation of investment and operation costs, different studies developed at an international level were collected. According to World Bank estimates [43] referenced by the Inter-American Development Bank [44], the investment cost of a MSW incineration plant is directly impacted by the size of the facility.

These estimates are quite close to those published by the International Solid Waste Association (ISWA) in 2013 [45], which sets different ranges depending on the level of income of the country where the project will be developed. For countries with high income and high environmental control standards as well as MSW with a high calorific value, this range is defined between 600 and 900 USD per ton/year of capacity; in middle income countries with some environmental control requirements and MSW with middle calorific value, this range is between 400 and 600 USD per ton/year of capacity; while in low-income countries with low environmental control standards and MSW with low calorific value, the range is estimated between 300 and 500 USD per ton/year of capacity.

In order to determine the reference investment costs for this study, the estimates proposed by the World Bank were used, which vary according to the size of the facility, bounded in the range proposed by ISWA for middle-income countries, which it is considered the most suitable to the Colombian characteristics.

The operating costs of a MSW incineration plant are mainly divided into three major concepts: fixed costs, variable costs and maintenance costs. Fixed costs refer to costs inherent to the existence of the plant, such as administration costs, insurances, taxes, payment of salaries and other expenses associated with the employment relationship. The variable costs are associated with the operational levels of the plant, since they correspond mainly to the cost of chemicals and elements of short useful life necessary for the environmental control system, both gas and liquid waste; the backup fuels, if necessary, as well as the final disposal costs of ash, slag, and other waste derived from the incineration process. Finally, the maintenance costs correspond to the costs associated with preventive, predictive and corrective maintenance of the thermal, mechanical and electrical infrastructure, as well as the maintenance of civil infrastructure.

As an industry standard, annual fixed costs are estimated at 2% of investment costs, while variable costs are estimated at between 12 and 17 USD/ton incinerated and annual maintenance costs at 1% of the investment costs of the civil infrastructure plus 2,5% of the investment costs of the thermal, mechanical and electrical infrastructure [46].

As mentioned for investment costs, according to World Bank estimates referenced by the Inter-American Development Bank, the operating cost of a MSW incineration plant is also directly impacted by the size of the facility.

In order to determine the reference operational costs for the present study, the estimates proposed by the World Bank were used, which vary according to the size of the facility, bounded according to the industry standard, that is, without being able to be less than the estimated value through the sum of fixed costs (2% of total investment costs), variable costs (15 USD/ton), and maintenance costs (1% of civil works + 2,5 % of the thermal, mechanical and electrical equipment) of each of the incineration plants evaluated. For this purpose, and considering the aforementioned, civil works and thermal, mechanical and electrical equipment were estimated as 15% and 65% of the total investment costs, respectively.

2.4. Environmental Impacts of Reference Technology

The MSW incineration generates a large number of impacts on the environment derived from the process waste streams, represented in the combustion gases that are discharged into the air through the chimney, the leachate from the waste handling prior to its incineration and liquid waste coming from environmental control systems of gases that must be treated before being discharged into the environment, and unusable solid waste derived from the combustion process that must be disposed in a landfill. In the same way, there are impacts of this activity associated with the generation of odors, the affectation of the natural landscape or the socioeconomic impacts in the area of influence of the project. For the purposes of this study, only environmental impacts associated with the emission of CO_2 were analyzed.

The Intergovernmental Panel on Climate Change - IPCC jointly established in 1988 by the World Meteorological Organization - WMO and the United Nations Environment Programme - UNEP works on defining methodologies for the inventory of greenhouse gases in support of the United Nations Framework Convention on Climate Change - UNFCCC. In compliance with this task, in 2006, it published the latest version of the IPCC Guidelines for National Greenhouse Gas Inventories. Within these guidelines, a chapter was devoted to estimate the emissions derived from the incineration of MSW, especially those associated with carbon dioxide - CO_2 [47].

The IPCC guides offer several levels of emission estimates derived from the MSW incineration based on the degree of information available; the first level defines emission factors and calculation parameters by default, the second level defines emission factors and parameters for each country, and the third level carries this information at the level of each plant. Considering that the incineration industry of MSW does not have much history in Colombia, it was considered that the most appropriate is the calculation of CO_2 emissions using the first level of estimation, which raises the possibility of estimating emissions from the MSW composition, as shown in Eq. (2).

$$CO_2\left(\frac{\text{kg } CO_2}{\text{ton MSW}}\right)=\sum_{j}(WF_j{*}dm_j{*}\ CF_j{*}\ OF_j){*}\frac{44}{12}{*}1.000 \quad (2)$$

where WF is the fraction of each of the MSW components, dm is the dry matter content of each component, CF is the carbon fraction in the dry matter, OF is the carbon oxidation factor, and 44/12 is the carbon to CO_2 conversion factor. It is emphasized that the original equation proposed by the IPCC also includes the carbon fraction of fossil origin of the compounds in order not to account for the contribution of emissions derived from the incineration of renewable compounds; however, for this study this variable was not included, since the objective is to estimate the total CO_2 emissions to be compared with the CO_2 equivalent emissions generated by the MSW disposal in landfills, the latter being originated mainly by the decomposition of organic matter, so it was considered that, if this variable were included, the comparison would not have been adequate. The variables used are presented in Table 1, which were extracted from the IPCC Waste Generation, Composition and Management Data Guide [48].

Table 1. Dry matter content, carbon fraction and oxidation factor for different MSW compounds. Source: own elaboration with data from [48].

Compounds	**Dry matter content %**	**Carbon fraction %**	**Oxidation factor %**
Raw organic waste	40	38	100
Trimming waste	40	49	100
Paper products	90	46	100
Cardboard products	90	46	100
Plastics	100	75	100
Textile	80	50	100
Metals	100	0	100
Wood	85	50	100
Rubber and leather	84	67	100
Ceramics, ashes, rock and rubble	90	3	100
Glass	100	0	100
Bones	90	3	100
Others	90	3	100

Based on the emission factors calculated with Eq. (2), the CO_2 emissions were estimated for each of the projects in the selected cities. Subsequently, its comparison was made with respect to the emissions associated with the final disposal of MSW in traditional landfills.

Although the estimation of biogas emissions from a landfill is a complex task, because production sources tend to have a high spatial and temporal variability, not only between each landfill, but also between each cell inside it, according to Johannessen [49] it is generally accepted that an approximate maximum volume of 200 m3 of biogas can be generated from a ton of MSW disposed in a landfill.

Moreover, the density of the biogas is between 1,1 and 1,28 kg/m3 and, normally, it is assumed that the proportion of methane - CH_4 and CO_2 of the biogas is 1:1, although this value is different for each particular case. Taking into account the above, and using the lower limit of the biogas density range, it can be affirmed that each ton of MSW generates approximately 110 kg of CH_4 and 110 kg of CO_2; however, considering the global warming potential of greenhouse gases, CH_4 has an impact 21 times greater than the impact caused by CO_2 in a period of 100 years [49]. Consequently, each ton of MSW disposed in a landfill, generates during the period of decomposition of organic matter, about 2.420 kg of CO_2 equivalent.

2.5. Market Conditions for Electrical Energy Generation in Colombia

In order to identify the primary market conditions for the sale of energy and associated services in which the MSW thermal treatment infrastructure could operate in Colombia, an analysis was made of the main commercial variables, seeking to estimate reference values that would allow the financial analysis.

The Wholesale Energy Market - WEM in Colombia is comprised of a set of information exchange systems between generators and marketers operating in the National Interconnected System - NIS. The WEM allows short and long-term electricity purchase and sale transactions, therefore, in it all the energy that is required to supply the demand of users connected to the NIS is transacted. Transactions in the WEM are mainly carried out under the following modalities: Hourly transactions in the energy stock, Bilateral financial energy contracts, and Auctions for the assignment of Firm Energy Obligations - FEO [50].

In the short-term market or energy stock, generators make daily price offers for the hourly availability of energy provided to the system. The demand, represented by the marketers, is a price taker with respect to the short-term price of energy (stock price), which is a single price for the whole system at each hour of the day, determined by means of the run of an hour optimization dispatch model without transmission restrictions, but considering the technical characteristics of the generation resources.

On the other hand, in the long-term market or bilateral contracts, the traders and generators register their energy purchase and sale contracts with the market operator, so that the latter can determine their transactions in the short-term market hour by hour, which correspond to the difference between their purchase obligations (demand cover, in the case of marketers) and sale (delivery of energy in the case of generators), valued at the market price (stock price) [51].

In terms of energy transactions in this market, the conditions of quantity and price of each contract, as well as the indexing mechanisms and other particularities, are freely defined by parties. Bearing in mind that in Colombia the regulated demand (generally users with low level of power and energy demand) covers about 70,3% of total demand [18], the weighted average price of contracts destined to serve regulated demand - Mc, is a good indicator of the price level feasible for both sellers and buyers. It is important to keep in mind that the Mc is the result of averaging contracts that are subscribed with higher and lower prices than this indicator; therefore, it does not mean that there is no possibility of selling energy above said value.

Finally, with the objective of providing the long-term economic signal for the expansion of the installed capacity required by the country, reflecting the level of reliability in the supply that is willing to pay the national demand, the Energy and Gas Regulation Commission, (CREG in Spanish), entity responsible for regulating the electricity sector in Colombia, established a market mechanism called Reliability Charge - RC, which has been in operation since December 1, 2006. One of the essential components of this mechanism is the existence of the FEO, which correspond to a commitment of generators, supported by generation assets capable of producing firm energy during critical supply conditions. These FEOs are auctioned among the generators to cover the demand of the system. The generator to which a FEO is assigned receives a well-known and stable remuneration during a determined period, and the generator commits to deliver a certain quantity of energy when the stock price exceeds a threshold previously established by the CREG called Scarcity Price. Said remuneration is settled and collected by the market operator and paid by the users, through the rates charged by the marketers.

In the case of reliability market, the Real Equivalent Cost of Energy - RECE, corresponds to the weighted average price of the remuneration to the generating agents participating in the RC mechanism [52] and is understood as a good indicator of the feasible price level for the generators that offer this service in the WEM.

For the three referenced markets, the price series (stock price, Mc and RECE) registered since December 2006 to December 2018 were constructed in order to determine the reference values used to estimate the income of projects in the financial analysis, applying statistical criteria.

Now, while in the short and long-term markets the generation of energy is the basis of the settlement of the income of a generating agent in the WEM, for the case of the reliability market the base for the settlement of the income is the firm energy that can offer.

In accordance with current regulations, the generators that connect to the NIS have the obligation of subjecting to a central dispatch all the units of their generation plants, when these have a total individual effective capacity greater than 20 MW and, on a voluntary basis, when the plant has a capacity greater than or equal to 10 MW and less than 20 MW [53]. These limits partially restrict the participation of the smaller plants within the RC mechanism and generate differentials in the technical and commercial treatment. In particular, for those plants not subject to central dispatch, they are not allowed to participate in the FEO assignment auctions, and they do not have the same physical delivery obligations as the plants subject to central dispatch that participate in the mechanism [52]. For the present study, it is considered that all plants are subject to central dispatch.

Resolution CREG 071 of 2006, by means of which the RC remuneration methodology was adopted in the

WEM, also incorporated the concept of Firm Energy for the Reliability Charge - FERC, which refers to the maximum amount of electrical energy that is able to deliver a generation plant continuously, in conditions of low hydrology, in a period of one year. The determination of the FERC, which is calculated by the agent and verified by the market operator, is one of the requirements for a generation plant to participate in FEO allocation auctions in the RC mechanism [52].

For the estimation of the FERC, the thermoelectric generation plants require calculating the index called "Historical Unavailability by Forced Outputs" - HFO for each of their units, which aims to reflect the time in which the generation unit is unavailable, or its operating power does not reach the total net declared capacity. For new units operated with natural gas and liquid fuels, the regulation allows an HFO of 0,2 to be used for the first year of operation; while if they are operated with coal and other fuels, an HFO of 0,3 is allowed for the first year of operation. In both cases, an HFO of 0,05 is allowed for the second year and up, while it is updated with actual data of its operation [52,54].

As a general rule, agents wishing to participate in the RC mechanism must guarantee the backing of their FEO with the supply and transport of the required fuel in sufficient quantities, to obtain the necessary energy to produce the electrical energy that is willing to commit. Associated with the above, the plants must also calculate the so-called "Fuel Supply Availability Index" - SAI, which aims to reflect the amount of energy guaranteed by fuel supply contracts, with respect to the maximum energy that the unit at full capacity can generate.

This study made an estimation for an electrical energy generation plant from thermal treatment systems by MSW incineration, based on the conceptual development established in current regulations in Colombia for the calculation of the FERC of a thermoelectric generation plant. The analysis was based on the application of Eq. (3), shown below:

$$\mathrm{FERC}_{\mathrm{TP\ MSW}}\ (\mathrm{MWh}) = \mathrm{NEC}*\beta*\mathrm{h} \qquad (3)$$

where NEC is the net effective capacity of the generation unit in MW, β is the lowest value between the availability of the plant (1 - HFO) and the SAI, and h are the hours of a year. As can be seen, the value of the variable β is what determines the value of the FERC.

Although a MSW incineration plant can achieve an availability of more than 90% [39], for the present study an HFO of 0,3 was used, corresponding to an availability of 70%, which is considered sufficiently conservative. Likewise, it is based on the premise that the MSW supply for the plant must be guaranteed through contracts with the collection and transport companies, so that the energy needed to operate at full load is understood as insured. Consequently, the variable β was assigned a value of 0,7 for all cases.

2.6. Financial Indicators Used for the Feasibility Analysis

In order to assess the results of the MSW incineration projects for the generation of electrical energy in the selected cities, cash flows were constructed taking into account the income and expenditures associated with the investment and operation of each plant.

Regarding project income, it was considered that they are associated with four concepts: sale of electrical energy, sale of the reliability service, sale of waste disposal service through incineration, and reduction of CO_2 emissions.

Then, it was assumed that there is some mechanism to sell the energy produced in the long term through bilateral contracts and that it participates in the reliability market with 90% of the FERC calculated based on Eq. (3). The MSW incineration rate (gate fee - GF) was estimated as the final disposal costs per ton that users of the public sanitation service must assume in the month of December 2018 in each of the landfills in the selected cities [55-57]; and the emission reduction rate was estimated at 10 USD/tonCO_2 equivalent.

Likewise, while for the rate of sale of energy and the provision of the incineration service it was considered that they increase annually with the inflation of the domestic market, it was estimated that the sale rate of the reliability service increases annually with inflation of the external market, and the price of carbon credits remains stable during the useful life of the installation. Inflation in the domestic market was estimated at 4%, a value close to the average of the years 2011 to 2018 in the country [58]. For the reference of external market inflation, the value used was the average of the years 2017 and 2018 of the Producer Price Index of the United States of America, corresponding to capital goods, reported by the Bureau of Labor Statistics of the United States (Series ID: WPSFD41312) [59], which is the same defined by the CREG as indexer of the RC price.

On the other hand, it was considered that the expenditures of the projects are associated to three concepts: initial investment, annual costs of operation and income tax.

It was estimated that the return on investment cannot be less than 12%, a percentage that is considered corresponding to the Weighted Average Cost of Capital - WACC for the investor. Likewise, a useful life of 30 years for the plants was considered.

The estimated annual cost of operation was considered to increase annually with respect to domestic market inflation, and a linear profile of investment depreciation (without salvage value) was determined throughout the useful life of the infrastructure for the calculation of the income tax, which was estimated at 33% and, in no case, its settlement can have values lower than 0. The tax and customs benefits established in Law 1715 of 2014 for generation projects from unconventional sources of renewable energy were considered applied, to the extent that the reference costs were not increased by tariffs or value added tax - VAT and, additionally, in cases where it was possible, the reduction of 50% of the income tax during the first 5 years was applied. The possibility of accelerated depreciation was not considered for financial analysis, insofar as, although this benefit initially releases cash flow, it was found that the project's financial indicators do not substantially improve with this measure.

Furthermore, for the feasibility analysis, three indicators were used: internal rate of return - IRR, simple repayment period, and benefit - cost ratio. The IRR corresponds to the rate at which the cash flow of the project during its useful life has a net present value equal to 0, as represented by Eq. (4).

$$\mathrm{IRR}= \sum_{T=0}^{n} \frac{\mathrm{Fn}}{(1+i)^{n}} = 0 \tag{4}$$

where the variable Fn corresponds to the net cash flow of each period, n represents the total number of periods and the variable i is the interest rate of payments.

On the other hand, simple repayment period corresponds to the time in which the positive cash flow generated by a project balances the negative cash flow caused by initial investment, without considering the cost of capital. Its calculation is made using Eq. (5).

$$\mathrm{Repayment}= a+ \left(\frac{b}{c}\right) \tag{5}$$

where variable a corresponds to the last period with negative accumulated cash flow, variable b represents the absolute value of the last negative accumulated cash flow, and variable c corresponds to the net cash flow value of the next period.

Finally, the benefit-cost ratio compares the net present value of income and project costs during its useful life, discounted with the WACC for the investor. It is represented by Eq. (6).

$$\frac{\mathrm{B}}{\mathrm{C}} = \frac{\mathrm{NPVi}= \sum_{T=1}^{n} \frac{\mathrm{Ip}}{(1+i)^{n}}}{\mathrm{NPVc}= \mathrm{Ii}+ \sum_{T=1}^{n} \frac{\mathrm{Cp}}{(1+i)^{n}}} \tag{6}$$

where the variable NPVi corresponds to the net present value of income of the project during its useful life and is calculated by discounting the periodic income Ip with the WACC i. Likewise, the NPVc variable corresponds to the net present value of project's costs during its useful life and is calculated by discounting the periodic costs Cp with the WACC i, adding them to the initial investment Ii.

3. Results and Discussion

3.1. MSW Production, Characterization and Energy Content

The three cities selected for this study correspond to the capital city of the country and the capitals of the departments of Bolívar and Caldas. The waste that receives the city of Bogotá D.C. is disposed in Doña Juana landfill, the waste of the city of Cartagena is disposed in Loma de los Cocos Environmental Park landfill, while the waste of the city of Manizales is sent to La Esmeralda landfill. The three landfills accumulate approximately 26% of MSW disposed in the country. Table 2 shows the monthly disposition values in each of the landfills from the selected cities during year 2016.

Table 2. MSW monthly disposed tons in Bogotá D.C, Cartagena and Manizales, 2016.

Month	Doña Juana landfill - Bogotá D.C.	Loma de los Cocos Environmental Park landfill - Cartagena	La Esmeralda landfill - Manizales
January	158.774	37.109	15.070
February	161.742	35.030	14.209
March	170.315	36.978	15.149
April	170.939	35.921	14.960
May	176.655	39.080	15.082
June	171.370	38.073	14.851
July	168.378	38.891	14.718
August	177.005	39.875	15.126
September	170.152	39.202	14.595
October	174.965	39.019	15.791
November	200.337	40.321	16.243
December	280.052	43.129	18.663
Total	2.180.685	462.629	184.459

Similarly, Table 3 presents the MSW characterization in each of the mentioned cities. It is important to point out that, despite the fact that all the sources consulted named the compounds to which the characterization mention in a different way, for the present study they were homologated as shown in said table.

Table 3. MSW typical characterization disposed in Bogotá D.C, Cartagena and Manizales, 2017.

Compound	**Doña Juana landfill - Bogotá D.C.**	**Loma de los Cocos Environmental Park landfill - Cartagena % by weight**	**La Esmeralda landfill - Manizales**
Raw organic waste	49,89	53,28	27,87
Trimming waste	1,43	N.A.	
Paper products	10,43	4,55	5,96
Cardboard products	3,23	5,14	6,48
Plastics	16,88	16,63	16,68
Textile	4,54	3,76	4,85
Metals	1,13	1,66	3,15
Wood	1,60	0,87	0,64
Rubber and leather	N.A.*	2,18	0,68
Ceramics, ashes, rock and rubble	2,27	0,62	0,49
Glass	3,67	4,86	5,04
Bones	N.A.	0,24	0,17
Others	4,93	6,21	27,99

** Not Available*

In this sense, the operator of La Esmeralda landfill presented the composition of raw organic waste and trimming waste under the name "Food and Garden". Meanwhile, for the Loma de los Cocos Environmental Park landfill, there was no information associated with the trimming waste compound. While the operator of Doña Juana landfill discriminated between flexible and rigid plastic, the operator of the Enviromental Park Loma de los Cocos landfill discriminated in high density, low density and icopor plastics, and the operator of La Esmeralda landfill discriminated in plastics and polyethylene terephthalate - PET. In any case, these compounds were homologated under the generic name "Plastics".

The compound "Other" included the compounds reported by the operator of Doña Juana Landfill under the names of "Dangerous", "Complexes" and "Others", as well as those reported by the Loma de los Cocos Environmental Park landfill, with the names of "Hygienic" and "Electrical". In the case of the La Esmeralda landfill, the percentage of this compound is particularly important since it corresponds to more than a quarter of the total waste.

The summations of the individual composition reported by two of the sources present differences with respect to the total maximum (100%). These differences were incorporated into the "Other" compound, taking into account, first, that they correspond to marginal values that do not exceed two hundredths and, secondly, that this compound does not account for greater contributions from the energy point of view.

Based on the characterization of Table 3 and using the mathematical model represented in Eq. (1), the estimation of the MSW LCV was obtained for the cities of Bogotá D.C, Cartagena and Manizales, which are shown in Table 4.

Table 4. Estimated LCV (MJ/kg) of MSW disposed in Bogotá D.C, Cartagena and Manizales.

Doña Juana landfill - Bogotá D.C.	**Loma de los Cocos Environmental Park landfill - Cartagena**	**La Esmeralda landfill - Manizales**
11,58	11,72	10,35

3.2. Selection of Reference Technology for MSW Thermal Treatment and Estimation of Expected Net Electrical Efficiency

The MSW thermal treatment can be carried out by incineration, gasification or pyrolysis [60, 61]. The mass burn incineration boiler is the most mature technology for the conversion of MSW and therefore the most commonly used within the large power plants that recover energy in the world. Within this type of treatment, the most widespread technology is the grate incinerator, which is used in about 90% of MSW thermal treatment plants in Europe [34, 35]. Similarly, there are various configurations and technologies that have been developed for treatment of MSW by gasification and pyrolysis, many of them at a demonstration or laboratory scale.

Incineration plants have recorded performances in terms of net electrical efficiency greater than 30% [37-39]. On the other hand, despite the numerous experiences identified in Japan and several European countries in the implementation of gasification and pyrolysis technologies for MSW thermal treatment and its exploitation for the electrical energy production, the truth is that information associated with technical, financial and environmental performance of these facilities is quite limited [28], so it is difficult to find operational references regarding the net electrical efficiency of the process.

From the review carried out, it was evidenced that information related to the net electric efficiency of the gasification and pyrolysis plants does not correspond to operational reports but to estimations made, which makes it impossible to determine with a reasonable certainty the expected results in terms of potential generation of electrical energy. The opposite occurs with MSW incineration plants, which most of them have the design parameters accessible, and some records of the operational efficiency achieved and the measures that were implemented for that purpose.

For the analysis, grate type mass burn incineration was used as a reference technology, which takes advantage of heat of the combustion gases for the generation of steam, which feeds turbines and generators of electrical energy. The possibility of heat delivery by the system is not considered since in Colombia, except in some cases, there is currently no widespread implementation of thermal districts and industrial demand may not be so easy to guarantee in the long term.

Now, in order to estimate the net electrical efficiency of incineration plants using the model presented in Fig. 2, the average input thermal energy for each of them was calculated from the volume of MSW defined in Table 2 and the LCV estimated in Table 4. The amount of MSW that arrive at each landfill was averaged and multiplied by the LCV. For the conversion of the energy units from MJ to kWh a factor of 0,2778 kWh/MJ was used.

Table 5 presents the input thermal energy calculated and the general parameters defined for the MSW incineration plants in each of the selected cities in order to carry out the analysis. The processing capacity per line was defined taking care not to exceed the international industry standard and the number of lines seeking to cover approximately the MSW average received by landfills of the same cities during 2016.

3.3. Electrical Energy Production Potential

Based on the information collected and processed, it is possible to estimate the electrical energy production that would be expected the MSW thermal treatment plants in each of the selected cities would be able to deliver to the national electricity system, with results as shown in Table 6.

The total treatment capacity of the plants was determined from the daily average of available MSW registered in 2016 approximated to the nearest lower tens.

Likewise, for the three cases a real availability percentage of 85% was applied, which aims to recognize the unavailability of the facilities, associated with the need to carry out maintenance, emergency or due to any circumstance arising from the temporary unavailability of MSW, although the latter case may be manageable insofar if there is some storage capacity. For the conversion of the energy units from MJ to kWh a factor of 0,2778 kWh/MJ was used.

Finally, in order to have a value of the rated power of the generator associated with the thermal treatment infrastructure, it was estimated from the total treatment capacity, the MSW calorific value and the net electrical efficiency. It is noteworthy that, obviously, it does not correspond to an in-depth analysis that allows optimizing the design; simply, it corresponds to a numerical exercise that allows having a reference value. For this purpose, the calculation of the estimated rated power approached the fifth lower unit.

As a result of the analysis it is observed that, under the assumptions defined in this study, the thermal treatment systems through MSW incineration from the cities of Bogotá D.C., Cartagena and Manizales, would potentially be able to generate 1.811, 376, and 122 GWh/year, respectively.

3.4. Reference Costs of Investment and Operation for MSW Incineration

Table 7 shows the investment costs in USD per ton/year of capacity defined for MSW incineration plants in each of the selected cities for the purpose of carrying out the analysis, using the total capacities proposed in the Table 5, and applying the methodology mentioned in numeral 2.3.

Similarly, Table 8 shows the operating costs in USD/ton defined for MSW incineration plants in each of the selected cities, using the same elements defined for investment costs.

3.5. Environmental Impacts Associated with MSW Incineration and CO_2 Emissions Balance

Applying Eq. (2) to the different MSW compositions defined in Table 3, the estimated emission factors in $kgCO_2$/ton of MSW are presented in Table 9 for the incineration plants in each of selected cities.

Likewise, the results of the annual balance of emissions generated by the thermal treatment infrastructure are presented, with respect to the estimation of the emissions derived from their final disposal in a landfill. For this case, the amounts of MSW that can incinerate the facilities in each of the selected cities are used, considering an estimated infrastructure availability of 85%.

As a result of the analysis, it is observed that the annual reduction of CO_2 emissions equivalent in the cities of Bogotá D.C., Cartagena and Manizales, would be 2.432.988, 520.454 and 219.083 tons, respectively.

Table 5. General parameters of the thermal treatment systems by incineration of MSW.

Parameter	Unit	Bogota D.C.	Cartagena	Manizales
Input thermal energy	MW	801	172	61
Processing capacity per line	ton/hour	30	25	10

Treatment lines	No.	8	2	2
Expected net electric efficiency	%	31,5	31	28,5

Table 6. Electrical energy production potential of thermal treatment systems by MSW incineration.

Parameter	Unit	Bogota D.C.	Cartagena	Manizales
Total treatment capacity	ton/hour	240	50	20
Estimated net electric efficiency	%	31,5	31	28,5
Availability	%	85	85	85
Estimated lower calorific value	MJ/kg	11,58	11,72	10,35
Estimated rated power	MW	240	50	15
Estimated annual electrical energy production	GWh/year	1.811	376	122

Table 7. Estimated investment cost of thermal treatment systems by MSW incineration.

Parameter	Unit	Bogota D.C.	Cartagena	Manizales
Capacity	Ton/year	2.102.400	438.000	175.200
Investment cost	USD/ton/year	400	411	514
Estimated total cost of investment	MUSD	841	180	90

Table 8. Estimated operational cost of thermal treatment systems by MSW incineration.

Parameter	Unit	Bogota D.C.	Cartagena	Manizales
Capacity	Ton/year	2.102.400	438.000	175.200
Operational cost	USD/ton	30,1	32,0	40,0
Estimated total annual cost of operation	MUSD/year	63,3	14,0	7,0

Table 9. Annual balance of CO_2 emissions to the atmosphere derived from the implementation of MSW incineration systems.

Parameter	Unit	Bogota D.C.	Cartagena	Manizales
Incineration emission factor	kg CO_2/ton MSW	1.059	1.022	949
MSW incinerated	ton/year	1.787.040	372.300	148.920
Estimated annual incineration emissions	ton CO_2/year	1.891.649	380.512	141.303
CO_2 emission factor - disposal in landfills	kg/ton	2.420	2.420	2.420
MSW disposed	ton/year	1.787.040	372.300	148.920
Estimated annual emissions from disposal	ton CO_2/year	4.324.637	900.966	360.386
Annual emissions reduction	ton CO_2/year	2.432.988	520.454	219.083
	%	56	58	61

3.6. Market Conditions for Electrical Energy Generation in Colombia

Figure 3 shows the historical data of short-term market or stock price in WEM since December 2006 to December 2018, indexed to this last month using the Internal Offer series of the Producer Price Index (IPP in Spanish) calculated and published by the National Department of Statistics (DANE in Spanish) [62], entity responsible for the production and dissemination of statistical information in the country. The right vertical axis presents the data in USD for an exchange rate of 3.249,75 COP/USD valid for December 31, 2018 [63] and which was used for all analyzes.

As can be seen, the stock price has ranged between 43,27 COP/kWh (1,33 cUSD/kWh) and 2.123,81 COP/kWh (65,35 cUSD/kWh), with an average of 188,43 COP/kWh (5,8 cUSD/kWh). This situation is the result of the high volatility of short-term prices imposed by the Colombian electricity system, associated with the significant participation of hydroelectric generation in national electricity matrix and the effects of climate variability events derived from the El Niño phenomenon that recurrently affect precipitation in the country.

Figure 3 also shows the stock price limited to the Scarcity Price, represented by the series called "Stock price bounded for RC", which is intended to reflect the real liquidation price for the sale of energy on the stock market for the generators, when said energy was compromised in the RC mechanism which, in practice, is the most frequent situation in the Colombian market, especially for thermoelectric generation plants connected to the NIS.

In this case, the remuneration price for sales on the stock exchange ranged between 43,27 COP/kWh (1,33 cUSD/kWh) and 571,32 COP/kWh (17,58 cUSD/kWh), with an average of 166,21 COP/kWh (5,12 cUSD/kWh). Taking into account that this series presents a coefficient of variation (relationship between the standard deviation of the sample and its mean) of 51,1% that reflects the aforementioned dispersion of the data, a frequency analysis was carried out in which an asymmetric distribution of data with positive trend was found; that is, the median, the value represented by the central position of the data set of the series, is less than the average. In effect, the value of the median is 147,92 COP/kWh (4,55 cUSD/kWh) which, is considered, the one that best represents the series.

Similarly, Fig. 4 presents the historical data of the Mc since December of 2006 to December of 2018, indexed to this last month using the series of Internal Offer of the Price Index of the Producer calculated and published by the National Department of Statistics - DANE [62].

Unlike the stock price, the Mc has a more stable and growing behavior in the long term, with some periods of decline in the short term. However, and in order to have conservative references for financial analysis, the third quartile of the series was calculated - Q3, the value below which is 75% of the data of the series. The value of Q3 is 174,29 COP/kWh (5,36 cUSD/kWh).

Finally, Fig. 5 presents the historical data of the Real Equivalent Cost of Energy - RECE, which corresponds to the weighted average price of the remuneration to the generation agents participating in the RC mechanism [52]. The information is presented for the period between the month of December 2006 and the month of December 2018, indexed to this last month using the Colombian Peso Market Exchange Rate - MER with respect to the US dollar on the last day of the year (12/31/2018), published by the Bank of the Republic of Colombia [63]. For this case, the MER is used as an index parameter, insofar as in the RC assignment auctions, the agents' offers are made in US dollars and the monthly settlement is made precisely using the current exchange rate of the last day of each month.

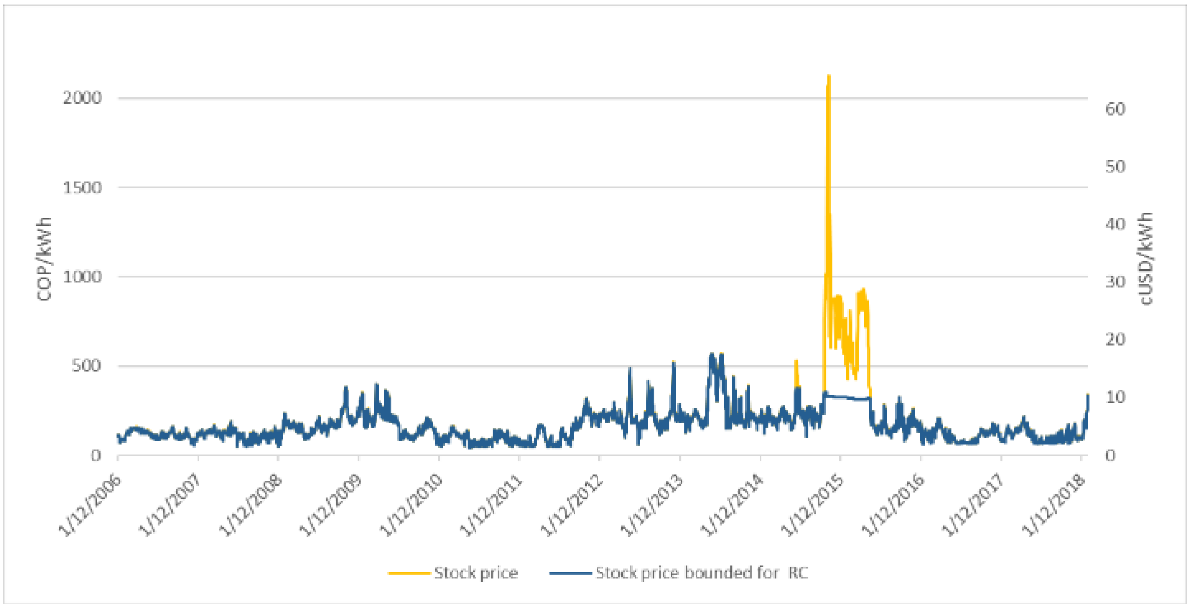

Fig. 3. Historical Stock Price - Sp and Stock Price bounded for plants participating in RC. Source: own elaboration with data from [64].

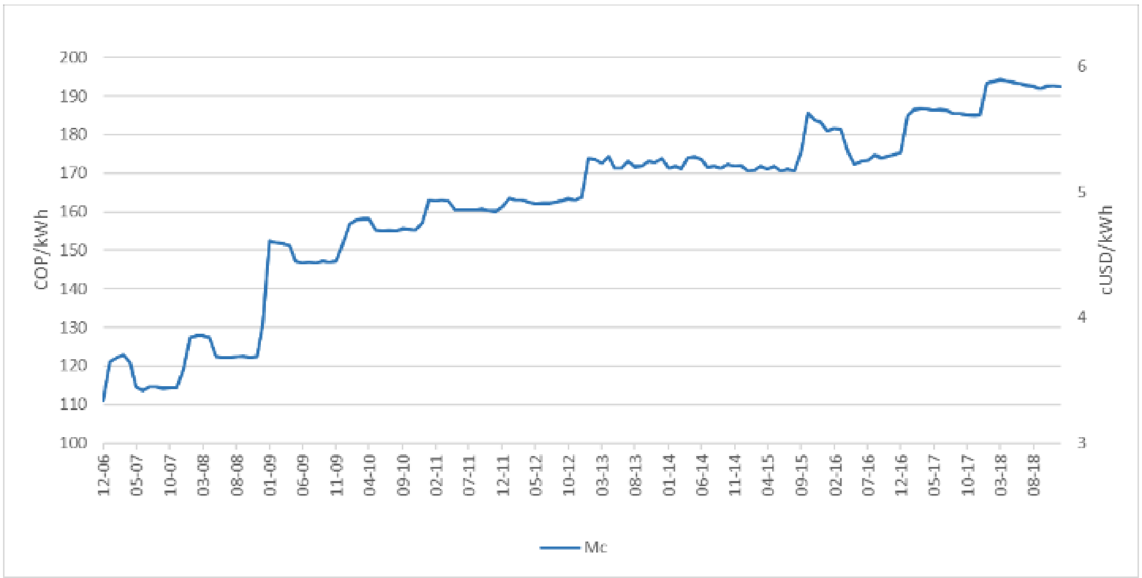

Fig. 4. Historical weighted average price of contracts destined to the regulated market. Source: own elaboration with data from [64].

Fig. 5. Historical Real Equivalent Cost of Energy - RECE for the Reliability Charge. Source: own elaboration with data from [64].

As proposed for the Mc, looking for conservative references for financial analysis and for the purposes of simplicity of the analysis, the third quartile of the series was calculated - Q3, the value below which is 75% of the data of the series. The value of Q3 is 58,68 COP / kWh (1,81 cUSD/kWh).

Bearing in mind that the WEM rules apply to all generation plants connected to the NIS, regardless of the location of the generation infrastructure, Table 10 shows the reference values of the potential revenues for services associated with the electrical energy generation, selected for the present study. It is clarified that these values were discounted the reference value of the reliability service, considering that reliability service is incorporated in the stock prices and contracts analyzed previously.

3.7. Financial Balance

Table 11 consolidates the information used for the financial analysis of the projects for each of the selected cities.

As a result of the analysis for the case of the project in the city of Bogota D.C., which is shown in Fig. 6, it was found that, under the aforementioned assumptions, the project would have an IRR of 7,1% and a repayment period of 13,1 years. The above, compared to the proposed WACC would not meet the expectations of the investor, yielding a benefit - cost ratio of 0,82.

Now, in order to identify the incineration rate that takes the financial indicators of the project to meet the expectations of the investor, the cash flow that reflects an IRR of 12% and a benefit - cost ratio of 1 was elaborated, which is shown in Fig. 7 with the series called "Cash Flow GF = 32,5 USD/ton". For this case, it was found that the incineration rate that would make the project comply with the expectations of the investor is 32,5 USD/ton (105.617 COP/ton); in other words, 21,3 USD/ton (69.220 COP/ton) more than the cost of disposal of MSW in the landfill of the city of Bogotá D.C.

Similarly, for the case of the project in the city of Cartagena, which is shown in Fig. 7, it was found that, under the assumptions, the project would have an IRR of 5,6% and a repayment period of 15,2 years. The above, compared with the proposed WACC would not meet the expectations of the investor, yielding a benefit - cost ratio of 0,77.

Performing the same exercise to identify the incineration rate that takes the financial indicators of the project to meet the expectations of the investor, the cash flow that reflects an IRR of 12% and a benefit - cost ratio of 1 was elaborated, which is shown in Fig. 7 with the series called "Cash Flow GF = 36 USD/ton". It was found that the incineration rate that would enforce the project in the city of Cartagena with the investor's expectations is 36 USD/ton (116.991 COP/ton); in other words, 27,5 USD/ton (89.368 COP/ton) more than what the disposal of MSW costs in the landfill of this city.

Finally, for the project in the city of Manizales, which is shown in Fig. 8, it was found that, under the aforementioned assumptions, the project would have a negative IRR of 3,7% and a repayment period exceeding the useful life of the infrastructure. Obviously, the project would not meet the expectations of the investor, yielding a benefit-cost ratio of 0,57, not being acceptable under any scenario.

Table 10. Reference values of income from sale of services associated with electrical energy generation from thermal treatment systems using MSW incineration.

Trade mechanism	**Rf Value (cUSD/kWh)**
Income from the sale of energy on the stock market	2,74
Income from energy sales in contracts	3,55
Income from the sale of reliability service	1,81

Table 11. Parameters for the financial analysis of MSW incineration projects.

Parameter	**Unit**	**Bogota D.C.**	**Cartagena**	**Manizales**
Total cost of investment	MUSD	841	180	90
Annual cost of operation for the first year	MUSD	63,3	14,0	7,0
Income tax rate	%	33	33	33
Estimated annual production of electrical energy	GWh/year	1.811	376	122
Energy sale rate for the first year	cUSD /kWh	3,55	3,55	3,55
FEO	GWh/year	1.324,5	275,9	82,8
Reliability service sale rate for the first year	cUSD /kWh	1,81	1,81	1,81
MSW incinerated	ton/year	1.787.040	372.300	148.920
MSW incineration rate for the first year	USD/ton	11,2	8,5	9,5
Annual reduction of CO_2 emissions	Ton CO_2/year	2.432.988	520.454	219.083
Carbon credits	USD/ton CO_2 eq	10	10	10
Average domestic market inflation	%	4	4	4
Average external market inflation	%	1,6	1,6	1,6
Weighted Average Cost of Capital - WACC for the investor	%	12	12	12
Service life of the installation	Years	30	30	30

However, by carrying out the exercise of identification of the incineration rate that takes the financial indicators of the project to comply with the expectations of the investor, the cash flow that reflects an IRR of 12% and a benefit - cost ratio of 1 was elaborated, which is shown in Fig. 8 with the series called "Cash flow GF = 68 USD/ton". It was found that the incineration rate that would make the project comply with the expectations of the investor is 68 USD/ton (220.983 COP/ton); that is, 58,5 USD/ton (190.110 COP/ton) more than the costs to have MSW in the landfill of the city of Manizales.

4. Conclusion

This study evaluated the potential of electrical energy production using MSW thermal treatment technologies in three cities of Colombia. The environmental balance derived from its implementation was calculated to replace traditional final disposal methods through landfills and its financial analysis, based on international benchmarks.

The results indicate that, under the assumptions defined in the study, the thermal treatment systems through the MSW incineration of the cities of Bogota D.C., Cartagena and Manizales, would potentially be able to generate 1.811, 376, and 122 GWh/year, respectively. Similarly, the annual reduction of CO_2 emissions equivalent, for the same cities as a result of the implementation of this technology would be, in the same order, 2.432.988, 520.454 and 219.083 tons.

The MSW incineration projects in the cities of Bogotá D.C, Cartagena and Manizales would have an IRR of 7,1%, 5,6% and -3,7%, respectively, under the assumptions raised in the study; evidencing that the project in the city of Bogotá D.C presents a positive return that deserves greater research efforts insofar as any improvement in the efficiency of the system, costs reduction or additional benefits, could improve its performance. In any case, the cases of the cities of Cartagena and Manizales, may be susceptible of further analysis since as regionalization projects can be identified, which increase the volumes of MSW to take advantage of.

Likewise, it was found that the incineration rate that would make the projects comply with the expectations of an investor with a WACC of 12%, is 32,5 USD/ton for the city of Bogota D.C., 36 USD/ton for the city of Cartagena, and 68 USD/ton for the city of Manizales. In all cases, this rate is higher than the final disposal rate that users of the cleaning service in each of these cities must assume; however, the smallest difference occurs in the city of Bogotá D.C. with 21,3 USD/ton.

With adequate design and necessary investments, urban solid waste deposited in landfills can stop becoming a risk to public health, reduce greenhouse gas emissions, and become sources of energy, helping to recover disposal costs. Moreover, efforts to capture and use landfill emissions allow the entire chain of generation, capture and disposal of waste to be organized. This includes separation of origin; organization, provision and formalization of more dignified working conditions for people working in the landfill. Also, it is necessary to plan the disposal of waste for the long term and develop the entire associated infrastructure in order to minimize the economic, social and environmental impacts of urban solid waste.

In practical cases, the technical-economic feasibility of electricity production from urban solid waste should be studied. It is necessary to analyze the costs of electricity production for the entire duration of the projects, including the costs of investment, operation and maintenance of the generation system, and the present value of the cost of production per unit of energy generated must be determined. It is necessary to make estimates of reduction of greenhouse emissions for different operating scenarios including primary and secondary treatments. Finally, regulatory frameworks for the generation of electrical energy from biogas and the connection to the electricity grid should be studied.

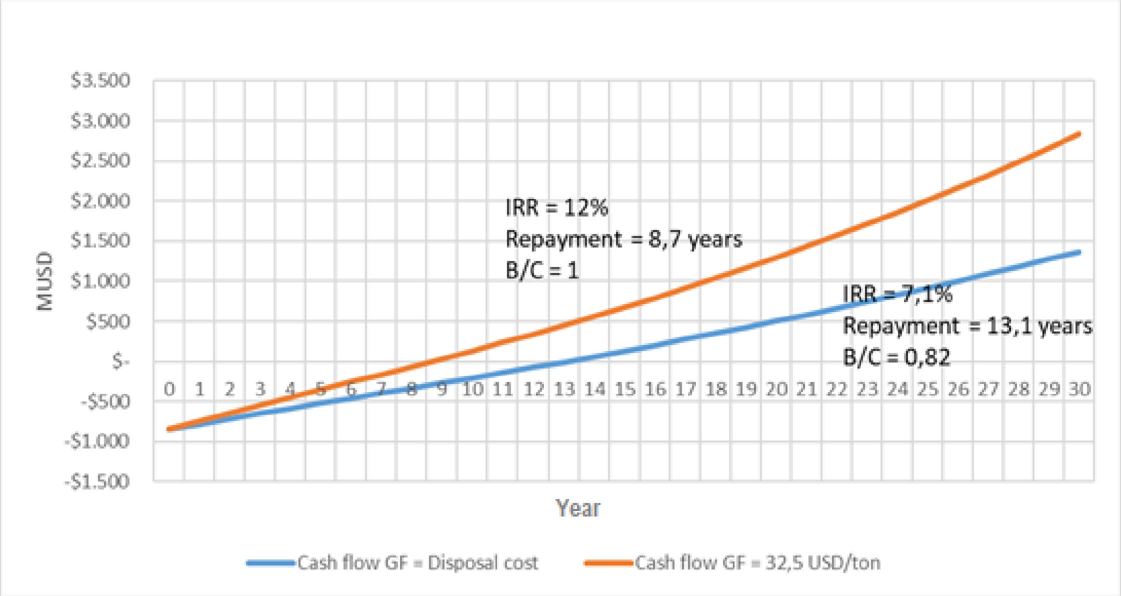

Fig. 6. Accumulated cash flow for the MSW incineration project in the city of Bogotá D.C. Source: Authors.

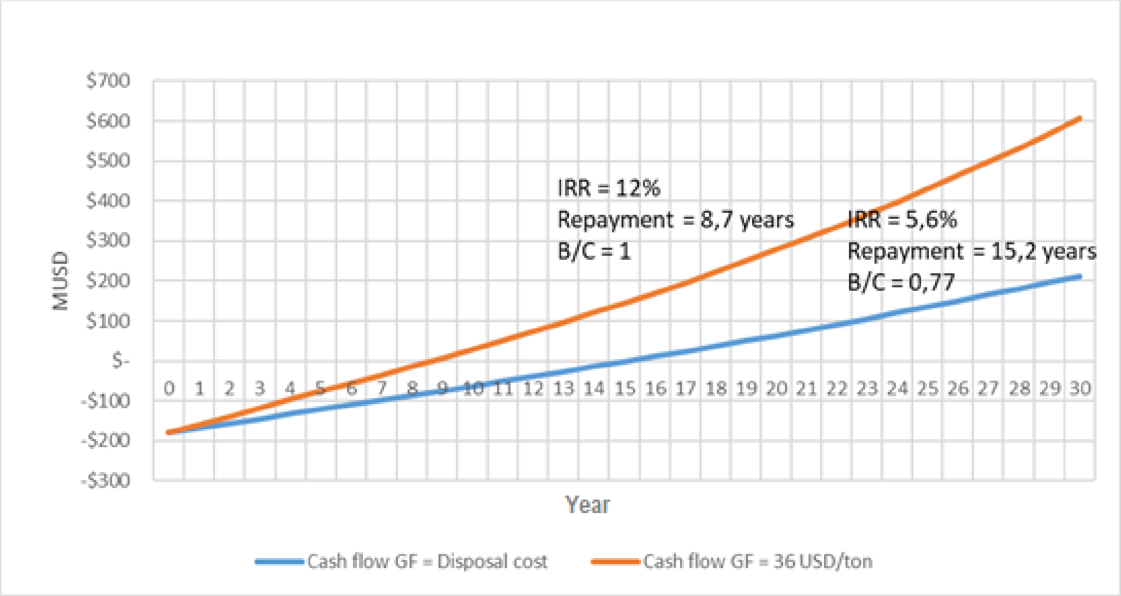

Fig. 7. Accumulated cash flow for the MSW incineration project in the city of Cartagena. Source: Authors.

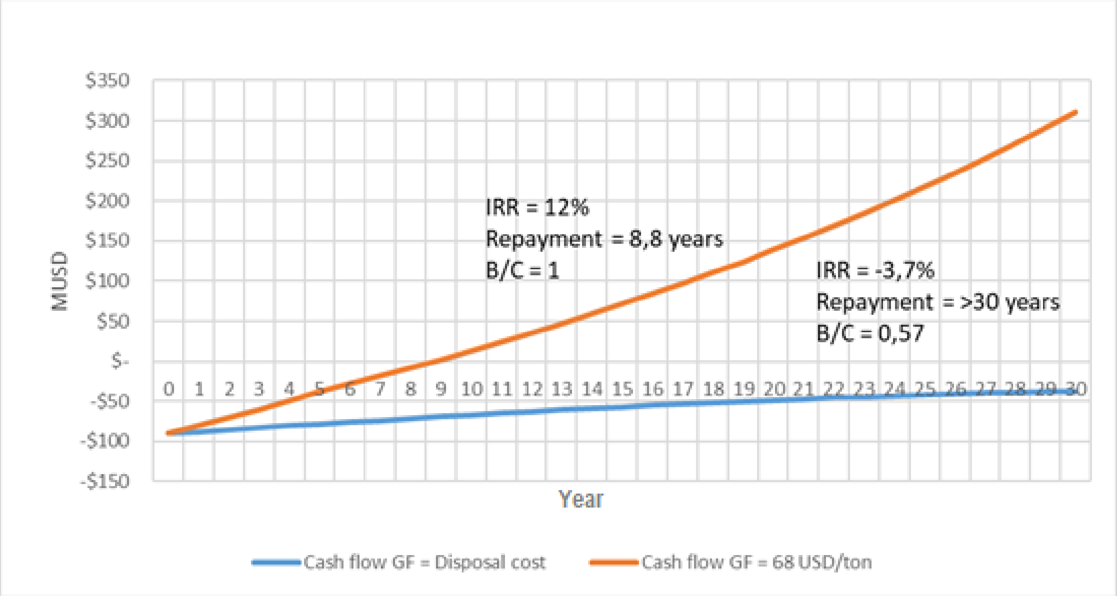

Fig. 8. Accumulated cash flow for the MSW incineration project in the city of Manizales. Source: Authors.

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