A Preliminary Assessment of the Quantity of Methane from Landfill Gas on the Island of Trinidad using the IPCC 2006 Model

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Abstract

Air pollutant emissions from landfills contribute to climate change through high concentrations of greenhouse gases and are a human health concern through their role in exacerbating non-communicable diseases. It is important that solutions are found to mitigate the release of landfill gases into the atmosphere, such as conversion into useful products. However, the quantity of landfill gas available first must be estimated. In Trinidad and Tobago (T&T), 1800 tonnes of waste is generated daily from the country's three major landfill sites: Beetham, Forres Park, and Guanapo. In this study, the available methane from these landfills is quantified.

A Tier 2 approach using the Intergovernmental Panel on Climate Change 2006 Model was used to estimate the quantity of methane gas being released by the landfills in T&T. Using this method, it is estimated that the methane generation at each of the three landfills is as follows: Guanapo 2292.83 m^3/h; Forres Park 3706.89 m^3/h and Beetham 5166.37 m^3/h. An error adjustment of +/-17% was applied, followed by a collection efficiency of 40%. The estimated available methane directly affects any technoeconomic analysis regarding potential uses of the landfill gas. Thus, accurately quantifying the potential amount of methane produced, as presented in this publication, is the first step towards the goal of utilising the landfill gas of T&T in a safe, sustainable, and economic manner.

Keywords: IPCC 2006 model; landfill gas; Non-Engineered Landfill; Climate Change; Trinidad & Tobago; Caribbean Small Island Developing State

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Introduction

Climate change has been credibly associated with anthropogenic greenhouse gases in the atmosphere. One of the main greenhouse gases of concern is methane. Poorly managed landfills are known to emit large amounts of methane (IPCC, 2007). Not only is this a concern in terms of long-term environmental effects, but there are also immediate negative impacts. Specifically, in Trinidad and Tobago (T&T), methane emitted from one of the largest dumpsites in the country, the Beetham landfill, has fuelled fires that lasted for days in the past. These fires have led to hazardous air quality conditions, affected the health of people with respiratory issues, and affected the visibility and odour around the landfill for near-by residents and commuters who must drive past it. Safely collecting, processing, and utilising the methane produced in the landfills of Trinidad and Tobago can reduce the impact of anthropogenic methane locally. In order to utilise the methane produced by landfills in T&T, it must first be quantified. This can be achieved by using published landfill gas estimation models. Landfill gas (LFG) estimation models are essential tools used in landfill project development to estimate the amount of recoverable LFG that is generated over time. Landfill gas comprises several gases (see
Table ***1***) with the main gases being methane and carbon dioxide.

Table 1

Typical Landfill Gas Composition (Wellinger et al., 2013)

Compound (unit)	Landfill gas
Methane (mol%)	30 – 60
Carbon dioxide (mol%)	15 – 40
Nitrogen (mol%)	0 - 50
Oxygen (mol%)	0 – 10
Hydrogen sulphide (mg/m^3)	0 – 1000
Ammonia (mg/m^3)	0 – 5
Total chlorine (mg/m^3)	0 – 800
Total fluorine (mg/m^3)	0 – 800
Siloxanes (mg/m^3)	0 - 50

The most widely used models for estimating the methane emission from landfills are the Landfill Gas Emission Model (LandGEM), proposed by US Environmental Protection Agency (EPA), and the Intergovernmental Panel on Climate Change 2006 Model (IPCC 2006) (Cossu & Stegmann, 2019). These are both first order decay models (FOD) in that they assume that the degradable organic carbon (DOC) in waste decays slowly over a few decades, during which methane (CH_4) and carbon dioxide (CO_2) are formed. If conditions are constant, the rate of CH_4 production depends solely on the amount of carbon remaining in the waste. As a result, emissions of CH_4 from waste deposited in a disposal site are highest in the first few years after deposition, then gradually decline as the degradable carbon in the waste is consumed by the bacteria responsible for the decay (Cossu & Stegmann, 2019). Pillai and Riverol (2018) also conducted a study estimating methane emissions from the landfills in T&T using the LandGem model. However, the IPCC 2006 model is favoured for the Caribbean region as key variables such as the methane generation rate can be modified to align with the region's climate. The use of specific country variables also facilitates comparison of methane generation estimates among countries within the same region. The IPCC 2006 model includes other features that make it appropriate for modelling landfill gas generation in the Caribbean region:

1. Other data specific to the landfills in the country can be entered, such as the composition data for different waste categories such as food waste, garden, paper, wood and straw, textiles etc.
2. The model includes a Methane Correction factor (MCF) to account for (non-methane generating) waste decay.

In this study, for the first time, the IPCC 2006 model was used to determine the methane gas production at T&T's three largest landfills: the Beetham landfill, the Forres Park landfill, and the Guanapo landfill. This article describes in detail the landfill sites, the equations and input values used to determine methane gas production, and the results for the three landfills in T&T.

Background

The Beetham, Forres Park, and Guanapo landfills constitute the three largest main waste disposal sites in Trinidad. All three sites (Figure 1) receive both municipal solid waste from residents as well as commercial waste from haulage contractors that provide services to other businesses. Landfills in Trinidad are managed by the Trinidad and Tobago Solid Waste Management Company Ltd (SWMCOL).

The Beetham Landfill is the largest main disposal site, with a size of 92 hectares (229 acres) and receiving approximately 500 tonnes of waste per day. It is located east of Port of Spain, at coordinates 10.64018, -61.48422, and services the communities within the Diego Martin Municipal Corporation, the Port of Spain Corporation, and the San Juan/Laventille Municipal Corporation (SWMCOL, 2023).

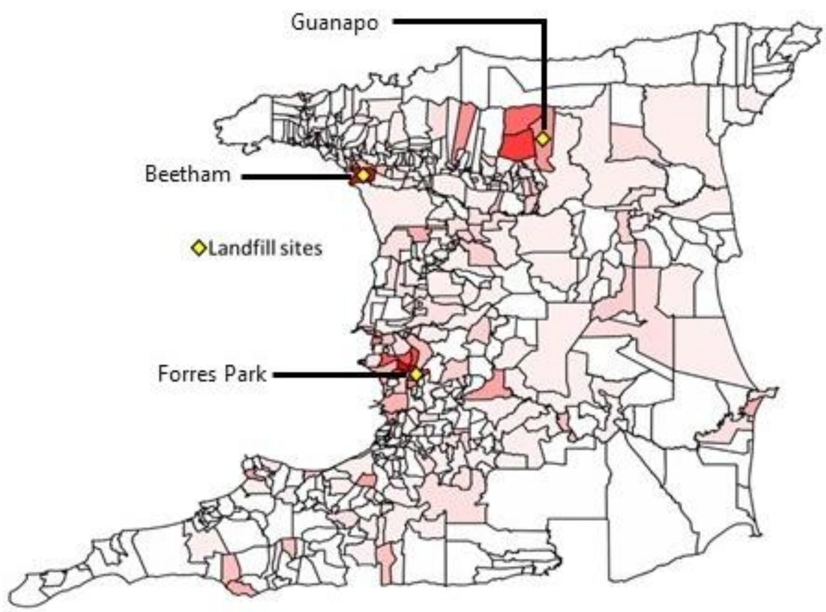
The Forres Park landfill has a size of 22 hectares (55 acres) and receives approximately 300 tonnes of waste per day. It is located east of the Sir Solomon Hochoy Highway, at coordinates 10.37664, -61.41213. This landfill services communities within the Boroughs of Chaguanas and Point Fortin, City of San Fernando and Regions of Penal/Debe, Princes Town, and Siparia (SWMCOL, 2023).

The Guanapo landfill is the smallest main disposal site in Trinidad with an area of 12 hectares (30 acres) yet receives approximately 300 tonnes of waste per day. It is located at 10.65700, -61.26944, 2 km east of the Borough of Arima. It receives waste from communities within the

Regions of Tunapuna/Piarco, Arima, Couva/Tabaquite/Talparo, and the Sangre Grande, and Mayaro/Rio Claro (SWMCOL, 2023).

Figure 1

Landfill Site Locations in Trinidad

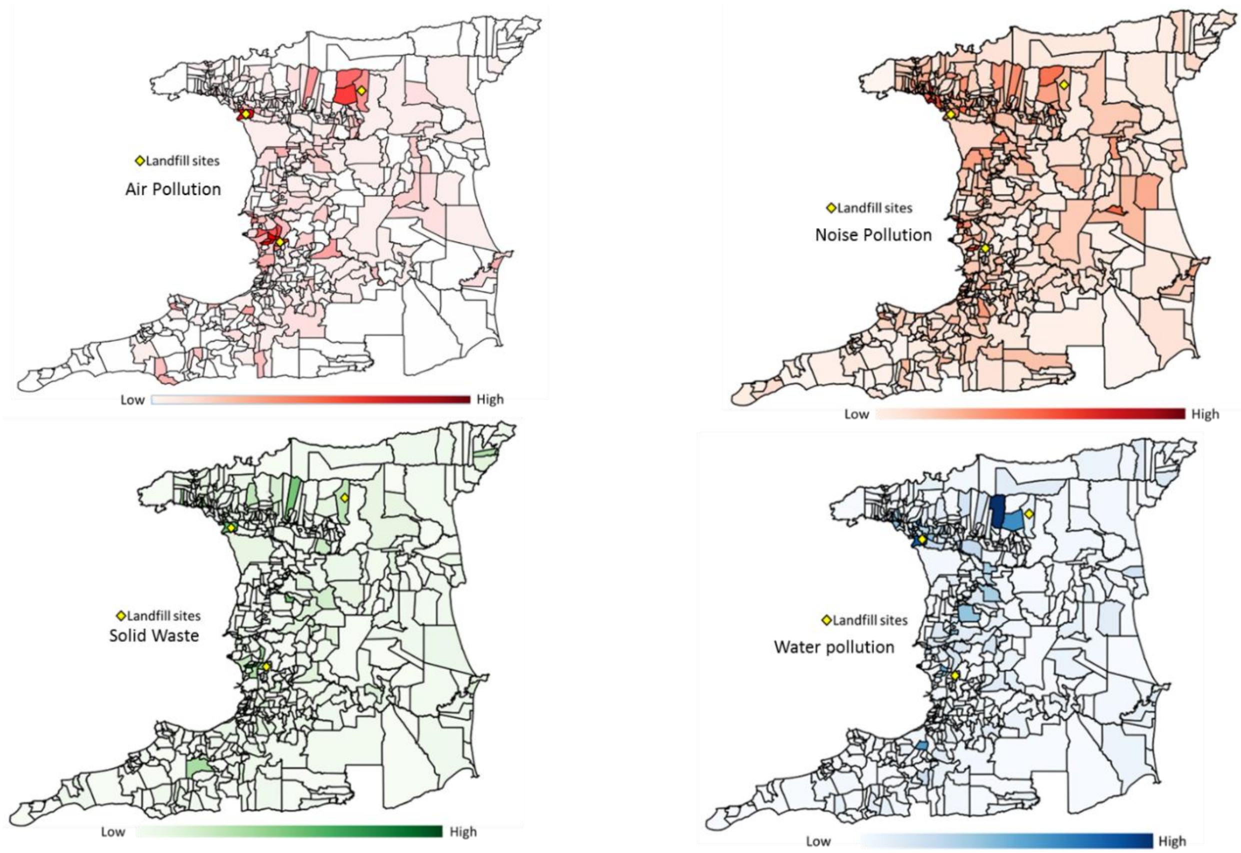


Environmental Issues

While the focus of this paper is on estimating the methane emissions, the landfill sites have significant effects on the environment and the respective fence line communities. Figure 2 shows the geographic distribution of self-reported environmental issues which were collected during Trinidad and Tobago's 2011 Population and Housing Census. This remains the latest available census data on these variables as at 2024. Evidenced from the data, communities within close proximity to the three landfill sites were more impacted by air pollution, solid waste, noise, and water contamination than most other communities (GORTT, Trinidad and Tobago 2011 Population and Housing Census Demographic Report, 2012). Air pollution, which includes methane and other gaseous emissions, stood out as the main reported environmental issue affecting communities within close proximity to the three landfill sites. The situation more significantly impacted those communities than the rest of the island. Additionally, the community closest to the Beetham landfill experienced higher levels of environmental issues compared to the Guanapo and Forres Park landfills.

Figure 2

Households Impacted by Air, Noise, Water, and Solid Waste Contamination



Note: The GORTT Trinidad and Tobago 2011 Population and Housing Census Demographic Report (2012) was used to develop these images.

Methodology

The IPCC 2006 model for determining methane gas production comprises of estimating the methane emissions rate and calculating the methane generated. The detailed equations are presented.

Step 1: Calculate rate of methane emissions.
The methane emissions rate follows a basic accounting of methane generated:

$$Rate\ of\ Methane\ emissions = (Rate\ of\ Methane\ generated - Rate\ of\ Methane\ recovered)(\%\ methane\ not\ oxidised) \quad (Equation\ 1)$$

which can be written mathematically as

$$CH_4\ Emissions = \left(\sum_x CH_4\ \ generated_{x,T} - R_T\right)(1 - OX_T)$$
(*Equation 2*)

where,

$CH_4\ Emissions$	$CH_4\ emitted\ in\ year\ T, Gg$
T	$year\ evaluated$
x	$waste\ category\ or\ type$
R_T	$recovered\ CH_4\ in\ year\ T, Gg$
OX_T	$Oxidation\ factor\ in\ year\ T, (indicates\ the\ amount\ of\ methane\ oxidised\ in\ the\ soil)$

For this analysis, R_T is zero as there are currently no methane recovery processes at any of the landfills being considered.

Step Two: Calculate methane generated.
For the IPCC 2006 model the methane generated, $CH_4\, generated,$ is a function of the decomposable organic carbon. Accumulated, deposited, and decomposed decomposable organic carbon are all considered as seen in (Equation 4 and (Equation 5.

$$CH_4\ generated = DDOCm\ decomp_T \cdot F \cdot 16/12$$
(*Equation 3*)

where,

$DDOCm\ decomp_T$	$Decomposable\ organic\ carbon, decomposed\ in\ year\ T$
F	$fraction\ of\ CH_4\ by\ volume\ in\ generated\ landfill\ gas\ (fraction)$
$16/12$	$molecular\ weight\ ratio\ CH_4/C$

The decomposable organic carbon decomposed in year T is calculated using the following equation (4)

$$DDOCm\ decomp_T = \ DDOCma_{T-1} \cdot (1 - e^{-k})$$
(*Equation 4*)

and $DDOCma_T = DDOCmd_T + (DDOCma_{T-1} \cdot e^{-k})$
(Equation 5)

where,

T	$inventory\ year$

$DDOCma_T$ — $DDOCm\ accumulated\ in\ the\ landfill\ at\ the\ end\ of\ year\ T, Gg$

$DDOCma_{T-1}$ — $DDOCm\ accumulated\ in\ the\ landfill\ at\ the\ end\ of\ year\ T-1, Gg$

$DDOCmd_T$ — $DDOCm\ deposited\ into\ the\ landfill\ at\ the\ end\ of\ year\ T, Gg$

$DDOCm\ decomp_T$ — $DDOCm\ decomposed\ in\ the\ landfill\ at\ the\ end\ of\ year\ T, Gg$

k — $reaction\ constant, k = \frac{ln(2)}{t_{\frac{1}{2}}}\quad (y^{-1})$

where

$$t_{\frac{1}{2}} = half - life\ time\ \ (y)$$

and

$DDOCm = W \cdot DOC \cdot DOC_f \cdot MCF$

where

$DDOCm$ — $mass\ of\ decomposable\ DOC\ deposited, Gg$

W — $mass\ of\ waste\ deposited, Gg$

DOC — $degradable\ organic\ carbon\ in\ the\ year\ of\ deposition, fraction, Gg\ C\ per\ Gg\ waste, Gg$

DOC_f — $fraction\ of\ the\ DOC\ that\ can\ be\ decompose$

MCF — $CH_4\ \ correction\ factor\ for\ aerobic\ decomposition\ in\ the\ year\ of\ deposition$

Input Values

Default values used

The IPCC 2006 model estimates methane generation based on the biodegradable carbon content of waste compounds. The model also assigns different DOC and k values for each waste type based on the amount of degradable organic carbon and the temperature and moisture of the region, respectively. Table 2 shows some of the default values used by the IPCC 2006 model to determine the methane generated in this study.

Table 2
Default Values Used by the IPCC 2006 Model to Estimate Methane Generated

		Food	Garden	Paper	Wood	Textiles	Nappies
DOC		0.15	0.2	0.4	0.43	0.24	0.24
DOCf		0.500	0.500	0.500	0.500	0.500	0.500
Methane generation rate constant	**k**	0.400	0.170	0.070	0.035	0.070	0.170
Half-life time (t1/2, years):	**h = ln(2)/k**	1.7	4.1	9.9	19.8	9.9	4.1
Fraction to CH_4	**F**	0.500	0.500	0.500	0.500	0.500	0.500

Waste Accepted at Landfill
The IPCC 2006 model requires waste data projections up to the year 2030. Actual waste collection data from 1990 to 2010 were used to estimate both future and historical waste quantities, extending back to 1983. At the time of this research, the 2010 waste characterisation study provided the most recent data available. The estimation method involved plotting the total waste collected per year between 1990 and 2010 and determining the best-fit curve to represent the data. The best-fit curves, with R^2 values greater than 0.90, were then used to estimate the unknown waste quantity values at each landfill (Figures 3-5).

The IPCC model, as demonstrated in studies such as those by Lando et al. (2021) and Cakir et al. (2016), has been widely validated and employed for estimating landfill gas production over extended periods, including up to 30 years into the future. This model is grounded in robust methodologies that account for waste composition, degradation rates, and other site-specific factors, ensuring its applicability and reliability even for extended forecasts. For example, Lando et al. (2021) utilised the IPCC Waste Model to project methane emissions from the Tamangapa landfill in Makassar City, Indonesia, over a ten-year period. Their study relied on historical waste generation data and incorporated considerations for population growth and waste composition, achieving consistent predictions aligned with observed trends. Similarly, Cakir et al. (2016) applied the IPCC model to the Harmandali landfill in Izmir, Turkey, successfully estimating gas potential from waste data spanning 1992–2010, with projections extending to 2050.

Figure 3

Annual Waste Quantities at the Beetham Landfill

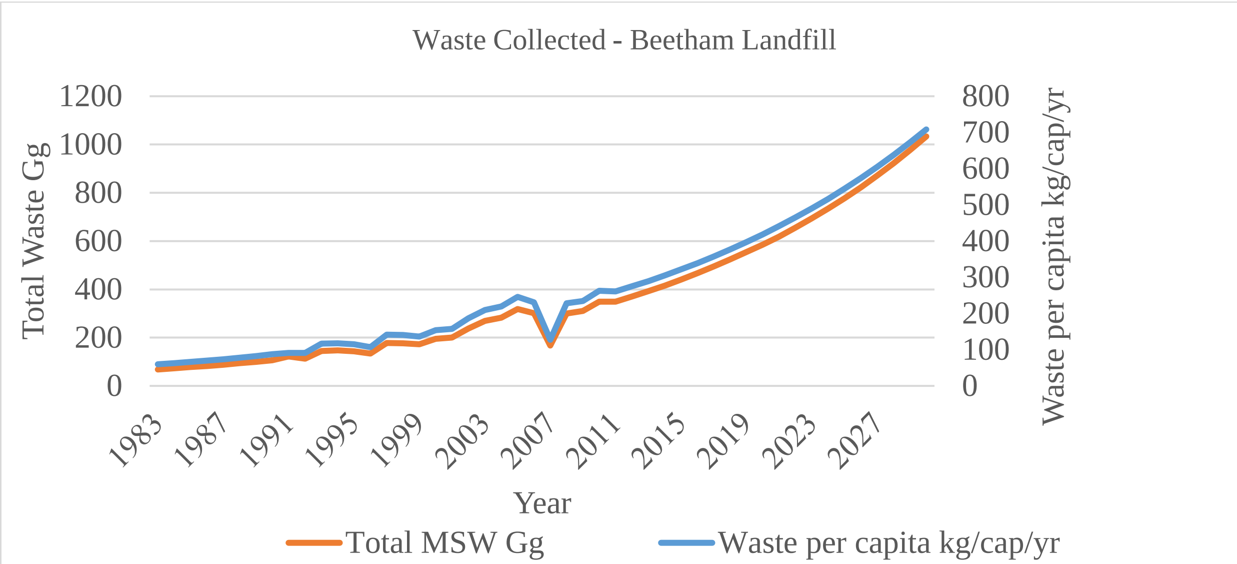


Figure 4

Annual Waste Quantities at the Forres Park Landfill

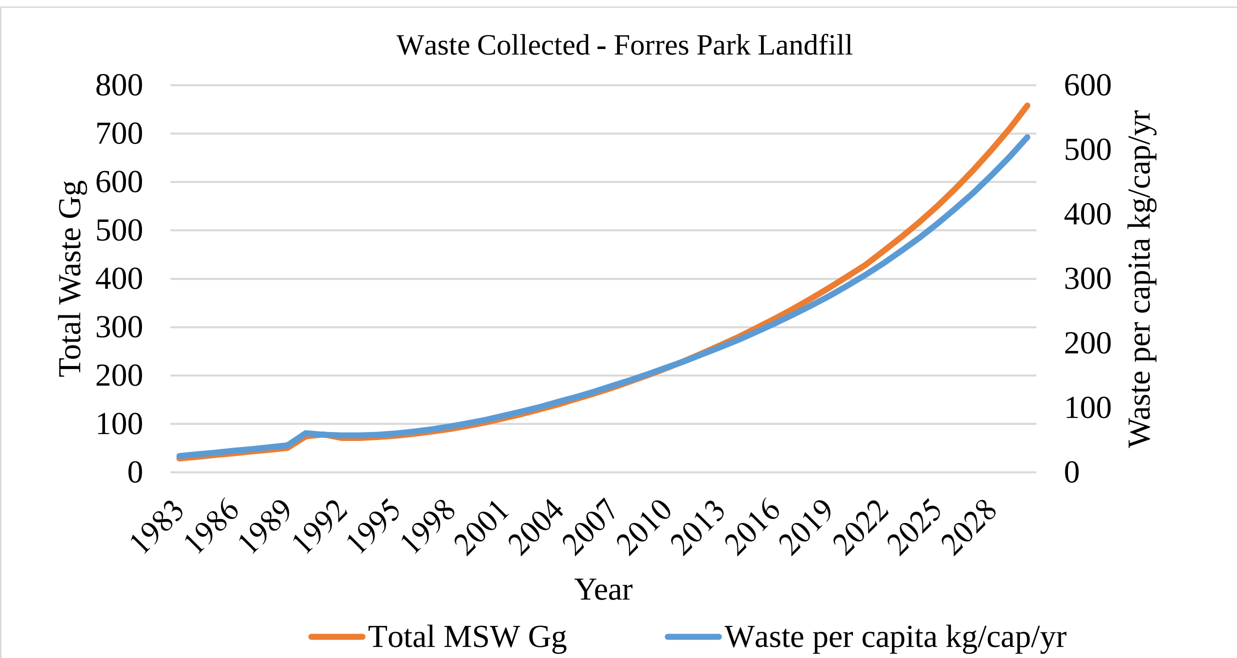
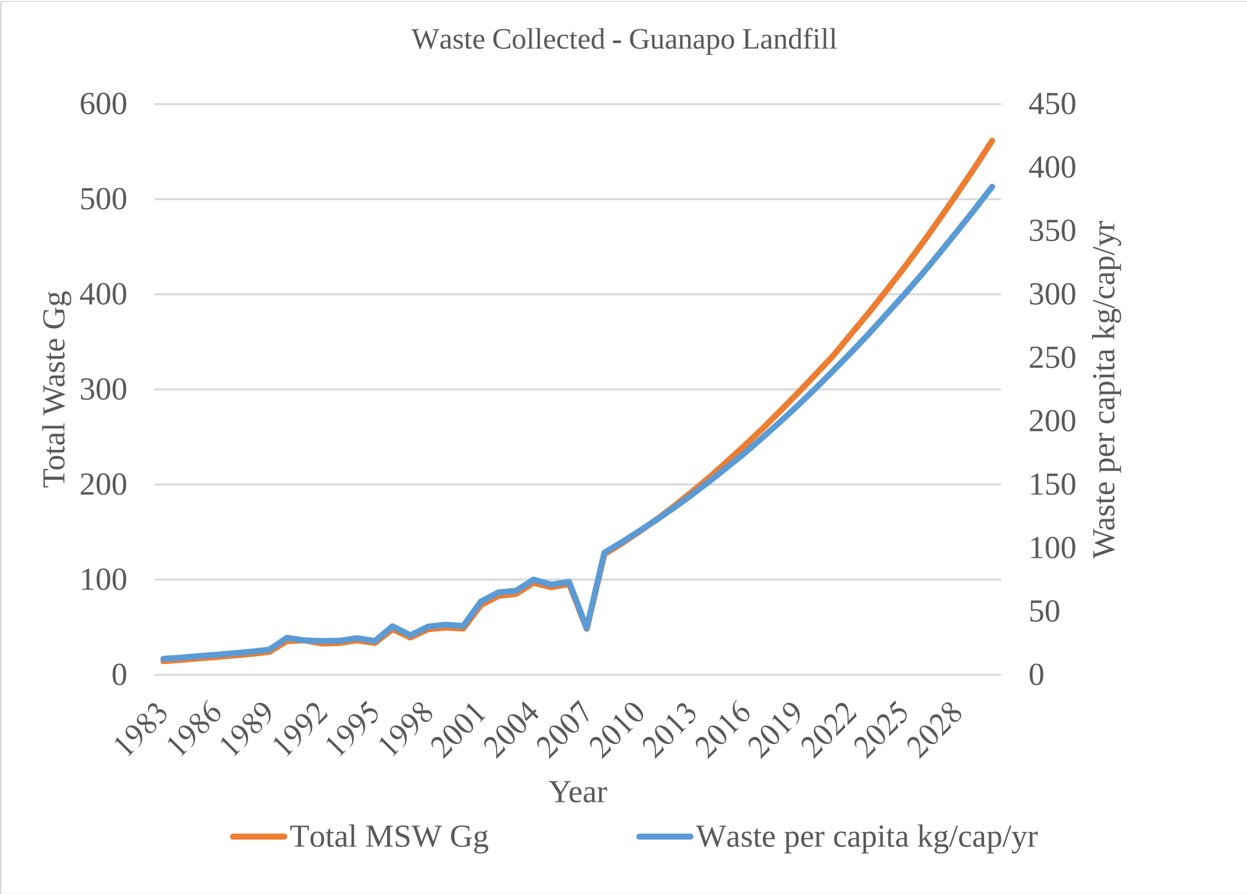


Figure 5

Annual Waste Quantities at the Guanapo Landfill



Waste Composition

The IPCC 2006 model requires data on solid waste composition. The composition of the waste at each of the three landfills was taken from the CBCL waste characterisation report (CBCL Limited, 2010). The composition categories used in the IPCC 2006 model are as follows: food, garden, paper, wood, textile, nappies, and plastics with inert waste which comprises non-degradable organic carbon material such as glass and metal. The contribution of each waste category is shown in Table 3.

Table 3

Waste Composition by Category at Each Landfill Site

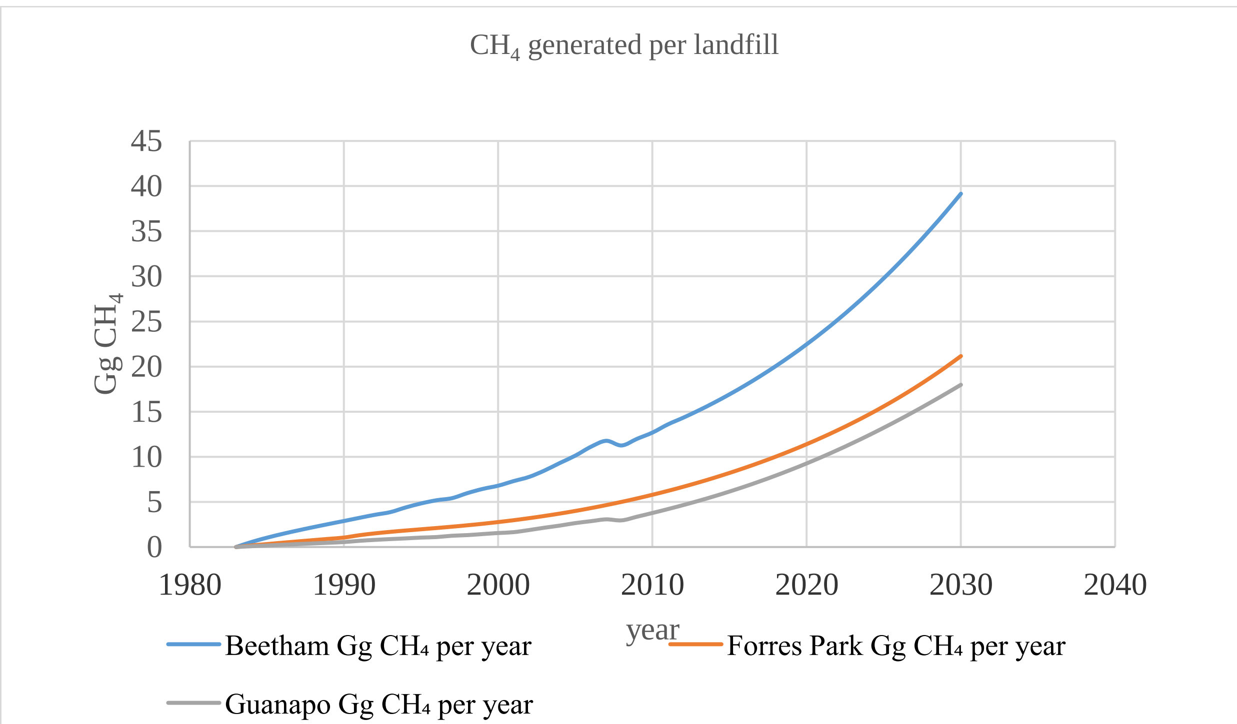
Landfill	Waste Comp.	Food (%)	Garden (%)	Paper (%)	Wood (%)	Textile (%)	Nappies (%)	Plastics, other inert (%)
Beetham		24.98	5.87	25.47	0.63	8.09	4.91	30.05
Forres Park		15.65	5.19	20.05	1.3	7.77	3.49	46.55
Guanapo		12.22	8.11	24.33	1.2	6.72	5.37	42.05

Results and Discussion

The estimated annual methane generated from each landfill is shown in Figure 6.

Figure 6

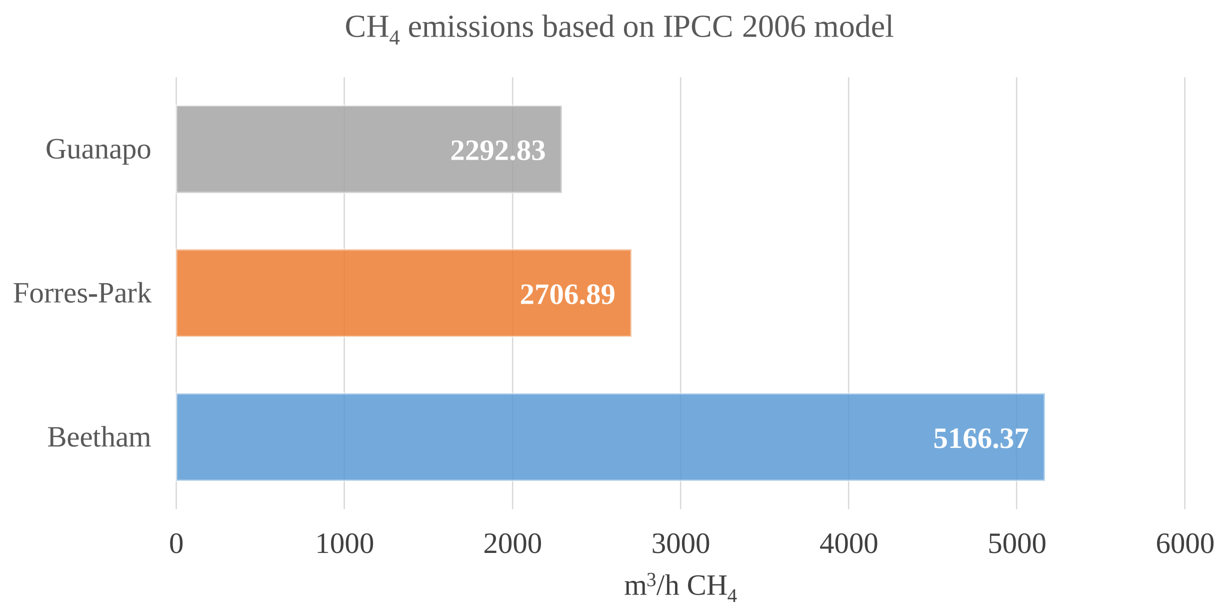
Graph Showing the Estimated Methane Generated Annually



For this study, the average methane generated over a period of 5 years from 2023 to 2027 was used for the economic analysis, similar to Lando et al. (2021). The equivalent volume flowrate was calculated using an average density of methane of 0.66kg/m^3. The equivalent volume flowrate generated in m^3/h is shown in Figure 7.

Figure 7

Graph Showing the Estimated Average Amount of Methane Generated between 2023 and 2027



The results show the estimated quantity of methane produced based on the annual quantity of waste delivered to each landfill. The estimated methane generated at Beetham is the largest at over 5000 m^3/h.

Validating Results

To validate the findings, the results for the Beetham landfill were compared with those for the Barbados landfill for the year 2010. Barbados is an island in the Caribbean which lies 330 km north of Trinidad. The weather patterns of the two countries are very similar. The estimated methane generated in Barbados for 2010 was published in the report, Barbados' *Second National Communication Under the United Nations Framework Convention on Climate Change* (Government of Barbados, 2018). The IPCC 2006 Model was also used for the Barbados study. A comparison with the Barbados landfill was also done since the waste quantities and composition is quite similar to that of Beetham's (Simmons & Associates Ltd., 2016) (see Figure 8). As stated before, the waste quantity, composition and weather type have the biggest impact on methane production and are key parameters to consider when comparing the methane generated between countries.

Figure 8

Waste Composition Comparison between Barbados Landfill and the Beetham Landfill

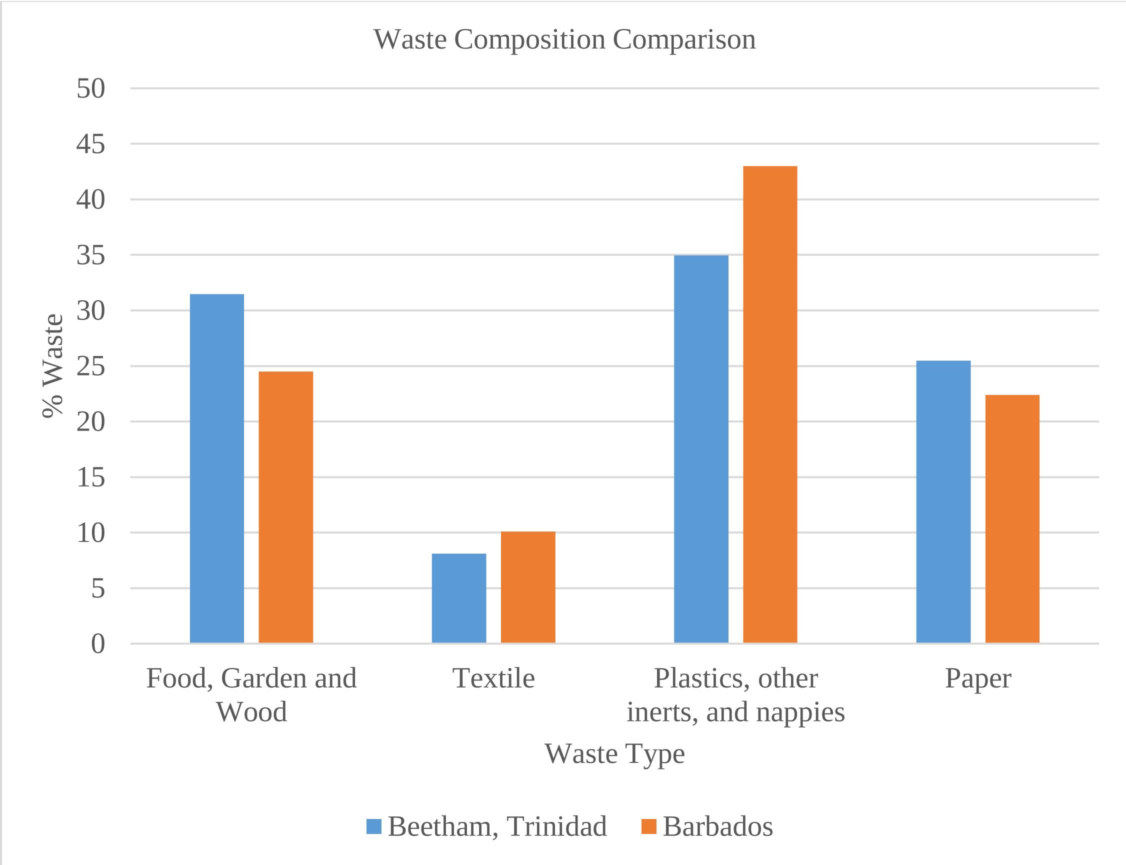


Table 4

Comparison of the Estimated Values of Methane Produced by Barbados and Beetham in 2010

Region	Barbados**	Beetham, Trinidad
Year	2010	2010
Amount of waste generated	354.9 Gg	350 Gg
Methane generated using IPCC 2006 method	10 Gg	13 Gg

Note: Data taken from: Barbados' Second National Communication under the United Nations Framework Convention on Climate Change, UNFCCC

Table 4 shows the methane generated in 2010 for the Barbados landfill and the Beetham landfill. The difference in value is relatively small and is largely due to the higher organic content found in the Beetham waste.

Model Errors

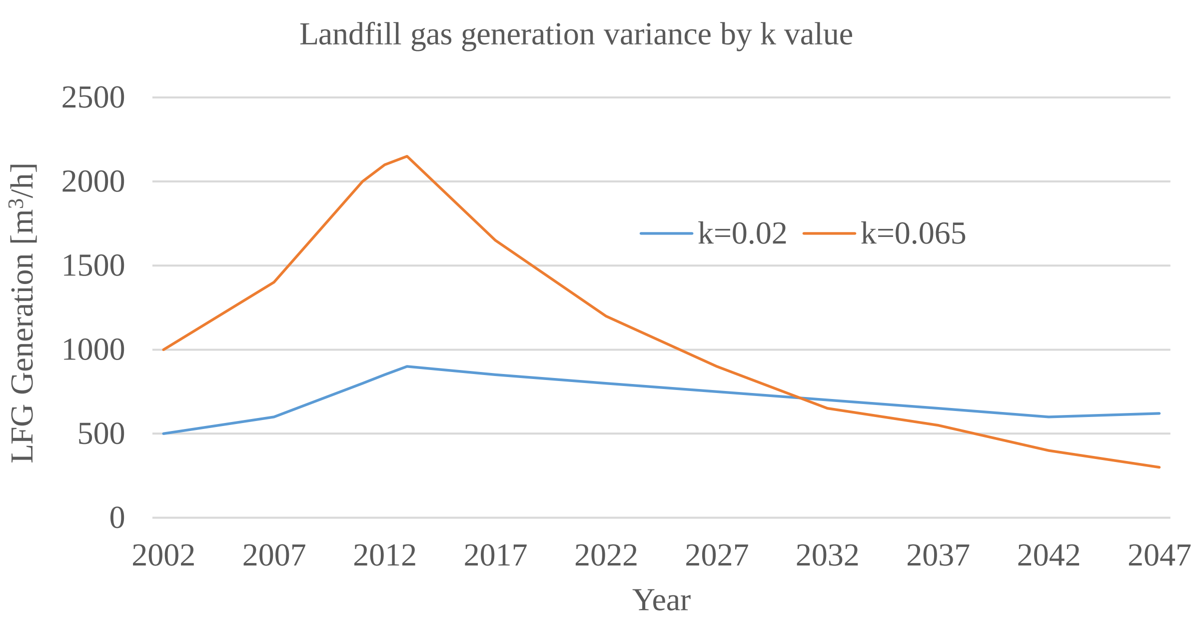
In the literature (IPCC 2018, IPCC 2006) the authors cited two areas of uncertainty in the estimating of CH_4 emissions from landfills: (i) the uncertainty attributable to the method; and (ii) the uncertainty attributable to the data.

Method Related Errors

The FOD model consists of terms which describe the amount of CH_4 generated throughout the lifetime of the landfill, and how this CH_4 is generated over time. Therefore, the uncertainties in using the FOD model can be divided into uncertainties in the total amount of CH_4 formed throughout the lifetime of the landfill and uncertainties in the distribution of this amount over the years. The model assumes the composition of the waste disposed is consistent throughout the years as well as the decomposition rate of the waste, k. It is recommended that a sensitivity analysis varying the k-values within the error ranges ought to be performed in the future. Figure 9 shows how the values of k can significantly affect the estimation of the methane generated.

Figure 9

Landfill Gas Generation Variance by k Value (Source: Cossu & Stegmann, 2019)



In addition, the decay of carbon compounds to CH_4 involves a series of complex chemical reactions and may not always follow a first-order decay reaction. Higher order reactions may be involved, and reaction rates will vary with conditions at the specific landfills. Reactions may be limited by restricted access to water and local variations in populations of bacteria (IPCC, IPCC 2006; Solid waste disposal, 2006).

Data related errors

The quality of CH_4 emission estimates is directly related to the quality and availability of the waste generation, composition, and management data used to derive these estimates. It is important to note that all data used from the waste characterisation study will also include any error associated with such a study. In addition, errors incurred in predicting future data sets must also be considered. Lastly, waste scavenging data were not considered as the quantities were assumed to be small in size and to have a negligible impact on the methane produced.

Correction factors for induced errors

In 2009, researchers Wangyao et al. from Thailand compared the findings of methane from field measurements to that calculated from the IPCC 2006 model (Wangyao, 2010). Their results were analysed to determine the error percentage that should be applied to tropical countries utilising the IPCC model. The results from four of their sites MD1, MD2, MD4 and MD5 were plotted (Figure 10). Sites not selected were considered outliers. Based on the graphs obtained, an error range of +/-17% was noted and applied to this study. Figure 11 shows the adjustments made to the methane results based on the IPCC 2006 model.

Figure 10

Methane Emissions Comparison between Field Measurements in Thailand and the IPCC model

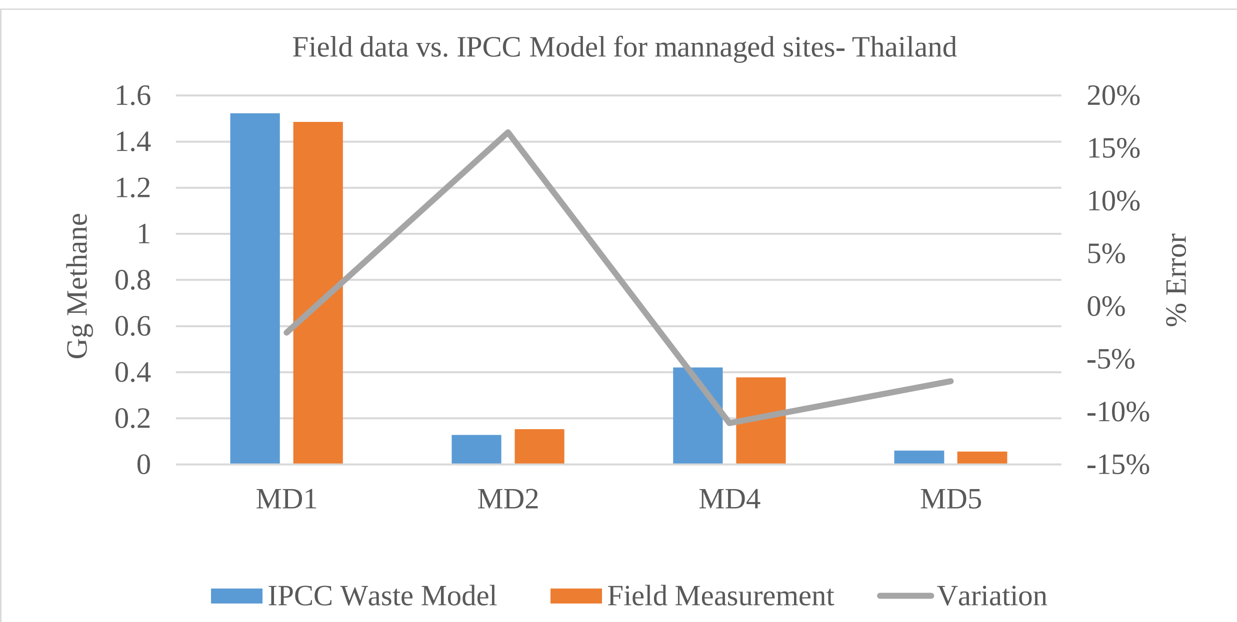
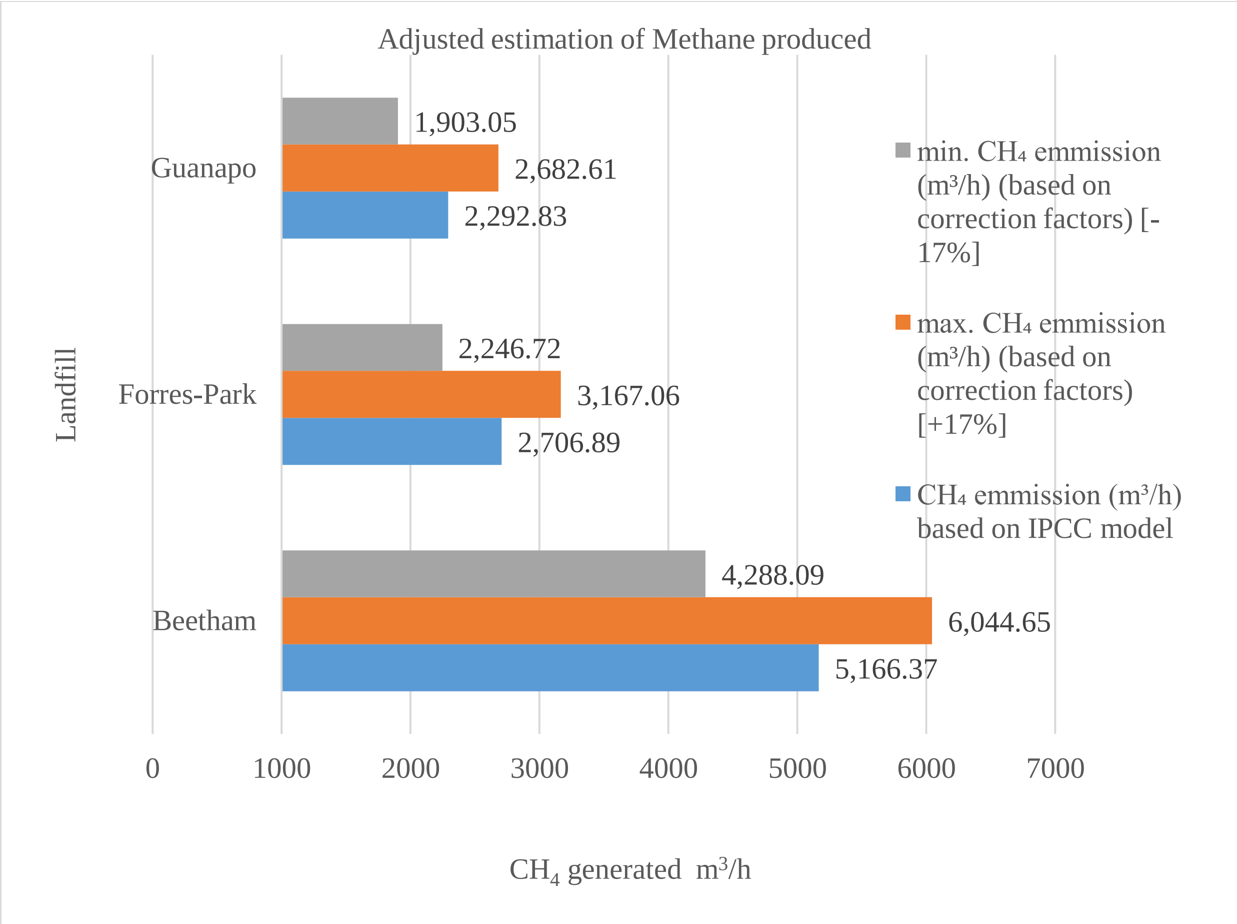


Figure 11

The Adjustment Made to the Methane Generated Based on the IPCC 2006 Model



Collection efficiency

Collection efficiency is defined broadly as the ratio of the landfill gas collected to the amount generated (Wang & Achari, 2012). This efficiency can be expressed at a specific moment in time or over the landfill's lifetime. Collection efficiencies vary in accordance with the type of the landfill as shown in

Table ***5***, with highly engineered landfills having the highest collection efficiency (Oonk, 2012).

Table 5

Collection Efficiencies of Various Types of Landfills (Source: Oonk, 2012)

Type of landfill	**Collection efficiency**
Landfills with state-of-the-art liners	90% - 100%
Closed landfills	10% - 90%
Landfills in operation	10% -80%

In research work published by the EPA, collection efficiencies as high as 95% have been reported for well-designed and maintained LFG collection systems. The EPA also indicated that the collection efficiencies for a landfill that is unlined, contains only a soil or porous clay cap and does not employ an aggressive operation and maintenance program vary between 50% to 60% (United States Environmental Protection Agency, 2008).

However, researcher Oonk (2012) believes these efficiencies are grossly overestimated and provided a table showing the collection efficiencies of various types of landfills, either in operation or partially capped. The authors considered the landfills which closely matched the landfills being studied (non-engineered, partially capped) and selected the collection efficiency of 40%. With this collection efficiency, the estimated range of methane to be collected is shown in Table ***6***.

Table 6

Estimated Range of Methane that Can Be Collected from Each Landfill

	Beetham	**Forres-Park**	**Guanapo**
CH_4 generation/ with error adjustment (m^3/h)	(4,288.1 – 6,044.7)	(2,246.7 – 3,167.1)	(1,903.1 – 2,682.6)
CH_4 collection (m^3/h) @40% collection efficiency	(1,715.2 – 2,417.9)	(898.6 – 1,266.8)	(761.2 – 1,073.0)

Conclusion

It has been demonstrated that it is possible to collect as much as 4757.7 m^3/h of methane from the three landfills (Beetham, Forres-Park, and Guanapo combined) in Trinidad using the IPCC 2006 model and a collection efficiency of 40%. A similar study carried out on the three landfills and using the LandGem model estimates that approximately 3030 m^3/h can be collected at an 85% collection efficiency (Pillai & Riverol, 2018). The use of the IPCC 2006 model and the 40% collection efficiency align closely with the climate of the island and the type of landfills on the island. The latter ensures that a more accurate estimation of the methane available from landfills is attained. The estimated available methane directly affects any technoeconomic analysis regarding potential uses of the landfill gas, such as landfill gas-to-energy (LFGE) projects, which are currently being considered by the Government of the Republic of Trinidad and Tobago (GORTT, SWMCOL Partners With NGC to Use Landfill Gas Emissions, 2021).

LFGE projects in Trinidad and Tobago offer an important opportunity to both build climate change resilience and advance sustainable development. This is accomplished by providing significant environmental benefits over the current landfill waste management practice (reductions in greenhouse gas emissions, utilisation of a wasted resource and provision of opportunities for waste recovery), as well as formalising the local waste recovery sector and increasing job opportunity and diversification. However, this form of waste management, if implemented in isolation from other strategies, would be insufficient to address the complex and interrelated adverse environmental impacts of landfill waste and their associated health issues. Additionally, LFGE projects may increase the risk of indirectly funding unsustainable waste management practices and limit the fiscal space available to support reuse and recycling initiatives (UNEP, 2019). While it is clear that conversion of landfill gas could contribute to the economy, it is important that the benefits of such projects are shared equitably with local communities who have been -- and will continue to be --- the main recipients of environmental pollution from the landfill operations. Therefore, future studies should include perspectives from local community stakeholder groups. A pilot study investigating actual methane production and the composition of the emissions of the landfills in Trinidad and Tobago would further support future work in the analysis of potential sustainable uses of the landfill gas being produced in Trinidad. Accurately quantifying the potential amount of methane produced, as presented in this publication, is the first step towards the goal of utilising the landfill gas of T&T in a safe, sustainable, and economic manner.

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