Journal of Engineering Science and Technology
Vol. 21, No. 4 (2026) 974 - 998

RESOURCE RECOVERY AND ENERGY DIVERSIFICATION THROUGH LANDFILL GAS UTILIZATION IN URBAN WASTE MANAGEMENT

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Abstract

The escalating challenges of municipal solid waste (MSW) management and energy scarcity in rapidly urbanizing regions demand integrated and sustainable solutions. This study proposes a circular economy approach by converting landfill gas (LFG), primarily methane, into renewable electricity through a waste-to-energy system enhanced with methanation technology. A comprehensive life cycle assessment was conducted to evaluate environmental, energy, and economic performance over a 35-year operational period. Results indicate that approximately 35 million tons of MSW can be transformed into 8,250 GWh of electricity, reducing coal consumption by 3.3 million tons and mitigating 2.11 million tons of CO_2 emissions. The methanation system further enables surplus energy storage, captures 311,000 tons of CO_2, and produces oxygen as a valuable by-product, contributing to resource recovery and greenhouse gas reduction. Overall, the integrated LFG-to-energy and methanation model demonstrates a viable pathway for sustainable waste management, aligning with multiple UN Sustainable Development Goals by promoting clean energy, climate action, and responsible resource utilization.

Keywords: Circular economy, Landfill Gas (LFG) Utilization, Life Cycle Assessment (LCA), Methanation, Sustainable waste management; Waste-to-energy (WTE).

1. Introduction

Countries worldwide are working towards achieving the 17 Sustainable Development Goals (SDGs) outlined in the United Nations' 2030 Agenda for Sustainable Development [1, 2] Nevertheless, the swift urbanisation and population increase are linked to a significant rise in energy consumption and the production of substantial quantities of municipal solid waste (MSW) in metropolitan regions [3]. Improper waste management can have adverse effects on society and the environment.

Landfills are the predominant technique for disposing of MSW due to their cost-effectiveness, leading to the production of significant amounts of landfill gas (LFG) [4]. The composition of LFG is primarily methane (CH_4) and carbon dioxide (CO_2). The global warming potential (GWP) of CH_4 is 84 times that of CO_2 on a 20-year scale and 28 times that of CO_2 on a 100-year scale [5]. Inadequate monitoring of landfills results in the release of substantial amounts of LFG into the atmosphere, worsening the impacts of climate change and creating notable environmental and public health hazards. Effective management of MSW disposal is crucial for achieving economic sustainability and providing economic benefits to society [6].

To combat the environmental problems caused by LFG escaping into the air, the gas needs to be captured and utilized as a renewable energy source. As an anthropogenic product, if LFG cannot be managed scientifically, it is expected that the proportion of global greenhouse gas emissions will increase from 14% to 62.5% by 2050, equivalent to 2.6 billion tons of carbon dioxide equivalent [7]. In order to curb this trend, technological means are needed to convert the LFG generated in landfills into sustainable electricity, biodiesel, or biofuels. Using LFG to generate electricity is a common conversion method.

Although the GWP generated by burning LFG has been reduced to a certain extent, a large amount of carbon is still emitted into the air, which has negative consequences for the environment and public health. Governments therefore need to address this issue by promoting the implementation of environmentally sound in waste management [8]. This transformation needs to adopt a circular economy and resource recovery, so that every country can be involved in contributing to the UN SDGs.

As one of the most populous countries in Africa, Nigeria has taken full advantage of its strong demographic dividend. With its rapid growth, more than half of the population has migrated to urban cities, raising serious questions about energy demand and clean water supply [9]. However, the rapid development of cities puts them at risk of garbage siege. As a party to the United Nations Framework Convention on Climate Change (UNFCCC) and a signatory to the 2015 Paris Climate Agreement, some cities in Nigeria have taken active steps to build landfills to capture and utilize their unused waste.

As one of the country's major cities, Lagos is actively implementing a zero-waste management model [10]. Landfilling is a common way to dispose of domestic waste, which results in the generation of large amounts of LFG. Since the CH_4 in LFG has a high calorific value, it can be used as a renewable energy source [11]. LFG power generation is considered a promising energy recovery strategy that can effectively process 90% of waste volume while minimizing costs and environmental issues [12].

Although this has significant advantages on an economic level, as compared to traditional fossil energy, LFG power generation uses gas generated from waste, and the acquisition cost is low. Moreover, LFG is produced from MSW, which is more economical than mining and refining fossil energy such as oil and natural gas [3]. Because wind and solar energy are subject to seasonal and climatic conditions, their energy output fluctuates intermittently, whereas WTE is relatively more stable and can provide a reliable source of electricity [13, 14]. But although traditional LFG power generation technology can recover valuable resources from unused waste, it still has shortcomings in terms of energy efficiency and environmental benefits. Therefore, researchers have intensified their research on this recently [15].

Rios et al. outlined methodologies for assessing the theoretical, technical, and economic viability of biogas power generation from organic waste in Mexico [16]. Banja et al. conducted a comparative analysis of biogas power generation in European countries over 7 years (2010-2017). The researchers found that biogas power market dynamics are still maintained in European countries in the face of downward trends [17]. Previous studies by Kurniawan et al. focused on the technical and economic aspects of LFG power generation [18]. Wang et al. studied the impact of LFG power generation on reducing GHG emissions and proposed relevant policy recommendations [19].

Preliminary, by Levenda et al. found that LFG power generation technology not only provides clean energy for cities, but also creates job opportunities and social welfare, which is of great significance to improving the level of sustainable development of cities [20]. Ciuła et al. proposed a new biogas collection and utilization system that can improve biogas collection efficiency and power generation efficiency and reduce GHG emissions [21]. While their studies were novel, they did not delve into solutions for the intermittent nature of users' energy consumption, which led to an imbalance in electricity supply, nor did they take into account the serious environmental impacts of LFG power generation tailpipe [22].

To bridge the research gaps, this study explores the use of methane from LFG in a WTE plant to fulfil the city's energy requirements. Here are the key contributions: (1) We proposed a life cycle assessment-based waste-to-electricity (LCA-based WTE) model. This model integrates methanation technology into the WTE power plant and establishes a comprehensive lifecycle process. (2) A methanation-dominated energy storage method is proposed to contribute to the eco-energetic benefit, and the stored power and saved carbon emissions are evaluated. (3) The environment, energy, and economic benefits are analysed in this work, as well as the significant promotion of the community’s long-term SDGs.

The rest of the paper is organised as follows: Section 2 provides the research proposal and design. Section 3 presents the methodology. Section 4 details the empirical results and discusses the performance of the proposed method. Section 5 concludes.

2. Problem Formulation

2.1. Research region

Geographically, Lagos (Nigeria) is located at 6°31' North latitude and 3°22' East longitude (Fig. 1) [23]. As Nigeria’s former capital, the city is presently grappling with the issues of energy insufficiency and waste disposal. Lagos generates an estimated 15,000 tonnes of MSW on a daily basis, which translates to an average of around 0.72 kg per capita per day [9]. Nevertheless, the four main landfills located in Lagos are approaching their maximum capacity. Due to the lack of professional waste management capabilities, the landfills are about to be overwhelmed by garbage.

Fig. 1. Map of Lagos.

2.2. Research framework

Figure 2 illustrates the process of collecting and transporting MSW to a designated landfill site for disposal. In this context, the production of LFG is a consequence of anaerobic processes [24]. CH_4 constitutes a significant proportion of LFG and undergoes conversion into thermal energy within an internal combustion engine (ICE) for the purpose of propelling a generator and producing electrical power [25]. Subsequently, the electricity is conveyed to consumers through a transmission system, originating from the power facility. The methanation system effectively harnesses and utilises the residual electricity and the exhaust gas generated during the power generation.

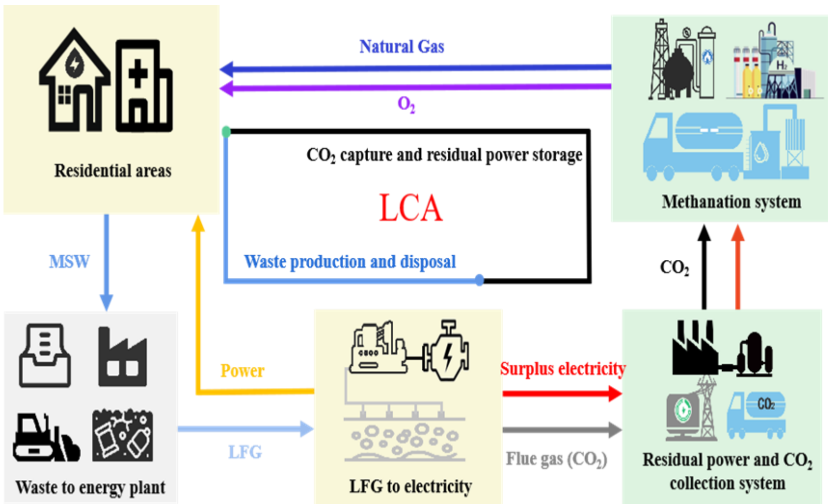


Fig. 2. The lifecycle assessment framework of landfill gas-based waste-to-energy systems.

The methanation system generates natural gas and oxygen as by-products, which are then distributed to specified clients with the aim of enhancing economic efficiency. Furthermore, the methanation system effectively collects the CO_2 emissions generated during power generation. To assess the viability of this study, a comprehensive analysis was conducted on the complete lifecycle of MSW, encompassing collection, transportation, utilisation, and reproduction.

Practically, electricity is generated through the utilisation of an internal combustion engine. The ICE is widely recognised as the key equipment for power generation using LFG due to its high efficiency [11]. Initially, a combination of LFG and air is blended and introduced into the cylinder of the ICE. Subsequently, this mixture undergoes compression before being ignited and exploded by the utilisation of a high-voltage electric spark plug. The purpose of this process is to generate energy [26]. Subsequently, the electrical energy is conveyed by transmission lines to end-users. Furthermore, the flue gases, primarily composed of CO_2, as well as the residual electricity generated, are efficiently repurposed. The utilisation of residual electricity and CO_2 in the methanation system can enhance the energy efficiency of power generation from LFG and lead to a substantial reduction in environmental pollution due to GHG.

Methanation consists of an electrolyzer and two isothermal counter current reactors. Treated industrial wastewater enters the electrolysis cell and travels through it to produce H_2 and O_2 from water at a low cost using residual electricity. The produced H_2 is then combined with compressed CO_2 at the reactor's inlet. The intended products (CH_4 and steam) are obtained by altering the chemical equilibrium [27]. The CO_2 used in the methanation procedure is derived from flue gas produced during power generation. The produced CH_4 is transported directly to the end user via the existing natural gas pipeline infrastructure. In addition, the O_2 produced through electrolysis can be sold in the market, reducing costs.

Implementing a methanation system in the context of energy supply optimises the conversion of LFG into consumable energy, hence improving the overall efficiency of LFG utilisation. Concerning environmental conservation, the methanation system effectively seizes and retains CO_2, resulting in a notable reduction in GHG emissions and a significant enhancement of the environmental advantages associated with the WTE system. With respect to the energy cycle, MSW needs to undergo a conversion process resulting in the production of electricity and CH_4. This initiative may help Lagos meet its energy needs and contribute to the achievement of SDGs.

2.3. Life cycle assessment

This study aims to verify the energy efficiency and environmental benefits of the WTE system using LCA tools to quantitatively analyse the environmental impacts of the WTE system. This was achieved by quantifying the conversion of materials and energy at every stage of the lifecycle [28]. The Simapro9.4 software was utilized in this study to conduct a comprehensive quantitative analysis of the WTE solution. This analysis covered the entire MSW lifecycle, incorporating key stages such as collection, transportation, disposal, and energy conversion. The analysis of the results was conducted in order to assess the feasibility of WTE and to furnish decision-makers with scientific data and practical recommendations. The adoption of this solution was expected to significantly enhance the WTE conversion capacity and mitigates the environmental consequences associated with waste management. Consequently, it would rectify the existing disparity between waste management practices and the prevailing energy supply and demands in Lagos, Nigeria.

3. Method

3.1. Mission and scope of LCA-based WTE systems

The objective of this study was to assess the energy efficiency and environmental implications associated with the management of MSW in Lagos, Nigeria, employing the ISO 14040 standard as a framework for evaluation. As depicted in Fig. 3, the LCA-based WTE system incorporated residual power storage and considered 1 kg of MSW as the functional unit for analysis. The LCA model integrates the energy inputs and outputs associated with the four stages of MSW collection and transportation, landfill, power generation, and residual power storage, as well as waste emissions. This integrated approach enabled a comprehensive assessment of the energy efficiency and environmental impact of a WTE system throughout its operation.

Hence, the implementation of a WTE system incorporating methanated energy storage and accounting for residual power storage through LCA showcased a notable enhancement in energy efficiency and a substantial decrease in GHG emissions, from a holistic standpoint. Based on the findings of the LCA, stakeholders were able to make more informed and logical decisions pertaining to waste management alternatives and governmental legislation.

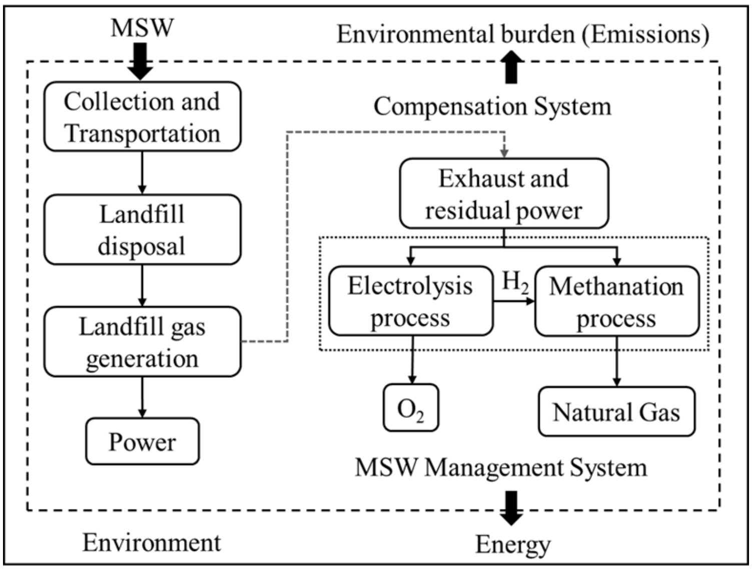


Fig. 3. Lifecycle assessment-based waste-to-energy processes and system boundaries.

3.2. LFG generation from landfilled MSW

LFG is predominantly generated by organic matter decomposition inside MSW. CH4 and CO_2 are generated through intricate biological and chemical processes.

The creation of LFG involves a series of five distinct stages: hydrolysis/aerobic decomposition, anaerobic oxidation, CH_4 production, and humus production. The duration of the initial two phases is short. At the outset, aerobic bacteria engage in the degradation of a significant amount of waste proteins, carbohydrates, and lipids. As the amount of oxygen in the landfill falls, degradation takes place. Over time, soluble organic molecules undergo anaerobic reactions, resulting in the production of organic acids, hydrogen, and CO_2. Subsequently, organic acids undergo conversion into methanol, ethanol, and CO_2 in an oxygen-deprived environment. The subsequent equation depicts the primary reactions occurring in this phase:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \quad (1)$$

The initiation of CH_4 synthesis is facilitated by anaerobic bacteria through the consumption of acetate. The consumption of acetate in landfills leads to a shift towards a neutral environment, which promotes the growth and multiplication of methanogenic microbes. The anaerobic decomposition of organic matter results in the production of a significant quantity of LFG, primarily composed of CH_4 and CO_2. The following equation offers a succinct depiction of the process involved in the generation of CH_4.

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (2)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (3)$$

The conversion of the majority of biodegradable organic matter found in MSW into CH_4 and CO_2 leads to the gasification of the remaining biodegradable organic matter. This gasification contributes to the stabilisation of LFG production until all the organic waste undergoes complete degradation. CH_4 plays a pivotal part in the process of converting MSW into energy. An accurate estimation of CH_4 production is essential for determining the production capacity and potential value of LFG. The assumptions made for this study are: (i) MSW is collected and transported to a landfill timely and (ii) LFG production begins concurrently.

3.3. Production potential of methane

To estimate the methane production potential, this study uses the Landfill Generated Emissions (Land Gem) model developed by the United States Environmental Protection Agency (US EPA) in 2005. The Land Gem model utilises a first-order decomposition rate equation to estimate the emissions generated by the decomposition of MSW deposited at a specific landfill site. The equation for calculating emissions is presented as follows:

$$Q_{CH_4} = \sum_{j=1}^{n} \sum_{j=0.1}^{1} kL_0 \left(\frac{M_{LFGTE}}{10}\right) e^{-kt_{ij}} \quad (4)$$

where Q_{CH_4} is the annual CH_4 generation in the calculation year (m^3/year), i is the time increment of one year, n is (calculation year) - (initial year of waste acceptance), j is the time increment of 1 year, k is the CH_4 generation rate, L_0 is the potential CH_4 generation capacity (m^3/Mg), M_{LFGTE} is the amount of landfilled waste per year (Mg/year), t_{ij} = age of the j^{th} portion of waste received at the landfill in the j^{th} year.

The production of LFG involves a series of five distinct stages: hydrolysis/aerobic decomposition, anaerobic oxidation, CH_4 production, and humus production. However, CH_4 is mainly produced in large quantities through the decomposition of organic acids in anaerobic environments. The production potential of CH_4 is also determined by a combination of factors. For example, the total amount of MSW landfilled, the content of organic matter in the waste, and the set volume fraction of CH_4 in the LFG are represented by L_0. Determining L_0 is often achieved based on the following equations [29]:

$$L_0 = M_F \times MCF \times DOC \times DOC_F \times F \times \frac{16}{12} \quad (5)$$

$$DOC = 0.4 \times P + 0.15 \times K + 0.3 \times W + 0.24 \times T \quad (6)$$

$$DOC_F = 0.014 \times T_{emp} + 0.28 \quad (7)$$

where M_F is the amount of waste destined to the landfill, MCF is the CH_4 correction factor (set to 0.6 for unmanaged landfills), DOC is the percentage of degradable organic carbon, $DOCF$ is the percentage of organic carbon actually degraded to total DOC, F is the volume fraction of CH_4 in the landfill, (set to 0.5), P is the percentage of paper in MSW, K is the percentage of kitchen waste in MSW, W is the percentage of wood/leaves in MSW, T is the percentage of textiles in MSW, and T_{emp} is the temperature of the landfill area (K).

Substituting Eq. (5) into Eq. (4) gives the annual production of CH_4 as Eq.(8):

$$Q_{CH_4} = \sum_{j=1}^{n} \sum_{j=0.1}^{1} kM_F \times MCF \times DOC \times DOC_F \times F \times \frac{16}{12} \times \left(\frac{M_{LFGTE}}{10}\right) e^{-kt_{ij}} \quad (8)$$

3.4. LFG to electricity generation

The electrical energy conversion potential of LFG is predominantly influenced by the calorific value of CH_4, the efficiency of LFG collection, and the performance of an internal combustion engine. Its equation is presented as follows:

$$Q_{P(LFGTE)} = \frac{LHV \times 0.9 \times Q_{CH_4} \times \eta}{3.6} \quad (9)$$

where: $Q_{P(LFGTE)}$ is the amount of electricity generated from LFG (kWh), LHV is the low heating value of CH_4, taken as 37.2 MJ/m^3, Q_{CH_4} is the average amount of CH_4 collected per year (m^3/year), and η is the conversion efficiency of the internal combustion engine of 33%, where the annual volume of CH_4 is proportional to the LFG production in the landfill.

The economic advantages associated with the production of power from the landfills can be attained through the sale of the generated electricity to utility companies. These benefits can be quantified by employing Eq. (10) [30]:

$$S = Q \times P_{LFG} \quad (10)$$

where S is the economic benefit of selling electricity to the grid (USD) and P_{LFG} is the feed-in tariff of LFG for electricity generation (USD/kWh). Changes in electricity prices, power losses during transmission, and power consumption at the landfill are not considered because their impact is weak, as compared to WTE power plants.

3.5. Methanation system to store residual power

To store excess electrical energy, this process of methanization technology was used. This process consisted of two stages. The first stage was the electrolysis stage. Excess electricity was used to electrolyze water to produce high concentrations of hydrogen and oxygen. In a polymer electrolyte membrane (PEM) electrolyzer, oxygen and hydrogen were produced by various electrolysis reactions as follows:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{11}$$

When using electro-gas conversion for energy storage, electrolysis efficiency is particularly crucial. The electro-hydrogen efficiency of PEM can be calculated using the following model:

$$\eta_{SOEC} = \frac{L_{H_2}^{-} \cdot HHV^{H_2}}{L_{ele}^{+}} \tag{12}$$

where HHV^{H_2} represents the high calorific value of H_2, which is taken as 141746 kJ/kg.

The reference quantity of electrical energy input to the energy flow is:

$$L_{ele}^{+} = L_{H_2}^{-} \cdot \frac{HHV^{H_2}}{\eta^{el,H}} \ \forall \in T \tag{13}$$

The reference flow rate of H_2O in the input reaction stream is 1 kg/s, and the reference flow rate of the output product is:

$$L^{H_2} = L^{H_2O} \cdot Param^{H_2O-H_2} \tag{14}$$

$$Param^{H_2O-H_2} = {mol^{H_2}}/{mol^{H_2O}} \tag{15}$$

where, L^{H_2O} represents the reference flow rate of H_2O in the input reaction stream, with a value of 1 kg/s; $Param^{H_2O-H_2}$ represents the proportionality coefficient for the electrolysis of H_2O to produce H_2, with a value of 0.11.

The second stage was methanation, a thermochemical process in which CO_2 and H_2 react in the presence of a metal catalyst at 250-300 °C and 100 bar of pressure. The key reactions in the methanation process are presented as follows [31, 32]:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{16}$$

In the reactor, H_2, CO_2, and electrical energy are used as input streams, and CH_4 is used as the output stream. The reference input flow rate of H_2 is set to 1 kg/s, and the reference input flow rate of CO_2 can be calculated using the following model:

$$L^{CO_2} = L^{H_2} \cdot Param^{H_2 \rightarrow CO_2} \tag{17}$$

$$Param^{H_2-CO_2} = {mol^{CO_2}}/{mol^{H_2}} \tag{18}$$

where L^{H_2} represents the reference flow rate of H_2, which is 1 kg/s; $Param^{H_2 \rightarrow CO_2}$ represents the proportionality coefficient of H_2 to CO_2 conversion during methanation, which is 5.5; mol^{CO_2} represents the molar mass of CO_2, which is 44 g/mol; and mol^{H_2} represents the molar mass of H_2, which is 2 g/mol.

The reference flow rate of electrical energy as input is 564.23 kW. This electrical energy mainly comes from the surplus power generated by the LFG and is primarily used for the compression of H_2 and CO_2, as well as the production of CH_4. The calculation formula is shown in Eq. (19).

$$L^{+}_{elec,MET,T} = L^{+}_{eleref} \cdot \frac{L^{H_2}}{L^{H_2}_{ref}} \quad (19)$$

As the output stream, the reference flow rate of CH_4 is calculated using the formula shown in Eqs. (3)-(17):

$$L^{CH_4} = L^{H_2} \cdot Param^{H_2 \to CH_4} \quad (20)$$

$$Param^{H_2 \to CH_4} = {mol^{CH_4}}/{mol^{H_2}} \quad (21)$$

where L^{H_2} represents the reference flow rate of H_2, which is 1 kg/s; $Param^{H_2 \to CH_4}$ represents the proportionality coefficient of H_2 to CH_4 conversion during methanation, which is 2; mol^{CH_4} represents the molar mass of CH_4, which is 16 g/mol; and mol^{H_2} represents the molar mass of H_2, which is 2 g/mol.

The potential of methanization systems to store excess electricity and capture CO_2 was calculated based on the data studied [33, 34].

3.6. Life cycle inventory

In order to conduct an assessment and evaluation of the lifecycle of the WTE system, data were gathered for the life cycle inventory (LCI). The task necessitated the gathering of conveyance data through transit modes, including road transportation. The projected diesel consumption for road transport was recorded as 8.8 L per metric tonne. The study's correctness and reliability were bolstered by the utilisation of data derived from technical reports, scholarly literature, and published works. In areas characterised by insufficiently developed waste management initiatives, such as Lagos, acceptable assumptions were applied to enhance the accuracy of these evaluation findings. Given the prevailing condition of waste management, it was assumed that MSW was transported straight to landfills for disposal.

Furthermore, an extensive assessment of the WTE system's performance was conducted by analysing various data points, including CH_4 generation, electricity statistics, and emissions [10, 35]. Furthermore, this study involved the computation and analysis of data related to electrolysis and methanation processes within the methanation system.

The rigorous procedure for collecting and analysing data ensured the scientific validity and reliability of the study, providing a reliable database for conducting the LCA of WTE systems for calculating and acquiring data related to electrolysis and methanation processes [36].

3.7. Model validation and data reliability

To ensure the technical reliability of the predictive model and minimize hypothetical bias, the input parameters were rigorously sourced from localized empirical studies in Lagos and internationally validated engineering standards. Specifically, the MSW composition and generation rates are based on the field characterization studies by and (e.g., Okoye et al. [23] and Akinshilo [24]), reflecting the specific waste stream. The LandGem model, a first-order decomposition kinetic tool developed by the US EPA, was utilized to project LFG generation, providing a technically sound basis for long-term energy yield estimation. Furthermore, the thermodynamic efficiencies for the ICE and methanation units were aligned with current commercial plant specifications, ensuring that the energy recovery outputs are grounded in existing technological capabilities rather than theoretical maximums.

The detailed technical data, life cycle inventory, model parameters, and calculation inputs used in this study are provided in Appendix A (Tables A-1 to A-11).

4. Results and Discussion

4.1. CH_4 production and electricity generation in Lagos

As MSW contributes to the generation of CH_4, this model determined its utilization rate based on the annual cumulative amount of methane after 2023. Depending on the size of the landfill, CH_4 production was expected to increase annually until year 36 (2059).

As illustrated in Fig. 4, the yearly production of CH_4 demonstrates an initial phase reflected by a rapid growth, followed by a later period of gradual decline. The production of CH_4 occurred as a consequence of the progressive buildup of MSW over the operational phase of a landfill. This was facilitated by the biological decomposition of MSW. After the landfill operated for 35 years, the landfill has reached its maximum capacity.

Hence, no new waste was landfilled, and the organic waste gradually decreased, resulting in attenuated microbial activity and a consequent reduction in CH_4 production. New organic matter might not necessarily replace the degrading organic matter in landfill sites, potentially impacting the generation of LFG over time. This assumption was based on the observed waste composition and management practices in Lagos, Nigeria, where there might be limitations in the availability of new organic waste inputs to replenish the degraded organic matter efficiently. However, further investigation and data analysis were required to validate this assumption conclusively.

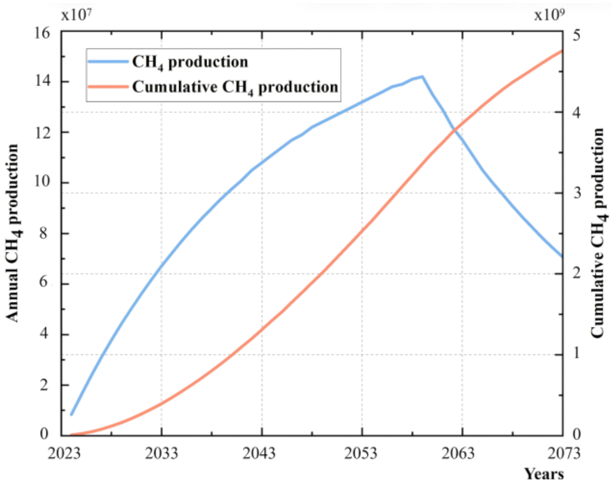


Fig. 4. Projected annual CH_4 production of municipal solid waste input after 2023.

In the initial year, the CH_4 output amounts to 8.312×10^6 m^3 per year. However, in the 36^{th} year, it experienced a significant increase to 1.423×10^8 m^3 per year. The data reveal a substantial increase in CH_4 production, with a fold change of 17.12 between the two time points. The observed disparity was ascribed to the protracted accumulation of waste over a span of 35 years in the landfill, leading to an augmented generation of CH_4. However, at the closure of the landfill, the replenishment of biodegraded MSW came to a halt, resulting in a notable reduction in CH_4 production.

Figure 5 illustrates the power generation projections that have been calculated from the predicted CH_4 production. The visual representation illustrates a notable disparity in electricity generation between the 1^{st} and 35^{th} years. Specifically, the initial year recorded a production of 2.04×10^7 kWh, while the 35^{th} year exhibited a substantial increase to 3.49×10^8 kWh. The estimated electricity generating potential of 1 m^3 of CH_4 was estimated to be 3 kWh.

Consequently, the application of LFG for generating power was expected to lead to a decrease in coal consumption of about 1.202×10^8 tons over the landfill's operational period of 35 years. In addition, under the assumption that all electricity produced is consistently sold at a rate of USD 0.1 per kWh, the aggregate revenue derived from electricity generation would reach 2.041 million USD in the first year and 34.9 million USD in the 35^{th} year. The effective utilisation of LFG not only enhances the dependability and variety of energy provision but also presents a substantial possibility for landfill operators to obtain revenue from the sale of electricity.

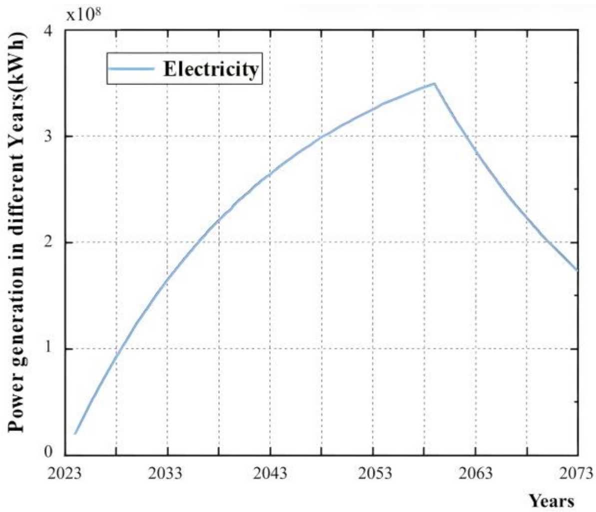


Fig. 5. Power generation of a waste-to-energy plant.

4.2. Using methanization technology for energy storage

Lagos currently has a power deficit; although power demand is higher than supply, there might be a power surplus during certain periods or areas. This excess power might be caused by infrastructure bottlenecks, asymmetries in production and consumption, or other factors. Despite this deficit, there were intermittent periods or areas where excess power might be generated due to infrastructure bottlenecks, asymmetries in production and consumption, or other factors. Therefore, this work proposed a solution to increase the reliability and uniformity of electricity supply by utilizing a methanation system to store the 30% surplus electricity generated by the LFG power plant in Lagos. It was assumed that during a certain period of time, the Lagos power generation system might produce more power than what is needed. This excess electricity could be used to power electrolysis units that drive the methanation process.

Based on Fig. 6, it is evident that the methanation system exhibited the capability to generate 2.81×10^5 m^3 of synthetic natural gas, while concurrently sequestering 5.43×10^5 kg of CO_2 throughout the initial year of its operational period. The observed results aligned with the dominant patterns in the field of electricity generation. In the 36^{th} year, the system achieved a storage capacity of approximately 5.2×10^7 kWh of energy, produced 2.39×10^6 m^3 of synthetic natural gas, and mitigated the emission of 4.61×10^6 kg of CO_2.

The efficiency of the methanization system in the conversion of electrical energy into synthetic natural gas was 30%. Over the course of 35 years, following the closure of the landfill, there has been a cumulative production of 1.61×10^8 m^3 of synthetic natural gas. This production is accompanied by a notable reduction in CO_2 emissions, amounting to 311×10^5 kg.

Furthermore, the methanization process results in the production of a useful by-product, such as oxygen. During the 35^{th} year time period, the total production of O_2 is recorded to be 4.89×10^8 kg. If O_2 were to be commercially sold at USD 0.17 per kg, the potential economic revenue generated from the sales of oxygen would reach USD 831×10^7. However, it is possible to achieve higher economic gains by selling oxygen at prices that are consistent with those commonly observed in the medical oxygen market. The O_2 sale helps reduce the running costs of LFG management [37]. In addition, the utilisation of stored synthetic natural gas offers a variety of energy supply options that go beyond the scope of electricity, hence improving the stability, cost-effectiveness, and environmental sustainability of WTE conversion operations.

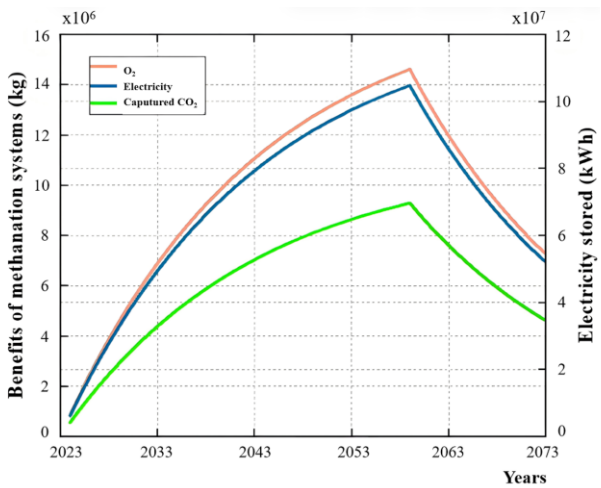


Fig. 6. Benefits of methanization systems for energy and the environment.

4.3. Lifecycle assessment of waste to LFG

In the context of global warming potential (GWP), despite concerted efforts to capture and use LFG for energy, the landfilled waste stood out as the primary contributor, releasing 572.16 kg of CO_2-eq. This was followed by the power generation stage of LFG systems, which contributed 170.69 kg CO_2-eq. Operational efficiency challenges during the waste collection process contributed to a cumulative emission of 840.57 kg CO_2-eq for the entire WTE system.

Fossil Resource Scarcity (FRS) is primarily associated with the use of diesel fuel and electricity in the collection and transportation of MSW, accounting for 43.33% of total resource depletion (Fig. 7). The integration of low-carbon technologies and the improvement of waste management practices, in particular sorting and recycling has emerged as one of promising strategies to mitigate the impact on fossil resource use.

The assessment of potential human health impacts reveals significant amounts of nitrogen oxides (NO_x) and particulate matter ($PM_{2.5}$), particularly pronounced during the LFG to energy (LFGTE) phase (9.02 kg NO_x-eq). The entire WTE system contributed 9.32 kg NO_x-eq and 0.347 kg $PM_{2.5}$-eq, underscoring the need for careful management throughout the lifecycle of the waste.

Acidification Potential (AP) analysis identified the LFG to energy phase as the main contributor (0.477 kg SO_2-eq), closely followed by MSW landfilling (0.407 kg SO_2-eq). The eutrophication potential (EP) is significant during the methanization phase, highlighting the importance of a balanced nitrogen supply to prevent adverse environmental impacts.

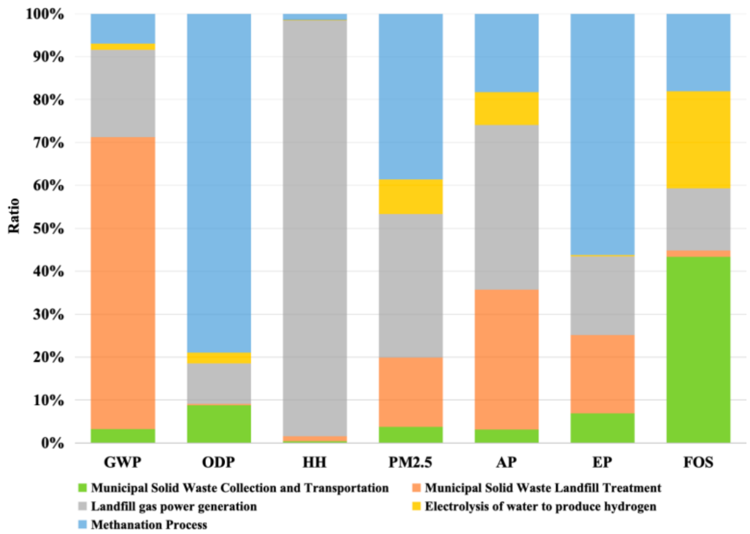


Fig. 7. Lifecycle assessment of waste-to-energy systems including residual power storage.

4.4. Energy and economic benefits

The use of MSW has facilitated a mutually beneficial improvement by converting it into power or fuel. Over a period of 35 years since the commissioning of the landfill, a total amount of 35 billion kg of MSW has been successfully repurposed, leading to the production of about 8.2×10^9 kWh of electricity. In this work, this analysis focuses on the generation potential of the LFG generation and the revenue that can be obtained from selling it, rather than the overall profit of the system. When calculating the revenue numbers, market data and sales price models were used to estimate expected sales revenue. The electricity generated could generate approximately USD 825 million of revenue. LFGTE possesses the capability not only to offer proficient waste management for MSW and function as a power generation source, but also to generates economic advantages.

In addition, the implementation of the LFGTE system facilitates a notable decrease in the consumption of coal for electricity production, amounting to a reduction of 3.32×10^6 kg. Consequently, this led to a substantial decline of 2.11×10^9 kg in CO_2 emissions. Hence, this approach possessed the capacity to mitigate the detrimental impacts of GHG emissions stemming from waste management and the operation of coal-fired power plants.

The electricity generated by this approach presents a dependable and consistent energy supply that efficiently addresses energy deficiencies across various applications. It is worth noting that the electrolysis process exhibited the capacity to generate a substantial quantity of 4.89×10^8 kg of O_2, which offered a lucrative business for commercialization and revenue generation. The funds can thereafter be employed to address the initial investment costs linked to the WTE system. Therefore, the strategy possessed the capacity to provide significant energy and economic benefits for Lagos, which provided a valuable contribution to MSW management and maintained a reliable electricity supply.

4.5. Sensitivity analysis

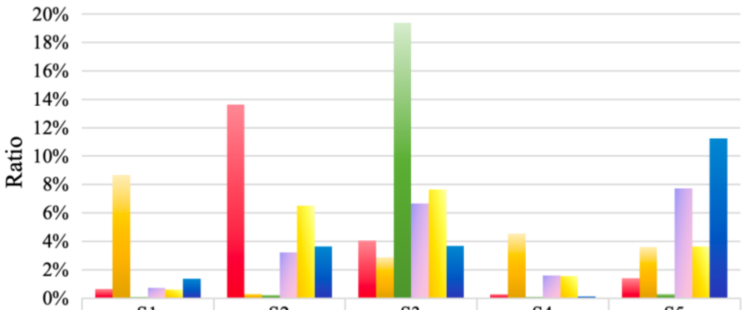
The environmental assessment results of a WTE system are subject to variations due to changes in input parameters at different stages [12]. In particular, during the transition from LFG collection to combustion, the release of CH_4 plays a significant role in global warming. The amount of CH_4 sequestered in landfills has a significant impact on electricity generation, which affects various environmental aspects of MSW management. To assess the sensitivity of the system, perturbations were introduced to 20% of its input parameters, followed by an analysis to investigate the impact of these changes on the environmental impact categories at different stages.

The sensitivity analysis results are presented in Fig. 8. The S1-S5 represent the various stages of waste to energy (WTE) conversion in this study. S1: Transportation of waste; S2: Landfill; S3: Power generation from LFG; S4: Electrolysis process; S5: Methanation process.

Figure 8 shows a clear relationship between a 20% increase in waste collection and a 9% escalation in FRS. This increase corresponded to a conversion factor of 1.71 kg of oil equivalent. Conversely, a 20% increase in CH_4 losses leads to a significant amplification of the global warming potential, with an increase of 14%, reaching a final value of 114.43 kg CO_2 eq. Therefore, implementing technical strategies to improve LFG collection efficiency can effectively mitigate the consequences of the GHG effects.

It is necessary to examine the significant impact on public health caused by NO_x and $PM_{2.5}$, both important pollutants. A 20% increase in energy output leads to a corresponding 19% increase in its potential impact on public health, comparable to the emission of 1.8 kg of NO_x. At the same time, the concentration of the $PM_{2.5}$ increased by 7% (equivalent to 0.023 kg $PM_{2.5}$ eq), while the acidification potential of the system also increased by 8% due to NO_x (equivalent to 0.095 kg SO_2 eq). In the methanization phase, a 20% increase in the conversion efficiency of the energy consumed into CH_4 resulted in a substantial increase in the eutrophication potential of 11%.

This result suggests that the efficiency of LFG capture was the main determinant of global warming potential. In contrast, LFG power generation and methanation technologies had significant environmental impacts in all categories. However, the impacts were intrinsic to the WTE system. Overall, the incorporation of technological interventions could improve the efficiency of power generation and methanation, thereby mitigating the environmental impact of the system [38].



	S1	S2	S3	S4	S5
GWP	0.64%	13.61%	4.06%	0.29%	1.39%
FOS	8.67%	0.30%	2.89%	4.53%	3.62%
HH	0.08%	0.23%	19.36%	0.02%	0.30%
PM2.5	0.74%	3.23%	6.68%	1.61%	7.73%
AP	0.62%	6.53%	7.66%	1.54%	3.65%
EP	1.38%	3.65%	3.68%	0.06%	11.24%

GWP FOS HH PM2.5 AP EP

Fig. 8. Sensitivity analysis results.

4.6. Contributions to SDGs

Based on this framework, LFG was considered a sustainable resource for power generation. During the 35 years of operation of the landfill, the production of electricity generated from the LFG has continuously increased, and it was estimated that approximately 8.25×10^9 kWh of electricity was generated. The process of converting CH_4 into electricity has the specific purpose of increasing the reliability of the energy supply. This goal is aligned with the UN SDGs, specifically Goal 7, which aims to ensure access to affordable and clean energy. While LFG is converted into energy, approximately 3.5×10^{10} kg of MSW is effectively managed and converted into energy.

The implementation of this plan can strengthen the recycling and reuse of resources, while helping to create an original and improved living environment for the local community and reducing environmental pollution. Utilizing MSW for energy production through the WTE method not only enables an efficient recycling of resources but also provides a feasible and eco-friendly method for sustainable energy generation, thereby making a valuable contribution to social progress. Therefore, WTE systems operate as an economically viable waste management strategy, making a significant contribution to the achievement of SDG#12, which focuses on 'Responsible consumption and production' [39].

The greenhouse gas (GHG) effect is a prominent issue in the current global discussion of sustainable development. Within this framework, the flue gas produced consists of CO_2 and serves as the main input to the methanation system. While the remaining electrical energy is effectively stored, approximately 3.11×10^8 kg CO_2 could be captured, which alleviates the global warming effect to a great extent. The initiative therefore also makes a tangible contribution to the pursuit of action on climate change (SDG#13) [40].

5. Conclusions

This study has demonstrated that LFG can be a potential option for energy diversification in Lagos (Nigeria). An example of resource recovery has been implemented where garbage is converted into energy and used to provide electricity to local people. This technology has transformed unused LFG into green electricity. Furthermore, implementing methanation technology in WTE power plants has enhanced the reliability of electricity provision.

This exploratory study has also demonstrated that utilising LFG as a renewable energy source in Lagos can effectively mitigate environmental degradation caused by excessive MSW creation. This is an innovative approach to ensure a consistent energy supply, while safeguarding the environment through waste management.

Based on this modelling study, it is evident that in the last 35 years, an estimated quantity of approximately 3.5×10^{10} kg of MSW has been effectively managed, resulting in the generation of approximately 8.25×10^9 kWh of electricity. This led to a significant reduction in the utilisation of fossil energy of 3.3×10^9 kg of coal equivalent. Furthermore, the surplus electricity accumulated by the methanation system possessed the capability to mitigate the release of 3.11×10^8 kg of CO_2, while concurrently generating 4.89×10^8 kg of O_2 as a by-product. This could reduce costs and diversify the energy supply, while minimizing environmental pollution, as confirmed by the results of the LCA studies. Converting unused LFG into renewable energy has environmental benefits, optimises the energy mix, and enhances energy supply reliability. This offers interesting incentives for stakeholders, including government, policymakers, and investors.

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Appendix A

Data Supplementary

A. 1. Introduction

To provide more comprehensive data supporting the methodology, the relevant data and assumptions are attached to the manuscript in this section. The appendix will contain specific assumptions regarding the annual waste landfilling rates, as well as the technical parameters and process data used in the calculations.

A. 2. Technical settings and data set

Table A-1. Relevant technical data for thermochemical methanation plants [35, 41].

Categories	Technical data	Unit
CO_2 input	1.84	kg
CH_4 production	1	Nm^3
Water	6	kg
H_2 input	4	Nm^3
Electricity consumption	20.76	kWh

Table A-2. Inventory of emissions from collection and transportation of MSW in Lagos [42].

Diesel consumption(L/t)	Emissions	Emission Factors (Kg/L)	Emission (Kg/t)
8.8	CO_2	2.663	23.4344
	CO	0.01195	0.10516
	NO_X	0.00236	0.020768
	Hydrocarbons	0.00175	0.0154
	Particulate Matter	0.00062	0.005456

Table A-3. Life cycle inventory of MSW landfill process [10, 11, 35].

	Unit (per tonne of waste input)	Value
Input		
Diesel	L	0.30
Output		
Emissions into air		
Methane (CH_4)	kg	28.40
Carbon monoxide (CO)	g	0.437
Ammonia	g	190
Nitrogen oxides (NO_X)	g	74
Sulphur dioxide (SO_2)	g	7.0
Hydrogen sulphide (HS)	g	380
NMVOC	g	189
Particulates	g	6.40
Hydrogen chloride (HCL)	mg	39.6
Hydrogen fluoride (HF)	mg	4.20

Table A-3 (Continued). Life cycle inventory of MSW landfill process [10, 11, 35].

	Unit (per tonne of waste input)	Value
Emissions into water		
Chemical oxygen demand	kg	0.23
Biochemical oxygen demand	kg	0.08
Total nitrogen	kg	0.20
Total phosphorus	g	2.38
Lead	g	0.10
Copper	g	0.29
Nickel	g	0.067
Chromium	g	0.402
Iron	g	3.12
Mercury	mg	7.22
Arsenic	mg	6.32
Cadmium	mg	8.53
Zinc	mg	54

Table A-4. Life cycle inventory of landfill gas to electricity conversion [11, 43].

	Unit (per tonne of waste input)	Value
Input（Energy/fuel）		
Disel	L	1.26
Electricity	kWh	15.20
Output		
Avoided burden		
Electricity production	kWh	54
Emissions into air		
Methane (CH_4)	kg	4.60
Carbon monoxide (CO)	kg	0.68
Ammonia	kg	0.08
Nitrogen oxides (NO_X)	kg	0.68
Sulphur dioxide (SO_2)	kg	0.053
Hydrogen sulphide (HS)	kg	0.17
NMVOC	g	46
Particulates	g	6.40
Hydrogen chloride (HCL)	g	3.0
Hydrogen fluoride (HF)	g	3.0
Mercury	mg	1.20
Cadmium	mg	71
Arsenic	mg	1.20
Nickel	mg	9.50
Emissions into water		
Chemical oxygen demand	kg	0.23
Biochemical oxygen demand	kg	0.08
Total nitrogen	kg	0.20
Total phosphorus	g	2.38
Lead	g	0.10
Copper	g	0.29
Chromium	g	0.402
Iron	g	3.12
Nickel	mg	67
Mercury	mg	7.22
Arsenic	mg	6.32
Cadmium	mg	8.53
Zinc	mg	54

Table A-5. Life cycle inventory for hydrogen production from PEM electrolyzer [31].

	Unit (per tonne of waste input)	Value
Products		
Hydrogen (H_2)	Nm^3	1
oxygen (O_2)	kg	3.53E-01
Input		
Water	kg	1.1
PEM electrolyzer, Balance of Plant	p	2.65E-07
PEM electrolyzer, Operation and Maintenance	hr	1.65E-03
PEM electrolyzer, Stack	p	7.31E-07
PEM electrolyzer, ACDC Converter	p	2.65E-07
Storage module, high pressure	p	1.51E-08
Diaphragm compressor module, high pressure, at plant	p	1.51E-08
Electricity, remaining power	kWh	5.19

Table A-6. Life cycle inventory for thermochemical methanation [9, 44].

	Unit (per tonne of waste input)	Value
Products		
Methane (CH_4)	Nm^3	1
Waste heat	MJ	1056
Water	kg	1.5
Input		
Carbon dioxide (CO_2)	kg	1.84
Hydrogen (H_2)	Nm^3	4
Sabatier reaction methanation unit	p	5.71E-06
Ni-Based catalyst for methanation	kg	9.26E-06

Table A-7. Life cycle assessment results.

Category	Unit	Collection and transportation	Landfill	LFG power generation	Electrolysis	Methanation	Total
GWP	kg CO_2 eq	2.71E+01	5.72E+02	1.71E+02	1.23E+01	5.84E+01	8.41E+02
HH	kg NO_x eq	3.91E-02	1.09E-01	9.02E+00	9.43E-03	1.40E-01	9.32E+00
$PM_{2.5}$	kg $PM_{2.5}$ eq	1.29E-02	5.61E-02	1.16E-01	2.79E-02	1.34E-01	3.47E-01
AP	kg 1,4-DCB	1.26E+01	4.30E-01	1.71E+07	7.41E-02	2.28E+02	1.71E+07
EP	kg 1,4-DCB	4.10E-02	6.46E-02	1.07E+02	3.34E-02	3.08E+00	1.10E+02
FRS	kg oil eq	8.56E+00	2.92E-01	2.85E+00	4.47E+00	3.58E+00	1.98E+01

Table A-8. Parameters and corresponding values of LFG power generation [45].

Parameter	Value
Methane flow rate	30125018 m^3/year
Lower heating value of methane	37.5 MJ/kg
Methane density	0.717 kg/m^3
LFG recovery rate	70%
Generator efficiency	33%

Table A-9. Relevant input parameters for water electrolysis hydrogen production model in [46].

	T^{in}(℃)	T^{out}(℃)	Q^-(kW)	L^-	L^+
Calories	91	58	3.05		
Calories	58	27	1.66		
Battery					16662 kW
Water					1kg/s
Hydrogen				0.11 kg/s	

Table A-10. Temperature gradient and power parameters of methanation reactor [47, 48].

Thermal gradient	T^{in}(℃)	T^{out}(℃)	Q^-(kW)
Gradient 1	625.4	507.3	138.4
Gradient 2	507.3	507.1	0.3
Gradient 3	507.1	233.0	585.3
Gradient 4	233.0	228.0	9.3
Gradient 5	228.0	227.0	0.7
Gradient 6	227.0	215.0	12.7
Gradient 7	215.0	203.0	27.1
Gradient 8	203.0	186.7	25.3
Gradient 9	186.7	28.0	358.0

Table A-11. Temperature gradient and power parameters of methanation reactor [49, 50].

Category	Technical Data	Unit
Reaction Temperature	250	℃
Reaction Pressure	30	Bar
CO_2 (Input)	1.84	kg
CH_4 Yield	1	Nm^3
Water (Electrolysis)	6	kg
H_2 (Input)	4	Nm^3
Energy Consumption	20.76	kWh