

Energy Generation Potential from Landfill Gas Generated by the New Cells at the Robinson Deep Landfill Site in Johannesburg

Malillane Lillane * and Khomotso Semenya 

Department of Environmental Sciences, College of Agriculture and Environmental Sciences, University of South Africa, Johannesburg, Republic of South Africa

Email: 19975414@mylife.unisa.ac.za (M.L.); semenk@unisa.ac.za (K.S.)

*Corresponding author

Manuscript received January 12, 2026; revised February 23, 2026; accepted March 19, 2026; published September 24, 2026

Abstract—South Africa's continued reliance on coal-fired electricity generation, together with rising municipal solid waste volumes, highlights the need for integrated energy and waste management solutions. This study evaluates the future methane generation and electricity production potential of the Robinson Deep Phase 1 landfill extension in Johannesburg. Landfill design parameters, projected waste acceptance rates, and operational lifespans were obtained from the Draft Scoping Report and applied within the Landfill Gas Emissions Model to estimate methane generation. Electricity output was calculated assuming a landfill gas collection efficiency of 75% and an electrical conversion efficiency of 33%. The 2 new landfill cells could recover approximately 35 to 40 million cubic meters of methane, generating about 70 to 75 gigawatt-hours of electricity. This output is energy-equivalent to approximately 40,000 tons of South African bituminous coal, assuming a representative coal-fired power plant efficiency of 33%, equivalent to approximately 1.7 to 1.9 megawatt-hours per ton of coal.

Keywords—landfill gas-to-energy, methane, renewable energy, coal displacement, Robinson deep landfill, Johannesburg

I. INTRODUCTION

South Africa is currently experiencing a prolonged energy crisis marked by frequent load shedding, declining performance of ageing coal-fired power plants, and rising Greenhouse Gas (GHG) emissions. These challenges have intensified pressure on the country to diversify its energy mix and transition toward cleaner and more sustainable energy sources [1, 2]. Despite increasing policy attention to renewable energy, coal continues to dominate the national electricity system, contributing more than 80% of total generation and imposing high environmental, economic, and social costs [3]. At the same time, municipalities face growing waste management challenges, as conventional disposal practices in developing regions are widely recognized as inefficient, environmentally harmful, and inconsistent with circular economy principles [4, 5].

Landfill gas typically contains 50%–60% methane, a greenhouse gas with a global warming potential approximately 25 times greater than that of carbon dioxide. When captured and utilized for electricity generation, methane-rich landfill gas can be converted into measurable electrical energy. Methane possesses a high calorific value, enabling direct translation of landfill gas recovery into electricity generation potential. The lower heating value of methane is approximately 35.8–37.5 MJ/m³, which corresponds to about 10 kWh of thermal energy per cubic

meter. Assuming a typical electrical conversion efficiency of 33% for internal combustion gas engines, each cubic meter of methane can produce roughly 0.9–1.0 kWh of electricity. This relationship illustrates that relatively modest methane recovery volumes can yield measurable electricity outputs, thereby justifying the evaluation of Landfill Gas to Energy (LFGE) systems as viable distributed renewable energy resources [4]. Coal remains the dominant source of electricity in South Africa, contributing more than 80% of national generation, yet its continued use imposes high environmental, financial, and social costs. South Africa experienced widespread load shedding throughout 2023, underscoring the severity of the national electricity crisis and the urgent need for more reliable and sustainable energy sources [3]. In coal-dependent energy systems such as South Africa's, each unit of electricity generated from landfill gas directly offsets coal-fired generation, resulting in measurable reductions in greenhouse gas emissions, air pollutants, and coal consumption [6, 7]. In South Africa, several LFGE projects have been implemented, particularly in the City of Johannesburg, including Robinson Deep, Marie Louise, and Goudkoppies, where operational performance and emission reduction outcomes have been documented [8]. At the Robinson Deep landfill, existing landfill gas-to-energy operations have already demonstrated these benefits, and the planned Phase 1 extension provides an opportunity to quantify the future scale of methane conversion to electricity and associated emission reductions at the design stage of landfill development. International and local studies have demonstrated that LFGE projects can reduce landfill-related emissions, contribute to renewable energy supply, and generate economic benefits through electricity sales and carbon credits [9, 10].

Although existing studies provide valuable insights into the performance of operational landfill gas projects, the current body of literature remains largely retrospective in nature. Most research has focused on historical methane capture, electricity generation, and emission reductions at established landfill sites, with limited attention given to the future energy potential of newly engineered landfill cells [8]. Few studies have examined landfill gas generation at the design or expansion stage of landfill development, even though landfill design decisions have long-term implications for methane emissions and renewable energy potential [11].

This represents a critical gap in a coal-dependent energy system such as South Africa's, where understanding the extent to which waste-to-energy can substitute fossil-based

electricity is essential for energy planning and policy formulation. The underrepresentation of waste-to-energy technologies within national renewable procurement mechanisms, such as the Renewable Energy Independent Power Producer Procurement Programme, further underscores the need for empirical evidence that demonstrates their strategic value alongside wind and solar energy [8].

At the municipal level, the City of Johannesburg has committed to achieving carbon neutrality by 2050 through its Integrated Development Plan and Climate Action Plan, which promote renewable energy adoption and methane recovery from landfill sites [9]. Robinson Deep is one of the city's largest landfill gas-to-energy projects, with a designed generation capacity of approximately 5 MW and a history of significant greenhouse gas mitigation [8, 12]. However, the landfill is nearing its capacity and is expected to exhaust available airspace within the next 3 to 5 years, prompting the development of the Robinson Deep Phase 1 extension, which involves new engineered landfill cells [13]. This expansion presents a unique opportunity to assess landfill gas-to-energy potential proactively, rather than retrospectively, at the design stage of landfill development.

The significance of addressing these gaps lies in the growing need for integrated waste and energy planning in rapidly urbanizing cities such as Johannesburg. With more than 1.4 million tons of waste generated annually and increasing pressure on landfill airspace, municipal landfills are no longer merely waste disposal sites but potential sources of distributed renewable energy [9, 14]. Evaluating the methane generation and energy potential of new landfill cells can provide evidence to inform landfill design, renewable energy planning, and climate policy at the municipal and national levels.

This study, therefore, addresses a critical gap in the literature by modelling methane generation from the Robinson Deep Phase 1 extension and translating the results into electricity generation, coal displacement, and carbon mitigation metrics relevant for municipal energy planning and policy decision-making. By providing forward-looking evidence on landfill gas-to-energy potential at the design stage, the study contributes to advancing South Africa's just energy transition, supports circular economy objectives, and strengthens the role of waste-to-energy technologies within the country's broader renewable energy and climate change mitigation strategies [9, 15].

II. LITERATURE REVIEW

The potential of landfill gas as a renewable energy source has been widely examined in the literature, particularly in urban regions where increasing municipal solid waste generation coincides with rising electricity demand. Studies consistently demonstrate that landfill gas recovery can contribute meaningfully to renewable electricity supply while simultaneously mitigating greenhouse gas emissions, especially in developing-country contexts where landfilling remains the dominant waste disposal method [4, 6]. This dual benefit forms the central argument underpinning landfill gas to energy research and supports its relevance for coal-dependent energy systems such as that of South Africa.

A substantial body of international literature confirms that

methane generation from municipal solid waste is strongly influenced by landfill design, waste composition, waste acceptance rates, and operational lifespan [7, 10]. Engineered landfill cells, in particular, are shown to offer more predictable gas generation profiles due to controlled waste placement, improved compaction, and leachate management systems. These characteristics enhance both methane recovery efficiency and long-term energy generation potential, thereby strengthening the case for evaluating landfill gas at the design and expansion stages rather than only during operation.

Empirical studies conducted in South Africa largely support these findings but remain concentrated on existing operational landfill gas-to-energy projects. Research on sites such as Robinson Deep, Marie Louise, and Goudkoppies demonstrates that landfill gas recovery is technically feasible and capable of delivering sustained electricity generation under local climatic and waste conditions [8]. These studies report measurable reductions in methane emissions and confirm the viability of electricity generation from landfill gas within metropolitan municipalities. However, the literature predominantly evaluates historical performance, offering limited insight into the future energy potential associated with newly engineered landfill cells.

This gap is particularly relevant given South Africa's continued reliance on coal-fired electricity generation. While several studies quantify methane capture volumes and emission reductions, fewer translate landfill gas recovery into energy metrics that directly relate to fossil fuel displacement [11]. Where such assessments exist, they suggest that landfill gas to energy can provide a reliable source of baseload or dispatchable electricity, complementing variable renewable technologies. This finding supports the argument that landfill gas should be evaluated not only as a waste management intervention but also as a strategic contributor to energy diversification at the municipal level.

At the municipal scale, the literature increasingly recognizes the importance of aligning landfill gas recovery with local climate and energy planning objectives. Policy studies note that cities such as Johannesburg have prioritized methane recovery from landfills as part of broader climate mitigation and renewable energy strategies [9]. Given the sustained generation of municipal solid waste and the long operational lifespans of landfills, newly developed landfill cells represent long-term energy assets whose contribution extends beyond short-term emission reductions.

The Robinson Deep landfill features prominently in the South African landfill gas literature due to its scale and early adoption of landfill gas to energy technology. Previous studies document substantial methane destruction and electricity generation from the existing landfill footprint, reinforcing the argument that Robinson Deep possesses favourable conditions for energy recovery [8, 12]. However, as the existing landfill approaches capacity, the literature provides limited analysis of how the planned Phase 1 extension, comprising newly engineered landfill cells, will influence future methane generation and electricity output. Given that landfill expansion decisions determine gas generation trajectories for decades, this omission represents a significant research gap.

The estimation of landfill gas generation is commonly undertaken using mathematical modelling approaches, with first-order decay models dominating the literature. Among these, the United States Environmental Protection Agency's Landfill Gas Emissions Model is widely applied due to its transparent structure, modest data requirements, and suitability for long-term projections [10]. Numerous studies have demonstrated that this model provides robust screening-level estimates of methane generation where direct gas monitoring data are unavailable, particularly during landfill planning and design phases. Its extensive application in both developed and developing country contexts supports its use for evaluating the energy generation potential of newly engineered landfill cells.

This study builds on existing landfill gas and energy literature by focusing explicitly on the energy generation potential of methane produced by the new cells at the Robinson Deep landfill site. By applying an established landfill gas modelling approach and translating methane generation into electricity output and coal displacement metrics, the study extends the literature beyond operational performance assessments. It provides forward-looking

evidence to support integrated waste-to-energy planning in South Africa's coal-dominated energy system.

III. MATERIALS AND METHODS

Robinson Deep landfill is in southern Johannesburg, within the City of Johannesburg Metropolitan Municipality, Gauteng Province. As one of the city's major disposal sites, it has served as a critical hub for municipal solid waste management and has been identified as a priority site for landfill gas-to-energy development due to its large waste mass and sustained methane generation potential [8, 12]. Electricity generation at Robinson Deep commenced in 2016, marking its transition into the stable methane release phase (Phase IV) of landfill gas production, where microbial decomposition under anaerobic conditions generates a steady flow of methane [16]. The existing landfill shown in Fig. 1 has already been developed with landfill gas extraction infrastructure, including a network of gas wells and flaring systems, which have enabled electricity generation since 2016 [8]. These facilities have demonstrated the technical feasibility of landfill gas-to-energy projects in Johannesburg.

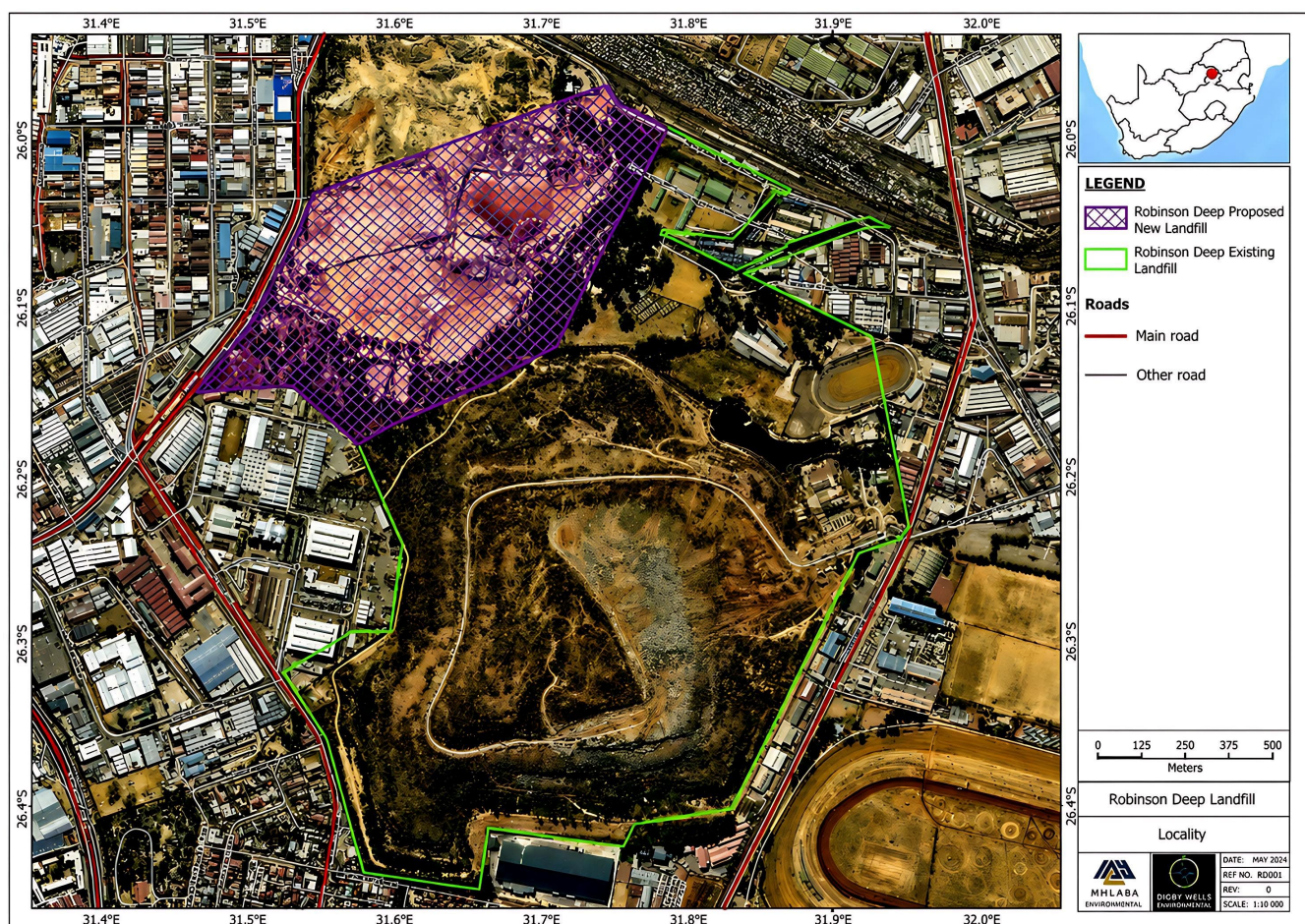


Fig. 1. Robinson deep landfill site [17].

This study focuses on the Phase 1 extension of Robinson Deep Landfill, which involves the construction of 2 new engineered landfill cells to increase capacity and ensure compliance with environmental standards. Cell 1 in Fig. 2 has a footprint of 15.6 hectares with an excavation volume of 246,790 m³, while Cell 2 in Fig. 3 extends over 10.8 hectares with an excavation volume of 268,830 m³. Together, the 2

cells provide more than 515,000 m³ of additional airspace, extending the operational lifespan of the landfill by approximately 16 years, 7 years for Cell 1 and 9 years for Cell 2 [13]. The expansion is not only critical for waste disposal management in Johannesburg but also creates opportunities for enhanced landfill gas recovery due to the significant increase in waste mass that will be deposited in the new cells.

The local climatic and geological conditions further strengthen the feasibility of landfill gas-to-energy generation at Robinson Deep. Johannesburg experiences a temperate climate with distinct summer rainfall, which directly affects the moisture content of waste and, consequently, the rates of microbial decomposition and methane production [14]. Seasonal rainfall variations are expected to drive fluctuations in landfill gas yields, with higher methane production during wetter periods. Geologically, the site is underlain by quartzite and shale formations that provide a stable foundation for landfill operations. To meet environmental and regulatory requirements, the new cells are equipped with engineered liners, leachate management systems, and gas extraction infrastructure designed to prevent groundwater contamination, control leachate migration, and maximise the capture of landfill gas [13]. Taken together, the additional capacity, favourable climatic influences, and robust engineering systems make Robinson Deep both environmentally compliant and technically viable for sustained landfill gas-to-energy generation [14].

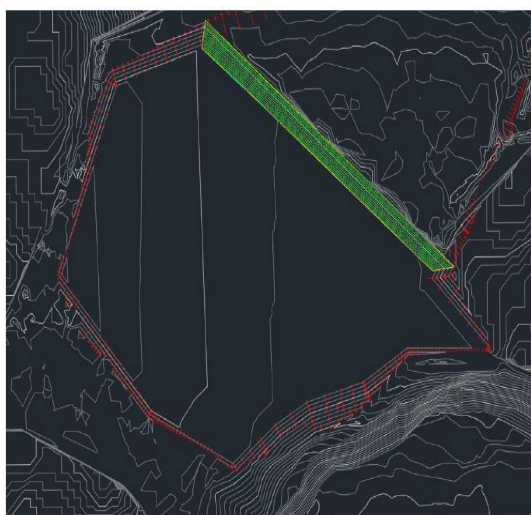


Fig. 2. Layout of cell 1 [17].

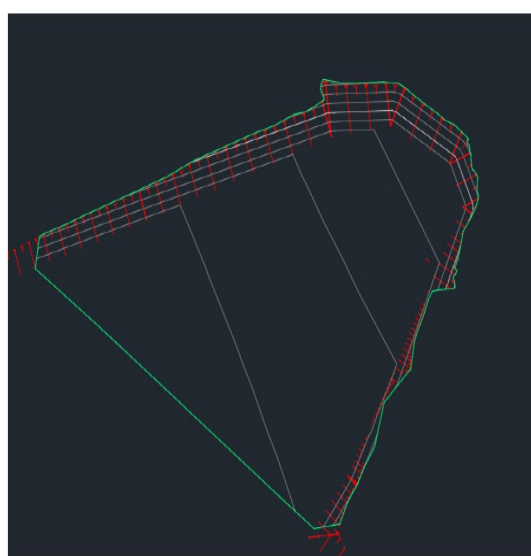


Fig. 3. Layout of cell 2 [17].

A. Data Collection

Data used in this study were obtained from a combination of primary site-specific information and secondary sources.

Primary data included landfill design and operational parameters for the Robinson Deep Phase 1 extension, as documented in the Draft Scoping Report [13]. These parameters included cell footprints, excavation volumes, anticipated operational lifespans, and projected waste acceptance rates. Operational data such as the current daily waste input, the proportion of organic content in municipal solid waste, and site infrastructure for gas extraction were also incorporated.

Although landfill capacity and cell dimensions are reported in volumetric units (m^3), the Landfill Gas Emissions Model (LandGEM) requires waste input in mass units (Mg). Therefore, waste volumes were converted to mass using an assumed compacted municipal solid waste density of 0.80 t/m^3 , consistent with values reported for engineered landfills in South Africa. This conversion ensured consistency between site design data and LandGEM modelling requirements while retaining volume (m^3) as the primary reporting unit throughout the study [16].

Secondary data were collected from published literature and technical reports on landfill gas generation and recovery. Specifically, values for methane generation potential (L_0), methane generation rate constant (k), and methane fraction in landfill gas were obtained from established studies in similar contexts [9, 18]. The methane generation rate constant (k) and potential methane generation capacity (L_0) used in this study were adopted from peer-reviewed literature reporting values for engineered municipal solid waste landfills operating under climatic and waste composition conditions comparable to those of Johannesburg. A k value of 0.04 year^{-1} and an L_0 value of $100 \text{ m}^3 \text{ CH}_4/\text{Mg}$ of waste were applied in the LandGEM simulations. These values fall within the ranges commonly reported for temperate, summer-rainfall regions with high organic waste fractions and engineered landfill systems [16, 19].

The selected parameter values are considered appropriate for Johannesburg due to the city's waste stream characteristics, which are dominated by biodegradable organic fractions, including food waste, garden waste, and paper, as documented in municipal waste characterization studies [14]. High organic content and favorable moisture conditions associated with seasonal rainfall support moderate methane generation rates consistent with the adopted k value, while engineered liners and leachate management systems enhance anaerobic decomposition and methane yield, supporting the selected L_0 value [8].

A sensitivity analysis was not conducted in this study, as the primary objective was to provide conservative, screening-level estimates of long-term methane and electricity generation potential at the design stage of landfill development. Instead, mid-range literature values were deliberately selected to avoid overestimation of landfill gas yields. This approach is consistent with established landfill gas feasibility assessments where long-term operational data are unavailable, and the emphasis is on comparative and planning evaluation rather than precise prediction [20, 21].

These data provided the baseline assumptions for modelling methane generation and estimating potential energy recovery. Climatic data for Johannesburg were reviewed to contextualize landfill gas generation conditions and to confirm the suitability of methane generation rate

constants (k) reported in comparable studies. Rather than recalculating site-specific k values, this study adopted literature-derived k parameters applicable to similar climatic regions, consistent with LandGEM applications in data-limited environments. This approach ensures methodological consistency while maintaining comparability with previous landfill gas assessments. These factors influence landfill gas generation by affecting moisture levels and biodegradation rates within the landfill [11].

Waste composition data were derived from municipal waste characterization studies, which indicate a high proportion of putrescible and biodegradable fractions in Johannesburg's waste stream [14]. The combination of site-specific design parameters, operational data, and literature-derived constants ensured that the input dataset was both representative of Robinson Deep's conditions and consistent with internationally recognized landfill gas modelling practices [11]. To ensure consistency and comparability of modelling outcomes, variability in dissolved organic carbon content and methane generation potential of the landfilled waste was normalized using representative, literature-derived landfill gas parameters.

In the LandGEM framework, the influence of waste composition and biodegradable organic content is implicitly incorporated within the methane generation potential parameter (L_0). Rather than modelling individual waste fractions separately, this study adopted a single, normalized L_0 value representative of mixed municipal solid waste streams typical of large metropolitan areas in South Africa.

This approach assumes that variations in organic content are averaged over time and across large waste volumes, which is appropriate for long-term, planning-level assessments of newly engineered landfill cells. Waste acceptance rates were held constant throughout the operational life of each cell, and no temporal variation in waste composition was assumed. These assumptions align with standard LandGEM applications and reduce the risk of overestimating methane generation while ensuring consistency across modelling years. Consequently, the resulting methane and electricity generation estimates reflect conservative, normalized projections suitable for feasibility assessment rather than short-term operational forecasting.

B. Landfill Lifespan and Waste Acceptance

The useful life of the Robinson Deep Phase 1 landfill extension was calculated from the engineered airspace capacity of each landfill cell and the projected rate of waste acceptance. The engineered excavation volumes of Cell 1 and Cell 2, estimated at approximately 246,790 m³ and 268,830 m³, respectively, were first converted to waste mass using an assumed compacted municipal solid waste density of 0.80 tons per m³. This density value is consistent with those reported in the literature for engineered sanitary landfills operating under South African conditions. The resulting mass-based capacities represent the maximum quantity of waste that can be accommodated within each cell. To estimate the operational lifespan of each cell, the calculated waste mass capacity was divided by the projected annual waste acceptance rate. Waste input data were obtained from the Draft Scoping Report for Robinson Deep.

The daily rate was converted to an annual value and

applied uniformly over the operational period of each cell. Based on this calculation and the planned sequencing of landfill operations, Cell 1 is expected to remain operational for approximately 7 years, while Cell 2 is projected to operate for approximately 9 years, resulting in a combined extension lifespan of approximately sixteen years. Projected waste generation for the Phase 1 extension was therefore not independently forecast but derived directly from current operational waste acceptance data. A constant annual waste input was assumed throughout the operational life of each cell. This approach reflects a conservative and widely adopted practice in landfill gas modelling, particularly where long-term waste growth projections are uncertain. Although future increases in waste generation associated with population growth and urbanization are anticipated, these were not explicitly modelled in order to avoid overestimation of methane generation. Consequently, the resulting landfill gas and electricity generation estimates represent conservative projections based on current waste acceptance conditions.

C. Landfill Gas Estimation

The estimation of Landfill Gas (LFG) emissions from the 2 new cells at Robinson Deep was conducted using the Landfill Gas Emissions Model (LandGEM). LandGEM was selected for this study over alternative landfill gas models due to its demonstrated suitability for data-limited environments and its extensive application in both developed and developing-country contexts, including South Africa. LandGEM applies a first-order decay formulation that requires a limited number of input parameters, making it particularly appropriate where long-term site-specific gas monitoring data are unavailable, as is often the case during landfill planning and expansion stages [19, 20].

In the South African context, several studies have successfully applied LandGEM or similar first-order decay models to estimate methane generation and electricity potential from municipal solid waste landfills, reporting results consistent with observed landfill gas recovery performance [8, 21]. Compared to more complex models such as Afvalzorg or the California Landfill Methane Inventory Model (CALMIM), which require detailed field measurements and site-specific calibration, LandGEM offers a transparent and conservative screening-level approach suitable for feasibility assessments and forward-looking evaluations of newly engineered landfill cells [20].

Given South Africa's waste composition characteristics, engineered landfill design standards, and the study's objective of estimating long-term energy generation potential at the design stage, LandGEM provides a practical and methodologically consistent tool for assessing landfill gas-to-energy potential at Robinson Deep.

LandGEM was selected as the sole modelling tool in this study because the objective was to estimate long-term methane generation and electricity potential at the design and planning stage of newly engineered landfill cells, where operational gas monitoring data are not yet available. Alternative modelling approaches, such as the Default Method, detailed First-Order Decay formulations, or triangulation methods, typically require site-specific calibration data, historical gas extraction records, or detailed

waste fraction decay profiles, which are unavailable for landfill cells that are yet to be constructed. In data-limited environments such as South Africa, LandGEM has been widely adopted as a screening-level model due to its transparent structure, modest data requirements, and suitability for forward-looking projections during landfill development and expansion phases. While comparative modelling using multiple approaches can improve precision, it was beyond the scope of this case study, which focuses on quantifying order-of-magnitude energy potential rather than producing calibrated operational forecasts. This approach is consistent with previous landfill gas studies conducted at the planning stage in developing-country contexts, where LandGEM has been used as a standalone model to support feasibility assessment and policy-relevant decision-making. Eq. (1) is used in the LandGEM model, and all inputs were expressed in mass units (Mg), obtained by converting annual waste volumes (m^3) to mass using the density [22].

$$Q_{CH_4} = \sum_{i=1}^n \sum_{j=0.1}^1 k L_o \frac{M_i}{10} e^{-kt_{ij}} \quad (1)$$

where:

Q_{CH_4} = Annual methane generation in the year (m^3 /year).

i = the yearly time increment.

n = difference of (year of the calculation, initial year of waste acceptance).

j = the 0.1-year time increment.

k = the methane generation constant ($year^{-1}$).

L_o = the potential methane generation capacity (m^3 /Mg).

M_i = mass of Municipal Solid Waste (MSW) in the i th year (Mg).

t_{ij} = the age of the j th section of waste M_i accepted in the i th year (decimal years).

When this methodology is utilised to determine the potential for methane generation from a site, it is dependent on the input parameters [23]. The model has 2 primary input parameters, which assist in making the predictions, namely the constant (k) from the waste and the generation potential (L_o) from the municipal solid waste. The methane generation potential of municipal solid waste depends on its organic fraction and moisture content. Eq. (2) shows how it is determined [19]. While LandGEM provides a simplified representation of landfill methane generation, it remains a widely accepted screening-level tool for estimating energy recovery potential at the planning stage, particularly where long-term operational data are unavailable.

$$K = 3.2 \times 10^{-5}(R) + 0.01 \quad (2)$$

where:

K = Methane generation rate constant ($year^{-1}$)

R = Average annual rainfall/precipitation (mm/year)

D. Electricity Generation Estimation

The annual methane volumes predicted by LandGEM were subsequently converted into electricity generation potential. Methane recovered from landfill gas contains a significant calorific value, which can be harnessed through suitable energy conversion technologies. To reflect realistic operating conditions while avoiding overestimating energy output, conservative, literature-supported assumptions were adopted

for landfill gas collection and electricity conversion efficiencies. A landfill gas collection efficiency of 75% was assumed, which is consistent with performance levels reported for engineered landfill gas recovery systems equipped with well-designed gas extraction networks, liners, and leachate management systems. Previous studies indicate that collection efficiencies typically range between 60% and 85% for modern sanitary landfills, with values near the mid-range considered appropriate for screening-level feasibility assessments where site-specific recovery data are unavailable. An electrical conversion efficiency of 33% was assumed for internal combustion gas engines, reflecting the typical efficiency range reported for commercially deployed landfill gas engines operating under stable methane concentrations. This value is widely used in landfill gas-to-energy studies and represents average performance under real-world operating conditions rather than optimal or nameplate efficiencies.

The selected efficiency values are therefore neither optimistic nor extreme but represent conservative, planning-level assumptions suitable for evaluating long-term electricity generation potential from newly engineered landfill cells. Given that the primary objective of this study is to assess order-of-magnitude energy potential at the landfill design stage, rather than predict short-term operational performance, the use of standardized literature-based efficiency assumptions ensures methodological consistency and comparability with previous landfill gas feasibility studies conducted in similar contexts. South African bituminous coal has a calorific value of approximately 19–21 MJ/kg (equivalent to about 5.3–5.8 MWh per ton on a thermal basis). Assuming a representative coal-fired power plant efficiency of 33%, this translates to roughly 1.7–1.9 MWh of electricity per ton of coal. This conversion factor enables estimation of the quantity of coal displaced by electricity generated from landfill gas. The potential to recover energy from methane emissions is calculated using Eq. (3) [21].

$$E_R = \text{Volume of methane}(m^3) \times \eta \times \mu \times LVH \quad (3)$$

where:

E_R = energy recovered (MJ).

η = gas collection efficiency (75%).

μ = efficiency of the gas engine (33%).

LVH = lower heating value of methane (37.5 MJ/ m^3).

Purmessur and Surroop [21] demonstrated that a methane flow of 30,125,018 m^3 /year could yield approximately 55.7 GWh/year of electricity under similar assumptions. By applying the same procedure to the methane outputs from Robinson Deep, the renewable electricity potential of the 2 new landfill cells was quantified.

E. Estimating the Amount of Coal Displaced and CO_2 Avoided from Landfill Gas (LFG)

South Africa's electricity sector remains overwhelmingly dependent on coal, which accounts for approximately 82% of national power generation [24]. This heavy reliance on a single fossil fuel has contributed to persistent energy insecurity, escalating greenhouse gas emissions, and significant environmental degradation, particularly in

coal-mining regions [25]. Moreover, although South Africa is endowed with substantial domestic coal reserves, the sector has increasingly faced supply and quality constraints, leading to periodic reliance on imported coal to stabilize Eskom's generation capacity [20]. In this context, diversifying the energy mix through renewable alternatives such as landfill gas-to-energy is not only an environmental imperative but also a strategic economic necessity. By generating electricity from methane captured at landfill sites, projects such as the Robinson Deep Phase 1 extension can offset coal-fired generation, thereby reducing both direct fuel consumption and associated emissions of carbon dioxide, sulphur dioxide, and particulate matter. The amount of coal displaced by utilising landfill gas from the newly engineered cells at Robinson Deep was therefore quantified in this study using Eq. (4) [21], which relates the energy recovered from LFG to the equivalent output from coal combustion. This calculation provides a tangible measure of the contribution of LFG projects to fossil fuel substitution and climate change mitigation within South Africa's electricity sector.

$$E_{LFG} = EF_{coal} \times m_{coal} \times \eta \times \tau \quad (4)$$

where:

E_{LFG} = electricity generated from landfill gas (MWh).

EF_{coal} = electricity generation per ton of coal (MWh/ton), derived from the calorific value of South African coal and the average efficiency of coal-fired power plants.

LVH_{coal} = calorific value of coal, which averages at 19–21 MJ/kg (5.3–5.8 MWh/ton) for the bituminous coal used in South Africa.

η = Typical Eskom coal plant efficiency of 33% and each ton of coal produces about 1.7–1.9 MWh of electricity.

τ = Operating time (h).

m_{coal} = Mass flow rate of coal (kg/s).

This equation is particularly relevant in the South African context because coal dominates the national electricity mix, with bituminous coal from the Mpumalanga coalfields serving as the primary fuel for Eskom's baseload power stations [25]. The approach reflects the reality that each unit of electricity generated from landfill gas directly offsets coal-based electricity generation, thereby reducing coal consumption and associated emissions [26].

IV. RESULTS AND DISCUSSION

Figs. 4 and 5 present the modelled methane generation profiles for Cell 1 and Cell 2 of the Robinson Deep Phase 1 extension, as estimated using the LandGEM first-order decay model. These figures illustrate the characteristic behaviour of engineered landfill cells, with methane production increasing during the active waste placement period, reaching a peak shortly after closure, and declining gradually thereafter. The temporal alignment between methane generation and landfill operational phases confirms that the applied modelling approach captures the expected decomposition dynamics of municipal solid waste under Johannesburg's climatic and operational conditions.

The corresponding electricity generation potentials derived from these methane outputs are shown in Figs. 6 and 7. As expected, electricity generation closely mirrors the methane production trends, with peak electricity output occurring in

the early post-closure years before progressively declining. This direct relationship highlights the importance of early gas capture and energy recovery infrastructure to maximize renewable electricity generation from newly engineered landfill cells.

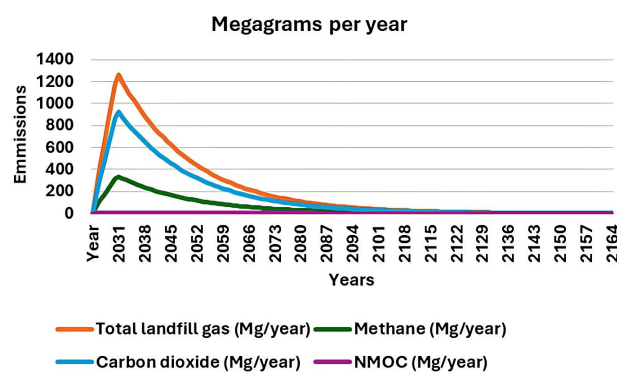


Fig. 4. Cell 1 at Robinson Deep landfill site.

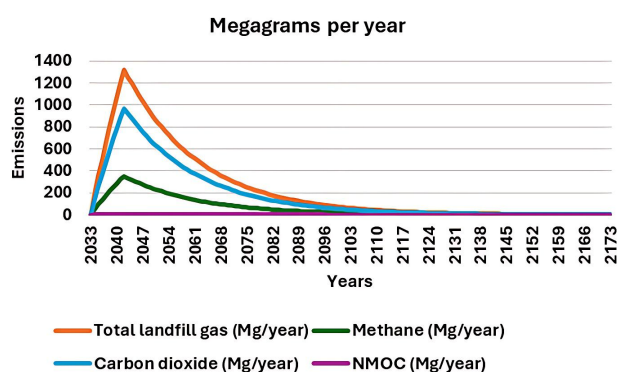


Fig. 5. Cell 2 at Robinson Deep landfill site.

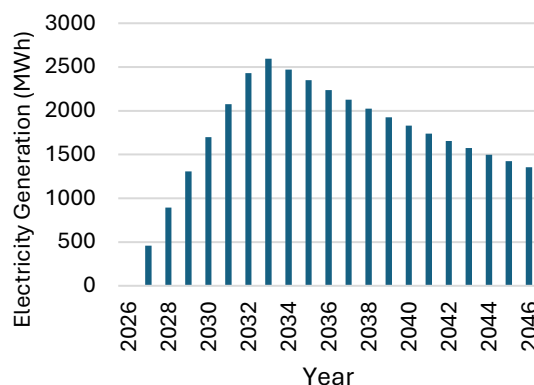


Fig. 6. Electricity generation potential from methane produced in cell 1.

The LandGEM simulation for the new landfill cells demonstrates the characteristic first-order decay profile of methane emissions. As shown in Fig. 4, Cell 1 exhibits a gradual rise in methane generation during the active filling phase, reaching a peak output immediately following the completion of waste placement. This peak represents the point at which the maximum proportion of biodegradable organic material is actively decomposing under anaerobic conditions. After this peak, the figure illustrates a steady decline in methane production, reflecting the progressive depletion of degradable substrates.

Similarly, Fig. 5 illustrates the methane generation trajectory for Cell 2. Owing to its slightly larger excavation volume and extended operational lifespan of nine years, Cell

2 produces methane for a longer period and achieves a marginally higher peak generation compared to Cell 1. The figure also underscores the sustained methane release potential, with production tapering gradually after closure.

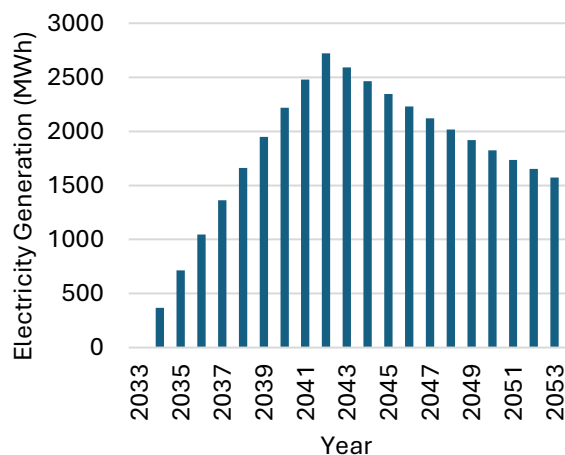


Fig. 7. Electricity generation potential from methane produced in cell 2.

A. Electricity Generation Estimation

The conversion of modelled methane outputs into electricity potential is presented in Fig. 6 for Cell 1 and Fig. 7 for Cell 2. In Fig. 6, Cell 1 demonstrates annual electricity generation that closely mirrors the methane production curve, peaking shortly after cell closure and subsequently declining. The figure confirms that Cell 1 can deliver substantial renewable energy during its early post-filling years, although its contribution diminishes over time as gas generation subsides. In contrast, Fig. 7 reveals a more prolonged and stable electricity generation profile for Cell 2, reflecting its larger gas reservoir and longer filling period. The higher sustained output shown in this figure suggests that Cell 2 will provide a more extended supply of renewable electricity, thereby reinforcing system stability. In addition to energy potential, the results highlight the displacement of fossil fuel consumption. Based on modelled generation, Cell 1 is expected to displace approximately 19,813 tons of coal, while Cell 2 is projected to offset 20,554 tons over its operational lifetime. Although the estimated coal displacement represents a small fraction of Johannesburg's total coal-based electricity consumption, it demonstrates the value of landfill gas-to-energy as a localized, dispatchable renewable resource.

This displacement not only contributes to reducing national dependence on coal-fired generation but also implies significant reductions in associated greenhouse gas emissions. Taken together, the figures confirm that both cells are technically capable of delivering measurable renewable electricity and climate mitigation benefits. Cell 1 provides an immediate but shorter-lived energy contribution, while Cell 2 ensures a longer-term and more stable electricity supply. These findings underscore the role of the Robinson Deep expansion in advancing Johannesburg's renewable energy and carbon reduction objectives. When compared with Johannesburg's annual electricity consumption of approximately 14–16 TWh, the combined electricity generation from the two landfill cells represents less than 1%

of total municipal demand. This confirms that landfill gas-to-energy is not a replacement for coal-based generation at the city scale but rather a supplementary and stabilising renewable energy source.

The electricity outputs modelled for the new cells fall within the range reported for similar-scale landfill developments and reinforce the suitability of Robinson Deep as a long-term landfill gas resource. Although the projected contribution from the Phase 1 extension represents a relatively small share of Johannesburg's total electricity demand, its value lies in providing dispatchable and locally generated renewable power that complements intermittent energy sources. This aligns with previous findings from Johannesburg landfill gas projects, which show that LFGE systems function most effectively as stabilizing components within a diversified urban energy mix rather than as large-scale replacement technologies for coal-fired generation [8]. The results confirm that landfill gas-to-energy at Robinson Deep should be viewed as a supplementary renewable energy source rather than a primary replacement for coal-fired electricity. Although the projected outputs represent a small fraction of Johannesburg's total electricity demand, their value lies in providing dispatchable, baseload renewable power while simultaneously mitigating methane emissions and displacing fossil fuel consumption. Similar findings have been reported in international contexts, where methane production typically peaks shortly after closure before gradually declining, yet remains a viable energy source for decades [20]. This long-term stability of gas flows is particularly important in South Africa, where chronic load shedding is a clear indication of the unreliability of energy generation from coal [1].

The electricity generation potential illustrated in Fig. 6 and Fig. 7 further underscores the viability of landfill gas-to-energy as a renewable option for the City of Johannesburg. Cell 1 in Fig. 6, despite its shorter operational lifespan, delivers an immediate renewable energy contribution in the years following closure, while Cell 2 in Fig. 7 provides a more extended and stable output. Together, these cells represent a strategic balance between short-term energy availability and long-term generation sustainability. Comparable studies in Mauritius and Iran have demonstrated that even medium-sized landfill projects can produce several tens of gigawatt-hours annually, significantly complementing local energy supply [19, 24]. This indicates that Robinson Deep's outputs are consistent with global benchmarks and technically feasible.

The displacement of approximately 40,000 tons of coal across the two cells offers additional systemic benefits. Given that coal-fired plants dominate South Africa's energy mix, contributing more than 80% of total electricity production [25], substituting coal with landfill gas-to-energy reduces associated greenhouse gas emissions. Previous studies have shown that methane capture is among the most cost-effective climate mitigation strategies in the waste sector, particularly in developing economies [10]. By offsetting coal combustion, Robinson Deep contributes to Johannesburg's Climate Action Plan and South Africa's Nationally Determined Contributions under the Paris Agreement. Furthermore, earlier phases of landfill gas-to-energy at Robinson Deep generated over 137,000

Certified Emission Reductions, demonstrating the site's ability to leverage carbon finance mechanisms [12].

From a policy and governance perspective, these findings emphasize the importance of scaling landfill gas to energy within broader renewable energy frameworks. Sustained outputs from Cell 2 and Cell 1 suggest that landfill gas to energy can provide stable baseload generation, complementing renewable energy technologies such as solar and wind. This aligns with lessons from international practices, where integrating landfill gas to energy into renewable procurement schemes and municipal energy strategies has proven effective [6, 26]. Moreover, embedding landfill gas recovery within circular economy models enhances its socio-economic impact. The planned integration of a dirty Materials Recovery Facility and provision for a future biogas plant at Robinson Deep reflects this systems approach, consistent with evidence that combining landfill gas to energy with material recovery and organic waste treatment maximises environmental and economic returns [13, 14]. Embedding landfill gas recovery within the design and operation of landfill infrastructure represents a practical application of circular economy principles, whereby waste streams are transformed into valuable energy resources rather than being treated solely as disposal liabilities. By capturing methane and converting it into electricity, landfill gas-to-energy projects close material and energy loops, extend the functional value of landfill sites, and reduce environmental externalities associated with waste disposal. In the case of Robinson Deep, the integration of landfill gas recovery alongside complementary facilities such as materials recovery and future biogas systems enhances resource efficiency and supports a systems-based approach to waste management. Beyond environmental benefits, landfill gas-to-energy projects generate socio-economic value through job creation in construction and operation, reduced municipal electricity expenditure, enhanced energy security, and potential revenue from electricity sales and carbon credits. These combined benefits illustrate how landfill gas recovery contributes to sustainable urban development while advancing both circular economy objectives and climate mitigation goals.

The discussion of the results indicates that Robinson Deep's new landfill cells are technically robust, environmentally beneficial, and strategically aligned with South Africa's energy transition objectives. The combination of immediate and long-term renewable energy contributions, coal displacement, and climate benefits positions the project as a cornerstone for sustainable urban development in Johannesburg. The value of this study lies not in methodological novelty but in its application to future landfill infrastructure planning. By quantifying coal displacement and framing landfill gas-to-energy as a dispatchable renewable complement to intermittent sources, the study provides actionable insights for municipalities in coal-dependent energy systems. Such planning assessments are critical in developing countries where waste growth, energy insecurity, and climate obligations intersect. The projected energy yields are comparable to reported landfill gas-to-energy projects in similar urban landfills in sub-Saharan Africa and other middle-income countries, reinforcing the plausibility of the estimates.

Comparable landfill gas-to-energy assessments from developing-country contexts provide useful benchmarks for evaluating the scale and behavior of landfill gas recovery systems. Studies from India report projected electricity generation potentials ranging from approximately 20 to 60 GWh over landfill lifetimes for medium to large municipal landfill sites modelled using first-order decay approaches such as LandGEM, with outcomes strongly influenced by waste intake rates and the proportion of biodegradable organic material [27, 28]. Research from China similarly demonstrates that newly engineered landfill cells can sustain methane generation over several decades, with electricity generation profiles typically peaking shortly after waste placement and declining gradually thereafter, reflecting the expected progression of anaerobic waste decomposition [17, 18]. Evidence from other rapidly urbanizing regions, including Southeast Asia and parts of Latin America, further indicates that landfill gas-to-energy projects generally contribute a modest but stable share of municipal electricity supply while delivering significant greenhouse gas mitigation benefits through methane capture and fossil fuel displacement [22, 23]. Collectively, these studies highlight that landfill gas-to-energy systems in waste-intensive and coal-dependent energy systems tend to deliver consistent, medium-scale electricity outputs rather than large contributions to total demand, underscoring their role as complementary and dispatchable renewable energy sources within diversified urban energy portfolios [8].

B. Uncertainty and Limitations

The results presented in this study are subject to uncertainties inherent in landfill gas modelling, particularly when applied at the planning and design stage of landfill development. The LandGEM model is sensitive to key input parameters, notably the methane generation rate constant (k), the methane generation potential (L_0), and the assumed landfill gas collection efficiency. Variations in waste composition, moisture content, compaction practices, and climatic conditions can influence these parameters and lead to deviations in methane generation over time.

In the absence of site-specific degradation data for the newly engineered cells, literature-derived parameter values representative of similar climatic and waste management conditions were applied. This introduces uncertainty typical of screening-level assessments. Additional uncertainty arises from the assumption of constant waste acceptance rates and uniform waste composition throughout the operational lifespan of each cell. In practice, municipal waste streams may change due to evolving consumption patterns, recycling initiatives, or regulatory interventions. However, holding these parameters constant represents a conservative modelling choice that avoids overstating methane generation and electricity potential. The assumed landfill gas collection efficiency of 75% reflects performance levels associated with well-managed engineered landfill systems, although actual recovery rates may vary spatially and temporally depending on wellfield design, operational practices, and maintenance. Despite these limitations, the first-order decay approach implemented in LandGEM has been widely shown to provide robust order-of-magnitude estimates of long-term methane generation, particularly for comparative and planning

analyses. When modelling large waste masses over extended periods, short-term variability tends to average out, thereby strengthening the reliability of long-term trends. Accordingly, while absolute values of methane and electricity generation may vary under alternative parameter assumptions, the overall conclusions regarding the technical feasibility, relative scale, and strategic value of landfill gas-to-energy at Robinson Deep remain robust. Future work could further refine these estimates through sensitivity analysis or calibration using operational gas extraction data once the new landfill cells become active.

V. CONCLUSION

This study evaluated the future landfill gas-to-energy potential of the Robinson Deep Phase 1 landfill extension by modelling methane generation from 2 newly engineered landfill cells and translating the results into electricity generation, coal displacement, and climate mitigation metrics relevant to South Africa's coal-dependent energy system. The findings demonstrate that the 2 new cells are capable of generating approximately 70–75 GWh of electricity over their operational lifetimes, corresponding to the utilization of 35–40 million m³ of methane and the displacement of nearly 40,000 tons of coal. These results confirm that landfill gas recovery at Robinson Deep remains technically viable and environmentally beneficial beyond the existing landfill footprint. The temporal profiles of methane and electricity generation indicate that energy output peaks shortly after landfill cell closure and declines gradually thereafter, consistent with first-order decay behavior observed in comparable landfill gas-to-energy projects in Johannesburg and other developing urban contexts. Cell 1 provides an immediate but shorter-term renewable energy contribution, while Cell 2 delivers a more sustained electricity output over a longer period. Together, the cells offer a balanced renewable energy profile that supports both short- and medium-term municipal energy planning. From a policy and planning perspective, the results highlight the importance of integrating landfill gas-to-energy considerations into landfill design and expansion decisions rather than treating energy recovery as a retrospective intervention. In coal-dependent systems such as South Africa's, landfill gas-to-energy should be understood as a dispatchable, baseload renewable resource that complements intermittent technologies such as solar and wind while delivering high-value methane mitigation benefits. Although the projected electricity contribution represents a small fraction of Johannesburg's total demand, its strategic value lies in localized generation, emissions reduction, and fuel substitution rather than large-scale power supply.

The findings further support the role of landfill gas-to-energy within Johannesburg's Climate Action Plan and South Africa's broader energy transition objectives. By quantifying coal displacement and long-term energy yields at the design stage, this study provides evidence to support more informed municipal decision-making, particularly with respect to landfill engineering standards, gas capture infrastructure investment, and the inclusion of landfill gas projects within renewable energy procurement and planning frameworks. Overall, the Robinson Deep Phase 1 extension demonstrates how engineered landfill infrastructure can

simultaneously extend landfill lifespan, enhance renewable energy generation, and contribute to climate mitigation goals. The value of this study lies not in methodological novelty but in its forward-looking application to landfill expansion planning. Similar planning assessments are recommended for other large municipal landfills in South Africa to strengthen the contribution of waste-to-energy technologies within an integrated, low-carbon urban energy system.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Malillane Lillane conducted the research and analyzed the data; Khomotso Semenya reviewed the paper; and all authors approved the final version.

ACKNOWLEDGMENT

The authors wish to thank the University of South Africa for the support.

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