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Regenerating Waste to Energy: A Scenario-Based Assessment of Lagos, Nigeria

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Abstract

This study uses scenario-based approaches to assess the regenerative capacity of transforming organic wastes into electric power for the City of Lagos, Nigeria. Lagos represents a rapidly growing city with a population of 21 million in a developing country where serious shortages are experienced in producing sufficient electric power. As in many developing countries, rapid urbanization has lead to mismanagement of solid waste disposal, illegal deposal methods, issues in landfill infrastructure, and inefficiencies in developing recycling industries and other regenerative systems. This paper examines the feasibility of regenerating organic waste into electricity by projecting the volume of methane gas that could have been harvested in two closed landfills and one still operating landfill. The analysis applies the United States Environmental Protection Agency Landfill Gas Emissions Model (U.S. EPA LandGEM) and Intergovernmental Panel on Climate Change (IPCC) models to measure waste to methane gas generation by developing data on organic waste capture, landfill physical characteristics and factors for methane production, and the quality of waste management. Utilizing existing conversion models, the methane gas amounts are assessed in terms of potential electricity generation. The study also projected the waste-to-energy production of three new proposed landfills in Lagos from 2017 to 2050 and found that methane-produced electricity could meet the later energy demands of the city.

Keywords: Waste to energy, Regeneration, Organic waste, Carbon emissions, Energy mix

1. Introduction

As urbanization rates continue to increase especially in developing countries, proper waste management methods such as regenerating waste into electrical power becomes a significant sustainability objective. Pijawka (2015) has noted that developing countries with growing urbanization rates often have weak resiliency in terms of infrastructure development to manage their waste streams. In these countries' megacities, managing waste has become burdensome due to the lack of infrastructure for reuse/recycling, limited land for new landfills, and most pressing, the significant levels of illegal solid waste dumping. In some countries, illegal dumping may reach as high as 40% percent of total generated waste.

From a sustainability point of view, landfill waste disposal is the least desirable option for effective waste management as it presents negative environmental and health impacts and takes land away from urban development objectives such as public housing. In his book *Regenerative Design for Sustainable Development*, Lyle (1994) states that the problem of handling solid waste is associated with its definition as unwanted and worthless material to be discarded after use. Arguing that this definition leans on the assumption that energy and used materials cease to exist in a functional sense, Lyle found that, based on the laws of thermodynamics, energy continuously degrades and materials change form and state. This includes waste that when it changes from one form to another can pose environmental dangers. Therefore, it is pertinent to adopt waste management strategies that assimilate, filter, store and produce new uses to reduce the adverse impacts and enhance ***regenerative*** uses, such as energy.

Waste management has been categorized into six approaches—prevention, minimization, reuse, recycling, energy recovery, and disposal from the most to least preferred as shown in Figure 1. The most economical of the methods is waste disposal in landfills and open dumps, which is why it is the most widely used approach. However, most developed countries have established policies to encourage cities to move up the hierarchy of waste management from landfilling to prevention, the most favored option for regenerative uses and environmental benefits. Prevention suggests activities that do not result in waste materials requiring further action. For example, permaculture requires that waste materials be used as fertilizer for support of natural systems.

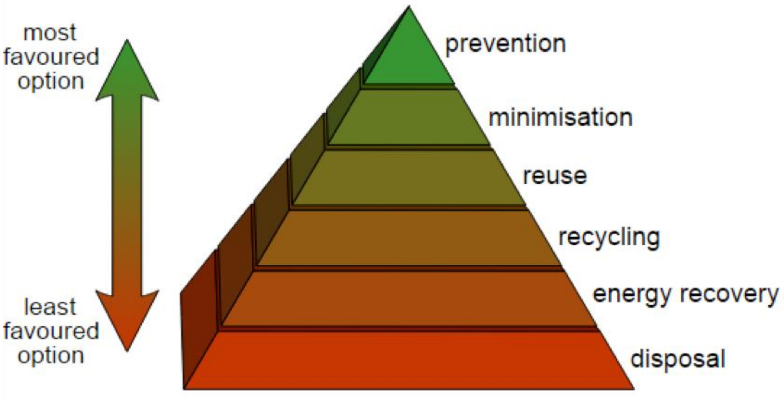

Figure 1. Waste management hierarchy. *Source: www.waste-to-energy.com*

Prevention is the most sustainable option but also the most difficult to achieve in developing countries with increasing population and lack of economic prosperity. However, regenerative systems for managing organic waste are gaining momentum. Hammarby Sjöstad in Stockholm, Sweden exemplifies this model through its closed-loop system where waste is integrated into the cycle to produce resources such as biogas and compost (Rutherford, 2013). As of 2013, only 5% of the waste generated in the city went to landfills; the remainder was used to generate energy (for every one ton of waste, 3000 kilowatt hours (kWh) of energy is generated) or converted to compost used to improve the quality of soil (Rutherford, 2013). In developing countries, there is an urgent need to adopt these more regenerative waste management systems rather than the traditional end-of-pipe solutions.

This paper looks at regenerative scenarios of converting organic waste landfill gas (LFG) from existing (both active and inactive) and planned landfills into electricity then measures the impacts in Lagos, Nigeria. Lagos was chosen as the case study due to its size (21 million people) and continued growth. The goal is to demonstrate the regenerative potential of organic waste and LFG for a more sustainable systems approach to future waste management. Using a scenario-based analysis, the study answers the following questions:

1) Considering the characteristics of waste, and existing and future landfill conditions, to what extent would it be possible to capture landfill methane to generate electricity?

2) How much methane has been produced in Lagos landfills since inception to closing, what could the potential electricity generation from this methane have been if the necessary infrastructure had been in place, and can the future generation of methane be projected?

3) What are the benefits that Lagos can derive from capturing landfill methane gas for electricity generation?

4) Could these regenerative methods be implemented in other developing country cities?

The rapid urbanization of the city has led to an increase in waste generation, which requires disposal in landfills or through other means such as recycling. According to Lagos Waste Management Authority (LAWMA), almost 50% of the 12,000 tons of waste generated per day in Lagos is organic waste, constituting the bulk of landfilled waste in the city. Out of the 2,058,600 tons of organic waste generated annually, only about 8% is converted into compost through local initiatives. It is important to note that out of the three current legal landfills in the city, two have less than five more years to operate, putting more pressure on the remaining landfill, which is estimated to have less than twenty more years to operate.

Adding to the urgency is the fact that these landfills are not sanitary. As a result, there are obnoxious odors emanating from uncollected methane gas as well as leachate contaminating the ground water. Methane, a greenhouse gas (GHG), is 21 times more potent than carbon dioxide (CO_2), staying in the atmosphere for a long time and contributing greatly to climate change. Thus, it has become imperative to find ways to reduce this caustic GHG from landfills. Regenerative processes are a significant sustainable solution.

1. Background Literature

The challenge of managing anthropogenic waste by-products is experienced in both developed and developing countries. Although the problem is more pronounced in the developing world due to lack of proper and advanced infrastructure, the ongoing debate on sustainability and climate change has exposed that waste infrastructure such as sanitary landfills are not completely problem-free. Hence, there have been initiatives to address the problems of solid waste. These programs vary from country to country, but include zero waste programs, waste-to-energy initiatives, cradle-to-cradle endeavors and others.

According to the United Nations Report on Sustainable Cities (HABITAT, 2009), one of the current global innovations for eco-efficiency is using waste products to satisfy urban energy and material resource needs. In his book *Regenerative Design for Sustainable Development,* Lyle makes a strong case for changing the perception of waste as ‘useless’ to waste as ‘resources’ that can be tapped by creating closed-loop management systems. This produces a cyclical system, known as a regenerative system, for products from “cradle to cradle.” The regenerative model is a resource management approach that advocates for the use of conversion and assimilation disposal methods, or ‘closing the loop,’ and returning both materials and nutrients to beneficial uses. It is based on the premise that all materials exist in a biological nutrient cycle or a technical nutrient cycle (Bergman, 2012).

The organic waste stream is composed of biological nutrient materials that can be safely returned to the earth through regenerative methods such as landfill gas capturing, anaerobic digestion or composting. Materials that cannot be processed by biological systems are considered part of the technical nutrient cycle (plastic, synthetic materials, computers, etc.). These materials typically do not biodegrade or take too long to biodegrade but can be reused or repurposed.

1.2 Landfill Characterization

While several studies have been carried out on waste characterization in different cities worldwide, few studies have explored the importance of managing waste based on these characteristics. An exception is the 52-week characterization study of municipal solid waste in Gumushane, Turkey conducted by Nas and Bayram (2008) to determine the percentage of components, their specification weight and the chemical components that influence management techniques. Furthermore, the majority of landfill characterization studies have focused on the entire waste stream. Gomez, Meneses, Ballinas, & Castells (2008) characterized waste generated in Chihuahua City, Mexico into organic, paper and plastic. They established a relationship between the rate and composition of the waste stream, and the socio-economic level of the residents. A recent World Bank report on Global Waste Management found that over 50% of waste in developing countries is organic (Hoornweg & Bhada-Tata, 2012). Organic waste is typically used for soil improvement, animal raising, and biofuel. It is important to note, however, that organic waste has diverse components with different chemical characteristics that impact its potential efficiency. For instance, wood chips, agricultural waste and other plant matter can be resistant to biodegradation due to the presence of lignin, cellulose and hemicellulose (Volger, 2014).

1.3 Landfill Methane to Electricity

Capturing and reusing landfill methane is a sustainable and environmentally friendly option for managing waste. This is especially true in developing countries where this can greatly benefit their energy mix and power supply. It is also one of the most economical and socially accepted methods with minimal environment consequences. Most of the studies done on LFGs to date have been geared towards methane as a contributor to climate change (Lou & Nair, 2009). Some focus on the efficiency rate of capturing landfill gases (LGFs) compared to using an anaerobic digestion reactor (Themelis & Uloa, 2007) or determine total methane balance and oxidation rates (Spokes et al., 2006). Our study focuses on quantifying the benefits in energy resources that can be accrued from landfill methane for Lagos.

2. Case Study

In a recent interview, the former Nigerian Minister for Power, Chinedu Nebo, stated that Lagos could benefit from the enormous amount of organic waste generated daily (Business, 2015). The city sits on a water-locked landmass of approximately 1533 km^2, which limits physical development. Located on the Gulf of Guinea in the Atlantic Ocean, it is built on several low-lying islands, tropical marshes, reclaimed lands, and a coastal mainland area that sprawls out into the neighboring state of Ogun. Its climate is that of a tropical rainforest and it sits below sea level, placing it at considerable risk for coastal flooding (Encyclopedia Britannica, 2015; Filani, 2012).

This megacity is the most populous city in Nigeria. It has great diversity in terms of population, income, education and ethnicity. With over 250 ethnic groups, the city receives people from every part of Nigeria and beyond. In its present form, Lagos' overflowing urban agglomeration area of 907 km^2 holds a UN-estimated population of 13 million people (Demographia World Urban Areas, 2015) while its metro footprint extends 1533 km^2(Filani, 2012) and includes over 21 million residents (Lagos Bureau of Statistics, 2015). It is the economic hub of Nigeria, generating over 25% of the country's total gross domestic product.

The volume of solid waste generation in Lagos increases every day with the influx of people, adding to an already congested city. The current population generates over 12,000 metric tons of waste per day, of which only about 50% makes it to landfills (LAWMA, 2014). According to LAWMA's 2014 report, 45% of waste generated in the city is organic, followed by plastic (15%), paper (10%), putrescibles or decomposables (8%), glass (5%) and textiles (4%). There is absolutely no doubt that Lagos will face more problems in the near future if a more sustainable approach to waste management is not found. This is especially true if the population actually reaches forty million people by 2050 as forecasted by United Nations (UN Dept of Economic and Social Affairs, 2015).

While the population of the city is increasing at an estimated annual rate of at least 3.6%, the municipal authority in charge of waste is collecting an average of 10% less refuse per capita every year (Onibokun, Adedipe, & Sridlier, 2000). A major cause of this is the city's vast informal settlements. With over 66% of the population living in these settlements, environmental management such as sanitation and solid waste has been a formidable task for the government.

Waste from these settlements is dumped indiscriminately in places such as rivers, canals, drainages or burned on illegal dumpsites or even in residents' backyards. Waste collected under the private sector partnership (PSP) is disposed of in the three legal landfills—Olushosun, Solus and Abule-Egba. However, there is growing concern over the environmental problems caused by the landfills as the city has developed rapidly in the areas where the landfills are located, thereby causing nuisance to residents living around this area. The incessant seasonal flooding experienced in most parts of the city exacerbates this. Fortunately, this flooding has started to increase the awareness of the need for better and safer disposal methods. To become more environmentally sustainable, managing organic waste is essential. This is especially true for Lagos with its projected population increase and the high costs of siting and operating new landfills.

3. Methodology

The volume of feasible landfill biofuel is dependent on conditions (temperature, soils, gas run-off, etc.) as well as the composition of materials. Using a multi-methods approach, a baseline composition study on organic waste streams in Lagos was performed and projections for the three proposed new landfills were made. The organic waste share of total waste and landfill quality factors were also estimated. This is important not only for revealing the potential benefits that could be tapped, but also in helping select technologies to yield optimal results. Data was collected from fieldwork, historical waste data, government reports and interviews.

The organic components of Lagos' Municipal Solid Waste (MSW) account for around 45% of the total waste generated on a daily basis (LAWMA, 2010). Based on parameters from the literature, the amount of methane gas expected to be generated in each landfill from inception to end of life was calculated using the United States Environmental Protection Agency Landfill Gas Emissions Model (US EPA LandGEM) software (Pipatti et al., 2006). The results were then used to evaluate how much electricity each year could be generated from the methane gas at the existing and proposed facilities. We used the annual baseline population growth rate of 3.19% estimated and multiplied it by the 0.65kg per capita of waste generation (LAWMA, 2010) for our projected estimations.

Projections were also made on the overall benefits to Lagos in terms of electricity generation that would be produced over the next 20 years based on population estimates for each year. Abraxas Energy Consulting’s Energy Conversion Calculator was used to estimate how much electricity could be generated from the methane gas produced in each of Lagos’ existing and proposed landfills every year. This enabled the calculation of methane gas in cubic meters to be converted to electricity in megawatts (MW). Abraxas Energy Consulting’s Energy Conversion Calculator is not the only energy calculator available for conversion, but it is the most popular among organizations that are running energy accounting. More so, it was used in the first Landfill Gas to Energy study conducted in Nigeria in 2010 (CPE, 2010).

In Lagos, a large portion of household and commercial waste generated is deposited in landfills across the city. The organic components of Municipal Solid Waste (MSW) account for an estimated 45% of the total waste generated on a daily basis (LAWMA, 2010). Decomposition transforms the organic waste to LFG composed of 50% methane gas. Presently, Lagos does not have LFG collection systems in any of its landfills. Therefore, the biogas is released into the atmosphere losing its potential for regenerative purposes. This presents not only a lost opportunity for resource efficiency but also contributes to global GHG emissions and climate change.

The Centre for People and Environment (CPE) conducted the only known LFG study conducted so far in Nigeria in 2010. The study explored the feasibility of producing landfill gas in Nigeria based on three landfills in different regions of the country. It was sponsored by the US EPA and used their LandGEM software Version 3.02 published in 2005.

For Lagos, the only study carried out on LFGs was done by Ably Carbon & Bionersis (2006). The study essentially assessed the suitability of capturing landfill gases for the Abule Egba, Solous and Olushosun landfills and specifically related to the possibility of earning carbon credits through the Clean Development Mechanism (CDM) established under the 1997 Kyoto Protocol. It analyzed factors such as soil conditions, temperature, and chemicals that together would conclude if methane gas could be captured at landfill sites and if yes, how much. Using the LandGEM model, this study also evaluated landfill conditions and factors that would contribute to the amount of methane gas generated. The factors included the use of two small landfills for producing methane. The data breaks down quantitatively into the amounts of methane and subsequently, how much electricity could be generated now and in the future, if the necessary infrastructure was in place.

Our analysis chose the LandGEM model as it was used in previous studies to analyze landfill methane in the three proposed landfills and it has been used widely in the United States and internationally (Global Methane Initiative, 2012). LandGEM is an automated estimation tool with a Microsoft Excel interface that can be used to estimate emission rates for total landfill gas, methane, carbon dioxide, non-methane organic compounds, and individual air pollutants from municipal solid waste landfills. The accuracy and reliability of the results generated using this model depends largely on a number of input data. The model (below) uses the first-order decomposition rate equation to estimate annual emissions of methane over a time period that is being defined by the user.

$$QCH_4 = \sum_{i=1}^{n} kL_0 \sum_{j=0.1}^{1} kL_0 \left[\frac{M_i}{10}\right] e$$

Where

QCH4 = annual methane generation in the year of the calculation (m3/year)

i = 1-year time increment

n = (year of the calculation) - (initial year of waste acceptance)

j = 0.1-year time increment

k = methane generation rate (year-1)

Lo = potential methane generation capacity (m3/Mg)

Mi = mass of waste accepted in the ith year (Mg)

tij = age of the jth section of waste mass Mi accepted in the ith year (decimal years, e.g., 3.2 years)

e= natural exponential scientific function used for continual decay

Note that the value of k is primarily a function of several factors such as moisture content of the waste mass, availability of the nutrients for microorganisms that break down the waste to form methane and carbon dioxide, pH of the waste mass, and temperature of the waste mass. The k value for Lagos landfills was obtained from the IPCC default values for developing countries and based on the number of urban inhabitants multiplied by the MSW disposal rate.

4. Results: Assessing the Waste to Energy Option for Lagos

4.1 Olushosun Landfill Analysis

This landfill accepted about 40% of the total waste generated in Lagos (LAWMA, 2012). Some parts of the landfill were closed in 2007 due to attainment of the 12 m desired height above the surface for the landfill as planned by the Waste Management Agency. New cells were opened up to receive waste starting from 2008, and the entire landfill is proposed to be closed by 2017 (Ably Carbon & Bionersis, 2012).

Table 1. Waste deposited in the Olushosun Landfill

Year	Waste Deposited (Metric Tons)	Cumulative Metric Tons
1992	165,909.09	165,909.09
1993	174,204.55	340,113.64
1994	182,914.55	523,028.19
1995	192,060.91	715,089.10
1996	201,663.64	916,752.74
1997	211,746.36	1,128,499.10
1998	222,333.64	1,350,832.74
1999	233,450.91	1,584,283.65
2000	245,123.64	1,829,407.29
2001	257,379.09	2,086,786.38
2002	270,248.18	2,357,034.56
2003	283,760.91	2,640,795.47
2004	297,949.09	2,938,744.56
2005	312,846.36	3,251,590.92
2006	328,489.09	3,580,080.01
2007	344,912.73	3,924,992.74
2008	567,814.55	4,492,807.29
2009	596,205.45	5,089,012.74
2010	626,015.45	5,715,028.19
2011	657,316.36	6,372,344.55
2012	690,181.82	7,062,526.37
2013	724,690.91	7,787,217.28
2014	760,925.45	8,548,142.73
2015	798,971.82	9,347,114.55
2016	838,920.00	10,186,034.55
2017	880,866.36	11,066,900.91

The historical amount of waste dumped in Olushosun landfill per metric ton from 1992 until 2017 is shown in Table 1.

In the study scenario, methane production was estimated from the year the landfill started operation in 1992 to 2020. Even though the landfill is expected to close in 2017, methane production was estimated until 2020 in the scenario, as the landfill will continue to generate methane for at least three years after closure. The scenario is based on landfill characteristics incorporated into the model but also assumes annual waste deposits over the entire time period and annual methane generation. The scenario assumes the volume of methane that could have been produced.

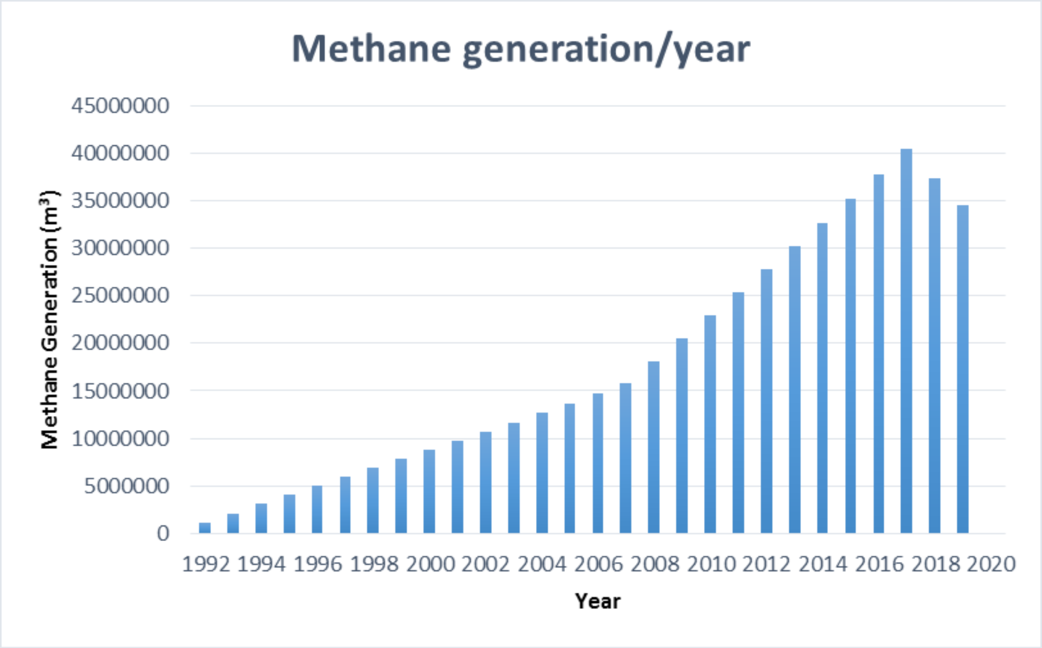

Figure 2. Olushosun Landfill Methane Generation (m^3/year)

The summary of methane recovery projections for the Olushosun landfill is illustrated in Figure 2. (See Appendix 1 for the complete estimation of methane and electricity generation at the Olushosun landfill.)

In the first year, methane production is zero. This is because it takes time for decomposition of organic waste to begin producing methane. Beginning in 1993, production steadily increases until 2018, a year after the landfill is scheduled to close. After 2018, methane production begins to decrease. This implies that capturing methane in this landfill requires quick action for a viable return on investment. The total accumulated methane over time is estimated at about 496,787,641 cubic meters. If full capture of this methane had taken place, approximately 5,244,440 megawatts of electricity would have been generated. Unfortunately, since no capturing has taken place to date, a significant amount of this gas has been lost to the atmosphere and it is impossible to determine the remaining quantity without further research. This scenario tells us how much electricity could have been generated if the capturing infrastructure and equipment for generating electricity was in place.

4.2 Abule Egba Landfill Analysis

A total of 2,628,726 metric tons of waste was deposited in the Abule-Egba landfill as of its closing in 2009 (e.g., Table 2). The waste tonnage data in this landfill may not be accurate due to the absence of a weighbridge during operations; however, the study assumed that the waste data used in the Ably Carbon & Bionersis report is correct, as it was provided by the LAWMA.

Table 2. Waste Tonnage of Abule- Egba Landfill

Year	**Waste Deposited (Metric Tons)**	**Cumulative Metric Tons**
1995	70,000	70,000
1996	74,200	144,200
1997	78,652	222,852
1998	83,371	306,223
1999	88,373	394,597
2000	93,676	488,272
2001	99,296	587,569
2002	105,254	692,823
2003	111,569	804,392
2004	111,569	915,961
2005	167,354	1,083,316
2006	251,031	1,334,316
2007	375,547	1,710,893
2008	564,820	2,275,713
2009	353,012	2,628,726

Source: LAWMA, 2012

The landfill has an average height of 11 meters above the surface and is considered ‘unmanaged.’ It served low-income neighborhoods in the Alimosho Local Government Area (LGA), the largest LGA in Lagos. The amount of landfill methane gas was calculated for each year of operation using LandGEM software. For each year in which waste was deposited from inception to closing and a projection to the year 2020 was completed, an assumed cap year for the three landfills in question for the sake of this research. A total of 149,105,317.6m^3 **(**cubic meter) of methane would have been produced. If capturing methane commenced at the start of the landfill, a total of 1,574,060.74 MW of electricity could have been generated. As stated earlier, capturing methane and generating electricity is contingent on the type of equipment used and the time operations begin.

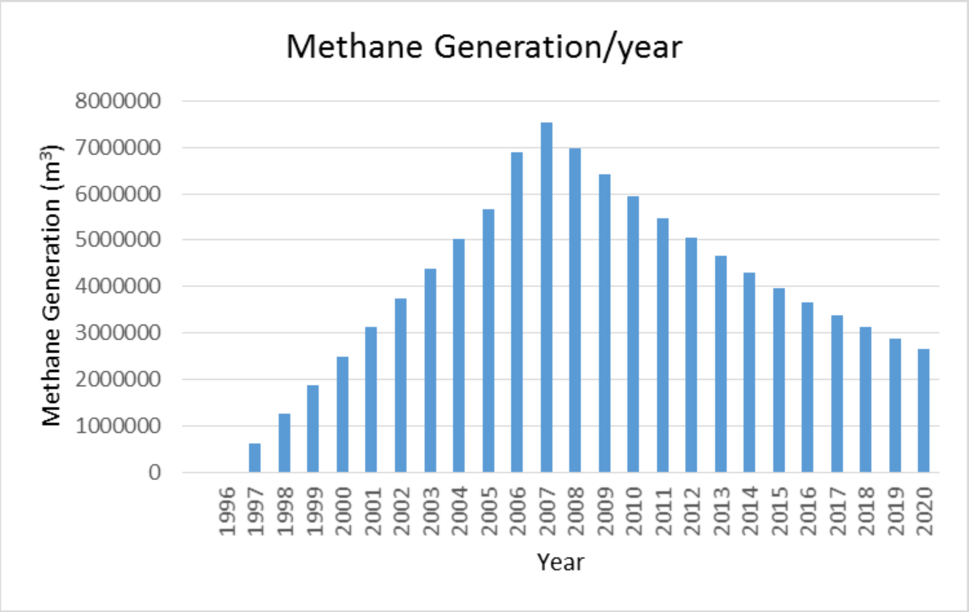

Figure 3. Graph of methane gas generation in Abule-Egba Landfill

The summary of methane recovery projections for the Abule-Egba landfill is illustrated in Figure 3. (See Appendix 2 for the complete estimation of methane and electricity generation at the Abule-Egba landfill.)

Solous 1 Landfill Analysis

The Solous landfill is divided into three parts called Solous I, Solous II and Solous III. Solous II and Solous III were ruled out of the possibility of capturing LFGs due to unfavorable landfill conditions (Ably Carbon & Bionersis, 2012). Again, waste deposit tonnage data in this landfill may not be accurate due the unavailability of a weighbridge, but the data from LAWMA was used and is deemed reliable.

Table 3. Waste deposited in Solous I landfill

Year	**Metric Tons Disposed**	**Cumulative Metric Tons**
1996	100,122	100,122
1997	106,512	206,634
1998	113,311	319,945
1999	120,544	440,489
2000	128,238	440,489
2001	136,423	705,150
2002	145,131	850,282
2003	154,395	1,004,677
2004	164,250	1,168,927
2005	264,375	1,415,302
2006	184,781	1,600,083

Source: LAWMA, 2012

Solous I has the least methane generation capability of the three landfills studied due to its relatively small size, period of waste deposition up to 2006 and quantity of organic waste deposited. Waste was only deposited at this landfill for a period of 10 years. The total quantity of methane estimated to have been generated from 1996 to 2006 when the landfill closed and projected out for fourteen years more years to 2020 for scenario purposes is 101,198,084.1 m^3. From this estimate, the potential energy generation was about 1068318.3 MW.

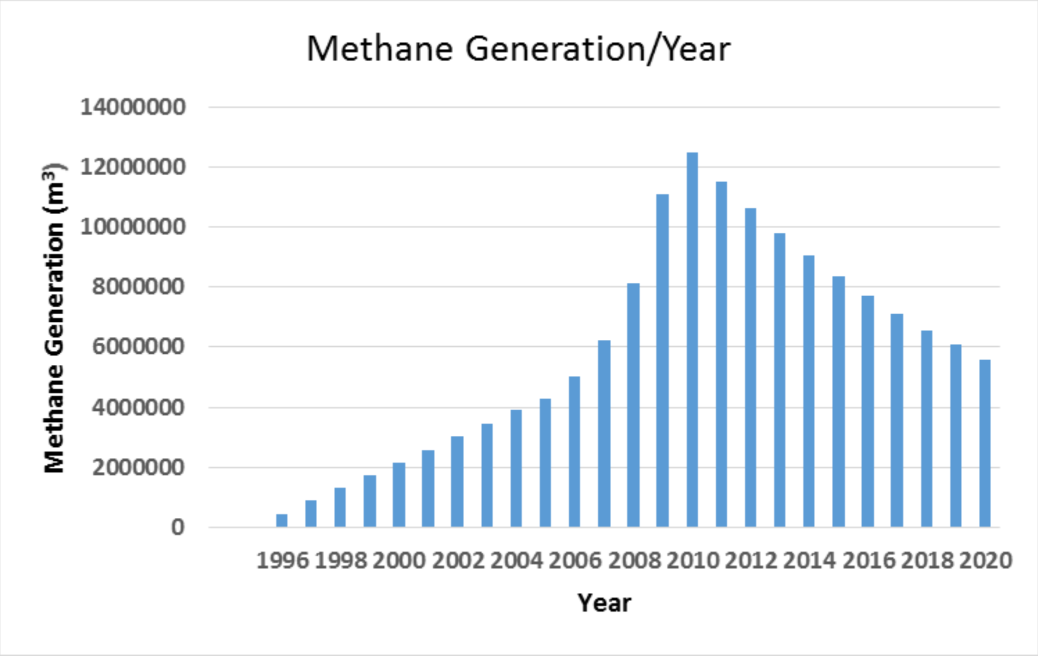

Figure 4. Graph of methane in Solous I Landfill (m^3/year)

The summary of methane recovery projections for the Solous I Landfill is illustrated in Figure 4. (See Appendix 3 for the complete estimation of methane and electricity generation at the Solus I landfill.)

5. Projection of Future Methane and Electricity Generation Capacity of Three Proposed Landfills

Our analysis shows that Lagos had the capacity to generate a significant amount of electricity from landfill gas in the past. Unfortunately, electricity generation infrastructure was not in place. However, all hope is not lost as there is still a considerable amount of methane gas present in the three existing landfills. To avoid further waste of landfill resources, this study also estimates how much methane and electricity Lagos can produce from future waste that will be disposed of in three new proposed landfills.

The analysis projected the population and waste generation in the city to the year 2050. According to the Lagos Bureau of Statistics data, Lagos had a population of 23,305,971 in 2015. Using this as the baseline year with an annual estimated growth rate of 3.19%, a population figure was estimated for each year up to 2050. Using the daily per/capita waste generation rate of 0.65kg in the city (LAWMA, 2012), an estimated projection of waste tonnage from 2015 to 2050 was also calculated. We anticipate that only 75% of the total waste generated each year will make it to landfills due to the city's history of indiscriminate and illegal dumping and the assumption that this practice will continue. In addition, we used the current rate of 45% of total waste generated as organic waste. Finally, we assumed in our model that the new landfills will be sanitary and well managed. These data assumptions facilitated the estimation of how much methane gas could be recovered from the estimated landfilled waste and how much electricity could then be generated from it over the scenario-based timeline.

Based on our estimates, the total methane that would be generated in Lagos from 2015 to 2050 from the three proposed landfills is 32,181,832,493 m^3. This could lead to a significant source of electrical energy for the city, as an estimated 339,051,195 megawatt hours (MWh) would be produced over time. The question then arises as to what percentage of the city's energy needs would be met with this electricity. Siemens' Green City Index report (Siemens, 2010) estimates the total electricity used by Lagos residents at 222 KWh per capita. In order to calculate the annual electricity needed for each projection year, the estimated population was multiplied by the per capita electricity in kWh to get an estimate of the city's energy demand for that year. The total cumulative energy demand from 2015 to 2050 is estimated at 340,811,241.8 MWh. Thus, the amount of electricity that could be generated from landfill methane would meet then surpass the electricity demands of Lagos' residents (see figure 5). Appendix 4 provides the detailed projections of waste, methane, future electricity, and electricity needs from 2015-2050.

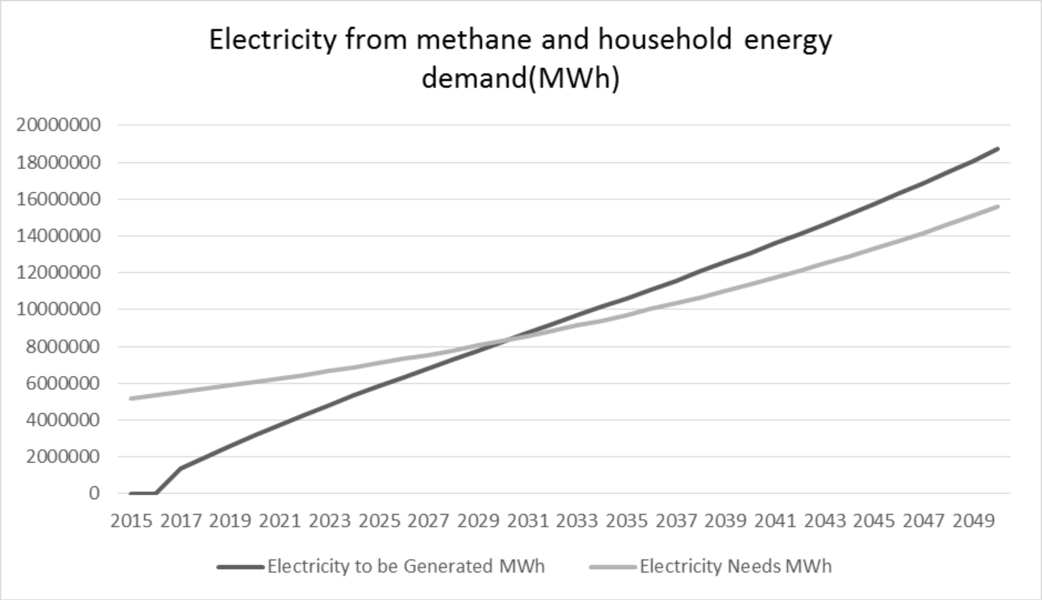

Figure 5. Annual electricity from methane and energy demand for Lagos in MWh.

The city currently gets its energy from hydro and thermal power sources that have failed to meet demand for several decades. Our study shows that investing in landfill methane capturing would add to the energy mix, strengthening the supply and meeting the city's electricity needs for years to come. Specifically, our projections indicate that regenerative waste-to-energy systems for landfill waste will have the capacity to meet all of Lagos' energy needs by around 2030. Until that time, a mixed fuel supply will continue to be required. It is worth noting that for the city to be able to harness this potential energy, there is a need for significant investment in green infrastructure to capture, transform and transmit the electricity.

6. Conclusions and Implications

Findings from this study show that there are significant opportunities for developing country megacities to meet their electricity demands by implementing sustainable practices and green infrastructure, particularly converting waste to energy through landfill methane capture. It is important to note that our analysis is scenario based; that is, we developed the analysis to determine the amount of methane that could have been generated from landfill waste and how much electricity could be generated from this methane from 1997 to 2050 if the infrastructure was in place. Because capturing equipment is not presently on these landfills, it is hard to ascertain how much gas is left that can be captured for electricity production. However, if action is taken sooner rather than later, a considerable amount of this gas could potentially still be captured from both closed and operating landfills.

Results estimated that Olushosun, the biggest and only currently operating landfill in Lagos, Nigeria, could generate around 497 million cubic meters (m^3) of methane gas from landfilled waste deposits from 1997 to the end of 2020 with the potential for generating over 5.2 million MWh of electricity over the 23 years period. Similar results were found for Lagos' other landfills, Abule-Egba and Solous 1, where an average of 149 million m^3 and 101 million m^3 methane gas could be generated cumulatively with the potential for producing 1.6 million MWh and 1.1 million MWh of electricity, respectively. Of particular importance is the estimate that Lagos has the potential to recover significant amounts of methane well into the future.

Lagos has plans to build three new landfills. These facilities present an opportunity to incorporate the green infrastructure and technology necessary to capture the methane for electricity production. Our models estimate that there is the possibility of recovering a total of 32.2 billon m^3 of methane from 2015 to 2050, which could be used to produce 339 million MWh of electricity. Cumulatively, we estimate that Lagos' total energy demand from 2015 to 2050 is slightly over 340 million MW. This is based on the 222 KWh per capita estimate obtained from Siemens' Green City Index report of 2010.

For decades, electricity generated in the city from hydro and thermal power has fallen short of demand resulting in incessant power outages, putting the city in darkness and forcing people to use liquefied gas generators. Adding the estimated annual average of 9.6 million MWh electricity produced from landfill methane gas to the country's energy mix would resolve this problem, even if the city were to reach its projected population growth of forty million people by 2050. Of course, it could be argued that to achieve this level of electricity generation, large infrastructure investments are needed to install equipment. The possibility of registering the construction and operation of the three new landfills as CDM-compliant facilities will enable Lagos to get supporting funds from carbon credits.

Waste management best practices in developed countries are leaning towards zero waste and diversion of organic waste from landfills to combat climate change and extend the lifespan of landfills. The diverted organic waste is sent to compost facilities or used to produce heat and electricity using Anaerobic Digestion (AD). A key factor that makes this possible is that organic waste is sorted at the source. This is a big challenge in developing countries' cities such as Nigeria, as wastes are comingled and never sorted before disposal. Thus, the diversion of organic waste in Lagos is not currently feasible. However, converting landfill methane to electricity is a viable waste management option for the city given its significant amount of organic waste. We speculate that this may be a feasible option for megacities in other developing countries as well as it adds to the energy mix of the city, enabling a more stable power supply to meet growing demand.

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Glossary

Anaerobic digestion – the use of microorganisms to decompose organic materials in a landfill to produce biogas.

Biofuel – Fuel derived from living matter.

Biogas – Landfill gas that is used as fuel.

First-order decomposition rate – decomposition that proceeds at a linear rate dependent upon the concentration of a single reactant. In this case study that reactant is methane.

Landfill gas (LFG) – a byproduct of decomposing landfilled organic materials. It consists of roughly 50% methane (CH_4), 50% carbon dioxide (CO_2) and traces of other organic compounds.

Regeneration – the use of heat (i.e., from landfilled organic material decomposition) or other components that would ordinarily be lost to produce a product (i.e., energy).

Sustainable systems approach – the integration of production, processing, distribution, consumption and waste management in order to enhance the environmental, economic and social health of a particular place.

Appendix

Appendix 1. Estimated Methane and Electricity generation at Olushosun landfill

Year	Waste Accepted	Waste-In-Place	Methane		Electricity
	Mg	*Mg*	*Mg*	*m^3*	*MWh*
1992	165909.09	0	0	0	0
1993	174204.55	165909.09	700.61	1050156.61	11086.19
1994	182914.55	340113.64	1382.39	2072081.17	21874.35
1995	192060.91	523028.18	2048.52	3070568.22	32415.08
1996	201663.64	715089.09	2702.07	4050181.78	42756.57
1997	211746.36	916752.73	3345.92	5015261.55	52944.63
1998	222333.64	1128499.1	3982.85	5969963.22	63023.14
1999	233450.91	1350832.7	4615.52	6918278.31	73034.22
2000	245123.64	1584283.6	5246.49	7864052.60	83018.48
2001	257379.09	1829407.3	5878.24	8810997.30	93015.09
2002	270248.18	2086786.4	6513.18	9762710.91	103062.05
2003	283760.91	2357034.5	7153.64	10722710.93	113196.49
2004	297949.09	2640795.5	7801.92	11694434.30	123454.68
2005	312846.36	2938744.5	8460.28	12681255.12	133872.26
2006	328489.09	3251590.9	9130.93	13686500.98	144484.34
2007	344912.73	3580080	9816.07	14713473.81	155325.79
2008	567814.55	3924992.7	10517.89	15765446.09	166431.15
2009	596205.45	4492807.3	12107.04	18147443.00	191577.19
2010	626015.45	5089012.7	13693.89	20526009.54	216687.01
2011	657316.36	5715028.2	15284.63	22910391.88	241858.23
2012	690181.82	6372344.5	16885.25	25309579.90	267185.75
2013	724690.91	7062526.4	18501.58	27732338.41	292762.09
2014	760925.45	7787217.3	20139.38	30187258.97	318677.96
2015	798971.82	8548142.7	21804.27	32682790.48	345022.55
2016	838920	9347114.5	23501.82	35227278.89	371883.96
2017	880866.36	10186035	25237.56	37828998.18	399349.54
2018	0	11066901	27016.97	40496196.15	427506.36
2019	0	11066901	24939.81	37382700.63	394638.11
2020	0	11066901	23022.34	34508582.03	364296.89
Total				**496787641**	**5244440.15**

Appendix 2. Estimated Methane and Electricity generation at Abule Egba Landfill

Year	Waste Accepted	Waste-In-Place	Methane		Electricity
	Mg	*Mg*	*Mg*	*m^3*	*MWh*
1995	70,000	0	0	0	0
1996	74,200	70,000	295.60	443,079.77	4,677.46

1997	78,652	144,200	586.21	878,678.74	9,275.95
1998	83,371	222,852	873.28	1,308,967.14	13,818.38
1999	88,373	306,223	1,158.20	1,736,043.31	18,326.9
2000	93,676	394,596	1,442.34	2,161,945.51	22,823.02
2001	99,296	488,272	1,727.03	2,588,669.26	27,327.82
2002	105,254	587,568	2,013.56	3,018,157.89	31,861.8
2003	111,569	692,822	2,303.22	3,452,338.30	36,445.31
2004	111,569	804,391	2,597.28	3,893,109.45	41,098.4
2005	167,354	915,960	2,868.73	4,299,992.50	45,393.75
2006	251,031	1,083,314	3,354.89	5,028,695.83	53,086.45
2007	375,547	1,334,345	4,157.02	6,231,025.02	65,779.09
2008	564,820	1,709,892	5,423.29	8,129,065.05	85,816.14
2009	353,012	2,274,712	7,391.48	11,079,220.23	116,960.05
2010	0	2,627,724	8,313.92	12,461,873.26	131,556.31
2011	0	2,627,724	7,674.71	11,503,758.91	121,441.78
2012	0	2,627,724	7,084.65	10,619,307.90	112,104.89
2013	0	2,627,724	6,539.96	9,802,856.71	103,485.86
2014	0	2,627,724	6,037.14	9,049,177.27	95,529.49
2015	0	2,627,724	5,572.99	8,353,443.46	88,184.83
2016	0	2,627,724	5,144.51	7,711,200.20	81,404.86
2017	0	2,627,724	4,748.99	7,118,334.96	75,146.16
2018	0	2,627,724	4,383.87	6,571,051.36	69,368.65
2019	0	2,627,724	4,046.82	6,065,844.92	64,035.33
2020	0	2,627,724	3,735.68	5,599,480.60	59,112.06
Total				**149,105,317.60**	**1,574,060.74**

Appendix 3. Potential Methane and Electricity generation in Solous I Landfill

Year	**Waste Accepted**	**Waste-In-Place**	**Methane**		**Electricity**
	Mg	***Mg***	***Mg***	m^3	***MWh***
1996	100,122	0	0.00	0.00	0.00
1997	106,512	100,122	422.80	633,743.33	6,690.24
1998	113,311	206,634	840.08	1,259,209.01	1,3293.1
1999	120,544	319,945	1,253.99	1,879,622.31	19,842.62
2000	128,238	440,489	1,666.62	2,498,118.77	26,371.9
2001	136,423	568,727	2,080.01	3,117,763.76	32,913.31
2002	145,131	705,150	2,496.19	3,741,576.86	39,498.72
2003	154,395	850,281	2,917.14	4,372,548.06	46,159.7
2004	164,250	1,004,676	3,344.85	5,013,646.33	52,927.58
2005	264,375	1,168,926	3,781.29	5,667,833.92	59,833.65
2006	184,781	1,433,301	4,606.98	6,905,487.50	72,899.19
2007	0	1,618,082	5,033.09	7,544,178.73	79,641.66
2008	0	1,618,082	4,646.12	6,964,154.71	73,518.52
2009	0	1,618,082	4,288.91	6,428,725.05	67,866.15
2010	0	1,618,082	3,959.17	5,934,461.18	62,648.35
2011	0	1,618,082	3,654.77	5,478,198.12	57,831.72
2012	0	1,618,082	3,373.78	5,057,014.24	53,385.4
2013	0	1,618,082	3,114.39	4,668,212.50	49,280.94
2014	0	1,618,082	2,874.94	4,309,303.27	45,492.04
2015	0	1,618,082	2,653.91	3,977,988.29	41,994.45
2016	0	1,618,082	2,449.87	3,672,146.02	38,765.76
2017	0	1,618,082	2,261.51	3,389,818.01	35,785.31
2018	0	1,618,082	2,087.64	3,129,196.42	3,3034.00
2019	0	1,618,082	1,927.13	2,888,612.37	30,494.23
2020	0	1,618,082	1,778.97	2,666,525.29	28,149.72
Total				**101,198,084.1**	**106,8318.3**

Appendix 4. Projection of future electricity that would be generated from Lagos landfills from 2015-2050

Year	**Waste Accepted**	**Waste-In-Place**	**Methane**		**Electricity Generated**	**Electricity Needs**
	Mg	***Mg***	***Mg***	***m*³**	***MWh***	***MWh***
2015	10328783	0	0	0	0	5173926
2016	10659304	10328783	43617	65378209	7286	5339491
2017	11000401	20988086	85276	127822006	1349379	5510355
2018	11352414	31988487	125173	187623944	1980690	5686686
2019	11715691	43340902	163489	245056232	2586986	5868660
2020	12090593	55056593	200393	300372354	3170942	6056457
2021	12477492	67147186	236043	353808593	3735053	6250264
2022	12876772	79624679	270586	405585418	4281645	6450272
2023	13288829	92501451	304159	455908777	4812894	6656681
2024	13714072	105790280	336891	504971292	5330833	6869695
2025	14169285	119504352	368902	552953365	5837365	7089525
2026	14605816	133673637	400374	600127773	6335371	7316390
2027	15073201	148279453	431270	646438350	6824258	7550514
2028	15555544	163352654	461765	692146816	7306789	7792131
2029	16053321	178908198	491951	737394139	7784452	8041479
2030	16567028	194961520	521919	782313469	8258652	8298806
2031	17097172	211528547	551752	827030849	8730720	8564368
2032	17644282	228625719	581531	871665857	9201919	8838428
2033	18208899	246270001	611330	916332208	9673448	9121258
2034	18791584	264478900	641222	961138311	10146453	9413138
2035	19392914	283270484	671277	1006187781	10622026	9714358
2036	20013488	302663399	701560	1051579933	11101218	10025218
2037	20653919	322676887	732136	1097410220	11585035	10346025
2038	21314845	343330806	763065	1143770653	12074448	10677098
2039	21996920	364645650	794407	1190750194	12570398	11018765
2040	22700821	386642570	826220	1238435114	13073793	11371365
2041	23427248	409343391	858560	1286909337	13585521	11735249
2042	24168056	432770639	891480	1336254754	14106446	12106337
2043	24950581	456938695	924998	1386495417	14636822	12498322
2044	25748999	481889276	959244	1437826552	15178710	12898268
2045	26572967	507638275	994228	1490264919	15732286	13311013
2046	27423302	534211242	1030002	1543887112	16298360	13736965
2047	28295087	561634545	1066616	1598769011	16877732	14173662
2048	29206475	589929631	1104097	1654949532	17470813	14630197
2049	30141083	619136107	1142545	1712579514	18079195	15098364
2050	31105597	649277189	1181983	1771694488	18703255	15581511
Total				**32181832493**	**339051195**	**340811242**

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