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ORIGINAL ARTICLE

Unlocking landfill biogas potential: a feasibility study on sustainable energy in the UAE

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Abstract

Landfill biogas (LFB) projects present a promising solution for sustainable energy generation, yet their feasibility in arid climates remains largely unexplored. This study investigates the feasibility of generating biogas from landfill waste in the UAE, focusing on energy generation potential, economic viability, and environmental benefits. The study evaluates landfill biogas production using internal combustion engine and gas turbine technologies across three scenarios with varying methane content (40%, 50%, and 60% by volume). The results indicate that internal combustion engine technology demonstrates greater economic feasibility compared to the gas turbine technology, yielding a net present value of up to $83 million. Additionally, implementing landfill biogas to energy projects has the potential to power between 68,412 and 136,824 households while cutting greenhouse gas emissions by up to 66% compared to existing waste management practices. However, the relatively high levelized cost of energy underscores the need for policy interventions and financial incentives to enhance project viability. By addressing this critical knowledge gap, the study provides a replicable framework for optimizing waste-to-energy (WTE) systems in arid environments and contributes actionable insights to global renewable energy efforts.

Keywords Landfill biogas · Methane · Internal combustion engine · Gas turbine

Nomenclature

LFB	Landfill Biogas
LFBtE	Landfill Biogas to Energy
P^{S}	Percentage of methane present in LFB by volume for scenario S
$E^{S}_{(T)}$	Annual energy generation potential by technology T for scenario S (kWh/year)
$Q^{S}_{CH_4}$	Quantity of recoverable methane gas emitted from landfill site for scenario (S) (m^3/year)
LHV_{CH_4}	Low heating value of the methane gas (MJ/m^3)
$\eta_{(T)}$	Electrical conversion efficiency for the technology T
λ	Collection efficiency of methane from landfill
$NPV^{S}_{(T)}$	Net Present Value of the LFBtE project using technology T for scenario S
$CF^{S}_{t(T)}$	Cash flow at time t of the LFBtE project using technology T for scenario S
$I^{S}_{(T)}$	Initial investment of the LFBtE project using technology T for scenario S
$O\&M^{S}_{cost,total(T)}$	Total operations and maintenance cost of the LFBtE project using technology T for scenario S
π	Feed-in-tariff
Tax_r	Marginal tax rate of UAE (%)
α	Nominal discount rate (%)
ν_r	Inflation rate (%)
W_n	Number of wells dug at the site
D_{well}	Depth of the well (feet)
$LFBtE^{S}_{size(T)}$	Rated capacity of technology T for scenario S (kW)
$CO^{S}_{2}eq_{(LFB)}$	Annual potential GHG emissions of LFB in ktonne of CO_2eq for scenario S (ktonne CO_2eq/year)
$Q^{S}_{C0_2}$	Annual $C0_2$ emissions for scenario S (m^3/year)

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$CO_{2\,combustion(T)}^{S}$	Annual CO_2 emissions attributable to the utilization of technology T in scenario S (kg/year)
$CO_2^S eq_{(T)}$	Annual potential GHG emissions in ktonne of CO_2eq for scenario S using technology T (ktonne CO_2eq/year)

Abbreviation

ICE	Internal Combustion Engine
GT	Gas Turbine
PBP	Payback Period
LCOE	Levelized Cost of Energy

1 Introduction

The escalating challenge of managing municipal solid waste (MSW) has emerged as a critical global concern, with rapid urbanization and population growth contributing to unprecedented levels of waste generation. This issue is particularly acute in high-income countries, such as the United States, Germany, and Japan, face challenges in managing large amounts of municipal solid waste due to their high per capita waste generation. The Middle East, characterized by its rapid economic development and urbanization, is facing substantial challenges in managing its growing volumes of waste. Among the nations in this region, the United Arab Emirates (UAE) exemplifies these challenges. As of 2021, the UAE generates approximately 1.8 kg of MSW per capita daily, one of the highest rates globally [1]. The reliance on landfills for waste disposal in the UAE has led to severe environmental risks, including the emission of greenhouse gases such as methane and carbon dioxide, and the potential contamination of soil and water through leachate. This study aims to fill a critical gap in the current understanding of waste-to-energy solutions in the UAE, providing a comprehensive analysis of the opportunities and challenges associated with landfill biogas (LFB) generation from landfill waste. While the findings directly contribute to the UAE's sustainability goals, they also offer scalable insights into sustainable waste management and renewable energy production that are applicable to other countries with similar climatic and demographic challenges, such as those in Africa, Central Asia, and the Middle East. By analyzing energy generation potential, economic viability, and environmental benefits, this research contributes to the global discourse on renewable energy strategies and informs waste management practices internationally. In addition to its practical implications, this study makes a significant academic contribution by providing a robust framework for evaluating LFB-to-energy (LFBtE) projects. The scenario-based analysis and comparison of internal combustion engines (ICE) and gas turbines (GT) technologies offer transferable methodologies that can guide technology selection globally. By addressing varying methane concentrations, the study highlights conditions under which LFBtE projects achieve optimal economic and environmental outcomes. These insights advance academic understanding and provide a reference for future research on waste-to-energy solutions in diverse contexts.

In the UAE, landfills are controlled dumpsites and are designed to accept non-hazardous solid waste, which includes household, commercial, agricultural, construction, and industrial waste [2, 3]. MSW is a comprehensive term that covers a wide variety of solid and non-hazardous waste generated from residential, commercial, and institutional sources. In this study, MSW sent to landfills is referred to as landfill waste to simplify classification, and LFB is referred to as methane when assessing its energy potential and economic feasibility. However, both methane and carbon dioxide are considered when evaluating the environmental impact of LFB. Landfills, frequently utilized for MSW, are approaching capacity and generating significant environmental hazards. Methane, a potent greenhouse gas, is emitted into the atmosphere, thereby contributing to climate change. In most GCC countries, around 60% of MSW is organic [4, 5]. The high moisture and organic content in MSW, primarily derived from biodegradable food waste, results in odors, volatile organic compounds, and leachate, which contaminate groundwater. Furthermore, health risks for workers managing MSW are escalating. To address these challenges, the UAE, as a high-income candidate, has set ambitious sustainability and renewable energy goals within its "Energy Strategy 2050." This strategy aims to achieve a 50% share of clean energy in the total energy mix and to reduce the carbon footprint of power generation by 70% by 2050. A promising yet underexplored opportunity within this framework is the conversion of MSW into LFB. It is composed of methane in a range of 30% to 65% by volume, carbon dioxide comprising 25% to 47% by volume, alongside minor quantities of water vapor, nitrogen, aromatic compounds, and hydrogen sulfide [6]. This initiative not only provides a sustainable method for waste management but also contributes significantly to the nation's renewable energy supply. By 2030, the UAE aims to generate 14 GW of clean energy [7, 8].

Studies have shown the feasibility of using organic waste from agricultural activities for LFB production, indicating the potential of various waste sources to generate electricity and reduce the carbon footprint [9, 10]. Methane, a powerful greenhouse gas, can be transformed into valuable resources such as heat, electricity, vehicle biofuel, refrigeration, generator power, and feedstock for hydrogen production [11]. This dual functionality of LFB not only enhances waste management but also plays a crucial role in mitigating climate change [12]. Among the various technologies for power generation from LFB approximately 70% of landfill biogas to energy (LFBtE) projects utilize internal combustion engines (ICE), gas turbines (GT), and microturbines. ICEs, suitable for larger projects exceeding 800 kW, generally achieve electricity efficiencies ranging from 35 to 45% [13, 14]. Gas Turbines, appropriate for larger projects above 3 MW, typically achieve electricity efficiencies of 20% to 35% [15, 16]. Microturbines, ideal for smaller-scale operations below 1 MW, offer efficiencies ranging from 22 to 30%. However, their initial investment and operating costs are the highest among the three technologies. Due to these factors, this study considers only ICE and GT technologies [17, 18]. The financial success of these systems depends on effectively balancing LFB production, electricity purchase, and the sale of surplus LFB. Furthermore, these projects contribute to employment generation and financial gains [19].

Globally, waste-to-energy (WTE) technologies have emerged as effective solutions for sustainable waste management. Among these, LFG utilization is a mature and cost-effective WTE technology that captures methane and carbon dioxide from decomposing waste for energy generation, requiring minimal pre-treatment and low capital and operational costs, but with low energy efficiency (10–20%). In contrast, anaerobic digestion (AD) achieves higher efficiencies (50–70%) and significant greenhouse gas reductions by converting organic waste into biogas and digestate, as demonstrated in Bahrain, where it is projected to generate 213.3 GWh annually, save USD 8.47 million in landfill costs, and reduce 535,251 tons of CO2-equivalent emissions, despite higher pre-treatment and infrastructure costs [20]. Incineration, with moderate efficiency (50–60%), effectively reduces waste volume but requires substantial investment in emission control systems, limiting adoption in regions like North America due to public resistance. Emerging technologies such as gasification and pyrolysis offer higher efficiencies (70–80%) and lower emissions, but high capital costs and feedstock sensitivity restrict their broader deployment [21, 22]. In the UAE, waste management aligns with sustainability goals such as Vision 2021, with projects like Dubai's energy-from-waste facility and Sharjah's zero-waste-to-landfill initiative supported by Federal Law No. 12 of 2018, though challenges such as limited organic recycling infrastructure and low public engagement remain. Globally, Europe leads in WTE adoption driven by stringent policies, Asia emphasizes incineration and gasification, North America focuses on LFG and AD, and Latin America relies on LFG supported by international funding. By addressing existing challenges and leveraging emerging technologies, the UAE can further advance its waste management systems and sustainability objectives [23, 24]. Amid these challenges, the UAE is exploring the potential of converting landfill waste into biogas, a renewable energy source that supports the nation's energy diversification goals and reduces its environmental impact. The production offers a sustainable approach to waste reduction while contributing to the UAE's objectives of decreasing reliance on fossil fuels and minimizing the carbon footprint of its energy sector. Moreover, the findings hold broader relevance for policymakers and stakeholders globally, providing a blueprint for integrating LFBtE projects into waste management and renewable energy strategies to meet international sustainability goals.

The primary objectives of this study are:

Energy Potential Assessment: Evaluate the capability of LFB generated from landfill waste to serve as a renewable energy source.
Economic Feasibility Analysis: Assess the financial viability of implementing LFB-to-energy (LFBtE) projects using internal combustion engine (ICE) and gas turbine (GT) technologies.
Environmental Impact Evaluation: Measure the potential environmental benefits, such as reductions in greenhouse gas emissions, of adopting LFBtE systems.

The research framework incorporates scenario-based analyses across varying methane concentrations (40%, 50%, 60%), aligning with practical methane production ranges to ensure realistic modeling. These scenarios are designed to offer insights into energy recovery, economic outcomes, and environmental impacts, contributing to global strategies in sustainable waste management and renewable energy.

Most Studies modeling LFB production consider methane content within the range of 40% to 60% by volume. Methane concentrations above 60% are typically excluded to avoid overestimating energy recovery potential,. Similarly, methane content below 40% is excluded, as such low concentrations in operational landfills result in inadequate energy generation [25].To evaluate the environmental impact of these scenarios, the study introduces two overarching cases: Baseline Case: This case examines the environmental consequences of releasing LFB into the atmosphere without energy recovery and LFBtE Case: This case evaluates the environmental impact when LFB is captured and utilized for energy recovery through LFBtE projects, employing technologies such as ICE and GT.

2 Methodology

Investigation on the LFB production was conducted at landfills situated in the UAE. This study focuses on the landfills located in Abu Dhabi and Dubai, the two major emirates of the UAE. Abu Dhabi, the largest emirate, encompasses 84%

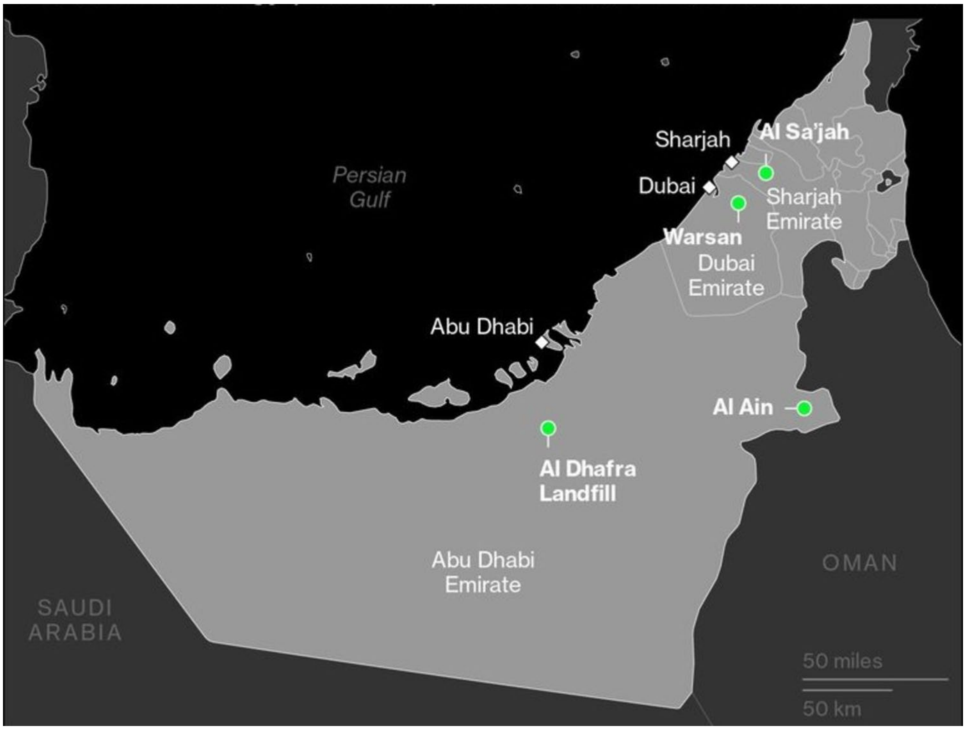

Fig. 1 Geographical locations of key landfill sites in the UAE, including Al Dhafra Landfill in Abu Dhabi and Warsan Landfill in Dubai

of the UAE's total land area. Figure 1 illustrates the geographical locations of key landfill sites in the UAE, including Al Dhafra Landfill in Abu Dhabi and Warsan Landfill in Dubai [26]. The Abu Dhabi Waste Management Company, Tadweer, administers the landfills in this region. Waste in Abu Dhabi is predominantly disposed of at nine controlled landfills, with Al Dhafra being the largest, covering nearly 1,000 hectares. Dubai, the second largest emirate, oversees its landfill sites through the Dubai Municipality. Dubai operates six landfill sites, covering approximately 160 hectares. In the UAE, landfills, though considered non-engineered waste disposal sites, still follow systematic waste management practices. These include waste segregation, spreading, grading, compacting, mixing with inert materials, and covering. This study combines and analyzes all the landfills in Abu Dhabi and Dubai as a single consolidated landfill. The consolidated landfill began operations in 2008, based on the opening date of the Al Dhafra landfill, covering a total disposal area of 1,628 hectares. Given the UAE's objective to stop sending waste to landfills by 2030, the closure date for this landfill is assumed to be by 2030. Figure 2 shows the methodological steps used to perform the calculations in this study.

2.1 Population and landfill waste generation estimation

Accurately estimating population growth and landfill waste generation is crucial for the effective planning and management of waste disposal and energy recovery from landfills. The incremental increase method is employed to project the populations of Abu Dhabi and Dubai. This method is selected as it combines the advantages of both arithmetic and geometric increase methods, thereby offering a balanced approach that reflects the complex growth dynamics characteristic of these urban areas. Although traditionally utilized for decade-level projections, this method is adapted for annual estimates as required. The future population is estimated using Eq. (1) [27]:

$$P_N = P + \left(N \times A_d\right) + \left[\frac{N \times (N+1) \times A_t}{2}\right] \tag{1}$$

where,

P_N	Future population after N decades
P	Present population
N	Number of decades
A_d	Average increase per decade
A_t	Average incremental increase per decade

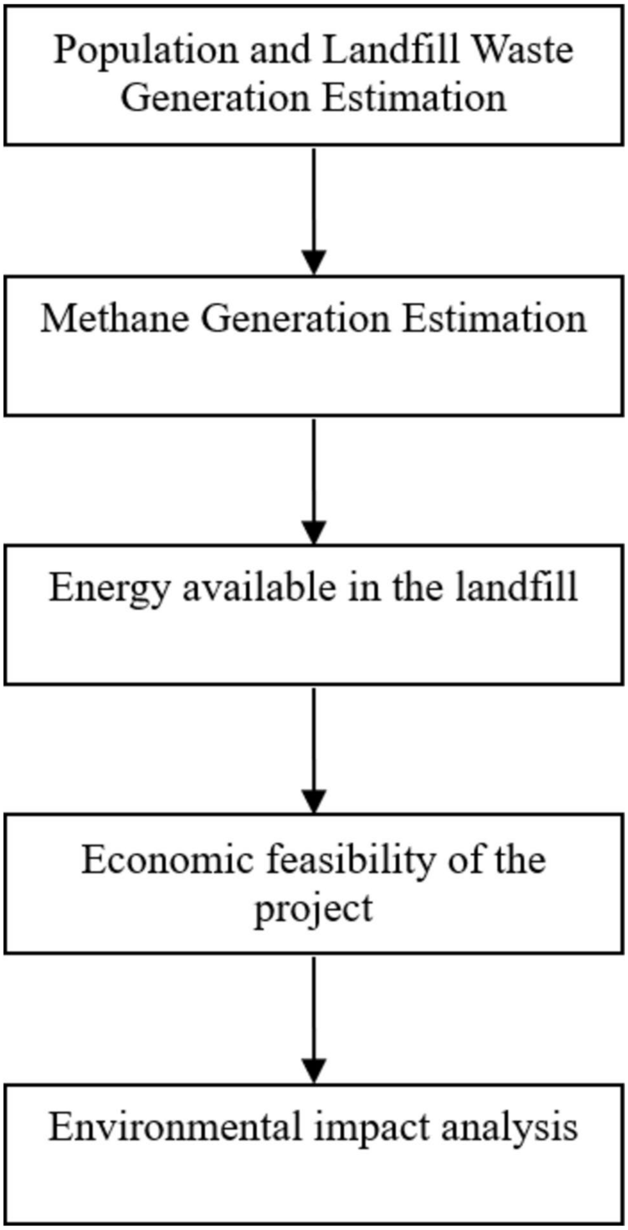

Fig. 2 Flowchart of the methodology used

To determine the number of decades (N) for any given year, Eq. (2) is used:

$$N = \frac{\text{Year} - \text{BaseYear}}{10} \tag{2}$$

Population data from the Statistics Centre Abu Dhabi (SCAD) and the Dubai Statistics Center are used [28–30]. Following the estimation of the populations of Abu Dhabi and Dubai up to the year 2030, the annual amount of landfill waste generated is calculated. This calculation employs data on per capita MSW generation in the UAE, which is 1.8 kg/day, with 77% of the MSW being deposited in landfills, according to the Dubai Chamber of Commerce in 2020. An annual increase of 1% in per capita MSW generation is assumed, reflecting global trends in urban waste production. This assumption also accounts for the UAE's proactive waste reduction strategies, which may mitigate some of the MSW increase over time. To calculate the annual amount of landfill waste generated in the UAE, the combined population of Abu Dhabi and Dubai is multiplied by the per capita MSW generated per year and the percentage of MSW sent to landfill.

2.2 Methane generation estimation

The Landfill Gas Emissions Model (LandGEM) version 3.03, developed by the U.S. Environmental Protection Agency (USEPA), was used to estimate the potential for methane generation in landfills [31]. LandGEM is specifically designed to project the volume of methane produced over time, based on the characteristics of the landfill and waste acceptance data. This automated tool operates within a Microsoft Excel interface and utilizes a first-order decay equation for these calculations, as shown in Eq. (3):

$$Q_{CH_4}^{S} = \sum_{i=1}^{y}\sum_{j=0.1}^{1} kL_0^{S}\left(\frac{M_i}{10}\right)e^{-kt_{ij}} \tag{3}$$

where,

$Q_{CH_4}^{S}$	Annual methane generation potential for scenario S (m³/year)
i	1 year time increment
y	(year of the calculation) - (initial year of waste acceptance)
j	0.1 year time increment
k	Methane generation rate (year^{-1})
L_0^{S}	Potential methane generation capacity for scenario S (m³/tonne)
M_i	Mass of waste accepted in the ithyear (tonne)
t_{ij}	Age of the jthsection of waste massM_i accepted in the ithyear

The model parameters are crucial in the estimation process. The methane generation rate (k) and the potential methane generation capacity for scenario S (L_0^{S}) of landfill waste are essential factors. The Methane generation rate (k) reflects the rate at which methane is produced from decomposing waste and is influenced by factors such as moisture content, nutrient availability, pH, and temperature of the waste mass. Given the arid climate of the UAE, which typically receives less than 25 inches of rainfall annually, this study utilizes the default k value of 0.02 year^{-1} provided by the LandGEM model.

The potential of methane generation capacity (L_0^S) from waste depends on the quantity of biodegradable waste, the level of separation, microbial usage rates, volatile solids, and climatic conditions such as humidity and temperature. This parameter depends on the composition of the waste, especially its organic portion. The methodology proposed by IPCC (2006) is used to determine L_0^S, as shown in Eq. (4) [32]:

$$L_0^S = \frac{\left(\mathrm{MCF} \times \mathrm{DOC} \times \mathrm{DOC_f} \times \mathrm{P^S} \times \frac{16}{12} \times 1000\right)}{0.667} \tag{4}$$

where,

L_0^S = Potential methane generation capacity for scenario S (m^3/tonne)

MCF = Methane correction factor

DOC = Degradable organic carbon

$\mathrm{DOC_f}$, = Dissociated DOC fraction

$\mathrm{P^S}$ = Percentage of methane present in LFB by volume for scenario S

(16/12) = the carbon to methane conversion factor

ρ_{CH_4} = Density of methane (0.667 kg/m^3)

1000 = Empirical value for the conversion from kg to tonne

The following describes the parameters described above [32]:

The methane correction factor (MCF) adjusts the estimated LFB generation in the model, accounting for the degree of anaerobic degradation of waste. The MCF varies depending on the depth of the waste and the type of landfill, as influenced by management practices. This parameter is adopted based on the default values proposed by the IPCC (2006), as presented in Table 1 [32]:

In the UAE, waste management practices for landfills adhere to the IPCC (2006) guidelines by applying a MCF value of 1.0 for anaerobically managed sites. The methane content percentages *(P^S)* in the LFB are 40%, 50%, and 60% by volume for Scenarios A, B, and C, respectively. The variable amount of Degradable Organic Carbon (DOC) is essential for calculating methane generation potential. It represents the portion of organic carbon in waste that is available for biochemical decomposition. It is calculated based on the average composition of MSW in the UAE in 2018, as presented in Table 2 [33], with the assumption that waste composition remains consistent across all landfill sites within the UAE. Degradable organic carbon is calculated using Eq. (5):

$$DOC = (0.40 \times A) + (0.17 \times B) + (0.15 \times C) + (0.30 \times D) \tag{5}$$

where:

A	Fraction of paper, cardboard, and textile waste
B	Fraction of park and garden debris waste
C	Fraction of food waste
D	Fraction of wood waste

The dissociated degradable organic carbon fraction ($\mathrm{DOC_f}$) refers to the portion of DOC that is capable of decomposing anaerobically, determined using Eq. (6):

$$DOC_f = (0.014 \times T) + 0.28 \tag{6}$$

where,

$\mathrm{DOC_f}$ = Dissociated DOC fraction

T = Temperature in the anaerobic zone (°C).

For this study, T is assumed to be 35 °C

Table 1 Classification of solid waste disposal sites and MCF

Type of Waste Disposal (Landfill)	Methane Correction Factor (MCF)
Managed – anaerobic	1.0
Managed – semi-aerobic	0.5
Unmanaged – deep (> 5 m waste) and/or high-water table	0.8
Unmanaged – shallow (< 5 m waste)	0.4
Uncategorized waste disposal	0.6

Table 2 MSW composition and quantities of the UAE in 2018

Waste	Recyclables				Non-recyclables				Total
	Paper	Plastic	Glass	Metals	Textiles	Food	Wood	Others	
Fraction (%)	25.0	19.0	4.0	3.0	3.0	39.0	3.0	4.0	100
Mass (tonne)	1,439,494	1,094,015	230,319	172,739	172,739	2,245,610	172,739	230,319	5,757,974

2.3 Energy available in the landfill

Methane is identified as the primary contributor to the energy content in LFB, as carbon dioxide is a non-combustible gas that does not contribute to energy generation. The energy source under consideration is electricity, which is generated by LFBtE projects through the combustion of LFB using ICE and GT technologies. The LFBtE project is scheduled to commence in 2025 and continue until 2045, providing an operational period of 21 years. During this period, the annual energy generation potential from LFB is assessed using Eq. (7) [34]:

$$E^{S}_{(T)} = \frac{(0\cdot 9 \times Q^{S}_{CH_4} \times LHV_{CH_4} \times \eta_{(T)} \times \lambda)}{3.6} \tag{7}$$

where,

$E^{S}_{(T)}$ = Annual energy generation potential by technology T for scenario S (kWh/year)

$Q^{S}_{CH_4}$ = Quantity of recoverable methane gas emitted from landfill site for scenario (S) (m³/year)

LHV_{CH_4} = Low heating value of the methane gas (MJ/m³)

$\eta_{(T)}$ = Electrical conversion efficiency for the technology T

λ = Collection efficiency of methane from landfill

0.9 = Oxidation factor in the landfill [35].

3.6 = Conversion factor from MJ to kWh

A critical factor influencing the energy generation potential from LFB is the efficiency of its recovery. Due to inherent losses during the extraction process, it is generally impractical to capture all produced gases. λ typically ranges from 70 to 75%, while the LHV_{CH_4} ranges from 15 to 35.8 MJ/m^3 [36]. In this study, a λ of 75% and an LHV_{CH_4} of 35 MJ/m^3 are assumed. The η of the ICE ($\eta_{(ICE)}$) is considered to be 40% and for GT ($\eta_{(GT)}$) is 30% [37, 38].

2.4 Economic feasibility of the project

The economic feasibility of LFBtE project in UAE is analyzed based on economic indicators such as Net Present Value (NPV), Payback Period (PBP) and Levelized cost of energy (LCOE).

Net Present Value is the sum of both positive and negative cash flows over the lifetime of a project, which is discounted to their present value. A project is economically feasible if the NPV is positive. The formula to calculate the NPV is described as follows in Eq. (8) [39]:

$$NPV^{S}_{(T)} = \sum_{t=1}^{n} \frac{CF^{S}_{t(T)}}{(1+r)^{t}} - I^{S}_{(T)} \tag{8}$$

where,

$NPV^{S}_{(T)}$ = Net Present Value of the LFBtE project using technology T for scenario S

n = Discount time of the last cash flow

t = Discount time for each cash entry

r = Real annual discount rate

$CF^{S}_{t(T)}$ = Cash flow at time t of the LFBtE project using technology T for scenario S

$I^{S}_{(T)}$ = Initial investment of the LFBtE project using technology T for scenario S

The net cash flow and real annual discount rate are key indicators of the project's financial viability. Net cash flow represents the difference between revenues and costs, while the real annual discount rate adjusts for inflation, ensuring that future cash flows are accurately discounted to present value. These calculations, detailed in Eqs. (9–11):

$$CF^{S}_{t(T)} = Rev^{S}_{(T)} - O\&M^{S}_{cost,total(T)} - Tax_{(paid)} - I^{S}_{(T)} \tag{9}$$

$$\begin{aligned} CF^{S}_{t(T)} = {} & (E^{S}_{(T)} \times \pi) - O\&M^{S}_{cost,total(T)} \\ & - ((Rev^{S}_{(T)} - O\&M^{S}_{cost,total(T)}) \times Tax_{r}) - I^{S}_{(T)} \end{aligned} \tag{10}$$

$$r = \left(\frac{1+\alpha}{1+\nu_r}\right) \tag{11}$$

where,

$Rev^{S}_{(T)}$ = Revenue from the LFBtE project using technology T for scenario S

$O\&M^{S}_{cost,total(T)}$ = Total operations and maintenance cost of the LFBtE project using technology T for scenario S

$Tax_{(paid)}$ = Tax paid on the profit made from the project

$E^{S}_{(T)}$ = Annual energy generation potential by technology T for scenario S (kWh/year)

π = Feed-in-tariff (\$/kWh)

$PF^{S}_{(T)}$ = Profit accrued from the LFBtE project using technology T for scenario S

Tax_{r} = Marginal tax rate of UAE (%)

α = Nominal discount rate (%)

ν_r = Inflation rate (%)

In accordance with recent economic trends in the UAE, π is \$0.11/kWh [35], Tax_r is 0%, α is 8% [40], and ν_r is 4.8%.

2.4.1 Initial investment cost

Understanding the initial investment cost is essential for determining the project's financial viability. The total initial investment cost is calculated by summing the costs associated with various components of the LFBtE project calculated according to Eqs. (12–16) [35, 41]:

$$I^{S}_{(T)} = Cst_{(1)} + Cst_{(2)} + Cst_{(3)} + Cst_{(4)} + Cst^{S}_{(T)} \tag{12}$$

$$I^S_{(T)} = \left(\$85 \times W_n \times \left(D_{well} - 10ft\right)\right) + \left(W_{(n)} - \$17000\right) + \left(\left(Q^S_{CH_4}\right)^{06} \times \$4600\right) + Cst_{(4)} = \left(W_{(n)} \times \$700\right) + Cst^S_{(T)} \tag{13}$$

$$\mathrm{Cst}^{\mathrm{S}}_{(\mathrm{T})} = \mathrm{Cst}^{\mathrm{S}}_{(\mathrm{ICE})} = (\$1300 \times \mathrm{LFBtE}^{\mathrm{S}}_{\mathrm{size(ICE)}}) + \$1,100,000 \tag{14}$$

$$\mathrm{Cst}^{\mathrm{S}}_{(\mathrm{T})} = \mathrm{Cst}^{\mathrm{S}}_{(\mathrm{GT})} = (\$1,015 \times \mathrm{LFBtE}^{\mathrm{S}}_{\mathrm{size(GT)}}) + \$250,000 \tag{15}$$

$$\mathrm{LFBtE}^{\mathrm{S}}_{\mathrm{size(T)}} = \frac{\mathrm{E}^{\mathrm{S}}_{\mathrm{max(T)}}}{\mathrm{H}_{\mathrm{day}} \times \mathrm{D}_{\mathrm{year}}} \tag{16}$$

where,

$\mathrm{Cst}_{(1)}$ = Capital cost of installing vertical gas extraction wells

$\mathrm{Cst}_{(2)}$ = Cost of installing wellheads and pipe gathering

$\mathrm{Cst}_{(3)}$ = Cost for installation of knockout, blower, and flare system

$\mathrm{Cst}_{(4)}$ = Cost of engineering, permitting, and surveying

$\mathrm{Cst}^{\mathrm{S}}_{(\mathrm{T})}$ = Cost of installing the LFBtE technology T for scenario S

$\mathrm{Cst}^{\mathrm{S}}_{(\mathrm{ICE})}$ = Cost of installing the ICE technology for scenario S

$\mathrm{Cst}^{\mathrm{S}}_{(\mathrm{GT})}$ = Cost of installing the GT technology for scenario S

W_{n} = Number of wells dug at the site

$\mathrm{D}_{\mathrm{well}}$ = Depth of the well (ft)

$\mathrm{LFBtE}^{\mathrm{S}}_{\mathrm{size(T)}}$ = Rated capacity of technology T for scenario S (kW)

$\mathrm{E}^{\mathrm{S}}_{\mathrm{max(T)}}$ = Highest annual energy generation potential by technology T for scenario S (kWh/year)

$\mathrm{H}_{\mathrm{day}}$ = Number of hours in a day

The required W_{n} for effective LFB extraction is 40, based on industry standards for medium-to-large-scale landfills, ensuring efficient and cost-effective gas extraction. The average $\mathrm{D}_{\mathrm{well}}$ is assumed to be 65ft, a standard depth used to estimate installation costs for vertical gas wells, balancing cost and extraction efficiency [40]. The operation will run 24 h/day for 365 days.

The lifespan of an ICE and GT used in LFBtE projects typically ranges from 15–20 years [42]. Acquiring new ICE or GT technology after 2038 was not considered due to the decline in LFB over time, which reduces energy generation. The high initial investment for new technology would make LFBtE projects unprofitable.

Total operations and maintenance costs ($\mathrm{O\&M}^{\mathrm{S}}_{\mathrm{cost,total(T)}}$) are crucial for ensuring the project's long-term viability. These costs are estimated to calculate the ongoing expenses required to keep the system operational. It is calculated using Eqs. (17–20) [35, 41]:

$$\mathrm{O\&M}^{\mathrm{S}}_{\mathrm{cost,total(T)}} = \mathrm{O\&M}_{\mathrm{cost(LF)}} + \mathrm{O\&M}^{\mathrm{S}}_{\mathrm{cost(T)}} \tag{17}$$

$$\mathrm{O\&M}_{\mathrm{cost(LF)}} = \$17000 \text{ x } \mathrm{W}_{\mathrm{n}} + \$5100 \tag{18}$$

$$\mathrm{O\&M}^{\mathrm{S}}_{\mathrm{cost(T)}} = \mathrm{O\&M}^{\mathrm{S}}_{\mathrm{cost(ICE)}} = \$0.025 \times \mathrm{E}^{\mathrm{S}}_{(\mathrm{ICE})} \tag{19}$$

$$\mathrm{O\&M}^{\mathrm{S}}_{\mathrm{cost(T)}} = \mathrm{O\&M}^{\mathrm{S}}_{\mathrm{cost(GT)}} = \$.0144 \times \mathrm{E}^{\mathrm{S}}_{(\mathrm{GT})} \tag{20}$$

where,

$\mathrm{O\&M}^{\mathrm{S}}_{\mathrm{cost,total(T)}}$ = Total operations and maintenance cost of the LFBtE project using technology T for scenario S

$\mathrm{O\&M}_{\mathrm{cost(LF)}}$ = Operation and maintenance cost of the landfill site

$\mathrm{O\&M}^{\mathrm{S}}_{\mathrm{cost(T)}}$ = Operations and maintenance cost of using technology T for scenario S

$\mathrm{O\&M}^{\mathrm{S}}_{\mathrm{cost(ICE)}}$ = Operations and maintenance cost of the ICE for scenario S

$\mathrm{O\&M}^{\mathrm{S}}_{\mathrm{cost(GT)}}$ = Operations and maintenance cost of the GT for scenario S

$\mathrm{E}^{\mathrm{S}}_{(\mathrm{ICE})}$ = Annual energy generation potential by ICE technology for scenario S (kWh/year)

$\mathrm{E}^{\mathrm{S}}_{(\mathrm{GT})}$ = Annual energy generation potential by GT technology for scenario S (kWh/year)

The discounted payback period (PBP) is a method used to determine the time required for the present value of the company's forecasted cash flows to equal the value of the initial investment, while also accounting for the time value of money. The payback period is the year where the cumulative discounted cash is greater than or equal to the initial investment.

The levelized cost of energy is the minimum price in $/kWh at which energy generated must be sold to break even over the project's lifespan. It is estimated using Eq. (21):

$$LCOE^S_{(T)} = \left[\frac{I^S_{(T)} + \sum_{t=1}^{n} \frac{O\&M_{cost}}{(1+\alpha)^t}}{\sum_{t=1}^{n} \frac{E^S_{(T)}}{(1+\alpha)^t}}\right] \tag{21}$$

where,

$\mathrm{LCOE}^{\mathrm{S}}_{\mathrm{T}}$ = Minimum price energy generated by technology T must be sold for scenario S

2.5 Environmental impact analysis

This study evaluates the environmental impact of LFB by comparing two distinct cases, each assessed based on its contribution to global warming potential (GWP). The analysis is conducted for the period from 2025 to 2045, corresponds to the operational lifespan of the LFBtE projects. Both CH_4 and CO_2 emissions significantly contribute to greenhouse gas (GHG) emissions. The environmental analysis for Scenarios A, B, and C is conducted within two overarching cases: the Baseline case and the LFBtE case.

2.5.1 Baseline case

The baseline case serves as a reference point, representing the current waste management practices in the UAE. In this case, the LFB produced from landfills is released directly into the atmosphere without being utilized for energy recovery, thereby contributing to global warming. The carbon dioxide equivalent (CO_2eq) for this case are determined using Eq. (22) [43]:

$$CO_2^S eq_{(LFB)} = \frac{\left(Q^S_{CH_4} \times GWP_{CH_4} \times \rho_{CH_4}\right) + (Q^S_{CO_2} \times GWP_{CO_2} \times \rho_{CO_2})}{1,000,000} \quad (22)$$

where,

$CO_2^S eq_{(LFB)}$ = Annual potential GHG emissions of LFB in ktonne of CO_2eq for scenario S (ktonneCO_2eq/year).

GWP_{CH_4} = Global Warming Potential of methane (21 kg CO_2eq /kg CH_4)

ρ_{CH_4} = Density of methane (0.667 kg/m^3)

$Q^S_{CO_2}$ = Annual CO_2 emissions for scenario S (m^3/year).

GWP_{CO_2} = Global Warming Potential of carbon dioxide (1 kg CO_2eq).

ρ_{CO_2} = Density of carbon dioxide (1.87 kg/m^3)

$1,000,000$ = Empirical value for its conversion from kg to ktonne

2.5.2 LFBtE case

In this case, the LFB generated by the landfill is captured and combusted in LFBtE projects using ICE or GT technology to generate energy. This study assumes a methane collection efficiency of 75%, indicating that 25% of the methane will still escape into the atmosphere, thereby contributing to global warming. To accurately assess the environmental impact of LFBtE projects, it is crucial to consider the CO_2 emissions generated by the combustion process in ICE and GT technologies. These emissions are calculated using Eq. (23) [44]:

$$CO^S_{2\,combustion(T)} = EF \times E^S_{(T)} \quad (23)$$

where,

$CO^S_{2\,combustion(T)}$ = Annual CO_2 emissions attributable to the utilization of technology T in scenario S (kg/year)

EF = CO_2 emission factor of biogas combustion (0.20196 kg/kWh)

$E^S_{(T)}$ = Annual energy generation potential by technology T for scenario S (kWh/year)

To determine the overall CO_2eq for this case, Eq. (24) is used:

$$CO_2^S eq_{(T)} = \frac{\left(Q^S_{CH_4} \times 0.25 \times GWP_{CH_4} \times \rho_{CH_4}\right) + \left(Q^S_{CO_2} \times GWP_{CO_2} \times \rho_{CO_2}\right) + CO^S_{2\,combustion(T)}}{1,000,000} \quad (24)$$

where,

$CO_2^S eq_{(T)}$ = Annual potential GHG emissions of LFB in ktonne of CO_2eq for scenario S using technology T (ktonne CO_2eq/year)

3 Results and discussion

3.1 Population estimates and landfill waste generation for UAE landfill

The projected populations for the UAE are calculated using Eq. (1), with the results shown in Fig. 3, showing the annual population, landfill waste generation, and accumulated landfill waste from the landfill's opening in 2008 until its closure in 2030.

As shown in Fig. 3, the population of the UAE is projected to reach approximately 8.68 million by 2030, leading to an increase in annual landfill waste generation from 1.63 million tonne in 2008 to over 5 million tonnes by 2030.This increase corresponds with a rise in per capita MSW disposed in landfills from 0.51 tonne/year in 2008 to 0.57 tonne/year in 2030. These findings align with previous studies by [45, 46], who underscore the economic viability of LFBtE projects with a minimum daily waste intake of 200 tonne to make LFB energy generation viable with a positive economic return. The daily average landfill waste disposal in this study is approximately 9252 tonne/day, which is significantly above this threshold, thereby confirming the economic viability of LFBtE projects in the UAE [45, 46]. However, this higher landfill waste disposal amount can be attributed to the higher population and per capita MSW generation rate of 1.8 kg/day in the

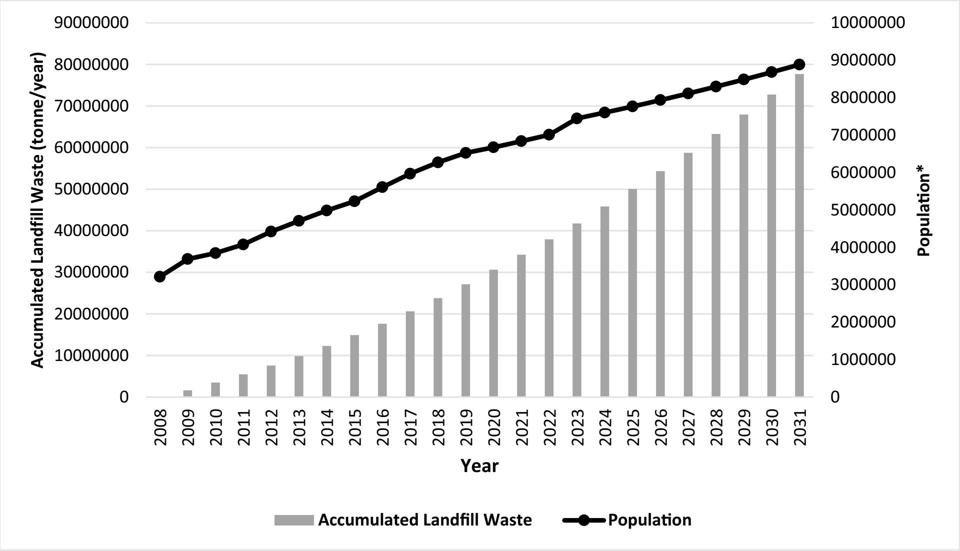

Fig. 3 Annual Population and Accumulated Landfill Waste in the UAE (2008–2030). *Population of UAE refers to the combined population of the emirates of Dubai and Abu Dhabi only, as these two emirates represent the primary focus of this study due to their significant waste generation and landfill capacity

UAE, thereby contributing to the increased landfill waste amounts, as shown in Fig. 3 [1].The strong correlation between population growth and landfill waste generation underscores the critical need for effective waste management strategies. As the population continues to grow, the pressure on landfills intensifies, necessitating the implementation of advanced waste processing and energy recovery techniques.

3.2 Estimation of the production of methane gas in the landfill

The annual methane generation potential is calculated using LandGEM, which employs a first-order decay equation to account for variations in landfill management and waste composition. The potential methane generation capacity for scenario S (L_0^S) are determined using Eq. 4, yielding values of 110,138,165 m^3/tonne for LFB with 40%, 50%, and 60% methane content by volume. Figure 4 shows the annual methane generation potential for the three scenarios with varying methane content by volume in LFB.

The analysis reveals a progressive increase in annual methane generation potential from the landfill starting from 2008, reaching a peak in 2031. After 2031, annual methane generation potential gradually declines. This trend is depicted in Fig. 4. The peak methane generation potential in 2031 can be attributed to the accumulation of waste and optimal conditions for anaerobic decomposition. In 2031,

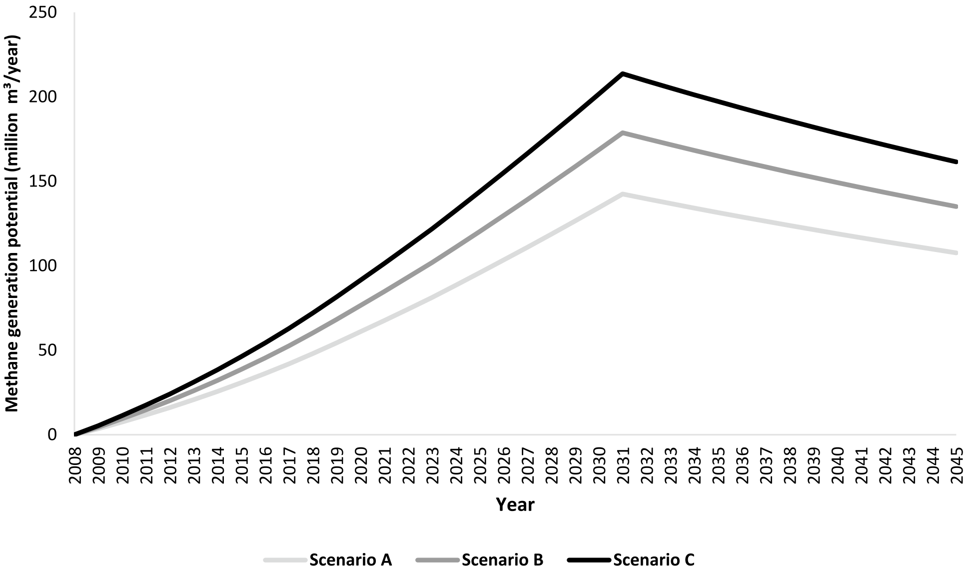

Fig. 4 Methane generation potential from landfill for Scenarios A, B and C (2008–2045)

the projected peak methane generation potential is expected to differ significantly across the three scenarios due to varying methane content by volume in LFB. For Scenario A, with the lowest methane content of 40% by volume in LFB, the highest methane generation potential is projected to be 142 million m^3. Scenario B, with 50% methane content by volume in LFB, is anticipated to reach a peak methane generation potential of 179 million m^3. Scenario C, with the highest methane content of 60% by volume in LFB, is projected to record the maximum methane generation potential of 214 million m^3. Following 2031, a decline in annual methane generation potential is anticipated for all scenarios, attributed to the reduction in available organic matter, as the landfill is projected to no longer receive additional waste after 2030. This trend aligns with the first-order decay model used in LandGEM.

These findings contrast with those reported by Fallahizadeh et al. (2019) and Goushki et al. (2023) in Iran, as well as Chandra and Ganguly (2022) in Kanpur, India, which utilized a model where potential methane generation capacity (L_0) was set at 170 m^3/tonne, the methane production rate (k) was 0.05year^{-1}, and with a methane content of 50% [47–49]. Despite these higher values for L_0 and k, these studies reported lower methane emissions than those projected in the current study. However, even Scenario A in this study, which has the lowest methane content by volume of 40%, projected higher annual methane generation potential compared to the annual methane generation potential reported in these studies. This finding suggests that while the methane content in LFB by volume is directly proportional to methane generation potential, as seen in Fig. 4, the substantial quantity of landfill waste significantly contributes to a higher annual methane generation potential, even when the methane content in LFB by volume is lower.

These findings underscore the significant impact of modeling assumptions, methane content, and waste management practices on methane generation potential. The progressive increase followed by a decline in annual methane generation potential highlights the importance of timely implementation of LFBtE projects and utilization systems to maximize energy recovery and minimize greenhouse gas emissions. Methane production in landfills is influenced by various factors. The composition of MSW is particularly significant. A higher proportion of biodegradable materials, such as food and yard waste, typically results in greater methane generation. Moisture content is another pivotal factor in methane production. Higher moisture levels, which can be achieved through leachate recirculation, enhance microbial activity and increase methane yields. Conversely, insufficient moisture, a common issue in arid climates like the UAE, significantly limits methanogenic efficiency. Temperature and pH also play crucial roles in methane production. Optimal methane production occurs within a temperature range of 35 to 42 °C and a pH range of 6.0 to 8.5 [50, 51]. Deviations from these ranges disrupt microbial processes and reduce methane output. Methane production evolves throughout the landfill lifecycle. In the early stages, aerobic decomposition produces primarily carbon dioxide. As anaerobic conditions develop, methane production increases and peaks when degradable materials are most abundant, then declines as these materials are depleted. In a study conducted in Colombia demonstrated that methane potential in 4 to 5 year old waste was significantly lower than in fresher waste due to the early depletion of easily degradable components [52].

Methane production in landfills is influenced by various factors, including waste composition and management practices. Landfills, while traditionally a primary method for waste disposal, are increasingly ranked lower in the waste management hierarchy compared to recycling, composting, and advanced treatment technologies. This hierarchy reflects global commitments to sustainability and resource recovery. Recycling and waste-to-energy (WTE) technologies have emerged as vital alternatives to landfill disposal. For instance, the UAE's first waste-to-energy (WTE) plant, developed by Masdar and BEEAH, diverted over 300,000 tonnes of waste from landfills in its first year, generating energy for 2,000 homes and offsetting 150,000 tonnes of CO_2 [53]. Similarly, BEEAH Recycling's Solid Recovered Fuel (SRF) facility in Sharjah represents an innovative approach to waste-to-energy solutions. This facility processes non-recyclable commercial residue waste into high-quality green fuels for use in cement factories, reducing reliance on coal and lowering carbon emissions. With a production capacity of 85,000 tonnes of alternative fuel annually, the SRF facility supplies 73,000 tonnes of fuel each year to Sharjah Cement, directly contributing to Sharjah's impressive 76% landfill diversion rate, the highest in the Middle East [54]. These initiatives illustrate how prioritizing alternatives to landfills not only reduces environmental impact but also supports a circular economy by repurposing waste into valuable resources. However, while such innovations reduce landfill reliance and greenhouse gas emissions, they also have implications for landfill gas (LFG) generation, a significant source of renewable energy. LFG, primarily composed of methane (CH_4), is produced during the anaerobic decomposition of organic waste. It has been observed that rapidly decomposing materials, such as food waste, produce high methane emissions in the early stages of decomposition, whereas slower-decomposing materials like yard trimmings contribute to prolonged methane production. Diverting biodegradable materials to alternatives decreases LFG production, thereby limiting its role in renewable energy generation but significantly reducing greenhouse gas emissions. The redirection of organic waste from landfills to alternatives such as anaerobic digestion, composting, and WTE systems introduces several trade-offs. For instance, studies have demonstrated that conventional landfilling of food waste emits approximately 2708 kg CO_2e per dry ton, a figure that can be reduced to 1524 kg CO_2e when active LFG collection and power generation are employed. Moreover, alternatives such as anaerobic digestion achieve comparable or lower emissions while simultaneously producing renewable energy [55]. Advanced WTE systems have been shown to mitigate the reductions in LFG availability by generating energy directly from non-recyclable waste. A case study in Shenzhen, China, found that over a 15-year period, 2.22×10^{11} kg of municipal solid waste produced 1.34×10^{10} kg of CH_4, which was converted into 9.68×10^{8} kWh of electricity and 1.75×10^{13} kJ of heating energy. This process utilized Combined Cooling, Heating, and Power (CCHP) systems to capture waste heat, thereby maximizing energy output and advancing the principles of the circular economy. These findings underscore the importance of adopting integrated approaches to waste management that balance the need for landfill diversion with the benefits of energy recovery. Technologies such as BEEAH's SRF facilities and Shenzhen's CCHP systems exemplify innovative solutions that enhance resource recovery while minimizing environmental impacts [56]. Furthermore, embracing a circular economy framework, wherein waste is continually recycled or repurposed, represents a critical pathway to optimizing both environmental and energy outcomes. By incorporating these strategies, waste management systems can achieve the dual objectives of sustainability and energy security, thereby aligning with global priorities in addressing the challenges of modern waste management. Understanding the dynamics between landfill gas production and waste management strategies is critical for optimizing Landfill Biogas to Energy (LFBtE) projects in the UAE. By prioritizing waste diversion while enhancing methane recovery from residual waste, the UAE can achieve dual objectives of sustainability and energy security.

3.3 Energy available in the landfill

The potential for generating energy from LFB emissions is evaluated from 2025 to 2045 using Eq. (7). The results, illustrated in Fig. 5, depict the potential energy generation for the three scenarios (A, B, and C) by implementing LFBtE projects using ICE and GT technology.

As seen in Fig. 5, the peak around 2031 corresponds to the period post-landfill closure when LFB emissions are the highest, contributing to greater potential energy generation. For Scenarios A, B, and C, the total potential energy generation using ICE technology is 6,704 million kWh, 8,411 million kWh and 10,057 million kWh. In comparison using GT technology, the total energy generation potential is 5,028.29 million kWh, 6,308 million kWh and 7,542 million kWh.

These results are substantially higher than those reported by Poma et al. (2021) who assumed a constant per capita waste generation and Ramprasad et al. (2022) who assumed a decline in per capita waste generation. In contrast, this study assumes a 1% annual increase in per capita waste generation. This assumption is based on the estimated population growth, which is projected to lead to an increase in the amount of waste generated [57]. Consequently, this increase in waste input contributes to higher methane emission and, therefore, greater potential energy generation potential, as seen in Fig. 5. It is particularly noteworthy that even in Scenario A that is LFB with the lowest methane content of 40% by volume while using GT technology which operates at a lower electricity conversion efficiency of 30%, the potential energy generation

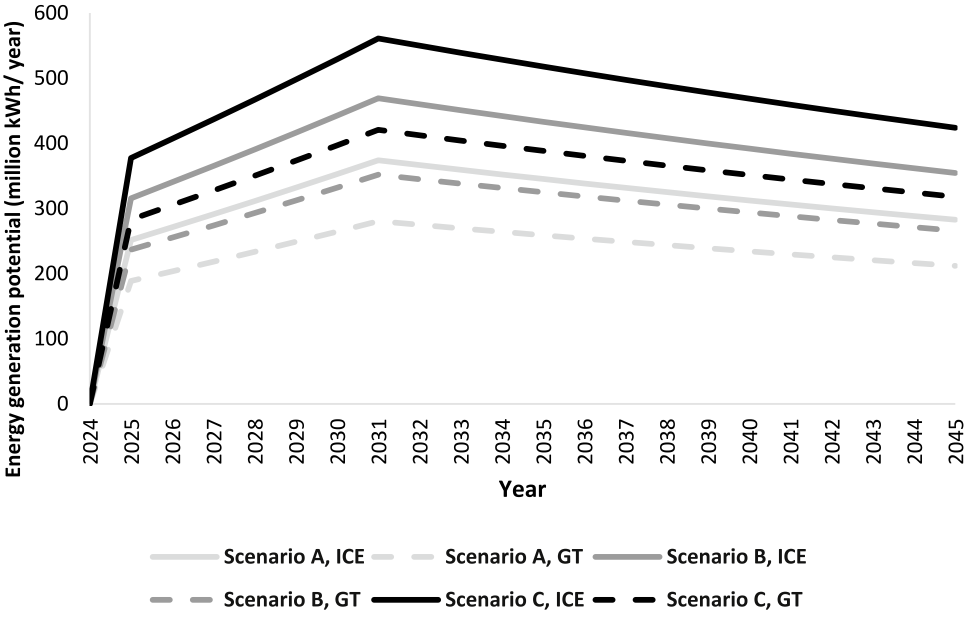

Fig. 5 Energy generation potential by LFBtE projects for Scenarios A, B and C (2025–2045)

exceeds that reported in other studies, which utilized higher electricity conversion efficiencies of 38% and higher methane contents of (50%, 56%, and 58% by volume) in LFB. This finding underscores the impact of the larger volume of landfill waste in the UAE, which leads to higher energy generation potential, irrespective of methane content and electricity conversion efficiency [37, 58].The total potential energy generation could supply a significant number of households in the UAE, given the average consumption rate of 15 MWh per person per year and an average household size of 4.9 people. For Scenarios A, B, and C, the total potential energy generation using ICE technology could supply 91,216, 114,435, and 136,824 households, respectively. Using GT technology, it could supply 68,412, 85,826, and 102,618 households, respectively. These results demonstrate that ICE technology outperforms GT technology, supplying approximately 33.33% more households across all scenarios, due to the higher electrical conversion efficiency of ICE compared to GT, as shown in Fig. 5. This is particularly significant in the context of the UAE's high per capita energy consumption, driven by demands for air conditioning and energy-intensive industries such as aluminum production. These findings highlight the importance of efficient LFB recovery and utilization, which not only provides a substantial renewable energy source but also mitigate greenhouse gas emissions, thereby contributing to environmental sustainability.

3.4 Economic feasibility of the project

The economic feasibility of the LFBtE project in the UAE is evaluated using key economic indicators, namely NPV, PBP, and LCOE, over a 21-year period from 2025 to 2045. Table 3 provides a summary of the economic feasibility indicators for LFBtE projects under Scenarios A, B, and C, utilizing ICE and GT technologies.

As shown in Table 3, the NPVs calculated using Eq. (8) indicate that ICE technology is economically feasible across all scenarios, demonstrating positive NPVs of $381,234, $40 million, and $83 million for LFB containing 40%, 50%, and 60% methane content by volume, respectively. In contrast, GT technology is not economically feasible for LFB containing 40% and 50% methane content by volume, as evidenced by negative NPVs of $41 million and $12 million, respectively, along with no feasible payback period or LCOE. However, for LFB containing 60% methane content by volume, GT technology becomes economically viable, presenting a positive NPV of $20 million. The positive NPVs suggest that the project is expected to generate more value than it incurs in costs, aligning with the principle that investments with positive NPVs are likely to be profitable and should be pursued. The PBP, evaluates the duration required for the project's cash flows to repay the initial investment. As shown in Table 3, the PBP for ICE with the highest methane content in LFB is 18 years, while GT technology achieves a payback period after 20 years. The PBPs increase as the methane content decreases, extending to 19 and 21 years for ICE in Scenarios B and A, respectively.

Table 3 illustrates that the average LCOE for the project, calculated using Eq. (21), decreases for ICE from $0.16/kWh to $0.15/kWh and $0.14/kWh for LFB containing 40%, 50%, and 60% methane content by volume, respectively. Conversely, for LFB containing 60% methane content, GT technology has an LCOE of $0.16/kWh. However, considering that the electricity price in the UAE is set at USD 0.11/kWh, as per the GCC's average cost of generating electricity in 2021, the data suggests that the cost of generating energy using LFBtE projects exceeds the potential revenue from energy sales, potentially resulting in a financial loss. Comparing these values with studies conducted by Barragán-Escandón et al. (2020), Francisca et al. (2017), and Pierre Doussoulin and Salazar Molina (2022) in Chile and Argentina reveals that the NPV in the UAE project is higher. This difference is attributed to the higher revenues generated through energy sales in the UAE. The payback period for the UAE projects is longer when compared to these studies. Similarly, a study conducted by Cudjoe and Han (2021) in various African urban areas finds that the LCOE in the UAE is comparatively higher than in countries such as Morocco and Egypt. This discrepancy can be attributed to the higher initial investment and operating costs in the UAE [39, 59–61].

Table 3 Summary of economic feasibility indicators for LFBtE projects for scenario A, B & C using ICE and GT technologies

Scenario	Technology	Initial Investment ($)	Net Present Value ($)	Payback Period (Years)	Levelized Cost of Energy ($ /kWh)
A	ICE	416,378,437	381,234	21	0.16
	GT	392,530,698	−41,244,807	-	-
B	ICE	482,814,120	40,457,919	19	0.15
	GT	453,112,412	−11,980,205	-	-
C	ICE	542,972,242	83,008,153	18	0.14
	GT	507,625,634	20,144,091	20	0.16

The economic analysis of the LFBtE project in the UAE demonstrates its feasibility and potential for profitability. The findings reveal that ICE technology is more economically viable than GT technology, despite the latter's lower initial investment and operating costs, as seen in Table 3. This difference is attributed to the higher electrical conversion efficiency of ICE, which results in greater revenue generation from energy sales. The positive NPV suggests that the project is expected to generate more value than it incurs in costs, thereby enhancing its appeal as an investment opportunity. However, the relatively long PBP and higher LCOE highlight the importance of carefully weighing long-term profitability against upfront costs, especially for large-scale infrastructure projects.

The inclusion of revenues from carbon markets significantly strengthens the economic feasibility of LFBtE projects. By capturing and utilizing methane emissions, these projects can generate substantial carbon credit revenues, particularly in high-methane scenarios like Scenario C, where greenhouse gas reductions are significant. At the current carbon pricing rate of \$30.81 per ton of CO_2 equivalent, avoided emissions in Scenario C, totaling 58,438 ktonne of CO_2 equivalent over the project's lifespan (2025–2045), are estimated to yield approximately \$1.8 billion in additional revenue. This revenue increases the NPV for ICE technology from \$83 million to \$1.883 billion, reduces the PBP from 18 years to 6–7 years, and lowers the LCOE from \$0.14/kWh to \$0.08/kWh, making the project competitive with the UAE's average electricity price of \$0.11/kWh. Furthermore, Abu Dhabi's NetZero by 2050 strategy projects a carbon price of \$200 per ton by 2050, which could significantly amplify the financial benefits of carbon markets, incentivizing the adoption of low-carbon technologies such as hydrogen production and Carbon Capture, Utilization, and Storage (CCUS) [62–64]. While high methane content scenarios like Scenario C exhibit strong economic potential, low methane content scenarios such as Scenarios A and B (with methane contents of 40% and 50% by volume, respectively) currently face significant challenges, including negative NPVs, infeasible PBPs, and high LCOEs due to reduced energy generation potential. However, avoided emissions in Scenario A (17,462 ktonne of CO_2 equivalent) and Scenario B (18,911 ktonne of CO_2 equivalent) could generate \$538 million and \$584 million in carbon credit revenues, respectively, improving their financial metrics. Additional measures such as government subsidies for capital investments, feed-in tariffs guaranteeing higher electricity purchase prices, and tax incentives like rebates on capital expenditures or reduced corporate tax rates could alleviate financial constraints. Regulatory measures, such as renewable energy purchase mandates or landfill gas utilization standards, could further enhance demand and ensure stable revenue streams. Collectively, these interventions could transform Scenarios A and B into viable projects, while the integration of these strategies across all scenarios would position the UAE as a global leader in clean energy and align its LFBtE projects with ambitious climate goals and international best practices [65, 66].

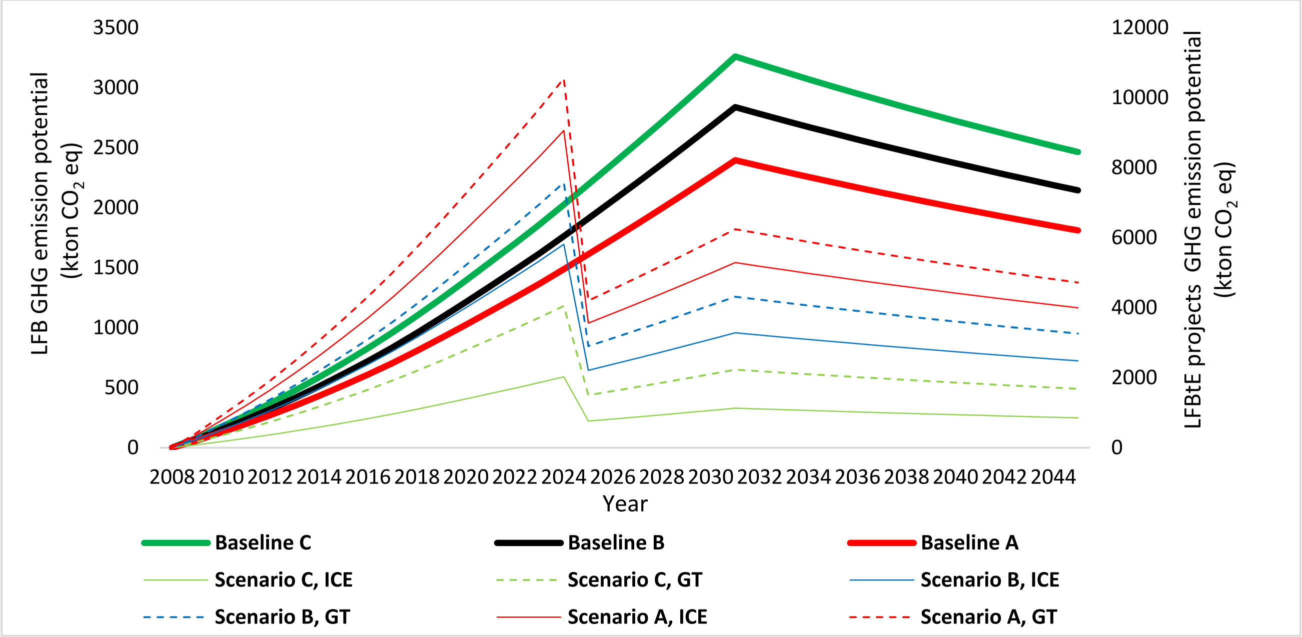

Fig. 6 Potential GHG emissions and reduction using LFBtE Projects across Scenarios A, B, and C

3.5 Environmental impact analysis

The environmental impact analysis for the period from 2025 to 2045 across Scenarios A, B, and C within the baseline and LFBtE cases offers a clear comparison of the environmental impacts of releasing LFB into the atmosphere versus capturing it for energy recovery. The potential GHG emissions, calculated using Eqs. (22) and (24), are summarized in Fig. 6.

As shown in Fig. 6, the highest GHG emissions reductions occur in Scenario C with GT technology, achieving up to 66.26%. Despite varying methane content, the differences in potential GHG emissions reductions among the scenarios are not substantial. This indicates that while higher methane content leads to slightly greater potential GHG emissions reduction, the overall impact of methane content variation is not as drastic as expected. This is due to the relatively high electrical conversion efficiency of both ICE and GT technologies in converting LFB to energy. The slightly lower emissions from GTs arise from their lower electrical conversion efficiency, which enhances their environmental benefits by approximately 0.8%.

These GHG emission reductions are lower than those described by Cudjoe and Han (2020), who reported a higher potential GHG emissions reduction of 72.3% with the implementation of LFBtE project using ICE technology with 50% methane content by volume in LFB. As shown in Fig. 6, this discrepancy between their results and the current study arises from their focus solely on CH_4 emissions, assuming that the amount of CO_2 emitted from decomposed waste is equal to that absorbed during its lifetime. In contrast, the current study includes both CH_4 and CO_2, acknowledging CO_2 emissions also significantly contribute to global warming, despite CH_4 having a global warming potential 21 times greater than CO_2. Including both gases provides a more comprehensive understanding of the environmental impact of LFB [34, 35, 67]. Nevertheless, the study by Oukili et al. (2014), included CO_2 emissions also reported higher potential GHG emissions reduction by 72% for 50% methane content by volume in LFB. However, the study does not account for CO_2 emissions resulting from the utilization of the technology, as included in the current study [43]. This study, which incorporates both CH_4 and CO_2, emissions from landfills, as well as CO_2 emissions from the LFBtE technologies themselves, provides a more accurate and nuanced assessment of the true environmental impact. Earlier studies that excluded CO_2 and LFBtE related emissions reported higher reductions, but neglecting these emissions results in an underestimation of the overall environmental impact, leading to overly optimistic conclusions about the effectiveness of LFBtE projects. By incorporating both gases, along with the emissions produced by the LFBtE technology itself, this analysis offers a more comprehensive assessment of the emissions landscape. This approach aligns the findings with real-world conditions and provides more reliable insights for policymakers and stakeholders making informed decisions. Overall, the results clearly demonstrate that implementing LFBtE projects using either ICE or GT technology significantly reduces GHG emissions compared to the baseline case. The reductions range from approximately 59–65% for ICE and 60–66% for GT. These findings imply that integrating LFBtE projects into waste management strategies can substantially mitigate the environmental impact of landfills, contributing to climate change mitigation efforts. While these results highlight the environmental benefits of capturing and utilizing LFB, further improvements can be achieved through advanced biogas upgrading technologies. In a study by Gkotsis et al. (2023), membrane separation and pressure swing adsorption (PSA) systems were identified as highly effective, achieving methane purities of 96–98% with minimal losses of 2–4%. These systems not only reduce methane emissions but also improve the quality of captured gas by removing harmful contaminants such as hydrogen sulfide (H_2S) and siloxanes. The removal of these impurities reduces toxic byproducts during combustion and prevents equipment corrosion, enhancing the environmental performance of LFBtE projects. For applications requiring higher methane purities (97–99%), chemical scrubbing and cryogenic separation are viable, though costlier, options. By improving methane recovery and upgrading, these technologies complement the LFBtE process and further amplify its contributions to climate change mitigation and sustainable waste management [68]. The study underscores the importance of optimizing LFB capture and utilization to maximize the environmental benefits of LFBtE projects.

4 Conclusions

In this study, a comprehensive analysis was conducted to evaluate the potential of LFB as a sustainable energy source in the UAE through the implementation of LFBtE projects. The research contributes to filling a critical gap by offering a comprehensive feasibility study for LFBtE projects in arid regions, identifying optimal conditions for energy generation. The study suggests that implementing such projects could reduce landfill methane emissions and reliance on fossil fuels, providing environmental and economic benefits. This research contributes to the academic literature by addressing the underexplored potential of LFB in arid regions with unique waste management challenges. The study not only introduces a replicable framework for assessing methane generation, energy recovery, and economic feasibility but also integrates interdisciplinary methods that bridge engineering, environmental science, and economics. This work sets a precedent for future studies in other regions facing similar challenges. For policymakers, the findings offer actionable insights that align with the UAE's "Energy Strategy 2050." The results demonstrate the viability of LFBtE projects in reducing greenhouse gas emissions and advancing renewable energy goals. Moreover, the study highlights the economic advantages of adopting ICE technology, which outperforms GT systems in efficiency and scalability. However, the relatively long payback period (PBP) and high levelized cost of energy (LCOE) necessitate strategies to optimize costs and efficiency. Policy measures such as incentivizing investments, promoting public-private partnerships, and integrating shared infrastructure could help overcome these barriers. Future studies should integrate advanced technologies, such as combined heat and power (CHP) systems, into energy generation projects. Combining ICE and GT with CHP systems increases overall efficiencies to 70% to 80%, compared to the typical 30% to 50% efficiency of ICE or GT alone. This integration enhances energy generation by simultaneously producing electricity and useful thermal energy from a single fuel source, reducing fuel costs and GHG emissions. Coupled with PSA systems, these advancements can enhance both the economic and environmental feasibility of LFBtE projects. Additionally, leveraging carbon credit revenues and implementing regulatory measures can further support the financial viability of these projects, particularly in high-methane scenarios. By addressing critical gaps and providing practical insights, this study underscores the transformative potential of LFBtE projects not only in the UAE but also globally. These initiatives offer a sustainable approach to waste management while contributing significantly to renewable energy supply, environmental sustainability, and economic resilience [68–71].

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