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Techno-economic and environmental assessment of the landfill gas to energy potential of major Colombian cities☆

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ABSTRACT

Landfills account for significant methane emissions worldwide. However, municipal solid wastes can be energetically revalorized using landfill gas-to-energy (LFGtE) systems. This study assesses from a technical, economic, and environmental point of view the potential to implement LFGtE in major Colombian cities, including Bogota, Medellin, Cali, Barranquilla, Cartagena, and Bucaramanga, and the smaller capital city of Sincelejo. Municipal solid waste disposal rates in these cities are forecasted using the exponential smoothing (ETS) method. Additionally, methane emissions are forecasted using the first-order decay model, in line with the U.S. EPA methodology. Moreover, the methane generation capacity of the decomposable organic fractions of MSW is calculated following guidelines from IPCC. The assessment includes four scenarios with electricity and heat generation for each city. These scenarios consider using gas turbines, reciprocating internal combustion engines, and cogenerating electricity and heat. The economic performance is assessed with the net present value (NPV), the internal rate of return (IRR), the profitability index, the benefits-costs ratio, and the economic sensitivity analysis. Finally, the environmental performance is assessed by calculating the GHG emissions reduction potential and avoidance potential. The results show an electric power generation potential of 1.6 MWe to 47.5 MWe, a heat potential of 9.6 MW to 54.8 MW to produce steam, and 1.7 MW to 49.2 MW to produce hot water. The scenarios show economic profitability with NPV values of 5.3 million USD to 201.9 million USD.[1] At the same time, IRR varies from 14.9 % to 31.1%, a profitability index of 2.4 to 7.0 million USD, and a benefits-costs ratio of 1.3 to 1.6 million USD. Overall, scenarios consider using combustion engines to show the best economic performance. The potential to reduce greenhouse gas emissions was quantified in 1.2 Mt_{CO2e} to 40.0 Mt_{CO2e}, while the avoidance potential of greenhouse gas emissions varies between 0.1 and 4.3 Mt_{CO2e} depending on the scenario and the city.

1. Introduction

Inappropriate municipal solid wastes (MSW) management is rapidly growing as a source of pollution globally [1]. This challenge is particularly true in cities with rapid economic and population growth due to the accelerated increase in MSW generation rates [2]. Inadequate management of MSW contributes to air, water, and soil pollution causing airborne emissions of greenhouse gases like methane (CH_4) and other pollutants. Furthermore, MSW contributes to groundwater pollution with leachates [3] and increases soil pollution with heavy metals like Cu, Cr, Mn, Co, Ni [4], Zn, Pb, or Cd [5], additionally impacting public health [4]. Likewise, rather costly MSW management approaches affect the economy of developing countries worldwide [6]. Worldwide, landfills generate up to 19 % of methane emissions [7] and 3 % to 4 % of the GHGs [8]. The generation of leachates further impacts the environment [9].

The conventional management of landfilling MSW demands up to 19 % of municipal governmental budgets [10]. However, MSW and landfills can contribute to energy security [11]. As a result, developed countries are promoting the end of convectional landfills, as other management alternatives are less polluting. Overall, it is recommended

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[1] M$: Millions of USD.

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Nomenclature

BCR	Benefits-Cost Ratio
CAPEX	Capital Expenditures
CHPE	Combined Heat and Power Reciprocating Internal Combustion Engine-Generator Set
CHPT	Combined Heat and Power Standard Gas Turbine-Generator Set
DOC	Degradable Organic Carbon
ENG	Reciprocating Internal Combustion Engine-Generator Set
ETS	Exponential Smoothing
FOD	First-Order Decay
GHG	Greenhouse Gas
HEXC	Heat Exchanger
HRSG	Heat Recovery Steam Generator
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hot Water
LCOS	Levelized Cost of Steam
LFG	Landfill Gas
LFGtE	Landfill Gas-to-Energy
MSW	Municipal Solid Waste
NPV	Net Present Value
OFMSW	Organic Fraction of Municipal Solid Waste
OPEX	Operational Expenditures
PI	Profitability Index
TUR	Standard Gas Turbine-Generator Set
WtE	Waste-to-Energy

Parameters

a_x:	Costs reference parameter
d:	Discount rate (%)
d_e:	Equipment inflation rate (%)
d_g:	General inflation rate (%)
d_{tr}:	General inflation rate (%)
ΔH_{NG}	Heating value of natural gas (MJ/m^3_{NG})
η_{NG}	Efficiency of natural gas-fired hot water/steam boiler (%)
η_x	Parasitic loss efficiency of project x (i.e., due to parasitic electric needs for compression and treatment) (%)
ρ_{CH_4}	Density of Methane ($kg_{CH_4}/kmol_{CH_4}$)
c_f	Gross capacity factor (%)
f_c	GHG emissions factor from conventional thermoelectric power plant (kg_{CO_2e}/ kWh)
f_{NG}	GHG emission factor from natural gas (kg_{CO_2e}/m^3_{NG})
F_x	Fuel (CH4) consumption rate of project x (MJ/kWh)
GWP_{CH_4}	Global Warming Potential of methane (kg_{CO_2e}/kg_{CH_4})
h_x	Steam/Hot water production rate from project x (MJ/ kWh_{net})
L_c	Gas piping length between compressor and turbine or engine (m)
L_u	Steam/Hot water piping length between compressor or turbine and the end user (m)
LHV_{CH_4}	Methane lower heating value ($MJ/m^3_{CH_4}$)
M_{CH_4}	Molecular weight of Methane ($kg_{CH_4}/kmol_{CH_4}$)
M_C	Molecular weight of Methane ($kg_C/kmol_C$)
MCF	Methane Correction Factor (dimensionless)
r	Landfill Gas collection efficiency (%)
r_{CandF}	Electricity consumption rate of the collection and flaring system (MWh/$m^3_{CH_4}$)
S_{oe}	System operating schedule in a business year (h/year)
y_{CH_4}	Volumetric fraction of methane in LFG (%)

Variables

AP	Average Annual precipitation of the city (mm)
BCR_x	Benefits-Cost Ratio of the project x ($/$)
$C_{p,x,i}$	Part of the Capital Expenditures for the technology x in year i
$CAPEX_{E,x,0}$:	CAPEX for electricity generation in project x in year i ($)
$CAPEX_{HRSG,0}$:	CAPEX for steam generation in project CHPT ($)
$CAPEX_{HEXC,0}$:	CAPEX for hot water production in project CHPE ($)
$CAPEX_{x,0}$:	CAPEX of the project x in first year of construction ($)
$CAPEX_{x,i}$:	Capital Expenditures in year i ($)
$D_{x,i}$:	CAPEX depreciation of the project x in year i ($)
DOC_q:	Degradable Organic Carbon content in the q fraction of DMSW (kg_C/kg_q)
$DOCF_q$	Fraction of DOC_q that can decay (%)
$E_{x,i}$	Net electric power generated from project x in the i^{th} year (kWh)
$EX_{x,i}$:	Expenditures of project x in year i ($)
$GHGAP_x$	GHG Avoidance Potential from project x (kg_{CO_2e})
$GHGRP_x$	GHG Reduction Potential from project x (kg_{CO_2e})
$H_{CHPE,i}$:	Hot water production in CHPE for year i (GJ)
$H_{x,i}$	Net steam/hot water generated from project x in the i^{th} year (GJ)
IRR_x	Internal Rate of Return of the project x (%)
k	Landfill methane generation rate ($year^{-1}$)
L_0	Methane generation potential of DMSW (m^3/t_{DMSW})
$LCOE_x$:	Levelized cost of electricity for the project x ($/kWh)
$LCOH$:	Levelized cost of hot water ($/GJ)
$LCOS$:	Levelized cost of steam ($/GJ)
NPV_x	Net Present Value of the project x ($)
$OPEX_{E,x,i}$:	OPEX for electricity generation in project x in year i ($)
$OPEX_{HRSG,i}$:	OPEX for steam generation in project CHPT in year i. ($),
$OPEX_{HEXC,i}$:	OPEX for hot water production in project CHPE in year i. ($).
$OPEX_{x,i}$	OPEX of the project x in year i ($)
$P_{x,i}$	Electric power capacity installed of project x in the i^{th} year (kW)
PI_x	Profitability index of the project x ($/$)
$PPE_{x,i}$:	Purchasing price of electricity for the project x in the i^{th} year ($/kWh)
PPH_i:	Purchasing price of hot water in the i^{th} year ($/GJ)
PPS_i:	Purchasing price of steam in the i^{th} year ($/GJ)
$Q_{CH_4,i}$	Methane emission in the i^{th} year ($m^3_{CH_4}$/year)
$R_{x,i}$	Revenues of the project x ($/$)
$S_{CHPT,i}$:	Steam generation in CHPT for year i (GJ)
$S_{C,x,i}$	Sales of Carbon Credit of the project x in year i ($)
$S_{E,x,i}$	Sales of the electricity of the project x in year i ($)
$S_{H,x,i}$	Sales of the Heat carrier of the project x in year i ($)
$T_{d,x,i}$	Total Taxes Deductions of the project x in the year i ($)
t_{ij}	Age of j^{th} landfilled waste section of the mass W_i disposed of in the j^{th} fraction of the i^{th} year (year)
$T_{x,i}$	Total Marginal Taxes of the project x in year i ($)
$\dot{W}_i$	DMSW disposed of in i^{th} year ($t_{DMSW}/year$)
w_q	Relative weight of q fraction in DMSW (%)
$DMSW$	Fractions of Municipal Solid Waste with Degradable Organic Carbon content (%)
$MASE$	Mean Absolute Scaled Error (%)

Subscripts

i	Integer time increments in the project lifespan (year).
j	Decimal time increments within a year (year).
m	Timespan for methane estimation (years).
n	Project lifespan (years).
q	Fractions of MSW that compose the DSMW (%).
s	Number of fractions of MSW that compose the DSMW (dimensionless).
x	Technology: TUR, ENG, CHPT, of CHPE.

Table 1
Average MSW composition of Colombian cities studied. (Data source: Bogota [45], Medellin [46], Cali [47], Barranquilla [48], Cartagena [49], Bucaramanga [50], and Sincelejo [51]).

Fraction	City (% wb)						
	Bogota	Medellin	Cali	Barranquilla	Cartagena	Bucaramanga	Sincelejo
Organic	51.3	55.4	52.6	52.6	52.5	33.3	61.5
Paper[a]	13.7	5.5	4.8	9.0	10.3	9.4	6.0
Textile	4.5	4.2	0.0	7.3	3.4	4.5	4.2
Wood	1.6	0.7	0.0	4.8	1.1	3.5	0.0
Glass	3.7	3.7	2.3	3.0	5.0	3.4	0.8
Plastic	16.9	8.6	10.1	11.8	14.7	8.8	19.8
Metal	1.1	1.4	0.8	0.9	1.8	2.1	0.5
Other	7.2	20.6	29.3	10.5	11.2	35.0	7.1
DMSW[b]	71.1	65.8	57.4	73.8	67.3	50.7	71.7

[a] Paper fraction includes cardboard.
[b] DMSW is the sum of organic, paper and cardboard, textile, and wood fractions of MSW.

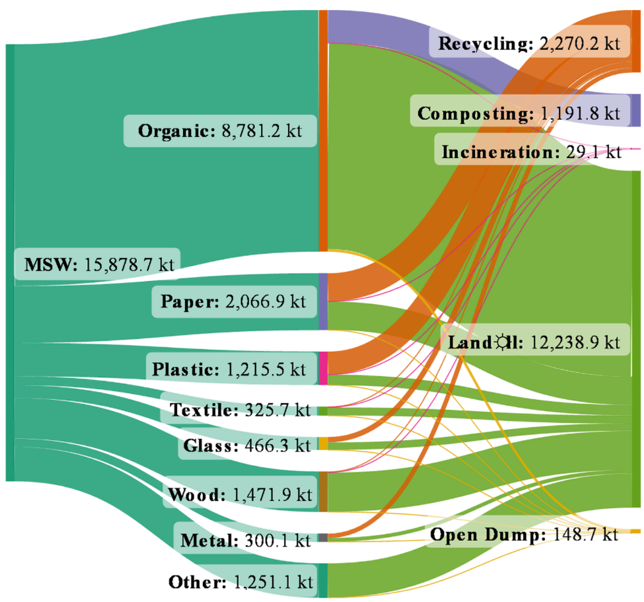


Fig. 1. MSW fractions management in Colombia in 2021. (Paper fraction includes cardboard). Data source: World Bank [37], SSPD [38], and UPME [52]).

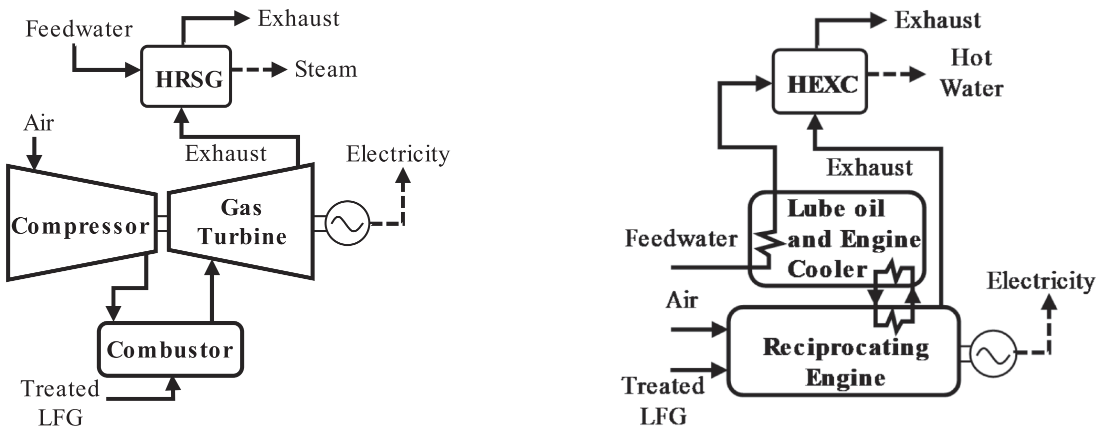
to landfill no more than 10 % to 15 % of MSW generation [12]. Europe reduced landfilling to 25 % of MSW generation, and countries like Switzerland, Sweden, Germany, and Denmark either landfill less than 1 % of MSW or no longer use landfills [13]. Moreover, developing countries landfill between 75 % and 100 % of MSW [14], making MSW management issues increasingly challenging [6].

Global MSW generation amounts to 2.1 Gt/year, and it is projected to increase by 64 % by 2050, with at least one-third managed inappropriately. Worldwide 36.6 % of MSW is landfilled and 33.0 % is openly dumped, while 13.5 % is recycled, 5.5 % is composted, and 11.1 % is valorized in Waste-to-Energy (WtE) systems [10]. To curb GHG emissions and cap the global temperature increase under 1.5 °C above pre-industrial levels, renewable-based electricity must increase by 70 % to 85 % by 2050 [15]. There is a global need to provide sustainable energy access and promote renewable energy sources [16]. However, the global energy mix is primarily supported by fossil fuels [17]. Currently, various WtE technologies are available to produce heat, electricity [18], and biofuels like biomethane and bioethanol from MSW [19]. Compared to landfills, WtE technologies are less polluting [20] and can reduce economic and environmental energy costs [15]. Furthermore, in developing countries, MSW can be a sustainable energy source [21] while helping to close the energy gap [22]. Specifically, valorizing the organic fraction of MSW (OFMSW) is critical to achieving a circular economy, which is driven on the one hand by more severe disposal regulations, and, on the other hand, to address the shortage of resources and environmental impacts like global warming globally [23]. In lower- and middle-income countries, the OFMSW is mainly openly dumped, or landfilled, wasting nutrients and other value-added materials [2].

Landfill Gas (LFG) is typically composed of 50 % to 60 (v/v) of CH_4, and 40 % to 50 % (v/v) of CO_2 [24]. Different technologies are available to produce electricity from LFG at an average 80.69 $/MWh levelized cost of electricity, which is 35 % lower than incineration and 79 % lower than anaerobic digestion [25]. LFG-to-Energy (LFGtE) projects can reduce landfill GHG emissions by 44 % [26]. Furthermore, economic and environmental assessments evidence the effective exploitation of LFGtE projects [26]. There are several models to estimate methane emissions from landfills. Particularly, the first-order decay (FOD) model [27] and its variations (e.g., Afvalzorg used by [28]), and the LandGEM from the U.S. Environmental Protection Agency (EPA) [29] are among the most widely used (e.g., used by [30;31]). These models focus on the Degradable Organic Carbon (DOC, i.e., the fractions of MSW with DOC (DMSW)) to estimate methane generation [32]. Moreover, the economic and environmental assessment of the LFGtE potential of MSW is assessed with LFGCost-WEB [33] (e.g., recently used by [34]). There are studies developed in Colombia using the FOD [35] and LandGEM [36] models.

Currently, according with the World Bank [37], and SSPD trough the national disposed of [38] and recycled [39] MSW reports, Colombia landfills 77.1 % of its MSW, recycling 14.3 %, composting 7.5 %, incinerating 0.2 %, and wasting in open dumps 0.9 %. In total, MSW management contributes to 3.5 % of Colombian GHG emissions [40]. Particularly, major Colombian cities [41] (i.e., Bogota, Medellin, Cali, Barranquilla, Cartagena, and Bucaramanga) account for 39 % of the MSW disposed of in the country [38]. However, only Bogota has an LFGtE project in the "Doña Juana" landfill. This project was initiated with no economic profitability because economic benefits like the sale of carbon credits were not considered [42]. Furthermore, the energy conversion systems have not been implemented. Between 2009 and 2022 this project reduced the emission of some 7.3 $Mt_{CO_{2e}}$ [43].

In summary, LFGtE is a suitable alternative to increasing renewable energy supply while mitigating GHGs [25]. Currently, the energy transition and the mitigation of GHGs are at the forefront of the government agenda in Colombia [44]. In this context, LFGtE surface as a viable alternative to address MSW management. Therefore, this study aims to assess the technical, environmental, and economic performance of LFGtE projects to highlight its benefits in major Colombian cities and the small capital city of Sincelejo. In this way, the project can contribute to the global discussion of how to address MSW in low- and middle-income economies, highlighting potential benefits to the energy transition, energy security, and environmental performance (particularly to curb GHG emissions).



(a) TUR (without HRSG) and CHPT technologies. (b) ENG (without HEXC) and CENG technologies.

Fig. 2. Technological scenarios analyzed in the study. ().
Adapted from: [61]

2. Data and methods.

This section describes and an overview of Colombian MSW Management and the data and methods used to develop the techno-economic and environmental assessment of the LFGtE potential from MSW in the Colombian cities studied.

2.1. An overview of Colombian MSW management.

Colombia is divided into six regions with different human developments, weathers, culture, and geography. These differences influence the composition and generation of MSW in regions, departments, and cities. Table 1 shows the average compositions of MSW in major Colombian cities.

MSWs in Colombian are mostly organic, and 75 % of them include DOC in their composition. The cities depicted in the table show an average DMSW lower than the national average. Particularly, Barranquilla has the highest DMSW, while Bucaramanga shows the lowest. Moreover, Bogota has the highest recycling rate in the country, yet it still disposes of a large fraction of DMSW that could be revalorized as a raw material or to generate energy. MSWs in Colombia are mainly landfilled and recycling and composting show marginal increments in recent years. Moreover, MSW incineration is only used in San Andres Island to manage 29.1 kt_{MSW}. Overall, large amounts of MSW are inadequately managed countrywide. Fig. 1 shows the management of MSW fractions in Colombia, highlighting the potentialities to address management issues.

Notably, while fractions of paper and cardboard, plastic, textile, wood, glass, and metal are recycled, most of the OFMSW is either dumped or landfilled accounting for 62 % of landfilled wastes. MSWs disposal rates in Colombia increased by 38 % since 2010. Particularly, in the major cities MSW disposal increased by 23 %, while disposal in the remaining cities increased by 50 %. Only in 2021 [38], MSW disposal in Colombia increased by 4.2% compared to 2020 [53]. In total, 97% of MSW landfilled were disposed in 161 landfills, of which 5 % have expired lifespans, 32 % have lifespans under 5 years, 19 % between 5 and 10 years, and 35 % of 10 years or greater. The accumulated landfilling of DMSW for years surfaces as an opportunity to exploit LFGtE systems, particularly in major cities concentrating the largest disposal rates.

2.2. Methane emissions estimations

Data on DMSW disposal rates were available in public government databases [54]. This study uses data for the period between 2010 and 2021 to forecast the disposal rate from 2022 to 2050. The data is combined with MSW composition (see Table 1) for the assessment. The assessment is developed in Microsoft Excel using the Exponential Smoothing (ETS) model depicted in [55], applied by reducing the Mean Absolute Scaled Error (MASE) as described in [56]. According with Hyndman and Athanasopoulos [57] Alternatives to ETS like Autoregressive Integrated Moving Average (ARIMA), Neural Networks Autoregression (NNAR), and Vector Autoregressive (VAR) can be used in this type of analysis. However, these alternatives are more complex and require larger amounts of data. This study calculates the feasibility of the LFG projects based on the future availability of MSW projected with the ETS method, which is conservative, simple, and easy to replicate.

Methane Emissions were calculated with Eq. (1) [29]. The values of k and L_0 were calculated for each city using Eqs. (2) and (3) [58] and adapted from IPCC [59] (see Appendix B.1 for more details). Furthermore, the average annual precipitation in the cities was taken from [60].

$$Q_{CH_4,i} = \sum_{i=1}^{n}\sum_{j=0.1}^{1.0} k \bullet L_0 \bullet \frac{\dot{W}_i}{10} \bullet e^{-k \bullet t_{ij}} \quad (1)$$

$$k = 32 \times 10^{-6} \bullet AP + 10^{-3} \quad (2)$$

$$L_0 = \frac{y_{CH_4} \bullet MCF \bullet M_{CH_4}}{\rho_{CH_4} \bullet M_C} \bullet \sum_{q=1}^{s} DOC_q \bullet DOCF_q \bullet w_q \quad (3)$$

Where:

$Q_{CH_4,i}$: Methane emissions in the i^{th} year ($m^3_{CH_4}$/year),
n: Timespan for methane estimation (80 years),
i: Integer time increments in the project lifespan (1 year),
j: Decimal time increments within a year i (0.1 year),
k: Landfill methane generation potential rate ($year^{-1}$),
L_0: Methane generation potential of DMSW (m^3/t_{DMSW}),
$\dot{W}_i$: DMSW disposed of in i^{th} year (t_{DMSW}/year),
t_{ij}: Age of j^{th} landfilled waste section of the mass W_i disposed of in the j^{th} fraction of the i^{th} year (year),
AP: Average Annual precipitation of the city (mm),
y_{CH_4}: Volumetric fraction of the methane in LFG (set to 50 %),
MCF: Methane Correction Factor (assumed as 1 for anaerobic landfills [59 Ch. 3].
M_{CH_4}: Molecular weight of Methane (16 $kg_{CH_4}/kmol_{CH_4}$),
M_C: Molecular weight of Carbon (12 $kg_C/kmol_C$),

Table 2
Equations for CAPEX and OPEX are disaggregated by project components. (Adapted from U.S. EPA [33]).

Variable	Part	Equation	
CAPEX[a] ($)	Part 1:	$C_{1,TUR,i} = \begin{cases} 2340 \bullet P_{x,i} - 0.103 \bullet P_{x,i}^2 for 3000kW \le P_{x,i} \le 12,864kW \\ 1015 \bullet P_{x,i} for P_{x,i} > 12,864kW \end{cases}$	(7)
		$C_{1,ENG,i} = 1300 \bullet P_{x,i} + 1.1 \times 10^6$	(8)
		$C_{1,CHPT,i} = \begin{cases} 2340 \bullet P_{x,i} - 0.103 \bullet P_{x,i}^2 for 3000kW \le P_{x,i} \le 9417kW \\ 1370 \bullet P_{x,i} for P_{x,i} > 9417kW \end{cases}$	(9)
		$C_{1,CHPE,i} = 1544 \bullet P_{x,i} + 1.3 \times 10^6$	(10)
	Part 2:	$C_{2,TUR,i} = C_{2,ENG,i} = C_{2,CHPT,i} = C_{2,CHPE,i} = 2.5 \times 10^5$	(11)
	Part 3:	$C_{3,CHPT,i} = C_{3,CHPE,i} = 1.2 \times 10^4$	(12)
	Part 4:	$C_{4,CHPT,i} = 355 \bullet P_{x,i}$	(13)
	Part 5:	$C_{5,CHPT,i} = C_{5,CHPE,i} = 19.2 \bullet L_c$	(14)
	Part 6:	$C_{6,CHPT,i} = C_{6,CHPE,i} = 32.3 \bullet L_u$	(15)
	Total:	$CAPEX_{x,i} = \sum_{p=1}^{6} C_{p,x,i} \bullet (1 + d_e)^{i+a_x}$	(16)
OPEX[a,b] ($/year)		$O_x = \begin{cases} 0.0144\$/kWh for x = TUR \\ 0.0250\$/kWh for x = ENG \\ 0.0180\$/kWh for x = CHPT \\ 0.0313\$/kWh for x = CHPE \end{cases}$	(17)
	Total:	$OPEX_{x,i} = O_x \bullet \frac{E_{x,i}}{\eta_x} \bullet (1 + d_g)^{i+a_x}$	(18)
Costs Reference (year)		$a_x = \begin{cases} 15 for x = TUR and CHPT \\ 10 for x = ENG and CHPE \end{cases}$	(19)

[a] Values of a_x was established as the difference between the first construction year of project (2023) and the year of reference for cost values of each technology: 2008 for TUR, CHPT and CHPE, and 2013 values for ENG [33] (e.g., for $x = TUR \Rightarrow a_{TUR} = 2023 - 2008 = 15$).
[b] An increase of 25 % for the $OPEX_{CHPT,i}$ and $OPEX_{CHPEi}$ due to HEXC and HRSG, was considered according to data reported by [67].

ρ_{CH_4}: Density of Methane ($657 \times 10^{-6} t_{CH_4}/m^3_{CH_4}$),
q: Fractions of MSW that compose the DSMW (category),
s: Number of fractions of MSW that compose the DSMW.
DOC_q: Degradable Organic Carbon content in the q fraction of DMSW (kg_C/kg_q),
$DOCF_q$: Fraction of DOC_q that can decay (%), and.
w_q: Relative weight of q fraction in DMSW (% wb).

2.3. Electric power and heat generation technologies

To diversify the electricity and energy mix in major Colombian cities toward the energy transition, the energy potential of LFGtE projects was considered for electricity and heat generation. Four electricity generation technologies were selected from the LFGCost-WebV3.05 tool to assess the energy potential of LFGtE projects (see, Fig. 2) [29]:

1. Standard turbine-generator set (TUR): Brayton cycle for electricity generation projects over 3.0 MWe.
2. Reciprocating engine-generator set (ENG): electricity generation for projects over 0.8 MWe.
3. Combined heat and power turbine–generator set (CHPT): Brayton cycle for electricity generation with a heat recovery steam generator (HRSG).
4. Combined heat and power reciprocating engine–generator set (CHPE): electricity generation with a heat exchanger (HEXC) for hot water production.

The minimum power ranges defined for TUR and ENG are the lowest recommended in LFGCost-WebV3.05 tool. Overall, these projects were selected based on their characteristics and potential for application in LFGtE projects in the discussed cities. Other technologies available in the tool did not show adequate characteristics for the projects discussed and were therefore omitted.

TUR, a Brayton cycle, operates to produce electricity and can run with a heat recovery steam generator (HRSG) to increase the energy efficiency of the system. Simultaneously, implementing an HRSG allows for additional heat production for industrial applications or to increased electricity generation (e.g., with a Rankine cycle to improve the electricity efficiency to 29 % to 43 % [62]). Brayton cycles can achieve electricity efficiencies of 24 % to 36 %. Moreover, thermal efficiencies range from 33 % to 42 % when using HRSG. Furthermore, the HRSG can produce steam at 160 °C and 1.13 MPa to 2.86 MPa [63]. Additionally, ENG can generate hot water with a heat recovery system. The cycle operates to produce electricity with efficiencies of 27 % to 36 %. Heat recovery for hot water production (110 °C and 2.86 MPa) can achieve thermal efficiencies of 35 % to 53 % [64].

2.4. Electric and heat power generation potentials

The net electricity generation, steam/hot water generation, and installed electric power generation capacity of the projects were determined using Eqs. (4)–(6) adapted from to U.S. EPA [33] as follows:

$$E_{x,i} = Q_{CH_4,i} \bullet LHV_{CH_4} \bullet r \bullet c_f \bullet \eta_x \bullet \frac{1}{F_x} \tag{4}$$

$$H_{x,i} = E_{x,i} \bullet h_x \bullet 10^{-3} \tag{5}$$

$$P_{x,i} = \frac{E_{x,i}}{S_{oe} \bullet \eta_x} \tag{6}$$

Where:

$E_{x,i}$: Net electric power generated from project x in the i^{th} year (kWh_{net}),
x: Technological projects: TUR, ENG, CHPT, or CHPE.
LHV_{CH_4}: Methane lower heating value,
r: Landfill Gas collection efficiency (85 %),
c_f: Gross capacity factor (93 %),
η_x: Parasitic loss efficiency of project x (i.e., due to parasitic electric needs for compression and treatment) (88 % for TUR/CHPT, and 93 % for ENG/CHPT),
F_x: Fuel (CH_4) consumption rate of project x (13.72 MJ/kWh for TUR/CHPT and 11.87 MJ/kWh for ENG/CHPE),

$H_{x,i}$: Net steam/hot water generated from project x in the i^{th} year (GJ),
h_x: Steam/Hot water production rate from project x (5.80 MJ/kWh_{net} for CHPT and 4.01 MJ/kWh_{net} for CHPE),
$P_{x,i}$: Electric power capacity installed of project x in the i^{th} year (kW), and.
S_{oe}: System operating schedule in a business year (8147 h/year).

Additionally, the yearly average household electricity consumption in the major cities [65] was used to assess the possible impact of the electricity generation potential on the residential sector. In general, household electricity consumption in Colombia increases with income level [66]. Moreover, with air conditioning demand, tropical cities like Barranquilla and Cartagena exhibit an electricity demand of 2 to over 3 times higher than the other cities discussed.

2.5. Economic analysis.

2.5.1. Capital and operational Expenditures

The capital costs (CAPEX) and operational and maintenance costs (OPEX) were calculated with Eqs. (7)–(19) [33], considering the equipment inflation rate (d_e), general inflation rate (d_g) for the reference prices, and a cost reference (a_x) parameter for each technology depicted in subsection 2.3, as described in Table 2. Annual OPEX includes the operation of collection and flaring systems, compression, treatment, turbine or engine, electricity generator, and HEXC or HRSG (only CHP options). The CAPEX of projects was calculated as the sum of the CAPEX of individual technologies:

Part 1: Compression and treatment, Turbine/Engine, generator, HEXC (only for CHPE), site work, housing, collection and flaring system, and facility engineering design and permits.
Part 2: Electrical interconnection equipment.
Part 3: Circulation pump.
Part 4: HRSG (only for CHPT).
Part 5: LFG pipeline from compressor to turbine or engine (L_c).
Part 6: Steam or Hot Water pipelines from turbine or engine to end user (2 lines: supply and return) (L_u).

The scenarios were developed considering a maximum distance (L_c) of 1 km between the landfill and the electricity generation system. This constraint was introduced to maintain gas compression costs in reasonable margins. Additionally, the maximum distance between the energy systems and industrial facilities (L_u) demanding electricity, steam, or hot water was limited to a maximum of 5 km, because profitability, in this case, is strongly influenced by piping cost [68]. The electricity consumption rate of the collection and flaring system (r_{CandF}) was set to 71 $MWh/m^3_{CH_4}$ according to U.S. EPA [33]. Additionally, assuming a constant installed capacity throughout the project's lifespan would prevent the opportunity to capture the increasing potential for methane emissions generated by landfills. Nevertheless, assuming the initial installed capacity to be equal to the maximum possible capacity during the project evaluation period would increase significantly the CAPEX. This approach would result in the suboptimal operation of the turbines or engines, reducing their efficiency and only using them to their full capacity in a single year when the highest methane emissions are expected. To overcome these limitations, we propose a gradual increase in the installed capacity, starting with an initial capacity equivalent to available Q_{CH_4} of the first year of project operation. The installed capacity must then be increased according to the evolution of the available Q_{CH_4}, considering the availability of capital to invest in new-generation capacities (see subsection 2.3). This approach balances the efficient use of resources with the maximization of the use of landfill methane production, resulting in optimal project performance. The proposed method provides a practical and effective solution for LFGtE projects and can be a valuable contribution to assessing similar projects in low- and middle-income economies.

2.5.2. Levelized and initial purchasing prices of electricity and heat

The Levelized Cost of Electricity (LCOE), defined as the ratio of the total cost rate to net generated electricity [69], is determined using Eq. (20) [36] to assess the LFGtE discussed. Similarly, it is possible to obtain Eqs. (21) and (22) to calculate the Levelized Cost of Steam (LCOS) and Levelized Cost of Hot Water (LCOH) (see Appendix B.3 for more details). Furthermore, levelized costs were considered as average values of the purchasing prices in the project's lifespan n. Initial prices for electricity, steam, and hot water were estimated using Eqs. (23)–(25) (see Appendix B.4 for more details).

$$LCOE_x = \frac{CAPEX_{E,x,0} + \sum_{i=1}^{n} \frac{OPEX_{E,x,i}}{(1+d_g)^i}}{\sum_{i=1}^{n} \frac{E_{x,i}}{(1+d_g)^i}} \tag{20}$$

$$LCOS_x = \frac{CAPEX_{HSGR,0} + \sum_{i=1}^{n} \frac{OPEX_{HRSG}}{(1+d_g)^i}}{\sum_{i=1}^{n} \frac{S_{CHPT,i}}{(1+d_g)^i}} \tag{21}$$

$$LCOH_x = \frac{CAPEX_{HEXC,0} + \sum_{i=1}^{n} \frac{OPEX_{HEXC,i}}{(1+d_g)^i}}{\sum_{i=1}^{n} \frac{H_{CPHE,i}}{(1+d_g)^i}} \tag{22}$$

$$PPE_{x,1} = LCOE_x \bullet \frac{n \bullet d_g}{(1+d_g)^n - 1} \tag{23}$$

$$PPS_1 = LCOS \bullet \frac{n \bullet d_g}{(1+d_g)^n - 1} \tag{24}$$

$$PPH_1 = LCOH \bullet \frac{n \bullet d_g}{(1+d_g)^n - 1} \tag{25}$$

Where:

$CAPEX_{E,x,0}$: CAPEX for electricity generation in project x in year i ($),
$OPEX_{E,x,i}$: OPEX for electricity generation in project x in year i ($),
$CAPEX_{HRSG,0}$: CAPEX for steam generation in project CHPT ($),
$CAPEX_{HEXC,0}$: CAPEX for hot water production in project CHPE ($),
$OPEX_{HRSG,i}$: OPEX for steam generation in project CHPT in year i. ($),
$OPEX_{HEXC,i}$: OPEX for hot water production in project CHPE in year i. ($).
$LCOE_x$: LCOE for project x ($/kWh),
$LCOS$: LCOS for CHPT ($/GJ),
$S_{CHPT,i}$: Steam generation in CHPT for year i (GJ),
$LCOH$: LCOH for CHPE ($/GJ),
$H_{CHPE,i}$: Hot water production in CHPE for year i (GJ),
$PPE_{x,1}$: Purchase price of electricity considered for project x at the initial operational year ($i = 1$),
PPS_1: Purchase price of steam considered in CHPT at the initial operational year ($i = 1$), and.
PPH_1: Purchase price hot water considered in CHPE at the initial operational year ($i = 1$).

2.5.3. Economic indicators

Net Present Value (NPV), Internal Rate of Return (IRR) [70], Profitability Index (PI) [71], and Benefit-Cost Ratio (BCR) [72] were calculated as economic indicators to assess the profitability of each project using Eqs. (26)–(31):

$$R_{x,i} = S_{E,x,i} + S_{H,x,i} + S_{C,x,i} \tag{26}$$

$$EX_{x,i} = OPEX_{x,i} + D_{x,i} + (T_{x,i} - T_{d,x,i}) \tag{27}$$

Table 3
Sensitivity analysis scenarios.

Sensitivity scenario	d_g %	C_p $\$/t_{CO_2e}$	d %	d_{tr} %
Case A: Very favorable	3.0	6.0	6.4	9.0
Case B: Challenging	7.0	4.0	9.0	20.0
Case C: Unfavorable	9.0	3.0	10.0	33.0
Case D: Hostile	12.0	1.0	12.0	35.0

$$NPV_x = \left[\sum_{i=1}^{n} \frac{R_{x,i} - EX_{x,i}}{(1+d)^i}\right] - CAPEX_{x,0} \tag{28}$$

$$0 = \left[\sum_{i=1}^{n} \frac{R_{x,i} - EX_{x,i}}{(1+IRR_x)^i}\right] - CAPEX_{x,0} \tag{29}$$

$$PI_x = \frac{NPV_x}{CAPEX_{x,0}} + 1 \tag{30}$$

$$BCR_x = \left[\sum_{i=1}^{n} \frac{R_{x,i}}{(1+d)^i}\right] \bullet \left\{\sum_{i=1}^{n} \frac{EX_{x,i}}{(1+d)^i} + CAPEX_{x,0}\right\}^{-1} \tag{31}$$

Where:

$R_{x,i}$: Revenues of project x in year i ($),
$EX_{x,i}$: Expenditures of project x in year i ($),
$S_{E,x,i}$: Sales of electricity of the project x in year i ($),
$S_{H,x,i}$: Sales of Heat carrier of the project x in year i ($),
$S_{C,x,i}$: Sales of Carbon Credit of the project x in year i ($),
$OPEX_{x,i}$: OPEX of the project x in year i ($),
$D_{x,i}$: CAPEX depreciation of the project x in year i ($),
$T_{x,i}$: Total Marginal Taxes of the project x in year i ($),
$T_{d,x,i}$: Total Taxes Deductions of the project x in year i ($),
NPV_x: NVP of the project x ($),
d: Discount rate (%),
n: Project lifespan (25 years).
$CAPEX_{x,0}$: CAPEX of the project x in first year of construction ($),
IRR_x: IRR of the project x (%),
PI_x: IRR of the project x ($/$), and.
BCR_x: BCR of the project x ($/$).

To consider a project profitable, it must meet the following Profitability Criteria (PC) simultaneously:

PC1: $NPV_x > 0$: This implies that the present value of cash inflows is greater than the present value of cash outflows, resulting in a net gain for the project,
PC2: $IRR_x > d$: IRR is the discount rate at which the NPV of a project becomes zero. If the IRR is higher than the discount rate, it means that the project is generating a return higher than the required rate of return, making it a profitable investment,
PC3: $PI > 1$: PI is the ratio of the present value of future cash flows to the initial investment cost. A PI greater than one indicates that the project is expected to generate more value than its initial investment cost,
PC4: $BCR > 1$: BCR is the ratio of the present value of benefits to the present value of costs. A BCR greater than one means that the benefits of the project outweigh its costs, making it a worthwhile investment.

The initial years to begin the implementation of the projects ($i = 0$) was set to 2023, with an operational lifespan from 2024 to 2048 ($i = 1$ to $i = 25$). To contextualize the projects within the Colombian legal framework, the benefits of Colombian law for promoting investment in non-conventional renewable energy projects and reducing national GHG emissions were considered.

Resolution 1092 of 2022 [73] specifies a discount rate of 6.4 % for public investment in environmental projects with lifespans between 6 and 25 years. The marginal tax rate for public enterprises is 9 % as per reference [74]. According to the benefits of Law 1715 of 2014 [75], equipment and supplies taxes for the implementation and operation of the projects are set to 0 %. Additionally, a tax deduction of 50 % of marginal taxes was considered for up to 15 years for renewable energy generation projects that reduce GHG emissions, and up to 50 % of the project's CAPEX. Carbon credit transactions can be traded in international markets, with a price varying with the market between 31 $\$/t_{CO_2e}$ in California and 99 $\$/t_{CO_2e}$ in the UK. In Colombia, the carbon tax is set at 5 $\$/t_{CO_2e}$ [76].

The equipment inflation rate (d_e) was taken at 2 % according to the U.S. EPA, because equipment price inflation depends on the inflation of the manufacturer country rather than the destination country. Moreover, the general inflation rate was set to 5.1 %, based on the average of the last five years (Apr., 2018–Mar., 2023) of Colombian inflation rates [77]. The Annual product escalation price rate was set equal to d_g. The expected operating life of TUR is 25 years [78] to 40 years [79], and for ENG is 20 years [80] to 25 years [81]. As a result, it was considered that the installed capacity was fully depreciated after 25 years.

2.5.4. Sensitivity analysis

The economic resilience of the projects was evaluated through an economic sensitivity analysis, considering various approaches and macroeconomic fluctuations. This assessment was conducted under different scenarios, as outlined in Table 3. This type of analysis helps to understand the potential impact of changes in key variables or conditions on the project's profitability and helps decision-makers to identify potential risks and opportunities.

Table 3 shows that the values between projects do not vary proportionally. The values considered in the economic analysis are according to the local conditions of the project. According to the law, four values were considered for d_{tr}. Scenario A corresponds to the income tax for companies with primarily public participation ($d_{tr} = 9\%$). Scenario B corresponds to companies in free economic zones ($d_{tr} = 20\%$). Finally, scenarios C and D represent projects where certain tax benefits, like the previous ones in cases A and B, are not applicable. The scenarios depicted in Table 3 permit stakeholders to make more informed decisions to invest and exploit LFGtE projects, based on their potential performance under different conditions.

2.6. Environmental assessment

The GHG emission Reduction Potential (GHGRP) because of the methane collected on each project was calculated with Eqs. (32)–(33), adapted from U.S. EPA [33]. Additionally, the GHG emissions Avoidance Potential (GHGAP), defined as the sum of GHG emissions that would be generated with natural gas in conventional power plants to produce the same amount of electricity, and the emissions to produce the same amount of steam and hot water obtained from LFGtE projects with natural gas, is calculated as:

$$GHGRP_x = GWP_{CH_4} \bullet \rho_{CH_4} \bullet \sum_{i=1}^{n} Q_{CH_4,i} \tag{32}$$

$$GHGAP_x = f_c \bullet \sum_{i=1}^{n} E_{x,i} + \frac{f_{NG}}{\eta_{NG} \bullet \Delta H_{NG}} \bullet \sum_{i=1}^{n} H_{x,i} \tag{33}$$

Where:

$GHGRP_x$: GHGRP from project x (kg_{CO_2e}),
$GHGAP_x$: GHGRP from project x (kg_{CO_2e}),
GWP_{CH_4}: Global Warming Potential of methane (25 kg_{CO_2e}/kg_{CH_4}),

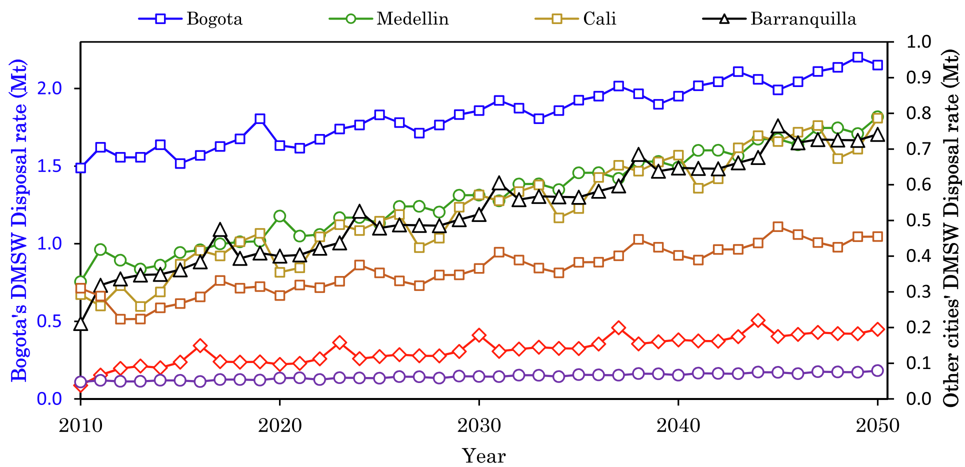


Fig. 3. Historical (2010 to 2021) and forecasted (2022 to 2050) DMSW disposal rates by city.

Table 4
Estimated FOD model parameters by city.

Parameter	*AP* mm	*k* $year^{-1}$	L_0 $m^3_{CH_4}/t_{DMSW}$
Bogota	797	0.027	137.4
Medellin	1685	0.055	129.9
Cali	1483	0.049	130.9
Barranquilla	822	0.027	128.4
Cartagena	1008	0.033	134.9
Bucaramanga	1303	0.043	133.1
Sincelejo	1099	0.036	130.7

f_c: GHG emissions factor from conventional power plants (0.43 kg_{CO_2e}/kWh).
f_{NG}: GHG emission factor from natural gas (1.93 kg_{CO_2e}/m^3_{NG}),
η_{NG}: Efficiency of natural gas-fired hot water/steam boiler (80 %), and.
ΔH_{NG}: Heating value of natural gas (39.12 MJ/m^3_{NG}).

Landfills account for different environmental impacts at the local, regional, and global scales. Particularly, GHG emissions from landfills stand as a significant source globally. Calculating the GHGRP and GHGAP of the different projects discussed permits assessing partially the environmental benefits of LFGtE projects in terms of GHG emissions. This information can help decision-makers when considering the implementation of energy projects and assessing their contributions to climate change mitigation efforts.

3. Results and discussions

This section presents and discusses the results of the techno-economic and environmental assessment of LFGtE projects for the cities under study. The data from governmental databases used in this study can be consulted in Appendix A.

3.1. Methane emission potential of cities studied

Fig. 3 shows the forecasted DMSW disposal rates for the cities studied.

Results show a good fit of the data with a MASE lower than 1.0 (ranging from 0.35 to 0.64 in the different cities). These results evidence that the forecasting model appropriately accounted for seasonal fluctuations. According to these results, DMSW disposal rates are projected to increase by 33 % to 114 % by 2050. Particularly, Sincelejo, Cartagena, and Bogota show the lowest projections to increase the DMSW by less than 42 %, while other cities are projected to increase from 73 % to 114 %. It is important to note that these projections may differ from the actual future DMSW disposal rates in major cities. However, the growing trend forecasted serves as a baseline for a preliminary feasibility study for methane availability required by the LFGtE projects.

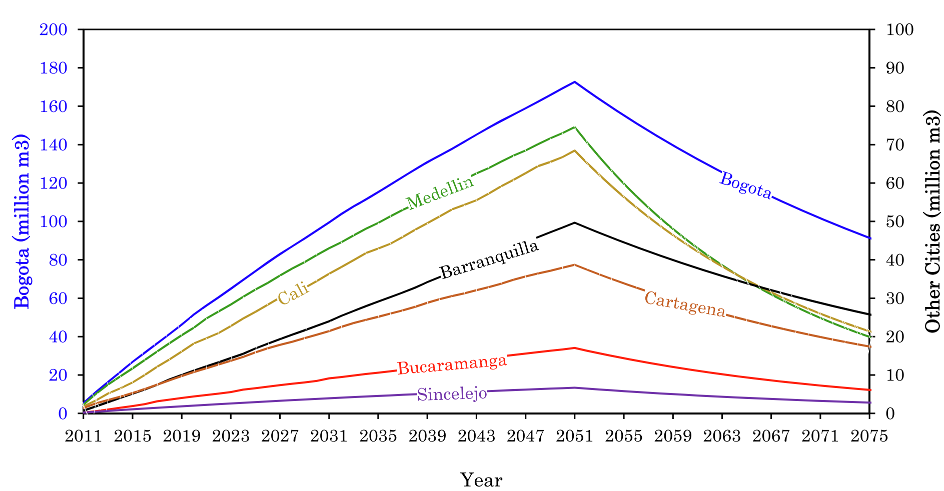


Fig. 4. Methane emission potential from DMSW disposal rates by city.

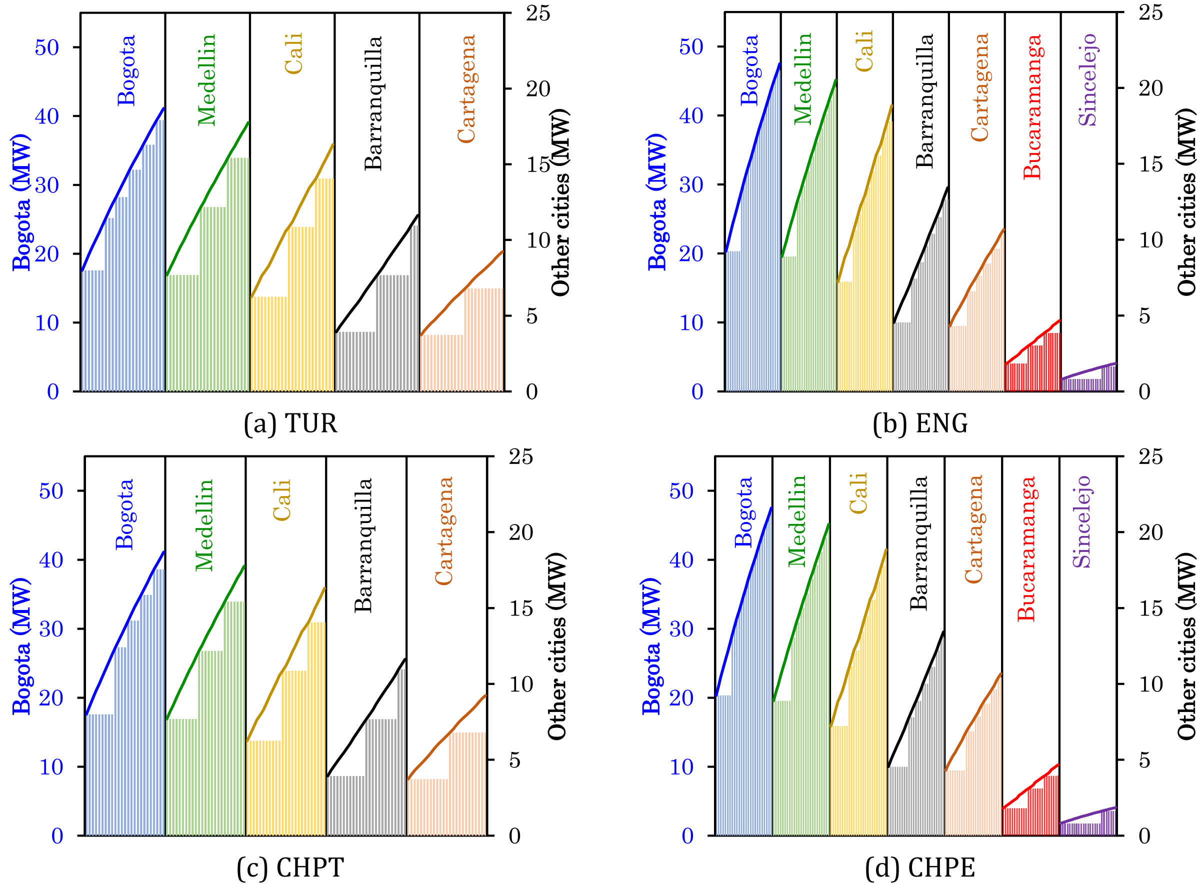


Fig. 5. Theorical (lines) and installed (shaded area) electric power generation capacities of projects by city.

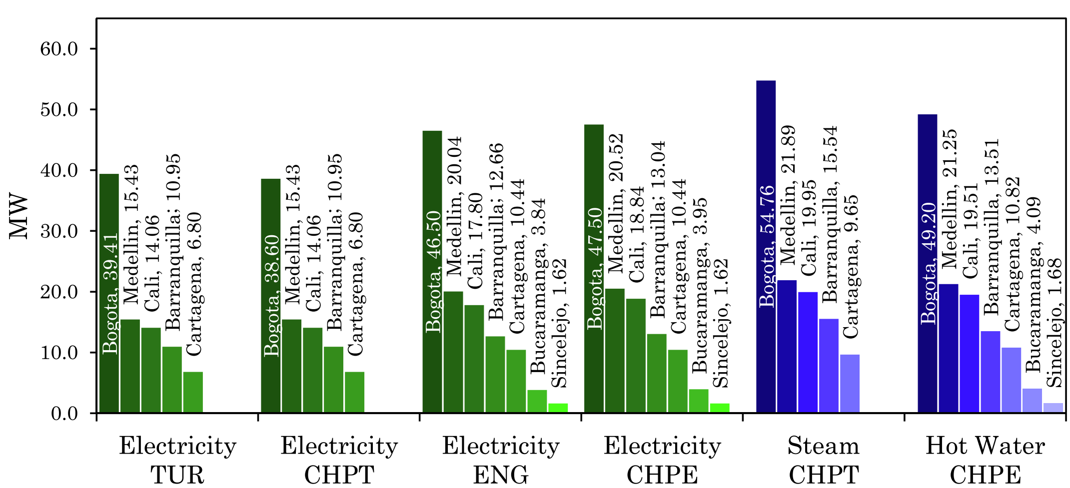


Fig. 6. Maximum power and heat installed capacity of projects by city.

Table 4 shows the estimated FOD model parameters by city for Eq. (1).

The results show average values in the cities studied for k and L_0 of 0.0385 ± 0.0099 year^{-1} and 132.2 ± 2.9 $m^3_{CH_4}/t_{DMSW}$ respectively. Moreover, Medellin, Cali, Bucaramanga, and Sincelejo k values of 0.04 year^{-1} to 0.05 year^{-1}, while Bogota, Barranquilla, and Cartagena show values typical of arid areas (0.02 year^{-1}). In the case of values of L_0, all cities show similar values between conventional (100 $m^3_{CH_4}/t_{DMSW}$) and arid areas (170 $m^3_{CH_4}/t_{DMSW}$). Consequently, it is expected that cities with higher values of k will generate more methane from the DMSW landfilled. Therefore, it is expected that Medellin and Cali with k up to 2 times higher than in Bogota will generate more methane per ton of DMSW landfill.

Fig. 4 shows the projected generation of methane from the DMSW disposal rates in each city.

The results show that Bogota has the highest potential for methane generation, followed by Medellin and Cali. The highest potential in Bogota is explained because of the highest volumes of MSW disposal rate. Additionally, Barranquilla and Cartagena exhibit similar methane generation potentials until 2030. However, in the long-term Barran-

Table 5
Estimated purchase prices of electricity, steam, and hot water by city.

City	TUR/CHPT		ENG/CHPE		CHPT		CHPE	
	LCOE $/MWh	$PPE_{x,1}$ $/MWh	LCOE $/MWh	$PPE_{x,1}$ $/MWh	LCOS $/GJ	PPS_1 $/GJ	LCOH $/GJ	PPH_1 $/GJ
Bogota	87.6	45.4	130.6	67.6	5.4	2.8	6.4	3.3
Medellin	87.7	45.4	131.1	67.9	5.4	2.8	6.5	3.4
Cali	89.8	46.5	134.0	69.4	5.6	2.9	6.6	3.4
Barranquilla	94.9	49.1	137.2	71.1	5.3	2.7	6.8	3.5
Cartagena	96.7	50.1	133.5	69.2	4.2	2.2	6.6	3.4
Bucaramanga	–	–	138.0	71.5	–	–	6.9	3.6
Sincelejo	–	–	141.9	73.5	–	–	7.3	3.8

Table 6
Economic assessments of projects by city.

Variable	Tech.	City Bogota	Medellin	Cali	Barranquilla	Cartagena	Bucaramanga	Sincelejo
CAPEX (M$)	TUR	24.4	16.4	14.6	10.6	10.2	–	–
	CHPT	41.4	20.3	17.9	12.7	12.2	–	–
	ENG	33.9	15.7	13.1	8.9	8.5	4.5	2.9
	CHPE	40.4	18.9	15.7	10.7	10.2	5.5	3.7
OPEX[a] (M$)	TUR	4.6	2.0	1.6	1.0	1.0	–	–
	CHPT	5.7	2.5	2.0	1.3	1.2	–	–
	ENG	7.1	3.1	2.5	1.6	1.5	0.6	0.3
	CHPE	8.9	3.9	3.2	2.0	1.9	0.8	0.4
NPV (M$)	TUR	146.6	55.6	47.6	31.2	29.1	–	–
	CHPT	157.3	63.0	54.4	34.4	29.6	–	–
	ENG	201.9	84.1	74.8	51.4	41.8	17.1	5.8
	CHPE	200.6	83.4	74.7	51.2	41.4	16.6	5.3
IRR (%)	TUR	31.1	22.2	21.3	20.2	20.0	–	–
	CHPT	23.4	21.0	20.5	19.2	18.3	–	–
	ENG	30.5	28.7	28.9	28.6	27.1	22.9	17.3
	CHPE	27.2	25.9	26.2	25.8	24.4	20.4	14.9
PI (M$/M$)	TUR	7.0	4.4	4.3	4.0	3.9	–	–
	CHPT	4.8	4.1	4.0	3.7	3.4	–	–
	ENG	7.0	6.3	6.7	6.8	5.9	4.8	3.0
	CHPE	6.0	5.4	5.7	5.8	5.0	4.0	2.4
BCR (M$/M$)	TUR	1.6	1.5	1.5	1.5	1.6	–	–
	CHPT	1.5	1.4	1.4	1.4	1.4	–	–
	ENG	1.6	1.5	1.6	1.6	1.5	1.5	1.4
	CHPE	1.4	1.4	1.4	1.4	1.4	1.4	1.3

[a] OPEX for the first operational year of the project.

quilla is projected to increase its DMSW disposal rates by 97 % contrasted to Cartagena. Bucaramanga and Sincelejo have lower methane generation potential due to their lowest MSW disposal rates. On the other hand, Medellin has the highest projections of methane generation per mass of DMSW landfilled (4.85 m^3/t_{DMSW}), which is 58 % higher than Bogota and Cali, 36 % higher than Barranquilla and Sincelejo, and 8 % higher than Cartagena. A similar projection is observed when considering the product of the k and L_0 parameters for each city.

This analysis helps to identify the cities with the highest methane generation potentials, providing valuable information to assess the implementation of LFGtE projects to reduce environmental impacts and promote sustainable energy sources.

3.2. Electric power, steam, and hot water generation potential

Fig. 5 shows the theoretical and installed electric power generation capacities of project alternatives by the city. Particularly for Bucaramanga and Sincelejo with an electric power potential lower than 3 MW, the projects with TUR and CHPT with a minimum of 3 MW were not considered (see Subsection 2.3).

The results indicate that ENG and CHPE have higher electric potential, primarily because of their lower parasitic losses of efficiency. The higher efficiency of these technologies results in higher revenues compared to TUR or CHPT. Higher revenues permit to increase in the installed capacity of ENG/CHPE plants more rapidly than when using TUR/CHPT technologies. Furthermore, the income from carbon credits significantly improves the financial performance of the projects. The higher the electric power capacity in the projects, the higher the GHGRP and GHGAP, which leads to higher income from carbon credits. Consequently, ENG/CHPE technologies appear as a more viable alternative for LFGtE projects.

Fig. 6 shows the maximum electric power and heat capacity installed of projects.

These results further highlight the highest energy potential for ENG and CHPE alternatives permitting higher installed electricity generation capacity. Moreover, in the long term, TUR and CHPT will reach the same electric power generation capacity. Overall, the CHPE scenario results in 2 % to 6 % higher electricity power generation capacity than in ENG, except for Cartagena and Sincelejo. These findings demonstrate the potential benefits of considering different technological scenarios in determining the optimal strategy for electric power generation in different cities. It highlights the need for a thorough analysis of the different factors influencing technology choices, like resource availability, environmental impact, and long-term sustainability.

Furthermore, CHPT has higher thermal power generation potential than CHPE, resulting in higher production of steam or hot water. Specifically, Bogota and Barranquilla would produce from 11 % to 15 % more thermal power generation potential using CHPT than using CHPE. Moreover, Medellin and Cali show a lower increase of 2 % to 3 % using CHPT technology compared to CHPE. Notably, Cartagena would have 12 % higher thermal power generation potential with CHPE than with CHPT. These findings underscore the significance of considering

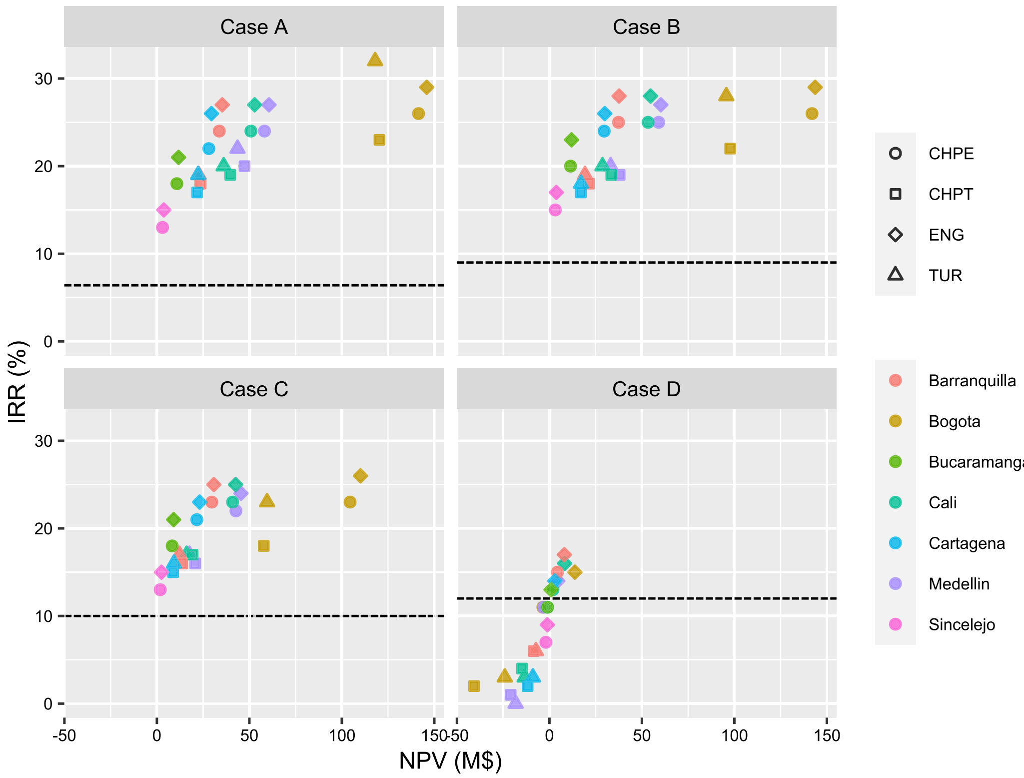
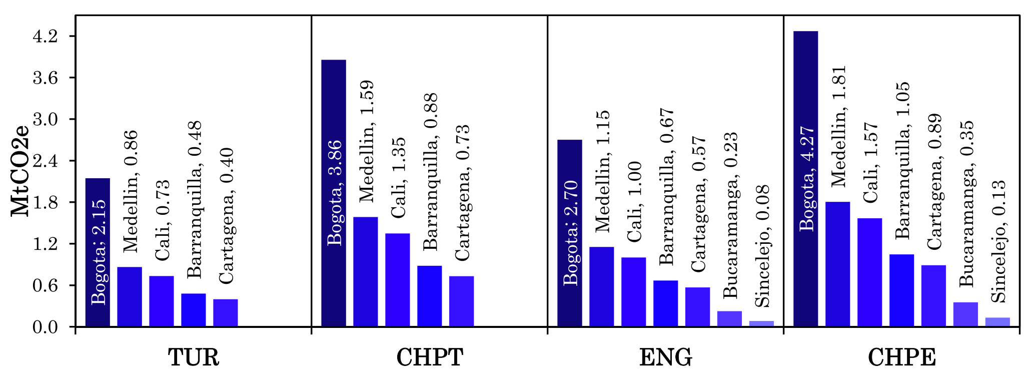
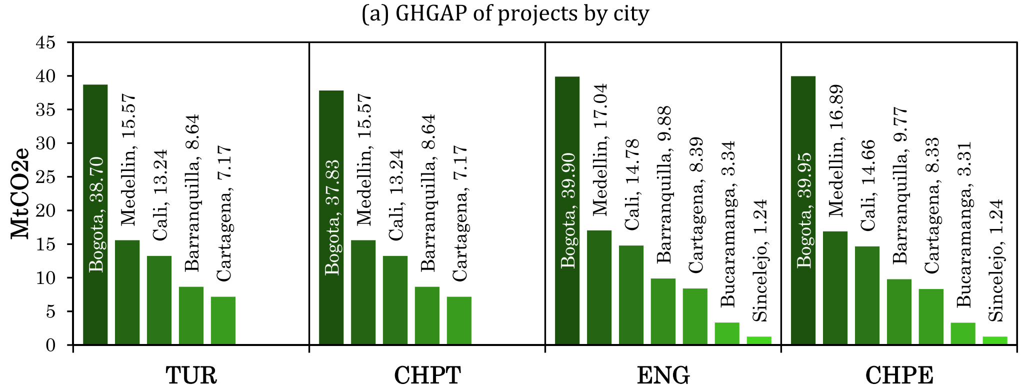


Fig. 7. Sensitivity analysis results by project (dashed lines represent the discount rate for each case).



(a) GHGAP of projects by city



(b) GHGRP of projects by city.

Fig. 8. Environmental performance of projects.

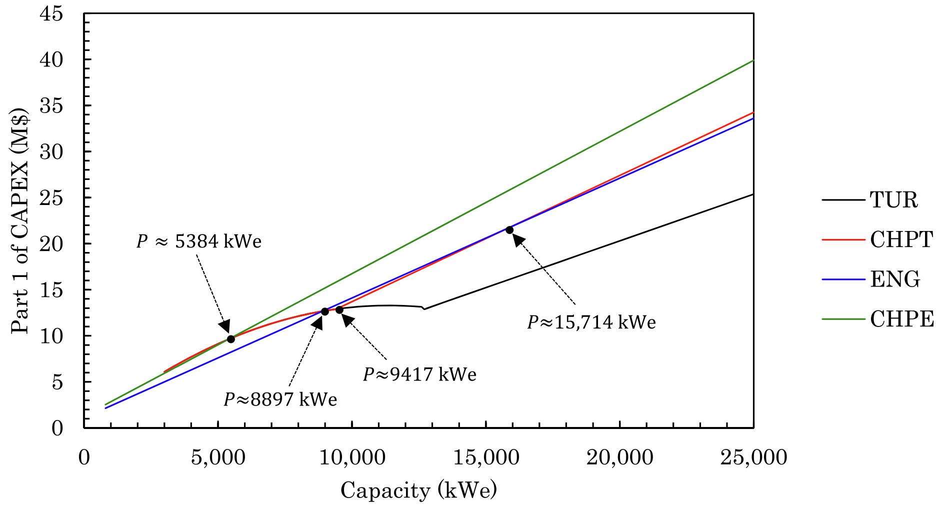


Fig. C1. Part 1 of CAPEX as a function of Installed Capacity of the projects.

different technological scenarios in determining the thermal power generation potential for LFGtE projects. It further highlights the need for tailored strategies and approaches for each case, to select the technological scenario most adequate to the needs and available resources.

Overall, these results suggest that major cities in Colombia implement LFGtE projects to support an average electricity production of 21 to 254 GWh/year for Bucaramanga and Bogota, respectively. The potential electricity generation of these projects coincides with 20 years of electricity demand from 17,100 to 205,200 low-income households. Moreover, smaller cities like Sincelejo could host ENG or CHPE projects, with an average electricity generation of 7.9 GWh/year, accounting for the electric consumption of 3900 low-income households. In general, if the projects with the highest performance were implemented (i.e., ENG scenarios), the installed electricity generation capacity would increase by up to 113 MWe, which would benefit up to 479,700 households.

On the other hand, CHP projects to generate electricity and either steam or hot water result in higher energy efficiency. However, to take advantage of the production of steam and hot water is necessary to identify potential heat demands in the vicinity of LFGtE projects. Among the cities discussed Bogota, Medellin, and Cali show the highest potential for steam and hot water production. A recent study [82] identified manufacturing company clusters within all major Colombian cities that could take advantage of the heat carriers in LFGtE projects. Concurrently, this study shows an increasing demand for heat in the residential and industrial sectors in urban areas, thus stressing the potential benefits of LFGtE projects. In the context of the energy transition with the increasing demand for sustainable energy solutions, LFGtE projects surface as an alternative to address part of urban energy demand while curbing GHG emissions and fostering a more sustainable future.

Smaller cities like Sincelejo could upgrade their territorial development plan. Specifically, in Sincelejo is possible to set a new free trading zone within a 5 km radius of the landfill. This would facilitate the use of steam and hot water to satisfy the heat demand in the industry (e.g., the dairy industry). Dairy plants in Sincelejo have been increasing because the city has a large production of livestock and agricultural resources. However, dairy plants currently face competitiveness challenges stemming from high production costs, among other factors [83]. The implementation of a LFGtE project could present an economically viable solution to address some of these challenges, reducing the energy costs of these plants and improving their competitiveness and reducing their carbon footprint. Sincelejo can largely benefit from exploiting LFGtE projects to power free trade zones which will drive economic growth and reduce environmental impacts. In addition, this strategy has the potential to significantly increase local employment opportunities.

3.3. Projects economic performance

Table 5 shows the electricity, steam and hot water purchase prices estimated for the first operational year of projects.

The average electricity purchasing in the Colombian market averaged some 62.7 ± 39.0 $/MWh in 2022 [84]. Furthermore, results in Table 5 indicate an average $PPE_{x,1}$ of 60.6 ± 11.4 $/MWh. Additionally, PPS_1 averaged some 2.7 ± 0.2 $/GJ for the different projects, which is particularly lower than the 3.3 $/GJ typical value of U.S. EPA for steam and hot water [33]. Overall, PPS_1 and PPH_1 values show more competitive costs than the 10 $/GJ[2] market price of natural gas, which in Colombia was the main fuel used for steam and hot water production at the industrial scale during 2022 [85].

Table 6 presents the economic assessment of the different projects considered by city.

The results suggest that the technological alternatives assessed would be economically feasible. Generally, contrasted to TUR the CAPEX of ENG would be lower in the projects discussed. In the case of Bogota, the CAPEX for ENG would be greater than TUR, as expected, because of the correlations from the US EPA created using hundreds of real data, which suggest that for installed capacity values greater than approximately 8897 kWe, Part 1 of ENG's CAPEX would be higher than in the case of TUR (see Appendix C for more details)., Furthermore, in some cities, like Barranquilla and Cartagena, the CAPEX for TUR would be like the CAPEX of CHPE. The cost difference between electricity and electricity and heat cogeneration projects reduces for smaller projects in all cases.

In the different cities, the OPEX would account for 10 % to 20 % of the CAPEX for the different technologies. As can be expected, the OPEX tends to increase with the power installed in the project. Overall, the OPEX varies from an average of 18.9 % in Bogotá to 9.8 % in Sincelejo. Specifically, the OPEX would be lower for TUR and CHPT technologies than for ENG and CHPT technologies.

On average, the NPV of ENG and CHPE technologies resulted in 41 % to 56 % higher than those of TUR and CHPT technologies. This indicates that ENG-based projects would be more profitable than TUR-based projects. Moreover, the IRR of electricity generation projects on average results in 7 % to 22 % higher values than cogeneration projects. Consistently, the PI and BCR values show similar trends pointing to TUR

[2] Estimated for large consumers of natural gas (consumption greater than 20 m^3_{NG}), using a currency conversion rate of 5000 COP$/USD$ and a natural gas heat content of 39.12 MJ/m^3_{NG}.

or ENG projects as more profitable than cogeneration projects. These results suggest that cogeneration projects would be more profitable with the use of Rankine cycles (organic or standard) to further improve the economic performance of projects. This might be explained by the larger infrastructure needed for the transport of steam and hot water, which in turn have lower market prices than electricity.

Although the economic assessment shows attractive results, it is the cornerstone to consider other factors like environmental impacts, local regulations, macroeconomic fluctuations of critical variables like inflation rate, and available infrastructure among others, towards more informed decision-making to identify the most suitable technology tailored to each city' according to its conditions.

Fig. 7 show a sensibility analysis for the different technologies.

The findings indicate that projects can face macroeconomic fluctuations under scenarios A, B, and C. However, most of the technology alternatives under scenario D show no economic feasibility. Particularly, projects based on ENG show profitability in all cities except for Sincelejo, while the CHPE alternative is feasible in Cali and Barranquilla. On the other hand, the TUR and CHPT options show no feasibility in any city. Notably, most of the profitability of the projects depends on carbon credits sales. Without the carbon credits, none of the projects discussed show profitability (see Appendix A for more details).

These results suggest that ENG projects are the most indicated for larger and smaller cities in Colombia. This is explained because of the better characteristics to cope with macroeconomic fluctuations due to higher efficiency and lower CAPEX and OPEX.

3.4. Environmental performance of the projects

Gradually increasing in installed capacity of the projects implies an increase in the LFG capture. The results indicates that, within the projects' lifespan, the LFGtE projects discussed can peak LFG capture in 76 $m^3_{CH_4}$ to 2432 $m^3_{CH_4}$ in the cities discussed. These values account for 65 % to 82 % of expected methane generation within the projects' lifespan. These figures also point that only in larger cities is possible to capture up to 5757 $m^3_{CH_4}$ which could reduce of up to 80 % of the methane emissions projected between 2024 and 2048 in these cities. Fig. 8 show GHGRP and GHGAP for the projects discussed.

Overall, Bogota shows the highest GHGRP and GHGAP because of the highest volume MSW landfilled. Moreover, CHPT and CHPE technologies show higher GHGAP than TUR and ENG scenarios, explained by the higher energy output of cogeneration contrasted to electricity generation. Furthermore, parasitic losses in TUR result in lower efficiency than ENG, leading to lower electricity outputs and lower GHGAP and GHGRP for TUR-based projects. Results show that regardless of the technological alternative, the GHGRP remains rather constant for a city because in all cases methane combustion equals methane capture in LFGtE projects. This is further explained because it is assumed in the projects that all captured methane is combusted either with power technology or by a flaring system. The collection efficiency was considered equal in all projects. Differences between technologies occur because the evolution of installed generation capacity vary with technology alternatives throughout the project's lifespan.

4. Conclusions

The techno-economic and GHG emissions assessment of landfill gas-to-energy projects in Colombia shows them as viable alternatives for renewable and sustainable energy sources in major and smaller cities to contribute to the energy transition and reduce de dependance on fossil-fuels. The technological alternatives assessed can produce electricity and heat at competitive prices for the Colombian market. overall, the engine-based technologies resulted in better energy, economic, and GHG emission performance than the alternative Brayton-based technologies. Implementing these technologies would reduce methane emissions by up to 80 % in the cities discussed. In total, it is possible to reduce GHG emissions by 4.6 to 10.7 million t of CO_2 equivalent in the cities discussed. Furthermore, electricity and heat production could prevent the emission of 82.5 to 94.1 million t of CO_2 equivalent by preventing the generation of electricity in fossil-based power plants.

Further discussion is needed to assess possible improvements by complementing MSW with other biomass sources available locally, like organic wastes from the dairy industry in Sincelejo. This requires assessing the geographical location of LFGtE projects and biomass alternative sources on a case-by-case basis. Moreover, to further highlight the potential benefits of landfill gas, it is needed to assess the reduction of environmental impacts on the soil, water, and air quality of these projects contrasted to landfills.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data, along with research data, for this work can be accessed at: https://doi.org/10.17632/ksw8w98wb3.1.

Appendix B. Procedure for obtain adapted equations used in this work

Appendix B.1 methane generation capacity

The IPCC guidelines define Eqs. (B.1)–(B.3).

$$DDOCm = W \bullet DOC \bullet DOC_f \bullet MCF \tag{B.1}$$

$$L_{0,IPCC} = DDOCm \bullet F \bullet \frac{16}{12} \tag{B.2}$$

$$DOC = \sum_q DOC_q \bullet W_q \tag{B.3}$$

Where:

$DDOCm$:Mass of decomposable DOC deposited (Gg),
W:mass of waste deposited (Gg),
DOC:degradable organic carbon in the year of deposition (Gg_C/Gg_{waste}),
DOC_f:fraction of DOC that can decompose (%),
MCF:CH_4 correction factor for aerobic decomposition in the year of deposition (fraction),
$L_{0,IPCC}$:CH_4 generation potential in IPCC guidelines (Gg_{CH_4}),
$DDOCm$:mass of decomposable DOC, Gg,
F:fraction of CH4 in generated landfill gas (volume fraction),
16/12:molecular weight ratio CH4/C (ratio),
DOC:fraction of degradable organic carbon in bulk waste (Gg_C/Gg_{waste}),
DOC_q:fraction of degradable organic carbon in q fraction of waste (% wb), and
W_q:q fraction of waste category (%).

Combining Eqs. (B.1)–(B.3), is obtained Eq. (B.4):

$$L_{0,IPCC} = W \bullet \sum_q DOC_q \bullet DOC_{f,q} \bullet W_q \bullet MCF \bullet F \bullet \frac{16}{12} \tag{B.4}$$

Dividing by W both sides of Eq. (B.4) is obtained Eq. (B.5):

$$\frac{L_{0,IPCC}}{W} = MCF \bullet F \bullet \frac{16}{12} \bullet \sum_q DOC_q \bullet DOC_{f,q} \bullet W_q \tag{B.5}$$

Now, by combining L_0 from U.S. EPA FOD model in $m^3_{CH_4}/Gg$, with Eq. (B.5), we obtain Eq. (B.6):

$$L_{0,EPA} = \frac{L_{0,IPCC}}{W \bullet \rho_{CH_4}} = \frac{MCF \bullet F \bullet 16}{W \bullet \rho_{CH_4} \bullet 12} \bullet \sum_q DOC_q \bullet DOC_{f,q} \bullet W_q \tag{B.6}$$

Simplifying is obtained Eq. (B.7) :

$$L_{0,EPA} = L_0 = \frac{y_{CH_4} \bullet MCF \bullet M_{CH_4}}{\rho_{CH_4} \bullet M_C} \bullet \sum_q DOC_q \bullet DOCF_q \bullet w_q \tag{B.7}$$

Appendix B2 Part 1 CAPEX of CHPE projects

According to U.S. EPA documentation, Part 1 of Capital Expenditure (CAPEX) for ENG technology is calculated using Eq. (B.8), based on the data from 2008.

$$C_{1,ENG,2008,i} = 1600 \bullet P \tag{B.8}$$

Furthermore, an update for Eq. (B.8) yields Equation (B.9), which incorporates 2013 values.

$$C_{1,ENG,2013,i} = 1300 \bullet P + 1.1 \times 10^6 \tag{B.9}$$

On the other hand, the Part 1 of CAPEX for combined Heat and Power Energy (CHPE) is calculated using Eq. (B.10), based on the data from 2008.

$$C_{1,CHPE,2008,i} = 1900 \bullet P \tag{B.10}$$

Assuming that the a proportionality between 2008 and 2013 values remains constant for both ENG and CHPE, the Part 1 of CHPT's CAPEX, considering the values from 2013, can be calculated as follows:

$$\frac{C_{1,ENG,2013,i}}{C_{1,ENG,2008,i}} = \frac{C_{1,CHPE,2013,i}}{C_{1,CHPE,2008,i}} \tag{B.11}$$

$$\frac{1300 \bullet P + 1.1 \times 10^6}{1600 \bullet P} = \frac{C_{1,CHPE,2013,i}}{1900 \bullet P} \tag{B.12}$$

$$C_{1,CHPE,2013,i} = 1544 \bullet P + 1.3 \times 10^6 \tag{B.13}$$

Appendix B3 Levelized costs

The following describes how to obtain the equations for calculating LCOE, LCOS, and LCOH:

$$CAPEX_{E,CHPT,0} = CAPEX_{TUR,0} \tag{B.14}$$

$$CAPEX_{E,CHPE,0} = CAPEX_{ENG,0} \tag{B.15}$$

$$OPEX_{E,CHPT,0} = OPEX_{TUR,0} \tag{B.16}$$

$$OPEX_{E,CHPE,0} = OPEX_{ENG,0} \tag{B.17}$$

$$CAPEX_{HRSG,0} = CAPEX_{CHPT,0} - CAPEX_{TUR,0} \tag{B.18}$$

$$CAPEX_{HEXC,0} = CAPEX_{CHPE,0} - CAPEX_{ENG,0} \tag{B.19}$$

$$OPEX_{HRSG,i} = 0.25 \bullet OPEX_{TUR,i} \tag{B.20}$$

$$OPEX_{HEXC,i} = 0.25 \bullet OPEX_{ENG,i} \tag{B.21}$$

$$LCOE_x = \frac{CAPEX_{E,x,0} + \sum_{i=1}^{n} \frac{OPEX_{E,x,i}}{(1+d_g)^i}}{\sum_{i=1}^{n} \frac{E_{x,i}}{(1+d_g)^i}} \tag{B.22}$$

$$LCOS = \frac{CAPEX_{HRSG,0} + \sum_{i=1}^{n} \frac{OPEX_{HRSG}}{(1+d_g)^i}}{\sum_{i=1}^{n} \frac{S_{CPHT,i}}{(1+d_g)^i}} \tag{B.23}$$

$$LCOH = \frac{CAPEX_{HEXC,0} + \sum_{i=1}^{n} \frac{OPEX_{HEXC,i}}{(1+d_g)^i}}{\sum_{i=1}^{n} \frac{S_{CPHE,i}}{(1+d_g)^i}} \tag{B.24}$$

Appendix B4 initial purchasing price of electricity, steam, and hot water

Levelized Cost of Electricity is assumed as the average electricity prices of each year *i*. That is:

$$LCOE = \frac{PPE_1 + PPE_2 + PPE_3 + \cdots + PPE_n}{n} \tag{B.25}$$

$$n \bullet LCOE = PPE_1 + PPE_{x,1} \bullet (1+d_g)^1 + PPE_{x,1} \bullet (1+d_g)^2 + \cdots + PPE_{x,1} \bullet (1+d_g)^{n-1} \tag{B.26}$$

$$n \bullet LCOE \bullet (1+d_g) = PPE_1 \bullet (1+d_g) + PPE_{x,1} \bullet (1+d_g)^2 + PPE_{x,1} \bullet (1+d_g)^3 + \cdots + PPE_{x,1} \bullet (1+d_g)^n \tag{B.27}$$

Then, subtracting Eq. (B.26) from Eq. (B.27):

$$n \bullet LCOE \bullet d_g = PPE_{x,1} \bullet (1+d_g)^n - PPE_1 \tag{B.28}$$

$$PPE_{x,1} = \frac{n \bullet LCOE \bullet d_g}{(1+d_g)^n - 1} \tag{B.29}$$

The same procedure can be applied to both LCOS and LCOH to obtain the following Eqs.

$$PPS_1 = \frac{n \bullet LCOS \bullet d_g}{(1+d_g)^n - 1} \tag{B.30}$$

$$PPH_1 = \frac{n \bullet LCOH \bullet d_g}{(1+d_g)^n - 1} \tag{B.31}$$

Appendix C. Analysis of Part 1 of CAPEX equations

When analyzing the equations for calculating Part 1 of the CAPEX (see, Eqs.(7)–(10) in Table 2), valuable information can be obtained when comparing the estimated CAPEX for the studied technological scenarios. Fig. C.1 shows the estimated CAPEX for each scenario as a function of the installed electrical capacity of each project. From this graph, it can be observed that the most significant portion of the CAPEX for some projects would be higher than others for values above a few hundred units of installed electrical capacity (e.g., ENG's Part 1 of CAPEX would be higher than TUR's for values above approximately 8897 kWe).

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