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Assessment of Power Generation Using Biogas from Landfills in an Equatorial Tropical Context

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Abstract: This work evaluates the biogas production potential of the Ceibales landfill for feeding a power plant in the southern region of Ecuador. Biogas production is estimated through mathematical models that consider energy generation and technologies available to supply electricity plants. Characteristic landfill data are accounted for to analyze and develop these mathematical models. Once the generation capability of each source is identified, a decision can be made on the most suitable electricity generation technology. A local model (Ecuadorian model) is applied to calculate the potential of biogas and is compared with other models commonly used for evaluating this type of project. This type of renewable energy is attractive because it produces electricity from waste; however, it is not an attractive option unless its application is encouraged, as hydro has been encouraged through the investment of taxpayer resources. Technologies require a boost to become profitable, and even more so if they compete with traditional technologies.

Keywords: renewable energy; landfill; biogas; economic viability

1. Introduction

Ecuador has maintained a consistent interest in introducing renewable energy (RE) sources, which are clean, non-polluting energy alternatives that also serve as a means of reducing greenhouse gas (GHG) emissions [1]. Ecuador has currently implemented six types of RE, including hydro (<50 MW), wind and solar energy (photovoltaic and solar thermal), biomass, and biogas. Among these energy generation sources, the principal source is hydro, accounting for 73.24% of the overall electricity production, as Ecuador has high hills and several rivers of different scales [2,3]. Biomass is another important energy source, mainly from forests, and at the local level, there are three generating plants with an installed capacity equivalent to 19.28% of the overall electricity production from RE. Another RE source already implemented is solar radiation, which takes advantage of radiation from the sun. Ecuador has a high potential but generates only 3.69% of overall electricity production from non-conventional RE sources (considering only hydropower as conventional) [4,5], mainly as a consequence of the current cost reduction. On the other hand, the wind potential in Ecuador is expected to increase with the installation of the Villonaco II and Villonaco III projects, which will provide 2.83% of the overall electricity production from RE [5]. Finally, biogas is one RE type that has been implemented at a reduced capacity; currently, there are two generating plants in the cities of Cuenca and Quito, and electricity generation from biogas represents only 0.97% of the overall electricity production from RE [6,7].

1.1. Importance and Justification

Ecuador generates mainly hydropower as its main RE source, and the development of other types of technologies must be continuously encouraged to improve power reliability. In 2018, the installed capacity of hydroelectric plants (over 50 MW) was 4518.24 MW, that of thermal power stations was 3395.15 MW, and that of alternative RE plants was 748.47 MW. RE accounts for 8.64% of the overall power generation in Ecuador, while 91.36% remains non-renewable [4,8]; this latter number includes hydro, which is no longer considered a renewable resource because it affects riverbeds and rugged areas [9].

Ecuador, despite its size (283,000 km^2), has marked climatic differences across regions (coast, tropical climate; mountains, cold weather; east, humid climate), which has an impact on energy consumption habits, as well as on the production of waste. This article explains and provides context for the production of electricity from biogas generated from urban solid waste in a tropical climate. The analysis applies a local model to guarantee the reliability of the results. This type of renewable energy is attractive because it produces electricity from waste; however, it is not viable if its application is not encouraged with incentives such as feed-in tariffs. As mentioned in [10], such technologies require a boost so that they can be profitable, and even more so if they compete with traditional technologies. It is also notable that this type of energy is still marginal, so that the recycling and separation of waste residues (organic or inorganic) can be promoted to reduce the amount of waste or increase the efficiency of the process.

1.2. Biogas from Waste

Biogas is produced by the decomposition of organic matter in the absence of oxygen. There are several ways in which it can be obtained, either in controlled tanks (biodigesters) or sanitary landfills (landfills). The main components of biogas are methane (CH_4) and carbon dioxide (CO_2). The CH_4 concentration usually ranges from 30% to 65%, and that of CO_2 ranges from 2% to 40%. Other chemical elements are present in landfill gases (LFG): Nitrogen (N), hydrogen (H), oxygen (O), argon (Ar), hydrogen sulphide (H2S), and sulphate (S) [11,12].

The methane (CH_4) content of biogas can be used for electrical or thermal generation or as a transport fuel. Currently, biogas is being rapidly developed as an effective method for generating renewable energy, so it plays an important role in production and environmental protection [13]. There are several sources for obtaining biogas in the city: Industrial waste, urban pruning waste, urban solid waste, the organic fraction of urban solid waste, municipal wastewater, or industrial wastewater [14].

There are various scientific studies that have analyzed the contribution of energy in different energy uses. Table 1 shows some of these studies, emphasizing the energy contribution, use, and location.

Table 1. Demand covered by biogas in different locations.

Place	Demand Coverage	Total Demand	Type of Energy	Reference
Cuenca (Ecuador)	1%	Urban part of the city of Cuenca	Electricity	[7]
Lombardy (Italy)	8.5% 11%	Energetic and agricultural systems	Electricity	[10]
Stockholm (Sweden)	11.44%	8300.00 kWh/per inhabitant/year	Thermal	[15]
Oakland (U.S.)	120.00%	55.00 GWh/year	Electric	[16]
Mexicali (Mexico)	6.00%	Given as a lighting requirement	Electric	[13]
Tijuana (Mexico)	40.00%			
Brazil cities (Brazil)	100.00%	107000 urban buses	Fuel	[17]
Saint Paul Rio de Janeiro (Brazil)	7.30% 6.73%	8723.60 GWh/year 5481.00 GWh/year	Electric	[18]
Tartu (Estonia)	54.50%	0.14 t of natural gas	Fuel	[19]

1.2.1. Biogas from Sewage Sludge

Wastewater treatment causes mud, as a product of the chemical, physical, and biological processes used to purify it. These sludges can have a solid concentration between 0.25% and 12%. Prior to final use (disposal in controlled landfills, compost, or incineration), they are stabilized in either aerobic or anaerobic form. To obtain methane, anaerobic stabilization is preferred because it produces biogas [20]. The portion of methane in biogas can be from 55% to 80%, with a calorific value greater than 36 MJ/m^3 [21], which implies that the equipment used for natural gas can be modified to use biomethane.

As in landfills, the amount of methane available in wastewater is of interest, and this depends on the amount of wastewater per capita (5 to 20 l per capita, equivalent to 50% to 70% of CH_4) [22]. Gas from wastewater can be used to generate electric, thermal, or cogenerated energy and vehicle fuel, or can be injected into natural gas networks [22,23]. The electricity produced can be used for the internal consumption of sewage treatment plants.

1.2.2. Biodegradable Fraction of Organic Urban Waste

Urban organic waste can be sent to bioreactors to produce biogas. The efficiency of the anaerobic digestion process can be increased by separating these wastes and diluting them in a fluid (wastewater) prior to treatment in an industrial anaerobic digestion reactor. In this case, the percentage of methane in the biogas can reach up to 75% [18]. Inorganic material can be sent to incinerators, which could prevent the need for disposal in landfills [24].

A study by Van Meerbeek et al. [25] of the Flanders region (Belgium) determines the biomass potential of the material obtained through the pruning of conservation areas and the edges of the roads. In this case, it would provide 721.00 GWh to supply 205,000 homes; but, it is considered not to be economically profitable.

Arodudu et al. [26] calculated the energy potential of biomass from roofs, parks, gardens or food waste, and seasonal yard waste in the Overijssel region (Netherlands). The use is based on anaerobic digestion for the production of biogas because, in this way, several types of biomass can be used. The use represents between 0.6% and 7.7% of the regional objectives for 2030.

1.2.3. Biogas from Controlled Landfills

Landfills, according to the American Society of Civil Engineers (ASCE), represent a technique for the final disposal of municipal solid waste (MSW) in a field that does not cause damage to the environment while preventing discomfort and health risks. This method requires the use of engineering principles to confine waste within the smallest possible area, i.e., minimizing its volume [17].

LFG is a mixture of gases produced as a result of chemical and physical processes that take place within confined MSW due to the biodegradation of organic waste under anaerobic conditions. LFG composition mainly depends on the digested material and the biodegradation process under confinement conditions [7,11,12]. In a controlled landfill, hundreds of tons of solid waste treated with technical processes are added daily. The waste is placed on a geomembrane that prevents leachate from entering the ground; then, it is compacted and coated. In the middle of these layers of waste, conduction systems are connected to chimneys. As a result of the decomposition of organic matter and other wastes, a series of gases are produced that are emitted into the atmosphere [27]. To use these gases as vehicle fuel requires a cleaning process, as the waste has a high concentration of nitrogen [28]. Biogas from urban solid waste is related to the composition and quantity of the latter. [13,17]. In developing countries where waste reduction is not consolidated (by reuse, recycling, or prevention), waste disposal is expected to increase, at least in the medium term [29].

Since methane is a greenhouse gas (GHG), its capture and oxidation to CO_2 is beneficial for the environment. If the methane portion is sufficiently high for electricity production, it can be used in internal combustion engines [30].

In Africa, which has high collection rates, 9% of the average per capita continental consumption of electricity could be supplied by biogas [29]. In the metropolitan cities of India, the disposal of waste in landfills would allow the recovery of 60% to 90% of biogas appropriate for energy production or for use as fuel [11]. In Mexicali and Tijuana (Mexico), the generation of energy from landfill biogas could supply 6% and 40% of the demand for lighting, respectively [13]. In São Paulo and Rio de Janeiro (Brazil), Souza and colleagues [18] establish that with the production of biogas, approximately 7% of electricity could be supplied.

Another option for biogas in Brazil is the provision of fuel for a bus fleet approximately nine times the size of the existing urban fleet (107,000 units) [17]. The positive effects, not yet fully valued, would be a reduction in the emissions and pollutants that affect the health of urban residents.

The use of methane not only guarantees a benefit through energy production, but also leads to the reduction of greenhouse gases. However, it is necessary to ensure that this process is optimal for the controlled management of waste disposal.

2. Materials and Methods

It is important to know the characteristic parameters of each landfill, as this will define its biogas generation potential. First, the characteristic parameters of the Ceibales landfill are obtained, and then biogas is estimated based on different mathematical models.

1. Location: The Ceibales landfill is in El Oro Province, 18 km from Machala city, and 23 km from the Santa Rosa community; in both cases, the entrance is via E25 (Balosa-Machala). Its exact geographical location is latitude –3.3200 and longitude –79.9491.
2. Climate: The climatic characteristics of Machala were based on data from web pages, such as the world climate sites (www.worldclimate.com), because the National Institute of Meteorology and Hydrology (INAMHI) weather station only provided outdated data. These data are required for estimating the parameters of the mathematical models.
3. Characteristics of municipal solid waste (MSW): The landfill began operation on September 18, 2010. On average, it receives 322.32 tonnes of MSW daily and 9933.32 tonnes monthly. In 2018, a total of 115,702 tonnes were deposited. The Ceibales landfill is scheduled to be closed in 2030 [31]. Table 3 lists the waste received per year, starting with the inauguration of the Ceibales

landfill. In Machala city, no recycling activities occur in the homes or areas where waste is generated, and there are no waste separation policies at the landfill [31].

4. Waste composition: There is no specific information regarding the composition of the waste sent to the landfill, and it varies over time. Since the city of Machala is the capital of the Oro province, referential data on the waste recorded for the province are used. This estimate is valid because the capital is the most representative city of the province of Oro. Table 2 summarizes the composition of the waste that arrives at the final disposal site [31].

Table 2. Estimated composition of organic waste [25].

Waste Category	**Composition (%)**
Food	62
Paper and paperboard	9
Humidity plastics	3
Metal	2
Glass	3
Garden waste Grass trimmings, fertilizer Construction debris including rubber Wood waste	12

Table 3. Amount of municipal solid waste (MSW) entering the Ceibales landfill from 2010 [24].

Year	**MSW [ton]**	**Year**	**MSW [ton]**
2010	26475.1	2015	101645.1
2011	91628.7	2016	105600.7
2012	93356.3	2017	110258.6
2013	95575.0	2018	115702.3
2014	98322.3	2019	51784.65

2.1. Estimation of MSW for Future Years

Because the landfill is still open, it is important to estimate the MSW amount over the next few years until closure. The annual MSW data listed in Table 3 were approximated with a quadratic equation. Equation (1) defines the waste amount at the Ceibales landfill. In this equation, y represents the MSW amount, and x is the number of years. In Equation (1) (R^2 = 0.99, that is, it has a significant adjustment), the data for 2010 and 2019 were omitted, since they did not represent full-year values, and if considered, would generate an incorrect projection.

$$y = 306.95x^2 + 647.25x + 90771 \quad (1)$$

Table 4 summarizes the values obtained for the future years until closure of the landfill.

Table 4. Estimation of waste entering the Ceibales landfill in future years.

Years	**MSW [ton]**	**Years**	**MSW [ton]**
2019	121459.2	2025	169543.5
2020	127938.5	2026	179706.2
2021	135031.7	2027	190482.8
2022	142738.8	2028	201873.3
2023	151059.8	2029	213877.7
2024	159994.7	2030	226496.0

2.2. Models to Estimate the Biogas Generation Potential

Three models considered relevant to the study were analyzed. First, the LandGem model developed by the United States Environmental Protection Agency (US EPA) is the most commonly used model. Together with the LandGem model, the Ecuadorian model was used, which was adapted to local weather conditions and was also developed by the US EPA. Finally, the Intergovernmental Panel on Climate Change (IPCC) model was considered.

2.2.1. LandGem Model

This model allows the emission rate over a period to be determined. It can assess the emissions of methane, carbon dioxide, volatile organic compounds, and individual air pollutants from landfills [32]. The model is based on a first-order decomposition equation and determines the methane mass generated from the deposited MSW in a landfill. It assumes that biogas generation reaches its maximum when anaerobic conditions are balanced within the MSW confinement, and then biogas production declines with a decreasing organic waste fraction [12,29]. In the LandGem model, Equation (2) calculates the biogas amount that can be generated in the year of calculation [32].

$$Q = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k \cdot L_0 \left(\frac{M_i}{10} \right) e^{-kt_{ij}} \tag{2}$$

where

Q is the annual methane generation potential (m^3/year),
i is the 1 year time increment,
n is the calculation year minus the initial year of waste acceptance,
j is the 0.1 year time increment,
k is the methane generation rate (1/y),
L_0 is the potential methane generation capacity (m^3/Mg),
M_i is the waste mass accepted in the ith year, and
t_{ij} is the age of the jth section of waste mass M_i accepted in the ith year (years).

2.2.2. The LandGem

The LandGem model provides most of the constants in accordance with US landfill standards. As such, it is necessary to calculate certain parameters, such as k and L_0. These parameters can be calculated according to the methods suggested by the IPCC [11,27,30]. Table 5 lists the required data and their replacement in the LandGem model.

Table 5. Parameters required for the model calculations.

Parameters	LandGem	IPCC	Ecuadorian Model
DOCi	-	0.1854	-
DOCF	-	0.7	-
MCF	-	1	-
k *	0.045	0.045	0.045
F	-	50%	50%
L_0 **	86.52	-	86.52
%CH_4	50%	-	50%
Beginning of operations	2010	2010	2010
Closing year	2030	2030	2030

Note: * The methane generation rate, k, determines the rate of methane generation for the mass of waste in the landfill [32]. Climate, precipitation, and degradation of organic waste were considered in the definition for the study area. The calculation followed that of [33]. The potential methane generation capacity, L_0, depends only on the type and composition of waste placed in the landfill. The calculation followed that of [32].

2.2.3. IPCC Model

This tool allows us to determine the emission rate over a period and can assess the emissions of methane, carbon dioxide, volatile organic compounds, and individual air pollutants from landfills [32]. This model predicts the biogas generation capacity in individual landfills, and it only requires data on the MSW characteristics and annual weights [27,30,34]. Biogas emissions are estimated with Equation (3) [34].

$$Q = \sum DDOC_{mi} \cdot \left(e^{-kt}\right) \tag{3}$$

where

Q is the methane generated per year (m3/y),

k is the methane generation rate (1/y),

t is time (years), and

$DDOC_{mi}$ is the mass of degraded decomposable organic carbon of waste component i.

Equation (4) calculates the value of $DDOC_{mi}$.

$$DDOC_{mi} = \sum (M_i \cdot DOC_i) \cdot DOC_F \cdot MCF \cdot \frac{16}{12} \cdot F \tag{4}$$

where

M_i is the waste mass,

DOC_i is the degradable organic carbon in the deposition year,

DOC_F is the biodegradable organic carbon fraction,

MCF is the methane correction factor,

16/12 is the stoichiometric constant, and

F is the methane fraction.

Table 5 summarizes the values obtained according to the IPCC model. It should be noted that some of these values coincide with the LandGem model because IPCC conditions were used to calculate certain LandGem model parameters.

2.2.4. Ecuadorian Model

This model (the Ecuador LFG model) is an extension of the Mexican model; the original model was developed by SCS engineers under a US EPA contract in 2003. The extended Mexican model was recalibrated based on two previous biogas generation studies conducted in Ecuador. These studies were performed at the Iguanas (Guayaquil) and Pichacay (Cuenca) landfills in March and April 2007, respectively. In addition, this process was complemented with evaluation reports of three landfills, Chabay (Azogues), El Valle (Cuenca), and Loja [35–38]. To estimate the generated biogas amount, the Ecuadorian model relied on Equation (5).

$$Q = \sum_{0}^{n} \frac{1}{\%vol} \cdot k \cdot M \cdot L_0 \cdot e^{-k(t - t_{lag})} \tag{5}$$

where

Q is the total biogas amount generated (m3/y),

n is the total number of years modeled,

%Vol is the estimated methane volumetric percentage in the landfill biogas,

k is the methane generation rate (1/year),

M is the annual waste mass disposed of (Mg),

L_0 is the potential methane generation capacity (m^3/Mg),

t is the time in years from the beginning of waste disposal, and

t_{lag} is the estimated time between waste deposition and methane generation.

In contrast to previous models, it was necessary to determine k and L_0. In the Ecuadorian model, they are already provided by default. Table 5 lists the values of K and L_0 suggested by the model.

- *Models to estimate the biogas generation potential*

Because each model provides a different level of biogas production, the average is calculated as suggested in previous studies [35,37–40] to approximate a more exact value. Another parameter to consider in this section is the recovery efficiency. In a sanitary landfill, not all biogas can be recovered and used because some gas is lost in the extraction process. In the case where an implanted extraction system is not utilized, the recovery efficiency can be assumed as suggested in the literature [35,38–40]. For the present case study, a system with an average recovery efficiency of 71% is assumed. Then, the recoverable biogas can be estimated with Equation (6).

$$Q = \frac{Q_{LandGem} + Q_{ecuatorian} + QIPCC}{3} \cdot \gamma \quad (6)$$

where
$Q_{LandGem}$ is the amount of biogas calculated with the LandGem model (m^3/y),
$Q_{ecuadorian}$ is the amount of biogas calculated with the Ecuadorian model (m^3/y),
Q_{IPCC} is the amount of biogas calculated with the IPCC model (m^3/y), and
γ is the efficiency of biogas recovery.

3. Power Potential Estimation from LFG

To determine the power capacity, it is necessary to assess the generation type. For the present case study, internal combustion engines (ICMs) were chosen because they have high efficiency and a low implementation cost. The choice basically depends on the amount of biogas flow available. Internal combustion engines have a low cost per kW compared to gas turbines and micro-turbines. In addition, they are available in various sizes for different gas potentials. Biogas turbines are used for large projects, where there is usually a high biogas generation flow capability of at least 3 MW and typically more than 5 MW. Some of the advantages are the low maintenance requirements, its facilities, and an efficiency that increases with size. The micro-turbines can be connected in series and can thus provide as much equipment as required. Micro-turbines do not require a high biogas treatment because they have good tolerance to the presence of hydrogen sulphide in biogas. Table 6 lists the characteristics of the three technologies that rely on biogas to generate electricity.

Table 6. Typical information on the technologies that use landfill gases (LFG) to generate electricity [17,30,41].

Technology	Flow [m^3/min]	Generated Power [mw]	Electrical Efficiency [%]	Cost [usd/kw]
ICM	8–30	0.8–3	32–45	1150–1700
Turbine	> 40	> 3	25–40	1400
Micro-turbine	< 8	0.03–0.2	26–32	5500

3.1. Available Energy Generated from LFG

To determine the electrical energy that could be available through biogas, Equation (7) is defined. This equation is related to the conversion of biogas to useful energy in the form of electricity and heat [30].

$$E_{dis} = \frac{LVH \cdot Q_{br} \cdot \eta}{\gamma_i} \quad (7)$$

where

E_{dis} is the available electrical power (kWh/y),
LHV is the lower biogas calorific value,
Q_{br} is the recoverable biogas flow (m^3/y),
η is the electrical efficiency of the generating element in transforming thermal energy into electrical energy (ICM, turbine or micro-turbine), and
γ_i is the conversion factor of MJ into kWh (1 MJ/0.28 kWh).

3.2. *Power of the Generating Element*

The power of the generator can be determined from Equation (8).

$$P = \frac{E_{dis}}{8760 \cdot CF} \tag{8}$$

where
P is the power of the generator (kWh/y) and
CF, or capacity factor, is the plant availability factor, which is commonly assumed to be between 80% and 90% [41].

Table 7 summarizes the values imposed for the calculation of energy and power at the Ceibales landfill.

Table 7. Values for the calculation of energy at the Ceibales landfill.

Variable	Value
Recovery efficiency (γ)	71% *
LHV (Lower heating value)	18 MJ/m^3 **
Plant availability factor (PF)	85%
ICM engine efficiency (η)	40%
Conversion factor of MJ to kWh (γ1)	3.57

* The average of studies conducted in Ecuador is taken for landfills in del Valle (63%), Iguanas (92%) and Chabay (60%) [35,38,39]. ** The calorific value of methane is approximately 36 MJ/m3. Biogas is considered to have 50% methane [7,27].

3.3. *Economic Viability*

This section establishes the project's profitability from an economic point of view. To this end, the initial investment, electrical energy sales value, and operation and maintenance costs are analyzed. Finally, the net present value (NPV), the internal rate of return (IRR), the levelized cost of energy (LCOE), and the period required to recover the investments, i.e., the payback period (PBP), are analyzed.

3.3.1. Determination of the Investment, Operation, and Maintenance Costs

To determine the cash flow, it is necessary to calculate the investment cost (Inv) and the operation and maintenance costs (O&M). These values directly depend on the type of technology used to generate electricity and on external factors. Barragan et al. [42] treated these values as quantitative, and they were retrieved from the reports of international institutions and from previous research to approximate real values.

Investment costs: These values depend on the costs generated in establishing the production plant, including engineering costs, permits, construction, surveying, equipment acquisition, and commissioning [12]. Equation (9) allows us to extrapolate the costs from a specific power plant to the costs of a projected plant.

$$\frac{C_1}{C_2} = \left(\frac{S_1}{S_2}\right)^p \tag{9}$$

where C is the costs and S is the nominal power of the plants, while subscripts 1 and 2 represent new and existing plants, respectively. For power generation, a factor p of 0.75 is commonly assigned [42].

For this work, four existing plants are referenced, among which local plants such as Inga I and II and Pichacay stand out, along with two plants that are mentioned in Reference [42]. The cost is obtained after calculating the average of the results.

The operation and maintenance costs considered for system operation are those associated with technical personnel, supplies, raw materials, and basic services. They are classified into two items: The first item is the fixed costs, and the second covers the variable costs. These costs are annual and, according to the literature [42], can be quantitatively valued through the cost of investment; in the case of a biogas plant, these costs will be 7.4% of the overall investment.

3.3.2. Levelized Cost of Energy

The economic benefits depend on electricity sales; therefore, it is necessary to predict the income and compensation rates. In Ecuador, a regulation was issued that set a certain USD/kWh price for biogas plants. However, a new regulation repealed these values, eliminating a reference price [5,42].

To calculate the income, the LCOE is used, which is the minimum cost in USD/kWh per generated unit of energy. It can serve as a basis for comparing different technologies in terms of economic viability. Equation (10) is used to calculate the LCOE [12].

$$\mathrm{LCOE} = \frac{\sum_t [\mathrm{Inv}_t + \mathrm{O\&M}_t]\cdot(1+r)^{-t}}{\sum_t \left[\mathrm{Elec}_t\cdot(1+r)^{-t}\right]} \quad (10)$$

where

LCOE is the cost of electrical energy production during the plant lifespan (USD/kWh),

Inv is the investment for one year (including interest during construction and all auxiliary elements and electrical infrastructure) [USD/kWh],

O&M is the operation and maintenance cost for one year t [USD/kWh],

r is the discount rate,

Elect is the electricity generated in year t (kWh), and

t is the plant lifetime operation (year).

3.3.3. Net Present Value (NPV) of the Levelized Cost of Energy

This concept refers to the present value of the total costs, less the present value of all revenues, which are the costs incurred during the entire useful project life. The method aims to analyze cash inflows and outflows. After measuring these flows and discounting the initial investment, the profit is calculated (11) with a typical NPV equation [12,43].

$$\mathrm{NPV} = \sum_{n=0}^{N} \frac{\mathrm{Fn}}{(1+r)^t} \quad (11)$$

where

F_n is the net cash flow rate,

r is the effective interest rate, and

t is the total number of study years.

3.3.4. Internal Rate of Return

The internal rate of return (IRR) is a quantitative measure and represents the highest interest rate that an investor is willing to pay considering minimal risk. It is strategic, especially when projects are financed by loans, and when a project must be financed, a net profit can be generated. The IRR is closely related to the NPV because it sets the latter to zero, and Equation (12) is typically used to calculate the IRR [43].

$$\sum_{n=0}^{N} \frac{Fn}{(1+IRR)^{t}} = 0 \quad (12)$$

where

Fn is the net cash flow rate,

IRR is the internal rate of return, and

n is the total number of years under study.

3.3.5. Payback Period (PBP)

Corresponding to the period in which the project cost is balanced, Equation (13) is the simplest calculation approach [12,42,43].

$$PBP(i) = \frac{Inv}{CF} \quad (13)$$

where

Inv is the cost of investment in the generation (USD) and

CF is the cash flow achieved by annual revenues from energy saved (USD/year).

4. Results and Discussion

The purpose of this section is to determine which factors influence power generation in a plant and the prices corresponding to power dispatch. Identifying these factors can start by considering the efficiency or technology applied in power generation and conclude by considering the price paid by distribution companies per kWh.

4.1. Usable Biogas in the Ceibales Landfill

Figure 1 shows that both the LandGem and Ecuadorian models attain similar results. The differences between these models are the values of constants K and L0. This variation occurs because in the LandGem model, it is necessary to calculate these parameters, but in the Ecuadorian model, they are already provided by default. The Ecuadorian model produces higher values, obtaining a maximum generation of 1971 m^3/h in 2031. The LandGem model, on the other hand, produced lower values, obtaining a maximum of 1799 m^3/h in 2031. The IPCC model, unlike the Ecuadorian and LandGem models, exhibited atypical behavior: Of the three models analyzed, it estimated the lowest biogas percentage, with a maximum biogas generation of 1469 m^3/h in 2031.

For the calculation of the biogas potential, the suggestion is to average the three values obtained by the models. The data obtained on the average biogas production and the estimated usable biogas are shown in Figure 2. This chart shows the biogas production of the landfill and the biogas recovered based on the proposed recovery efficiency. The figure reveals that the biogas generation rate is zero in 2010 (the initial year of waste deposition); subsequently, it increases exponentially until 2031, after closure. It is evident that in 2031, the landfill would reach a maximum biogas generation of 1240 m^3/h, after which it begins to decay.

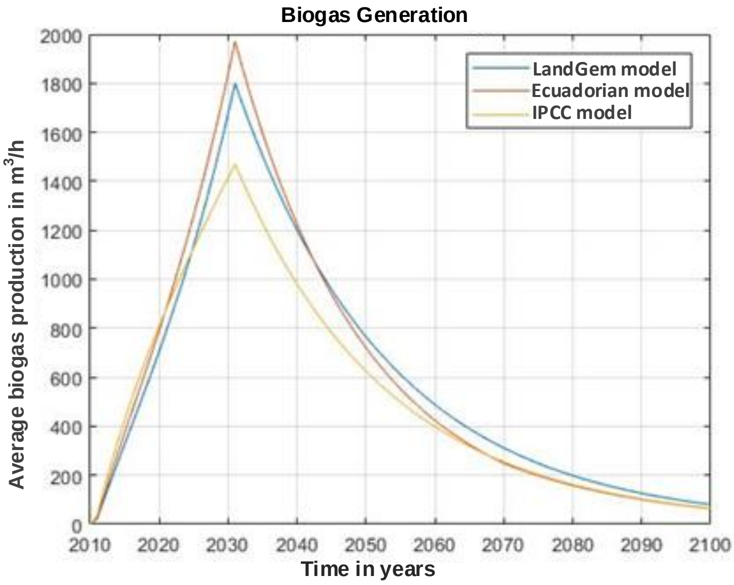

Figure 1. Biogas generation using the Intergovernmental Panel on Climate Change (IPCC), LandGem, and Ecuadorian models.

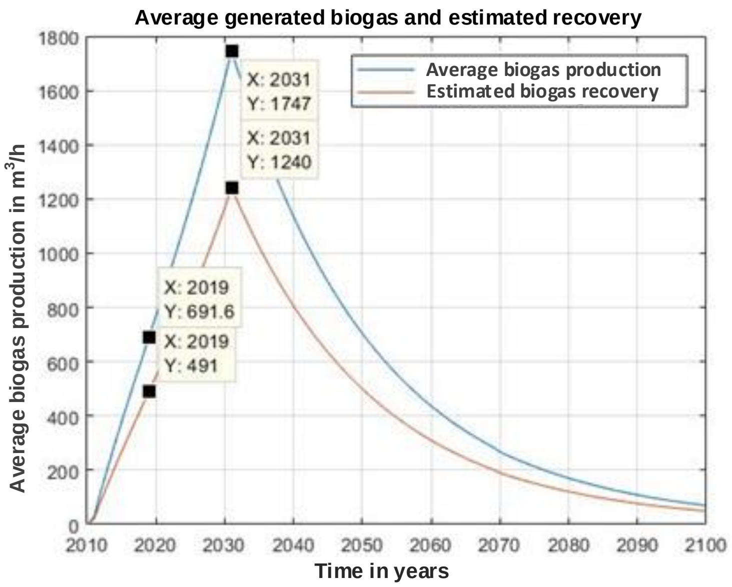

Figure 2. Biogas production and estimated recovery.

The biogas generation potential results were close to the values obtained at the Pichacay landfill [35], which had similar MSW amounts. Certain variations in biogas production are observed, mainly because the Pichacay landfill has different K and L_0 values. The difference is the usable biogas amount; in the case of Pichacay, a recovery of 79% is estimated, while in the case in this study, the estimated recovery is 71%.

Currently, in 2019, it is estimated that the Ceibales landfill emits 491 m^3/h of biogas and 245.5 m^3/h of CH_4 into the atmosphere. This amount is expected to increase until its ultimate closure in 2030.

4.2. Available Power in the Ceibales Landfill

Figure 3 shows the power availability in the Ceibales landfill and indicates that in 2019, a 1 MW generator could be installed, and this amount of power will be available until 2050. The red line represents the 1 MW generator and the years during which this power would be produced. In 2023, a second 800 kW generator could be installed, and this amount of power would be available until 2041. Similarly, the green line represents an additional 800 kW generator, as well as the time that this amount of power will be available.

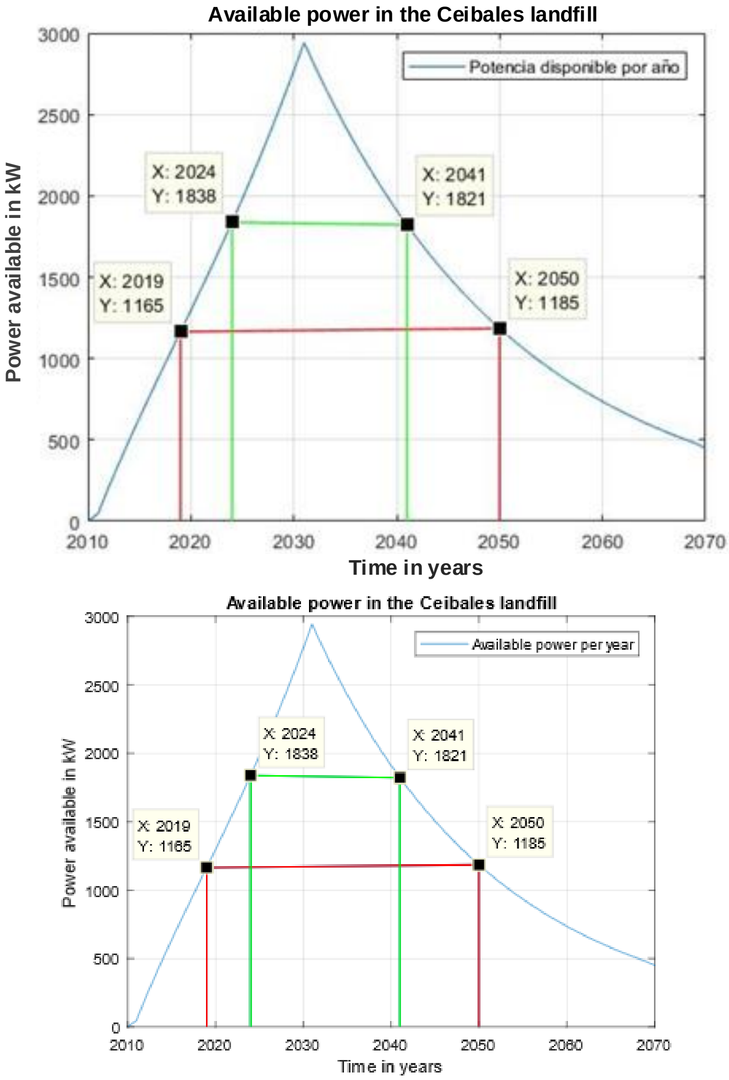

Figure 3. Biogas generation using the IPCC, LandGem, and Ecuadorian models.

Another aspect to be considered is the conversion equipment efficiency, which depends on the altitude above sea level where the generation plant is installed. Engines usually run with a stoichiometric mixture of fuel and oxygen. At higher altitudes, there is lower atmospheric pressure and, therefore, a lower oxygen concentration, which is the reason that engines attain lower performance. A reduction ranging from 1% to 1.5% for each 100 m above sea level (masl) is commonly considered. This aspect is important because the altitude of Machala is optimal for the installation of an ICM because the city is close to the sea.

The electricity production in 2019 with the 1 MW generator will be 722,632.52 kWh/month and 23,757.78 kWh/day. With an average electricity consumption of 120 kWh/month in Machala, it is estimated that this plant could provide 6022 homes with electricity. The available energy per year will increase with the increasing biogas amount from the landfill, to the point that by 2024, a second 800 kW generator could be installed, and energy would then be provided to a total of 9503 households.

- *Economic Viability*

With this analysis, it is possible to diagnose the impact and economic profitability of the project in the energy market, and it is also possible to compare the obtained results with current plans. When defining the energy costs, it will be determined whether power production with this technology is competitive compared to the current generation systems in Ecuador.

The economic analysis is conducted based on the NPV, IRR, and PBP. Thus, Table 8 lists the economic analysis results of previous studies [35,39] for the Inga I and II and the Iguanas generating plants (similar projects in Ecuador). It should be noted that the Iguanas plant is only a reference, since it has not yet been put into operation.

Table 8. Economic analysis for the 1.8 MW plant.

	Inga I & II	**Iguanas**	**Ceibales**
NPV	11,301,391.77 USD	449,294.84 USD	383,865.48 USD
IRR	21%	45.64%	10%
PBP	3 years, 5 months	3 years	9 years, 2 months

The values in Table 8 represent the profitability of the projects; the NPV and IRR meet the conditions for a project to be accepted. However, the Ceibales plant has the lowest profitability when compared to the other two plants, and the main reason is the income from the dispatch of electrical energy, since the Inga I and II and the Iguanas plants enjoyed preferential prices at the time that these studies were conducted, which further enabled their construction. Despite this drawback, the Ceibales project is still a good investment.

Regarding the PBP, the Ceibales plant has a recovery period of more than nine years. The Inga I and II and the Iguanas plants have a recovery period of approximately three years, an acceptable duration for any project. In any case, the PBP will depend largely on the management policies of the company or shareholders responsible for implementing the Ceibales project.

The energy sold by generation companies nationwide totaled 23,882.39 GWh, at an average price of 3.14 USD ¢/kWh, of which 62.58% was supplied by hydroelectric plants. This represents an unfavorable scenario for the Ceibales plant, since the price is 7.3 USD ¢/kWh, which is above the reference price. Table 8 shows the economic analysis results regarding the 1.8 MW plant of the Ceibales landfill.

Another aspect to be analyzed is the voltage level of the Ceibales plant, which will be 13.8 kV because the potential buyer of the energy is the electric company CNEL-El Oro (electricity distribution company of the ORO province), which utilizes this voltage level. This company bought energy in 2018 at an average price of 3.94 USD ¢/kWh, which includes transmission charges and other items of the electricity market [30].

The energy share sold by companies that use biogas as a raw material is 7.26 MW, mainly coming from two plants, Inga I and II (Pichincha) and Pichacay (Azuay). In 2018, they generated 45.52 GWh, which represents 0.08% of the total gross energy produced nationwide. For this reason, it is considered a modern and innovative technology at the national level.

In this context, the Ceibales plant will be a 1.8 MW plant and be competitive at a lower energy dispatch price than the Pichacay and Inga I and II plants. However, the price per kWh will be higher than that currently offered by the electric company CNEL-El Oro; in addition, it is a renewable technology with political and environmental impacts, which facilitates its implementation.

4.3. Local Implications

Other research that analyzes production/demand concludes that this type of technology provides a marginal supply of electricity. In Mexicali (Mexico), for example, it is estimated that it is possible to supply 6% of electricity [13], while in San Pablo and Rio de Janeiro (Brazil), it is possible to supply 7.30% and 6.73%, respectively [18]. The power available in 2019 through the ICM is 1 MW, and 6022 homes can be provided with energy. It is estimated that in 2024, a second 800 kW generator can be installed, thereby generating a total of 1.8 MW for that year, supplying power to 9503 homes. The 1.8 MW plant will be available until 2040, and thereafter, it will be necessary to leave a single generator operating, and only 1 MW will be available. It is a good complementary strategy to develop intermittent energy sources, such as solar and wind technologies, as these are expected to become major energy sources in the future.

Production costs for this technology are attractive (1150–1700 USD/kW) compared to other technologies that produce electricity: Biomass 7931 USD/kW [44], incineration 2359.37 USD/kW [45], small hydroelectric plant 6803.05 USD/kW [44], small wind 1574.59 USD/kW [46], and photovoltaic [45]. However, the cost per kW is influenced by the size of the reference plant, so for high power capability, there are lower costs than for small systems. The lower the cost is, the higher the preference, as less will be invested per kW. It is clear then that financial conditions or local contexts, rather than the variability in operating and maintenance costs, prevent generalizing the results. Although the cost per kWh is lower than that of other plants [42] that use biogas, the future Ceibales plant will no longer enjoy a reference price and will have to implement models or economic agreements with El CENACE (the electrical power control center of Ecuador) to allow electrical energy dispatch at 73 USD/MWh and facilitate plant construction under contract. The reason that other projects are operational is because preferential tariffs, which do not currently exist in the Ecuadorian electricity market, were in force. At the time, the preferential rate for this type of technology was 110 USD/MWh, which is higher than the calculated prices, so the profitability of this type of project was assured [7].

The economic analysis demonstrated the economic viability of the Ceibales project and indicated that municipal waste as a raw material offers profitable opportunities due to its low cost compared to other plants. One problem is the PBP, namely, the recovery period is long for a power generation project.

The city of Machala, by generating its own energy from biogas, could reduce the costs incurred from energy imports, and energy may become available for several nearby locations. Access to electrical energy is directly linked to improvement in the quality of life of residents, and biogas can be an important source of energy. When the biogas emitted from landfills is used, the air quality can be improved, and health risks to both personnel and nearby towns can be reduced.

5. Conclusions

The introduction of new RE sources is a relevant issue in Ecuador, which aims to reduce its dependence on fossil fuels, thereby decreasing its environmental impact. Some of the renewable alternatives have reached or are reaching technological maturity. However, for a private investor or the government to decide on their use on a large scale, it will be necessary for them to represent "good business". Thus, despite the existing potential, the incorporation of new technologies has drawbacks, since they are not competitive with traditional technologies, especially hydroelectric energy. For the estimation of the biogas in a sanitary landfill, several mathematical models have been developed. For the Ceibales landfill, the modeling concluded that up to 1.8 MW of power can be installed. However, the energy decays because it depends on the quality and quantity of gas. There comes a point when the amount of gas decreases until it reaches limits where energy use is no longer profitable. This is usually counteracted by increasing the extension of the landfill area, which would allow one to maintain or increase energy production.

The use of biogas offers another environmental benefit, as MSW decomposition in landfills would otherwise result in GHG emissions. The Ceibales landfill emits moderate CH_4 amounts into the atmosphere, causing local and environmental damage. The emitted CH_4 amounts represent a good opportunity for a biogas-based electric power project. The use of biogas represents a dual contribution: (i) Receiving remuneration for the sale of energy and (ii) reducing GHG emissions.

One of the advantages of installing an ICM at the Ceibales landfill is its altitude above sea level, as it can utilize most of the available power. It should be noted that an ICM emits a certain amount of

CO_2 into the atmosphere due to CH_4 combustion. However, it is advisable to burn CH_4 because its direct release into the atmosphere represents a contamination 21 times higher than that of CO_2.

The use of alternative energy sources in Machala City is a solution to growing energy consumption and to the increase in GHG emissions due to inadequate MSW disposal.

Currently, Machala City is encouraged to implement measures to address the gases generated by landfills. As the population grows, more waste will be generated, and a larger amount of GHG will be emitted into the environment. The direct or indirect release of these gases affects air quality, thereby impacting health conditions. The increase in population also implies a power shortage. This gas can be used as a fuel source, thereby preventing waste and gas release to the atmosphere. In addition, economic benefits can be achieved [47].

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