The Potential of Biomethane produced from Waste Landfill to Supplement Renewable Energy in Saudi Arabia

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ABSTRACT

This study investigates the potential of biomethane from waste landfills in five major cities of Saudi Arabia (Riyadh, Jeddah, Makkah, Madina, and Dammam) using the Landfill Gas Emissions (LandGEM) model to estimate methane emissions from 2015 to 2115. The research assesses the cumulative methane emissions, projected to reach nearly 25.5 billion m^3 by 2115, and quantifies the electricity generation potential from this biomethane, peaking at 1,299 GWh annually. Sensitivity analysis of key parameters, including the methane producing rate (k) and potential methane producing capacity (L_o), indicates that L_o has a more impact on methane output. These findings highlight the importance of methane capture and landfill management strategies to enhance the renewable energy capacity of Saudi Arabia. Policy implications are discussed, highlighting the opportunity for biomethane to supplement the country's energy mix in alignment with its Vision 2030 goals and commitment to reducing greenhouse gas emissions through the Global Methane Pledge.

Keywords-biomethane potential; landfill methane emissions; renewable energy; LandGEM model; waste-to-energy; methane capture strategies

I. INTRODUCTION

The shift toward renewable energy sources has become essential worldwide, motivated by cutting greenhouse gas emissions, addressing climate change, and enhancing energy security. Countries worldwide are exploring various pathways to diversify their energy portfolios, including Saudi Arabia, which has outlined its commitment to renewable energy through the Vision 2030 initiative. Vision 2030 establishes bold objectives aimed at decreasing the nation's reliance on non-renewable energy sources and promoting the use of sustainable energy alternatives [1]. Among the various renewable energy options, Waste-to-Energy (WtE) technologies, particularly those involving Landfill Gas (LFG) recovery, present a viable yet underexplored option for diversifying the energy mix [2, 3]. Biomethane, which is a product of the decomposition of organic waste in landfills, offers a renewable energy source that can be harnessed for electricity and heat generation. Given Saudi Arabia's rapid urbanization and high levels of waste production, there is a significant potential for utilizing landfill gas as an energy source.

In countries like the United States and Germany, LFG recovery systems are well-established and have shown the dual advantages of lowering greenhouse gas emissions while producing renewable energy. For example, the U.S. The Environmental Protection Agency (USEPA) has reported that as of 2021, over 500 operational landfill gas-to-energy projects are in place, contributing to both local energy grids and emission reduction targets [4]. Similarly, Germany has integrated WtE projects into its national energy strategy, converting waste materials into both heat and electricity, further reducing its reliance on fossil fuels [5]. In contrast, Saudi Arabia's waste management system has not yet fully embraced LFG recovery, despite the country's substantial waste generation [2]. Saudi Arabia generates approximately 1.15 – 2.04 kg/capita/day Municipal Solid Waste (MSW), with much of this waste ending up in landfills without any gas capture infrastructure [6]. The limited adoption of LFG recovery can be attributed to several factors, including the historical abundance of cheap fossil fuels, the lack of regulatory frameworks that incentivize renewable energy, and the relatively nascent state of WtE technologies in the country. Although the Kingdom has expressed interest in diversifying its energy portfolio through Vision 2030, the focus has largely been on solar and wind energy, leaving significant untapped potential in areas such as LFG or biomethane recovery from landfills [7, 8].

Methane (CH_4) is a greenhouse gas, possessing a Global Warming Potential (GWP) that is 25 times greater than that of carbon dioxide (CO_2) over 100 years [9]. MSW landfills produce approximately 11% of the global CH_4 emissions, rendering them among the primary contributors to human-caused methane emissions [4]. In 2020, global methane emissions from MSW landfills were estimated to be approximately 1.6 billion metric tons of CO_2-equivalent (CO_2-eq) [10]. These emissions are primarily due to the anaerobic decomposition of organic waste components such as food, paper, and yard debris. If captured, landfill methane can be processed into biomethane, which can serve as a renewable energy source. For instance, biomethane from landfills contributed approximately 18.2 terawatt-hours (TWh) of energy to the U.S. energy grid in 2020, enough to power over 1.5 million homes annually [4]. Thus, the capture and utilization of LFG offers dual benefits: mitigating harmful greenhouse gas emissions and generating renewable energy. Several studies have demonstrated that LFG recovery can reduce methane emissions by up to 60–90%, while contributing significantly to national energy grids, particularly in regions with high waste generation and limited renewable energy sources [11, 12].

Saudi Arabia, with a population surpassing 35 million by 2022, is witnessing rapid urbanization and economic growth, which has resulted in a substantial increase in MSW generation. The country produces approximately 15 million tons of MSW annually, with per capita waste production ranging from 1.4 to 1.8 kg/day in major cities like Riyadh, Jeddah, Makkah, Madina, and Dammam. These urban centers contribute a major portion of the nation's waste output, with estimates suggesting that around 43% of the total MSW originates from Riyadh (21%), Jeddah (14%), and Dammam (8%) alone [13]. The relationship between population growth, urbanization, and waste disposal practices in Saudi Arabia has created challenges for waste management. Most of the waste is sent to landfills for disposal, many of which are open dumpsites without gas capture systems. This is particularly problematic given the country's hot and arid climate, which can accelerate the decomposition of organic waste and methane production [14]. Organic waste that could be used for biomethane production is often mixed with recyclables and hazardous materials, complicating waste management efforts. Despite the potential for methane capture and the production of renewable energy, addressing these challenges requires not only technological investment in LFG recovery, but also reforms in waste disposal practices, improved waste segregation, and the creation of policies to incentivize renewable energy from waste [7, 15].

A commonly utilized model for assessing CH_4 emissions from landfills is the Landfill Gas Emissions (LandGEM) model, which was created by the USEPA [16]. LandGEM utilizes a first-order decay equation to predict CH_4 generation based on waste composition, landfill operation characteristics, and climate data. This model has gained global acceptance owing to its simplicity and adaptability to various environmental and operational conditions. The LandGEM model has been extensively applied in various countries to estimate methane emissions from MSW landfills, offering insights into both the energy production potential and greenhouse gas mitigation. In Morocco, for instance, a controlled landfill was projected to generate approximately 1.76×10^8 m³ of methane over 20 years, underscoring its potential for renewable energy generation and a reduced carbon footprint [17]. Similarly, in Sanandaj, Iran, CH_4 production is estimated to reach 671 m³/h by 2033, illustrating the significance of LFG capture in waste management strategies [18]. Another study in Yasuj, Iran, estimated peak methane production between 2010 and 2012 at 330 m³/h, reflecting the influence of waste characteristics on emission rates [19]. Although originally developed for U.S. conditions, the LandGEM model has also been adapted to suit different climates and waste compositions, as demonstrated by its application in India, where modifications were necessary to account for local waste and environmental factors [20]. Similar studies have been conducted by other researchers at different geographic locations [21-26].

Although the LandGEM model has been extensively utilized to estimate methane emissions from municipal solid waste landfills in various countries, its application in Saudi Arabia remains at an early stage. Few studies, such as [8, 11, 27], have examined methane generation in landfills in selected Saudi cities. However, despite Saudi Arabia's high rates of waste generation, there are limited local data on methane generation and energy recovery potential, with few comprehensive studies using models, such as LandGEM. This study aims to fill this research gap by applying the LandGEM model to landfills in Riyadh, Jeddah, Makkah, Madina, and Dammam. In doing so, it provides a more thorough understanding of methane generation across the nation and evaluates the potential for biomethane recovery to supplement Saudi Arabia's renewable energy strategies.

The specific objectives of this study are as follows:

1. Estimation of methane emissions using the LandGEM model for the period 2015–2115, providing a comprehensive overview of the methane generation potential in Saudi Arabia's five largest cities.
2. Calculation of potential energy generation from the estimated biomethane emissions.
3. Uncertainty analysis to evaluate the influence of key input parameters' variability on methane generation.

The originality of this research lies in its detailed estimation of methane emissions and the potential for energy recovery from landfills in Saudi Arabia, addressing a significant gap in regional LFG recovery data. By using the LandGEM model, the study performs an uncertainty analysis based on input parameters to provide a robust projection of methane generation. Additionally, it critically reviews Saudi Arabia's waste management practices and advocates for policy reforms and improved waste strategies to align with Vision 2030, emphasizing the untapped potential of biomethane in the national energy mix.

II. MATERIALS AND METHODS

A. Study Area

This study is focused on five key cities in Saudi Arabia: Riyadh, Jeddah, Makkah, Madina, and Dammam, chosen for their large populations and significant MSW generation. Riyadh, the capital and largest city of Saudi Arabia, experiences a dry desert climate, with extreme temperatures that can significantly impact landfill gas emissions. Jeddah, the second-largest city, is settled along the Red Sea and has a coastal climate that tends to be more humid, affecting waste decomposition rates differently. Makkah attracts a massive influx of visitors during the Hajj season, significantly increasing waste generation. Madina, located to the northwest, has a desert climate similar to Riyadh. Finally, Dammam lies in the eastern region near the Persian Gulf and experiences a hot and humid climate. These cities contribute to the majority of Saudi Arabia's MSW, making them ideal for studying the methane generation potential and exploring landfill gas recovery projects. The diverse climates and urbanization rates among these cities also provide important variables for understanding the regional variations in waste decomposition and methane emissions. Figure 1 shows the locations of the five cities.

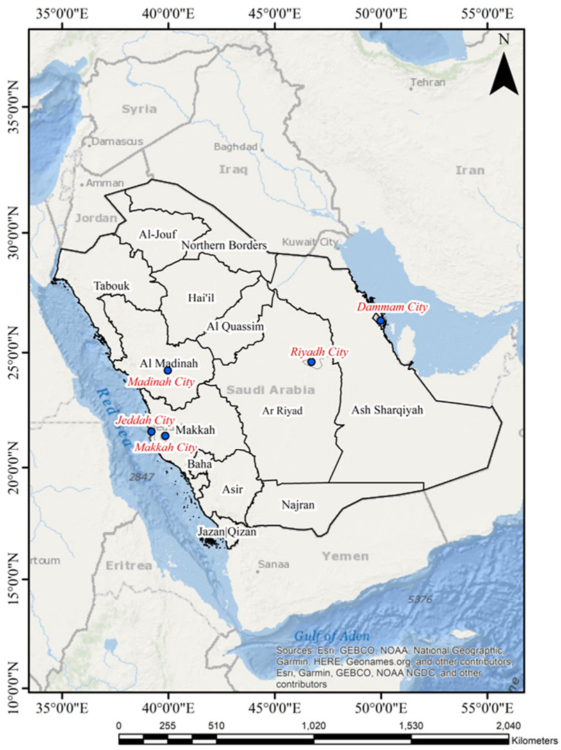

Fig. 1. The 5 major cities in Saudi Arabia considered in this research.

B. Methane Emissions Model

Methane emissions from landfills were assessed using the LandGEM model, which employs a first-order decay methodology to calculate CH_4 generation over time, and is based on the following equation:

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

Where, Q_{CH_4} is the methane generation rate (m^3/yr), L_0 is the methane generation capacity (m^3/Mg), k is the methane generation rate constant (yr^{-1}), M_i is the mass of waste at i-th year (Mg), t is the time since waste was deposited (in yrs). These parameters are crucial for accurately predicting methane emissions and assessing the feasibility of landfill gas-recovery projects. Table I shows the details of the parameters used in the LandGEM model. For modeling purposes, it was assumed that the landfill opened in 2015, and the closure year was 2035.

TABLE I. INPUT PARAMETERS USED IN THE LANDGEM MODEL

Parameters	The value used in the model	Comment
CH_4 generation rate constant, k (yr^{-1})	0.02	For arid areas. Clean Air Act (CAA) regulation
CH_4 generation capacity, L_0 (m^3/Mg)	170	For arid areas. CAA regulation
CH_4 content (% by volume)	50	Default
NMOC concentration (ppmv)	4000	CAA regulation

C. Estimation of Municipal Solid Waste Generation

The population dynamics in the study cities, Riyadh, Jeddah, Makkah, Madina, and Dammam, experienced substantial growth due to rapid urbanization, economic expansion, and inward migration. This population surge has led to increased waste generation, placing additional pressure on waste management systems. Population data for these cities from 2015 to 2025 were obtained from the United Nations population projections [28], which show a consistent rise. Using this trend, population growth was further projected to 2035 (Figure 2). According to the Intergovernmental Panel on Climate Change (IPCC) guidelines, the waste generation rate is estimated to be 470 kg/capita/year [29]. Using this generation rate and the projected population, the total MSW per year for the study areas was calculated using (2). This calculation is essential for estimating future waste volumes and for evaluating the potential for landfill gas recovery in these cities.

$$Total\ MSW = per\ capita\ generation\ of\ MSW \times projected\ population \quad (2)$$

The projected amounts of MSW for the studied cities are shown in Figure 2.

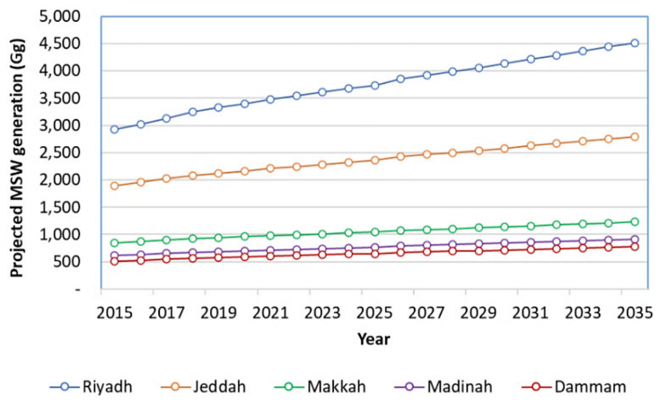

Fig. 2. Projected MSW generation for the studied cities [28].

D. Potential Energy Generation from the Biomethane

The electrical energy generation from biomethane was calculated using (3) [30]:

$$E_p = \frac{LHV_{CH_4} \times \eta \times \mu \times Q_{CH_4}}{3.6} \quad (3)$$

Where, E_p is the electrical energy generation (kWh/year), Q_{CH_4} is the amount of methane generated per year, calculated using the LandGEM model (m^3/yr), LHV_{CH_4} is the lower heating value of methane taken as 37.2 MJ/m^3 [31], η is the methane collection efficiency taken as 75% [32], μ is to the efficiency of a gas engine for converting methane to electricity taken as 33% [33]. The 3.6 is used as the conversion factor from MJ to kWh.

The steps involved in the modeling process are shown in Figure 3.

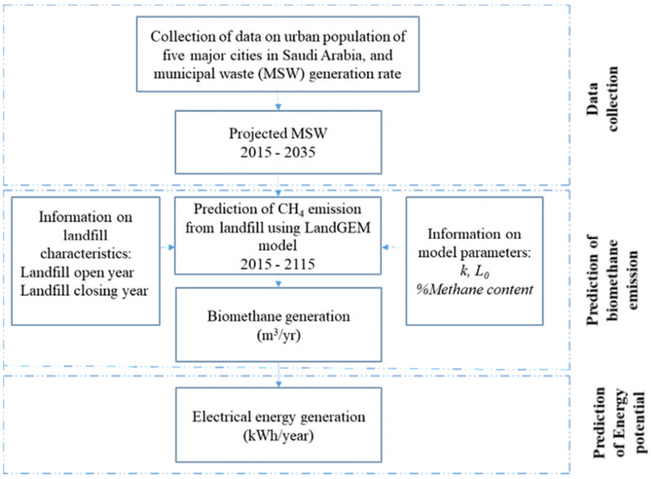

Fig. 3. Steps involved in the modeling process.

III. RESULTS AND DISCUSSION

This section outlines the results of methane emission estimates for the five studied cities. The findings were analyzed based on data generated by the LandGEM model for a 100-year projection from 2015 to 2115. The model considered various factors influencing methane generation from MSW landfills, including population growth, waste generation rates, and climate conditions. Additionally, the cumulative methane generation is discussed in the context of global methane emission trends and Saudi Arabia's efforts to reduce greenhouse gas emissions in line with its Vision 2030 goals. These results highlight the significance of mitigating methane emissions from landfills through waste management strategies, such as methane capture and energy conversion, which could play a crucial role in the country's renewable energy portfolio. The following sections present the specific methane emission profiles for each city and the overall trends observed throughout the study period.

A. Methane Emission from the Five Major Cities

Biomethane generation from the landfills of five cities is presented in Figure 4. In the context of Riyadh's landfill emissions, the model highlights an initial phase of increasing methane generation, driven by the rapid accumulation and anaerobic degradation of organic waste. During the first two decades (2015 to 2035), as organic waste undergoes accelerated decomposition, methane emissions rise steeply, as captured by the exponential growth in the emission data. LandGEM predicts such a trend due to the high availability of fresh organic material, which actively decomposes in the early years of landfill operation. The peak emissions in 2036, as simulated by LandGEM, reflect the maximum point of methane generation, where most of the deposited waste has entered the decomposition phase. After this peak, the emissions gradually decline, consistent with LandGEM's assumption that methane production slows as the organic content of the waste is exhausted. The decline continues as the landfill matures, and the residual waste stabilizes over time. The results obtained from LandGEM provide valuable insights for managing landfill emissions. For instance, during the peak methane production phase (up to 2036), methane capture systems could be installed to convert this potent greenhouse gas into a renewable energy source. Additionally, the model's long-term projection of declining emissions emphasizes the importance of implementing waste reduction and diversion strategies early on to reduce the organic content that contributes to future methane generation.

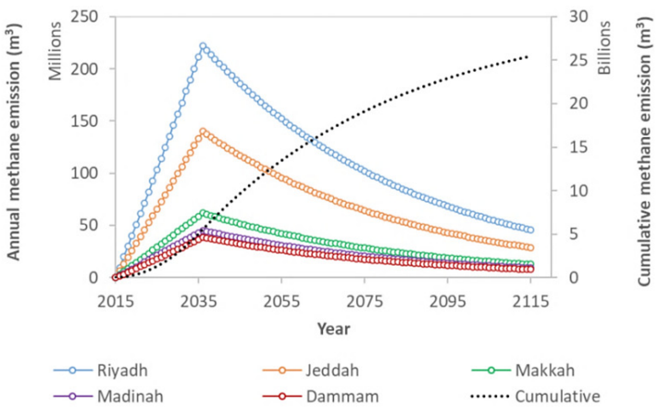

Fig. 4. Modelled biomethane generation in the studied areas.

A similar trend was observed in methane emissions for the other four cities (Jeddah, Makkah, Madinah, and Dammam), although the peak emission rates varied. Jeddah, being the second-largest city, recorded the highest emissions after Riyadh, peaking at approximately 137 million m^3 in 2036, slightly lower than Riyadh's peak of 222 million m^3. Makkah, known for its pilgrimage activities, had a peak emission of approximately 61.8 million m^3 in the same year. Madinah and Dammam, smaller in size and population, recorded their peak emissions at 45.3 million m^3 and 38.4 million m^3 respectively. These peak values reflect the varying population densities, economic activities, and waste generation patterns across the cities. Overall, while Riyadh led in emissions due to its size and urbanization, all cities demonstrated significant methane generation from their landfills, emphasizing the need for integrated waste management and methane recovery across the country.

The total methane emissions from the five studied cities in Saudi Arabia represent a significant contribution to the national greenhouse gas emissions. As demonstrated by the data, cumulative methane emissions will reach nearly 25.5 billion m^3 by 2115 (Figure 4), suggesting that methane, a potent greenhouse gas, will continue to have long-term environmental impact if left unmitigated. Comparing this result to Saudi Arabia's overall methane emissions landscape, the contribution from landfills is a critical factor to consider. According to the Global Methane Initiative [34], Saudi Arabia is estimated to produce approximately 7.3 million metric tons of CO_2-eq ($MTCO_2$-eq) methane annually in 2020, with a significant portion originating from the waste sector. Given that methane emissions from landfills, particularly MSW, constitute a substantial part of this figure, the cumulative emissions projected for these five cities over the next century will constitute a sizable portion of the country's methane budget. In a broader context, Saudi Arabia's commitment to methane reduction was further emphasized during the country's announcement of joining the Global Methane Pledge at COP26 [35], where nations pledged to minimize CH_4 emissions by at least 30% by 2030. Considering that CH_4 has a GWP 28-36 times greater than CO_2 over 100 years, addressing emissions from landfills, especially those forecasted to grow, as indicated by LandGEM, has become a priority. Given the Kingdom's arid climate, with less organic decomposition than in wetter climates, methane capture technologies might be a more feasible solution. In other regions, such as the United States, methane capture from landfills has shown significant potential. For instance, according to [4], approximately 17% of methane emissions in the U.S. come from landfills, but with robust LFG capture systems, much of this methane is harnessed for energy generation, reducing emissions while contributing to the renewable energy mix.

Although research on biomethane recovery from landfills in Saudi Arabia is relatively limited, some studies have addressed specific regions or cities. For example, a study conducted on methane emissions from the Kakia landfill in Makkah [27] used the LandGEM model and highlighted the potential for renewable energy recovery, aligning with our findings. This study predicted the generation of 952,996,960 m^3/year of methane from 2003 to 2143. However, the methane generation capacity (L_o) used in their study was 83.52 m^3/Mg, which is lower than the default L_o in our study (Table I). This lower L_o results in less methane generation compared to the estimates reported here. Similarly, another study by the same lead author [36] estimated methane generation from the Madinah landfill to be 881,358,352 m^3/year for the same period (2003 to 2143). International studies have also reported results consistent with ours. For example, the authors of [21] estimated 116 × 10^6 m^3/year of methane generation from a landfill in Kanpur, Andhra Pradesh, India, for the study period from 2015 to 2155. Abdelli et al. reported a potential total methane generation of 669,330,543 m^3 and 1921.98 GWh of electricity from four landfill sites in Algeria over a study period of approximately 140 years [22].

B. Estimation of Electrical Energy Potential

The methane-based electricity generation from the five major cities in Saudi Arabia demonstrate the role landfills can play in contributing to the country's renewable energy portfolio. As shown in Figure 5, the electricity generation from landfill methane rises from 58.44 GWh in 2016 to its peak of 1,299.88 GWh by 2036, after which it gradually declines to 267.74 GWh by 2115. The methane capture from these landfills provides a temporary but valuable source of renewable energy that supplements Saudi Arabia's national electricity grid. Landfill methane electricity generation in these cities aligns with Saudi Arabia's broader efforts to diversify its energy sources under the Vision 2030 framework. As of 2020, Saudi Arabia's total electricity production was approximately 338 TWh annually [37], of which landfill methane energy, even at its peak, would contribute around 0.35%. This small share indicates that while methane from landfills is not a major contributor to the total energy mix, it is still crucial for localized energy solutions and emission reductions. For instance, Riyadh's peak generation of 569 GWh alone could power a significant portion of the city, offering local benefits, even if the national impact remains limited. The declining trend in methane electricity generation post-2036 further emphasizes the need for an integrated, multi-pronged approach to renewable energy. While methane recovery provides immediate benefits, it cannot sustain the country's energy needs long-term. Therefore, investments in solar, wind, and other renewable technologies will be essential as the country moves towards its net-zero emissions targets. By integrating landfill gas recovery into the broader renewable energy strategy, Saudi Arabia can ensure that its efforts to mitigate climate change are both comprehensive and sustainable.

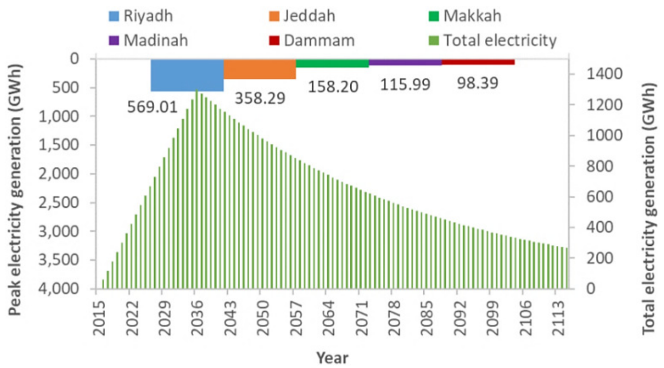

Fig. 5. Potential total energy generation from the study area landfills.

C. Sensitivity Analysis

The sensitivity analysis of the methane generation parameters (Figure 6) reveals important insights into their relative influence on average biomethane production over the 100 years from 2015 to 2115. By varying each parameter by ±25%, the impact on methane generation is quantified, allowing for a comparison of which parameter exerts more control over the total methane yield.

The methane generation rate constant, *k,* represents the rate at which methane is produced by the decomposition of organic matter in landfills. The data indicates that altering *k* by 25% results in a noticeable but moderate change in methane production. A 25% reduction in *k* leads to a 11.4% decrease in average methane production. On the other hand, a 25% increase in k results in a 7.3% increase in methane generation. This asymmetrical response, where a decrease in *k* results in a larger negative impact than the positive effect of an increase, suggests that, while *k* is an important factor in methane production, its influence is relatively constrained compared to other parameters. In contrast, the potential methane generation capacity (L_o), which indicates the total methane volume has a far greater impact on methane generation. The analysis shows that varying L_o by 25% leads to direct, proportional changes in methane production. A 25% reduction in L_o results in a 25% decrease in methane production. Similarly, a 25% increase in L_o leads to a corresponding 25% increase in methane production. These results demonstrate that L_o is a highly sensitive parameter, and even small changes in its value can lead to significant deviations in the overall methane yield from landfills. Accurate prediction and optimization of methane generation for energy production or environmental mitigation efforts should, therefore, focus on refining the estimation of L_o, while ensuring that *k* is also carefully considered to account for landfill-specific conditions.

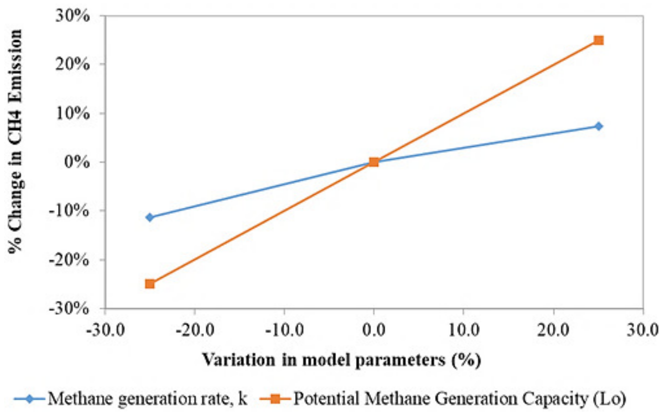

Fig. 6. Sensitivity analysis of model parameters.

D. Policy Implications

The results of this study have important implications for Saudi Arabia's renewable energy strategies, particularly in the context of Vision 2030 goals, which aim to diversify the country's energy mix and reduce its reliance on fossil fuels. The large-scale methane emissions projected from landfills in major cities such as Riyadh, Jeddah, Makkah, Madina, and Dammam underscore the urgent need for policies that integrate methane capture technologies as a vital part of the country's renewable energy efforts. By harnessing methane from landfills, Saudi Arabia has the potential to convert greenhouse gases into a valuable energy resource, contributing to both environmental sustainability and energy security.

Given that the potential methane generation capacity (L_o) has a profound impact on methane emissions, policymakers must establish stricter regulations on waste management practices. Mandating the segregation of organic waste and investing in waste-to-energy infrastructure could substantially reduce landfill emissions. Furthermore, adopting best practices from countries with advanced landfill gas capture systems, such as the U.S. and the EU, could enhance the efficiency of methane recovery in Saudi landfills.

Policy recommendations should also include incentives for private sector investment in methane capture and utilization technologies along with stronger enforcement of methane monitoring at landfill sites. These efforts can align with Saudi Arabia's commitment to global methane reduction targets, such as the Global Methane Pledge while creating opportunities for renewable energy generation and reducing the country's carbon footprint. By prioritizing landfill methane capture, Saudi Arabia can take a decisive step toward a greener and more diversified energy future.

IV. CONCLUSIONS

This study highlights the significant potential of biomethane recovery from landfills in Saudi Arabia's five largest cities—Riyadh, Jeddah, Makkah, Madina, and Dammam—over the next century. Methane emissions from these landfills are projected to reach nearly 25 billion m^3 by 2115, contributing substantially to the country's overall greenhouse gas emissions. If left unmanaged, these emissions could have long-term environmental impacts. However, they also present an opportunity for renewable energy generation, which aligns with Saudi Arabia's Vision 2030 and its commitments under the Global Methane Pledge. The analysis shows that methane recovery from landfills could generate up to 1,299 GWh of electricity annually by 2036, making it a valuable supplement to Saudi Arabia's renewable energy goals. Sensitivity analysis of key parameters i.e., *k* (methane generation rate constant) and L_o (methane generation capacity), revealed that the latter has a more significant influence on methane emissions. Thus, improving waste management practices and increasing the capacity for methane recovery could significantly boost biomethane production. These findings emphasize the importance of adopting comprehensive policies for landfill management, methane capture, and utilization. Implementing stricter regulations on waste segregation, incentivizing investment in methane capture technologies, and establishing monitoring systems are essential steps for reducing greenhouse gas emissions while enhancing energy security. Through proactive measures, Saudi Arabia can transform its landfills from environmental liabilities into sources of renewable energy, contributing to both its national and global sustainability goals. It is a critical area that requires further attention, research, and policy action to maximize its potential in the coming decades.

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