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Municipal Solid Waste as a Source of Electric Power Generation in Colombia: A Techno-Economic Evaluation under Different Scenarios

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Abstract: This work evaluates the techno-economic prefeasibility of waste to energy projects in Colombia using four different conversion technologies of incineration, gasification, anaerobic digestion and landfill gas. Three study cases were selected to represent typical urban centers in Colombia, which were namely Guayatá, Andes and Pasto. After feasible technologies were identified for each case, their energy recovery potential was calculated based on the mathematical models and publicly available information about the composition of the wastes produced in these three municipalities. A subsequent economic analysis was conducted by applying the incentives established in Law 1715 for projects involving non-conventional renewable energy sources. The cash flows produced by each technology in the three scenarios were evaluated to obtain the Internal Rate of Return (IRR), which was found to be influenced by the benefits of this legislation. However, the economic benefits were not significant in the small municipality of Guayatá. In turn, in Andes, a high electricity price (100 USD/MWh) would entail a positive IRR of 2.6%. In Pasto, which is the biggest city of the three, the maximum IRR of landfill gas and anaerobic digestion reached 13.59% and 14.27%, respectively. The results show that these types of projects can have positive economic results if tax and government incentives are taken into account.

Keywords: waste to energy; municipal solid waste; energy policies; techno-economic evaluation

1. Introduction

Waste to Energy (WTE) processes play an important role in the sustainable management of Municipal Solid Waste (MSW) worldwide. In some developed European countries, sustainable development policies are aimed at reducing and recycling waste as well as using it to produce electricity [1–4].

WTE involves the recovery of heat and electricity from waste, especially non-recyclable waste [5,6]. The United States Environmental Protection Agency has listed MSW as a renewable energy source. In turn, MSW can be defined as urban and rural waste, which consists mainly of waste paper, cardboard, food, organic material, mixed plastics and textiles among other elements. WTE is rapidly growing all over the world because it can reduce the demand for landfills, prevent dependence on fossil fuels; reduce greenhouse gas (GHG) emissions [1–4,6]; and have a positive impact on economic growth [7].

Biological conversion technologies enable the exploitation of biogas produced from the mass fraction of solid waste [8–10] and several studies have evaluated the potential of landfill biogas for producing electricity [11–15]. Some authors have also assessed the energy recovery potential of biogas from anaerobic digestion for generating electricity or thermal energy in Spain, Brazil, China and Tanzania [16–19]. In particular, Fernandez-González showed that this technology is appropriate in areas where waste generation ranges from low to medium levels [20].

In the field of thermal conversion, incineration is a widely used technology in developed countries as a waste management strategy and for the production of electricity and steam [2,21–24]. China, which produces more MSW than any other country and depends heavily on landfills, incinerated about 19% of the MSW that it produced in 2010 [25]. In Japan, there are around 1900 waste incineration plants but only 10% of them are equipped with appropriate technology for generating electricity [26].

In developing countries, incineration (generally without pretreatment) is considered to be the most reliable and economical form of WTE. Some of the advantages of this technology include waste volume reduction and the use of bottom and fly ash from incineration plants in road construction and cement production [26].

Gasification, another thermal conversion technology, is considered a potential candidate for recovering energy from MSW [27], which reduces the waste volume in 95% and produces less emissions compared to incineration [26].

In addition to the above-mentioned energy conversion technologies, other alternatives, such as microbial fuel cells and microbial electrolysis cells, are considered to be very promising in the future. They can convert MSW into electricity, hydrogen gas and other chemical feedstocks [28].

In Colombia, the per capita production of waste is approximately 0.5 kg/inhab-day, which ranges from 0.2 Kg/inhab-day in rural areas to 1.5 Kg/inhab-day in big cities. In 2009, the energy recovery potential of MSW from Bogotá, Medellín, Cali, Barranquilla and Bucaramanga reached 72.48 TJ/year (19.77 GW) [29]. Such potential can reduce our dependence on conventional sources, such as coal, oil and natural gas.

The indicators reported by the Colombian Superintendence of Domiciliary Public Utilities (SSPD, in Spanish) and the National Planning Department (DNP, in Spanish) show a trend in this Latin American country towards the massive use of sanitary landfills. The final disposal of solid waste in this nation is focused on authorized and unauthorized systems, which recover little or none of the energy potential in waste. However, such recovery is possible by the means of thermal conversion technologies (incineration, pyrolysis and gasification) and bioconversion (landfill gas and anaerobic digestion).

In 2014, on behalf of the national government of Colombia, the Ministry of Mines and Energy enacted Law 1715, which regulates the integration of non-conventional renewable energies into the National Energy System. In accordance with Article 18 of this piece of legislation, the energy content of solid waste that cannot be reused or recycled is considered to be a non-conventional energy source [30]. Additionally, the said law promotes the exploitation of MSW by offering several benefits in the form of the tax incentives described in Articles 11–14 (i.e., income tax, value added tax exemption (VAT exemption), tariff exemption and accelerated depreciation of assets). Such benefits will be explained below in Section 2.3.

On the other hand, traditional landfills are the most widely-used strategy for disposing of MSW in Colombia and their number has risen from 47 in 2011 to 65 in 2014 [31]. Unfortunately, most of them are about to reach the end of their lifespan.

As a result, the generation of electricity from the energy content of solid waste is proposed as an alternative solution to contribute to comprehensive waste management and to diversify the energy mix in Colombia.

From an economic standpoint, there are widely used concepts that allow for an economic evaluation of the prefeasibility of WTE projects. In references [32–34], the economic evaluation was performed using the concepts of Net Present Value (NPV) and cash flows, which consider the expected capital expenditures, operating expenditures, product revenue and other incomes/expenses.

Other important aspects, such as the Internal Rate of Return (IRR) and Payback Period, were also used to evaluate the economic prefeasibility.

Therefore, this work presents a techno-economic assessment of the biological and thermal technologies for converting solid waste into electricity, which was obtained from average urban centers characterized by the number of inhabitants, urban/rural population index and waste type and production. In addition, two evaluations are considered. Case 1 represents typical investment conditions (loan of 50% of the investment for 10 years and an 8% annual interest rate), while Case 2 does not consider a loan but includes the benefits of Law 1715 (accelerated depreciation and a tax deduction of up to 50% of the investment in the first year). Both cases are compared in order to evaluate the impact of the tax benefits in Law 1715 on the resulting IRR.

This study was divided into three stages: (1) selection of three municipalities of Colombia with consideration of the number of inhabitants, urban/rural population index (called Urban Population Index, UP) and the information available in their Solid Waste Management Plan (SWMP); (2) estimation of the energy potential from solid waste with four WTE technologies; and (3) techno-economic evaluation with consideration of the benefits established in Law 1715. Furthermore, both cases were compared to calculate the IRR for each type of technology and municipality. These results will be useful to promote WTE projects in Colombia.

2. Materials and Methods

2.1. Selection of Scenarios

To calculate the energy potential of their specific MSW, one municipality was selected from each group defined by The Colombian Law of Territorial Planning 388 of 1997:

- Group 1 (G_1): municipalities with less than 30,000 inhabitants.
- Group 2 (G_2): between 30,000 and 100,000 inhabitants.
- Group 3 (G_3): more than 100,000 inhabitants.

The population of each group was estimated based on the forecasts by the National Administrative Department of Statistic (DANE, in Spanish) [35]. The rural/urban ratio of each community was also evaluated using the Urban Population Index (UP).

The above-mentioned index showed that in G1, 76% of the municipalities were predominantly rural (UP > 1) while 93.5% of them were predominantly urban in G3 (UP < 1). Regarding G2, the trend was as marked as in the previous cases. Nevertheless, a significant number of municipalities can be found in the PU range of 0.5–1.5. For that reason, this indicator was used to classify the towns into G1 (rural), G2 (similar rural/urban populations) and G3 (urban).

Based on this rate, the subsets of the three aforementioned groups were created. As a result, the subset G1 only includes municipalities with an UP above 1, excluding those that do not meet this condition. The subset G2 is defined by the districts with an UP range of 0.9–1.1, i.e., approximately an equal proportion of urban and rural population. In the subset G3, the search was focused on municipalities with an UP index below 1. In this way, the subsets of municipalities that were defined by their population and rural/urban ratio were built.

After this, the authors filtered out the municipalities that do not make their Solid Waste Management Plan (SWMP) publicly available or do not offer sufficient information on the characteristics of their MSW.

2.2. Energy Recovery Potential from MSW

The technologies analyzed in this study were selected because they are mature, have a consolidated market and are manufactured and imported upon special request.

Incineration and gasification are the main thermal conversion technologies evaluated in this work. The production of MSW in Guayatá is limited and as a result, it is difficult to implement such technologies there [4,36–40] since the operating and maintenance costs are high and the global efficiency is low in that scale [41]. Conversely, both technologies are applicable in Andes and Pasto. The results in [12] show that gasification can be implemented after 3.0 t/day. In the case of incineration, facilities are justified above 100 t/day [36]. Both technologies require a constant supply of MSW and can be located near the municipalities in order to save transport costs.

Biological conversion technologies, anaerobic digestion and landfill gas were considered in the three scenarios because more than 50% of their solid wastes are organic material. Furthermore, small-scale facilities can be implemented for anaerobic digestion (30 kW). This technology offers environmental benefits, such as the control of greenhouse gas emissions. In Guayatá, a municipality that is mainly rural, more energy could be recovered if the waste from agricultural and livestock farming activities is evaluated. Landfill gas represents a low-cost option that utilizes unproductive land to turn it into productive areas. In accordance with the results in [42], this technology can be implemented in municipalities with more than 100,000 inhabitants, such as Pasto. Although there are no specific reference cases for districts with fewer inhabitants, population growth is expected to expand waste generation in Andres, which was subsequently included in this evaluation. However, these technologies were not assessed in Guayatá because of its low levels of waste production.

The information on the amount, physical composition and per capita production of solid waste of each scenario was analyzed to select the most appropriate technology for transforming their MSW into electricity from a technical point of view. Table 1 summarizes the technical conditions that make a technology feasible/infeasible in each municipality.

Table 1. Advantages, disadvantages and technical feasibility by technology and municipality.

Technology	Advantages	Disadvantages	Technical Viability
Incineration	Treatment of organic and inorganic waste Continuous feeding	Not viable for <100 t/day Low efficiency for wet waste High investment	✔ Pasto ✔ Andes x Guayatá
Gasification	It can be located near urban centers avoiding transport costs >3 t/day (biomass)	Waste selection and pretreatment	✔ Pasto ✔ Andes x Guayatá
Anaerobic digestion	Greenhouse gas emissions are avoided >2 t/day Organic waste and agricultural biomass	Only organic fraction Biogas treatment required	✔ Pasto ✔ Andes ✔Guayatá
Landfill gas	>100,000 inhabitants Reduced use of land Low investment	Uncontrolled conditions Biogas treatment required	✔ Pasto ✔ Andes x Guayatá

The energy recovery potential was calculated using the three mathematical models described below. The efficiency values selected for each technology are typical values reported in the literature for WTE facilities.

2.2.1. Incineration

Equation (1) presents the expressions to calculate the amount of electricity that can be obtained from incineration:

$$ERP_i = \eta \cdot M \cdot LCV_{MSW} / 1,000, \tag{1}$$

where ERP_i is the energy recovery potential (MWh/day); M is the the total mass of dry solid waste (t/day); and LCV_{MSW} is the Lower Calorific Value (LCV) of the waste (kWh/kg). The efficiency of the process (η) is 18% [42,43].

2.2.2. Gasification

Equation (2) includes the expressions that are used to calculate the amount of electricity, which can be obtained by means of gasification:

$$\mathrm{ERP_G} = 0.28 \cdot \mathrm{G} \cdot \mathrm{R_f} \cdot \eta \cdot \mathrm{LCV_{MSW}}\ , \tag{2}$$

where G is the number of tons processed per day (t/day) and R_f is the percentage of rejection after the mechanical treatment. The efficiency of the process is 23% [20].

2.2.3. Anaerobic Digestion

This method exploits the organic fraction of MSW, whose electricity production potential is calculated using Equation (3):

$$\mathrm{ERP_{AD}} = \mathrm{P} \cdot \mathrm{R_{AC}} \cdot \mathrm{f} \cdot \mathrm{M_{OFSW}} \cdot \mathrm{Q} \cdot \eta, \tag{3}$$

where P is the number of inhabitants (inhab); R_{AC} is the annual production of waste per capita in (t/inhab-day); f is the organic fraction of the solid waste (%); M_{OFSW} is the methane generation per ton of Organic Fraction of Solid Waste (OFSW) (Nm^3/t); Q is the LCV of biogas due to the methane (MJ/m^3); and η is the efficiency of the process, which is set to 26% [10].

2.2.4. Landfill Gas (Anaerobic Digestion)

The expression to calculate methane emissions from sanitary landfills is given by Equation (4) [13–15,44]:

$$\mathrm{Q_{CH4}} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} \mathrm{k} \cdot \mathrm{L_O} \cdot \left(\frac{\mathrm{M_i}}{10}\right) \cdot e^{-k.t_{ij}}, \tag{4}$$

where Q_{CH4} is the annual generation of methane in a year (m^3/year); M_i is the amount of disposed waste (t/year); L_0 is the methane generation potential (m^3/t); k is the constant of the methane generation index (1/year); n is the difference between the year of the calculation and the initial year of waste acceptance; i is a 1-year time increment; j is a 0.1-year time increment; and t_{ij} is the age of the jth section of waste accepted in year i.

Calculating Q_{CH4} is important because the amount of electricity generated by the biogas depends on that variable, as described in (5):

$$\mathrm{ERP_{LG}} = \mathrm{LCV_{biogas}} \cdot \mathrm{Q_{CH4}} \cdot \gamma \cdot \eta \tag{5}$$

where the LCV of the biogas is given in kWh/m^3; γ is the efficiency of the biogas recovery system (80%); and η is the electrical efficiency of the technology used to generate electricity (33%) [45,46].

2.3. The Benefits of Law 1715

Sanctioned by the national government of Colombia in May 2014, this piece of legislation established certain instruments to promote the exploitation of Non-Conventional Energy Sources (NCES) and invests in the research and development of clean technologies to produce electricity. In accordance with Article 18 of the said law, the energy content of SW that cannot be reused or recycled is a non-conventional energy source. Moreover, Articles 11–14 describe several benefits of tax incentives [30]:

2.3.1. Income Tax (Article 11)

This benefit means a yearly reduction of fifty percent (50%) for 5 years in the tax declaration after the fiscal year of the investment, under the following conditions:

- The value to be deduced should not exceed 50% of the liquid income of the taxpayer calculated before deducting the value of the investment.
- The environmental benefit of the investment is certified by the Ministry of Environment and Sustainable Development.

2.3.2. VAT Exemption (Article 12)

The equipment, items, machinery and national or imported services that are earmarked for preinvestments and investments to produce and use electricity from non-conventional sources as well as the measurement and evaluation of potential resources are exempt under two conditions:

- The Mining and Energy Planning Unit (UPME, in Spanish) must issue a list of the equipment and services that are used for those purposes.
- The VAT-exempt equipment and services are certified by the Ministry of Environment and Sustainable Development.

2.3.3. Tariff Exemption (Article 13)

This benefit applies to the import of machinery, equipment, materials and supplies for new NCES projects. The said products must be exclusively devoted to preinvestments and investments in NCES projects and should not be available from local manufacturers. In other words, they can only be purchased by importing them.

2.3.4. Accelerated Depreciation of Assets (Article 14)

This provision is applicable to machinery, equipment and civil works that are necessary for the preinvestment, investment and operation of electricity generation based on NCES, which are acquired and/or built exclusively for that purpose, starting from the entry into the enforcement of this law. Nevertheless, the annual depreciation rate will not exceed an annual global rate of twenty percent (20%). The said rate can be changed annually by the owner of the project by communicating with the National Directorate of Taxes and Customs (DIAN, in Spanish) without exceeding the limits established in Section 14, except in the cases where the law authorizes higher global percentages [30].

2.4. Economic Evaluation for Each Municipality

The economic evaluation in this work included Capital Expenditures (CAPEX) and Operating and Maintenance Expenditures (OPEX). It should be noted that the above-mentioned technologies are exempt from VAT and tariffs, as set out in Articles 12 and 13 of Law 1715 (see Section 2.3). The costs of each technology shown below are related to the same technologies evaluated in Section 2.2 at similar scales. The costs of each technology are presented in Table 2.

Table 2. Investment, operating and maintenance expenses.

<table>
<tr><th>Technology</th><th>Investment (CAPEX)</th><th>Operation and Maintenance (OPEX)</th></tr>
<tr><td>Incineration</td><td>Fluidized bed incinerator:
65,200 USD/T-day [36]</td><td>4% of the investment [10]</td></tr>
<tr><td rowspan="2">Gasification</td><td>Fluidized bed incinerator:</td><td>Fixed expenses: 4% of the investment.</td></tr>
<tr><td>3,925 USD/kW to be installed [47]</td><td>Variable expenses: 4 USD/MWh [47]</td></tr>
<tr><td rowspan="3">Landfill gas</td><td>Internal combustion engine:
1,200,000 USD/MW to be installed [46]</td><td>17 USD/MWh [46]</td></tr>
<tr><td>Biogas collection system:
3,220,000 USD [45]</td><td>100,000 USD/year [42]</td></tr>
<tr><td>Engineering services:
300,000 USD [42]</td><td>3% of the investment in collection system [42]</td></tr>
<tr><td>Anaerobic digestion</td><td>I(USD) = 101,522 + 3,500·X [48–51]
I: Investment in USD
X: value in kW to be installed</td><td>16% of the investment [10]</td></tr>
</table>

Other benefits were also considered: electricity sale, income for treatment of received ton of municipal solid waste and Certified Emission Reductions (CERs) obtained due to the reduction Greenhouse Gas (GHG) emissions. In addition, the benefits granted by Law 1715 for the commercialization of electricity from Non-Conventional Renewable Energy (NCRE) Sources (income tax deduction, VAT exemption, tariff exemption and accelerated depreciation of assets) were also calculated [30].

The financial evaluation of each project calculated the Internal Rate of Return (IRR) using a 10% discount rate. This rate was determined based on the Capital Asset Pricing Model (CAPM) in [52]. Moreover, the period of analysis of the project was 25 years in all three cases. For the years after 2020, a linear approximation of the previous year's trend was used, which equals 0.7% on average for the different areas in the country.

After the prefeasibility study is completed and the IRR is calculated (a critical point to accept or reject technological options), a decision can be made to continue or abandon the project in each scenario in G_1, G_2 and G_3.

3. Results

3.1. Analysis of the Selected Municipalities

A total of 357 municipalities with a UP > 1 were selected in G_1 (districts with less than 30,000 inhabitants). Out of them, only Guayatá had published sufficient information on its Solid Waste Management Plan (SWMP).

Likewise, in G_2, out of the 15 municipalities that meet the criterion (0.9 < UP < 1.1), only Andes provided information on its SWMP.

The total number of municipalities with a UP < 1 in G_3 is 58. Pasto was selected among this group because it has a complete and publicly available SWMP.

The production of MSW in the three cases under analysis depends on the number of inhabitants. In Guayatá, a small town, the urban and rural population is expected to experience a small decrease of 0.1% and change from 4,586 in 2015 to 4,555 in 2020. In turn, the population in Andes will increase by almost 1,700 inhabitants in the urban area and 220 in its rural counterpart. Overall, the number of inhabitants in that town will increase from 45,814 in 2015 to 47,747 in 2020, i.e., a 4% increase. The population growth in Pasto will be approximately 26,000 inhabitants in the urban area, while the rural component will not experience a significant expansion. The number of inhabitants in this city will rise from 440,040 in 2015 to 465,148 in 2020, i.e., a 5.39% increase. Table 3 presents the percentages of recoverable mass by the type of waste of each municipality.

Table 3. Percentage (%) of partial and total recoverable mass fraction.

	Reference LCV [MJ/kg]	Guayatá [53]	Andes [54]	Pasto [55]
Paper and cardboard	15.6	12.4	7.94	8.31
Mixed food waste	4.6	51.4	60.71	70
Mixed plastics	32.4	12.7	2.16	8.57
Textiles	18.4	0.7	-	1.41
Timber	15.4	1.2	-	0.73
	Recoverable mass	78.4	70.81	89.02

The per capita production of waste in the three municipalities is presented in Table 4. An increase in total waste production at 3% per year was considered based on the population growth in data available from DANE.

Table 4. Urban/Rural per capita production of waste.

Waste Per Capita [kg]	Guayatá	Andes	Pasto
Urban	0.47	0.48	0.55
Rural	0.3	0.28	0.28

The LCV of each municipality was calculated by weighing the mass fraction and the LCV per type of waste (Reference LCV) [56]. Thus, the LCVs of Guayatá, Andes and Pasto were 8.73 MJ/kg, 4.73 MJ/kg and 7.66 MJ/kg, respectively.

3.2. Estimation of the Energy Recovery Potential

Figures 1–3 present the daily electricity production of each technology from 2015 to 2020. It can be observed that by 2020, up to 1.01, 6.33 and 132.10 MWh/day can be recovered using the incineration in Guayatá, Andes and Pasto, respectively.

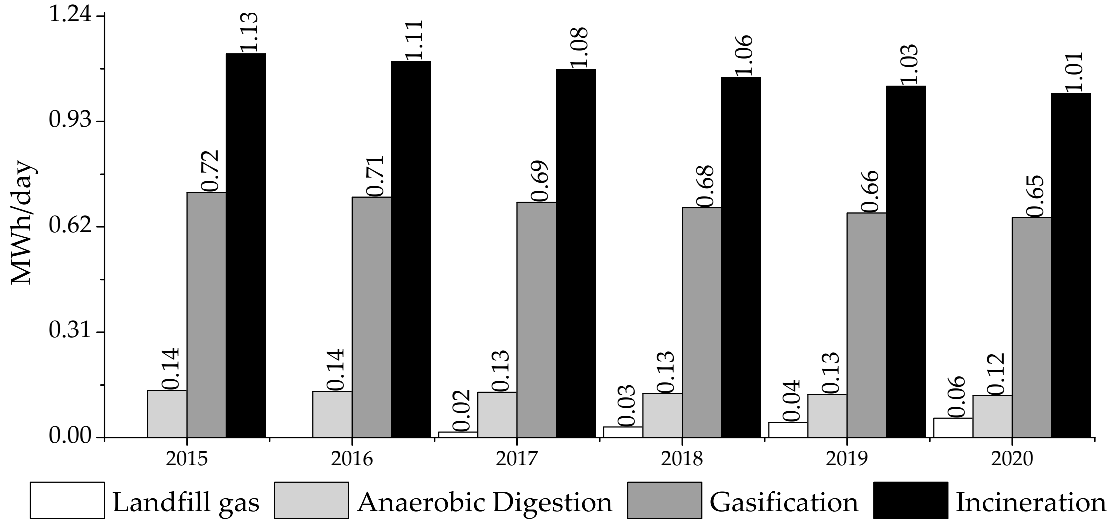

Figure 1. Energy recovery potential in Guayatá.

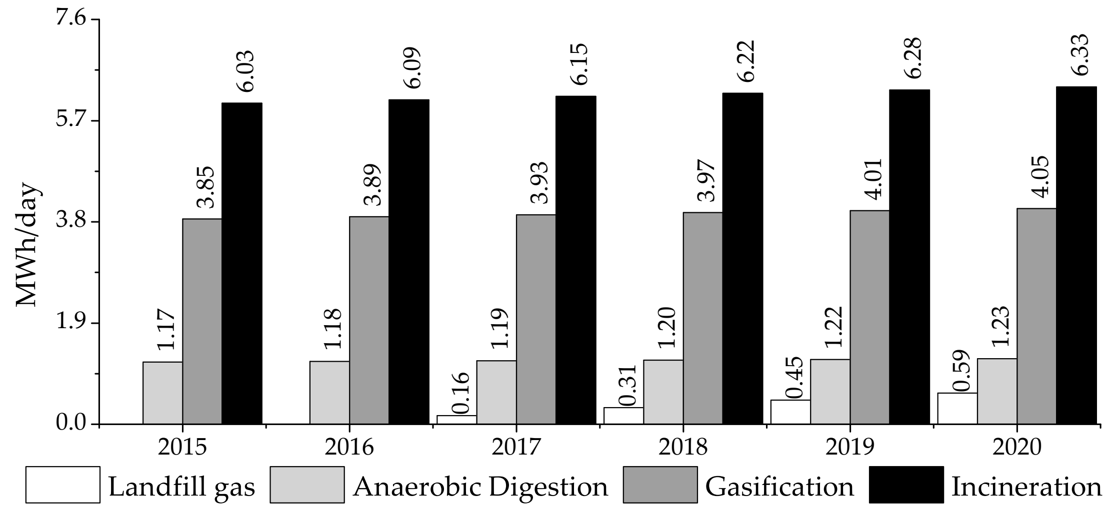

Figure 2. Energy recovery potential in Andes.

The other technologies produce less electricity because they process a smaller amount of waste compared to incineration. In particular, gasification uses 72.51% of the total mass after the mechanical treatment and drying, anaerobic digestion and landfill gas release of biogas from the organic fraction (50–70% of the total waste).

The amount of electricity produced by any of the technologies discussed in this work is directly proportional to the number of inhabitants and this subsequently increases according to the projected growth of the population. In that regard, there is only one available projection until 2020 by the DANE.

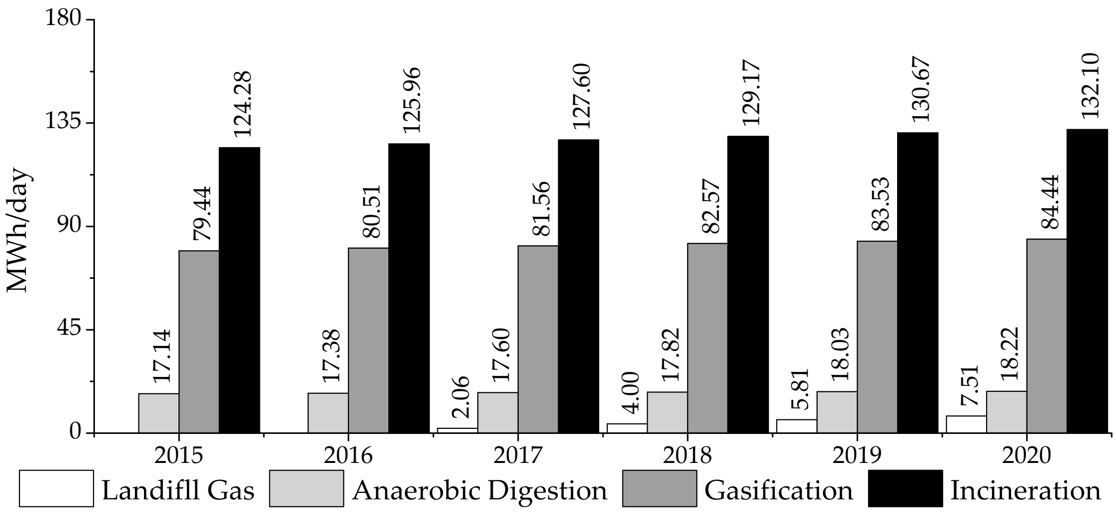

Figure 3. Energy recovery potential in Pasto.

3.3. Economic Analysis

This economic evaluation considered two situations: Case 1, which represents a project under typical investment conditions, and Case 2, which includes the tax benefits in Law 1715. Case 1 includes a 10-year loan for 50% of the investment with an annual interest rate of 8%. Case 2 does not include a loan, but it introduces accelerated depreciation and a tax deduction of up to 50% of the investment in the first year.

Additionally, the values of three variables were fixed as follows: price of electricity sold through regulated contracts as 50 USD/MWh [57]; income for treatment of received ton of municipal solid waste (i.e., tipping fee) as 10 USD/t [58]; and income for Certified Emission Reductions (CERs) obtained due to the reduction of the emissions of Greenhouse Gases (GHG) as 0.51 USD/tCO_2 [59]. The amount of CO_2 was calculated in tons based on the annual volume of biogas, which was estimated using the LandGEM application for the landfill gas in each scenario. Anaerobic digestion was calculated considering 71 m^3/t of waste.

3.3.1. Guayatá

The technically feasible technologies in this scenario (incineration, gasification and landfill gas) did not produce a return on investment. As a result, a special case is proposed to obtain the electricity from anaerobic codigestion by combining biogas (produced in a biodigester) with different types of biomass [60]. Thus, the benefit would be savings in kWh/year because the cost of buying from the grid operator (the company EBSA) amounts to 150 USD/MWh [61]. The investment costs or capital expenditures (CAPEX) and the operation and maintenance expenditures (OPEX) of the special case mentioned above in Guayatá are 0.0204 MUSD (Millions of USD) and 0.0061 MUSD, respectively.

3.3.2. Andes

The IRRs obtained for incineration and gasification were −3.06% and −5.35%, respectively, as observed in Figure 4. Such projects are viable if the electricity sale price is increased 10 times for incineration and 14 times for gasification. The reasonable IRR values could not be obtained in Case 1. Table 5 lists the initial costs by technology in the municipality of Andes.

Landfill gas and anaerobic digestion achieved IRRs of −0.88% and 2.6%, respectively. The electricity price of both technologies was fixed at 100 USD/MWh since lower prices do not enable a return on investment. The previous IRR values for the four technologies were obtained based on the assumptions of Case 2, which means that the income tax deduction of up to 50% of the investment value increases the IRR compared to Case 1, where an IRR of 0.32% was obtained with anaerobic digestion. Table 5 presents the investment costs and OPEX of the four technologies in Andes.

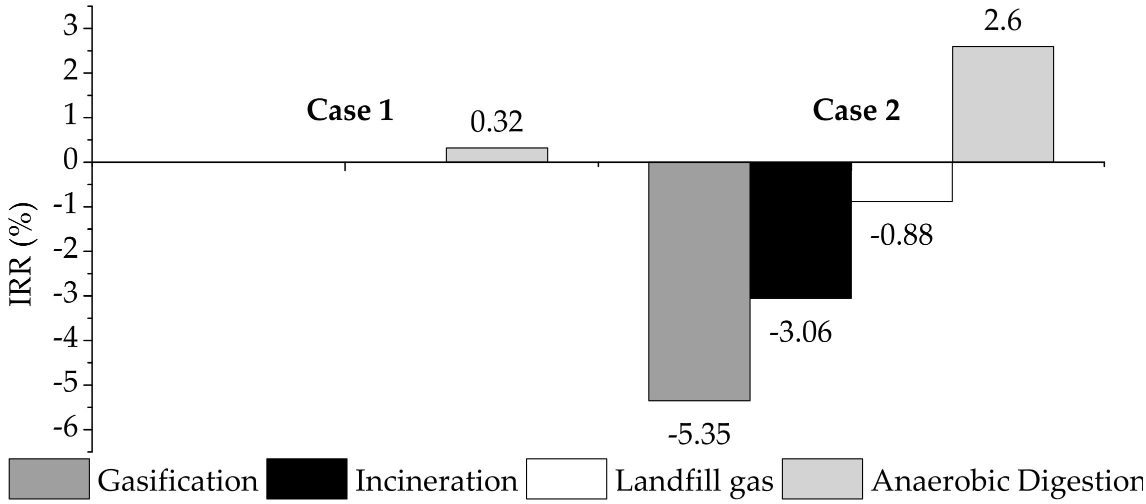

Figure 4. IRR in Andes.

Table 5. Initial costs by technology (Andes). Authors' own work.

	CAPEX (MUSD)	OPEX (MUSD)
Incineration	19.56	0.78
Gasification	17.66	0.71
Anaerobic Digestion	0.31	0.05
Landfill Gas	0.49	0.11

3.3.3. Pasto

Table 6 presents the investment costs and OPEX of the four technologies in Pasto. The corresponding cash flow and IRR values were calculated using the costs below.

Table 6. Initial costs by technology (Pasto). Authors' own work.

	CAPEX (MUSD)	OPEX (MUSD)
Incineration	19.56	0.78
Gasification	17.66	0.83
Anaerobic Digestion	2.49	0.4
Landfill Gas	4	0.24

Figure 5 summarizes the IRRs of different technologies in each case. The implementation of incineration produces an IRR of 11.18% in Case 2. In the same case, using gasification would result in a maximum IRR of 7.96%. In turn, the maximum IRR of landfill gas and anaerobic digestion reached 13.59% and 14.27%, respectively, in Case 2. This means that the tax deduction of up to 50% of the value of the investment, without considering the loan, boosted the IRR.

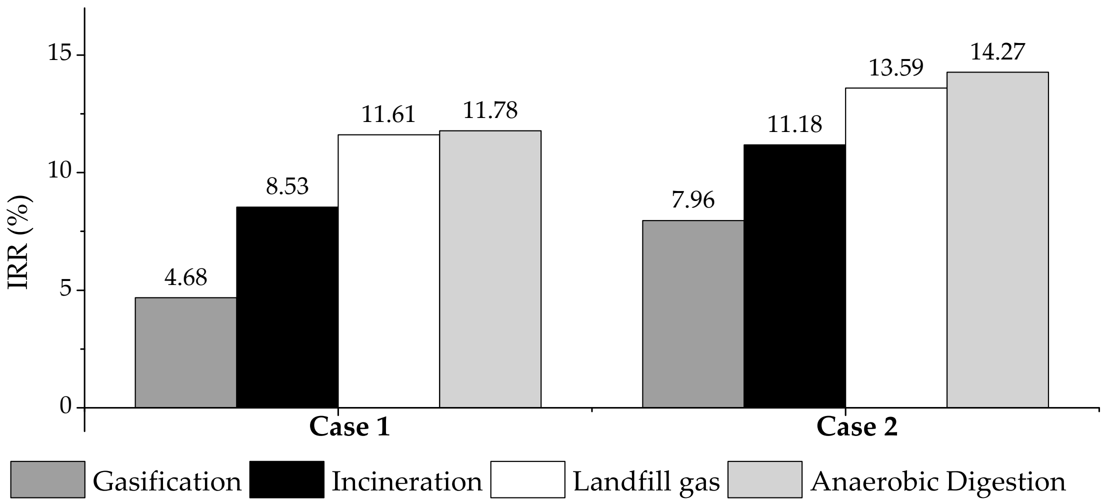

Figure 5. IRR in Pasto.

4. Discussion

This work considered MSW as a potential renewable energy source in three study cases in Colombia and evaluated the energy recovery potential of four different conversion technologies. The prefeasibility of each technology was also assessed in the three scenarios, considering the general characteristics of an investment and the benefits of Law 1715.

Suitable conversion technologies were selected for each scenario according to the amount of generated waste (tons per day), advantages, disadvantages and feasibility of the commercial acquisition of each plant. Incineration and gasification were the most convenient technologies for Pasto and Andes.

Anaerobic digestion can be implemented in the three municipalities because it can be acquired and exploits a high volume of food waste (more than 50% of the total MSW).

Landfill gas was the most adequate option for Pasto and Andes. Although Andes produces a low amount of waste and its number of inhabitants reaches 45,184, its projected population growth is expected to lead to an increase in waste generation.

The results of the economic evaluation show a positive economic income from incineration, gasification, anaerobic digestion and landfill gas in the municipality of Pasto, which is the scenario with the highest number of inhabitants in this work.

The income per ton of received waste (gate fee) and electricity sale as well as high investment costs have a substantial impact on the results of incineration and gasification. Likewise, the benefits of Law 1715 also influence IRRs. More specifically, the income per ton of received waste significantly determines the IRR of landfill gas while the treatment of organic waste defines the efficiency of anaerobic digestion.

Additionally, the economic benefit of selling CERs was evaluated and the results indicate that their current low prices do not represent a significant income in the economic analysis. Nevertheless, from an environmental standpoint, this mechanism for clean development is clearly important for the feasibility of projects.

In Andes, although the application of the incentives of the said law improves the IRR, a higher sale price of electricity would be required in order to ensure the viability of the WTE projects there.

WTE facilities can reduce the volume of waste by up to 95% in smaller areas compared to the traditional landfills. Moreover, they have a lower environmental impact on the soil compared to traditional waste disposal procedures. WTE facilities that meet international standards generate lower greenhouse gas emissions than traditional waste disposal methods and have a positive environmental impact.

Thermal facilities allow the recovery of metals from ashes and the ashes themselves are raw materials that can be used in metallurgic and construction sectors. This final waste can be an additional source of resources to promote new businesses.

Some analyses show that landfills have a greater environmental impact than most WTE technologies [42,62–64]. However, for a holistic evaluation, an environmental impact assessment must be conducted in accordance with the International Organization for Standardization (ISO) standards 14040 and 14044, using Life Cycle Assessment (LCA) [42]. The objective of such assessment is to calculate all the possible environmental consequences [64]: direct impacts, such as atmospheric emissions and water consumption, and indirect results, such as emissions generated by the process and transportation [63].

In accordance with the results presented in [20,42], a general scale of environmental impact can be established based on an LCA evaluation of each technology. Such evaluation and classification can include the following criteria: Abiotic Depletion Potential (ADP), Global Warming Potential (GWP), Ozone Layer Depletion Potential (ODP), Human Toxicity Potential (HTP), Acidification Potential (ACP) and Eutrophication Potential (ETP). Under the said criteria, the best WTE alternative would be anaerobic digestion, followed by incineration, gasification and landfill gas in this order. Regarding CO_2 emissions, WTE technologies can achieve reductions that range from 4.07% to 48.16% compared to the traditional disposal in sanitary landfills [20]. Anaerobic digestion could reduce the environmental impact even further in communities where waste generation is low to medium [42], as in the case of Andes and Guayatá.

The energy obtained from MSW contributes to diversify the energy mix in Colombia, which is based on big hydropower centrals. Such plants entail problems that arise during the El Niño phenomenon (droughts). Power generation from MSW reduces the energy imports in terms of both electricity and fuels. Nowadays, the use of MSW to produce energy is very limited, which means that such energy potential is being wasted.

The investment in WTE facilities can be an alternative to stimulate Colombian economy and attract foreign capital. New WTE processing units will require manpower, thus directly and indirectly creating new jobs to provide services for the operation of the facilities (collection, transportation, recycling, treatment and disposal of waste), which would reduce local unemployment and informal jobs.

Around a third of the landfills in Colombia will reach their lifespan in the next decade [65]. However, developing new landfills is a difficult task since it requires environmental and technical licenses that usually take several years and are not always obtained. Public opposition is one of the main obstacles to the development of WTE plants around the world. For instance, the No In My Backyard (NIMBY) phenomenon is a result of the negative publicity of ill-informed media and plants that present environmental pollution problems due to them operating below international standards [6]. Another element to consider in Colombia is that the Constitution allows communities to decide if these types of projects can be implemented in their environment. That aspect imposes further limitations on the construction of new landfills even when technical and environmental licenses can be obtained.

Another reason to oppose the development of WTE plants is a lack of public participation. Public consultations and information campaigns about the projects must be carried out before starting the construction of WTE facilities in order to avoid rejection from the population near the facilities [6].

The techno-economic evaluation in this work suggests that the costs of WTE plants are not affordable for most Colombian municipalities and such plants will only be feasible in the economically developed urban centers. In addition, as a consequence of the low economic income resulting from the operation of the plants, the government should offer more benefits or advantages for private investments without compromising the technical quality and standards of the plants, thus avoiding negative environmental impacts and public rejection [6,66].

Colombia has a relatively new legal framework of policies and incentives for developing WTE projects. In Latin America, nations, such as Uruguay, Peru and Mexico, have regulations that promote this type of projects. The experience of those countries, which share similar characteristics, could be the starting point to avoid and solve common problems. We must also consider that South America and the Caribbean currently suffer from institutional weakness and corruption, which limits their access to financial instruments to fund renewable energy projects that require public and private capital [67,68].

5. Conclusions

The techno-economic evaluation of WTE projects presented in this article highlights the positive impact of government support in the promotion of those technologies. In Colombia, the tax incentives proposed in Law 1715 of 2014 enabled improvements in the rate of return on investment.

However, the evaluation also showed that the certified emission reductions (CERs) do not have a significant economic impact due to their low value.

On the other hand, in addition to tax incentives, special energy sale prices should be considered for this type of renewable source of energy in order to ensure that they can be competitive in the electric power market.

Waste separation is a condition for the operation of WTE facilities. Therefore, classifying the waste at the source should be promoted among the population. To change people's behavior, campaigns should motivate citizens to demonstrate their moral commitment to the planet. Such campaigns should seek to raise environmental awareness. The commercialization of reusable waste should also be promoted to further motivate the separation, recycling and reuse of waste.

Colombia must embrace the practices of developed countries to implement WTE technologies. Government intervention is essential in the form of specialized regulatory agencies to promote and supervise the construction and operation of WTE facilities. Nevertheless, the environmental variables (leachate, fly ash and slag) should be constantly monitored and effective mechanisms to impose penalties should ensure that WTE companies comply with the standards for polluting emissions.

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