ALVIN F. TERRY

METHANE RECOVERY & ENERGY PRODUCTION FROM SOLID WASTE DISPOSAL MONTSERRADO, LIBERIA

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NEAR EAST UNIVERSITY

INSTITUTE OF GRADUATE STUDIES

DEPARTMENT OF BIOSTATISTICS

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M.SC. THESIS

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September 2022

Approval

We certify that we have read the thesis submitted by Alvin F. Terry titled **"Methane Recovery & Energy Production from Solid Waste Disposal in Montserrado County, Liberia"** and that in our combined opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Biostatistics.

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Declaration

I hereby declare that all information, documents, analysis, and results in this thesis have been collected and presented according to the academic rules and ethical guidelines of the Institute of Graduate Studies, Near East University. I also declare that as required by these rules and conduct, I have fully cited and referenced information and data that are not original to this study.

Alvin F. Terry

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Acknowledgments

There is a famous saying that "Life will cease to exist if it does not have its ups and down". This statement has actually proven to be true in my case. I have personally experienced many obstacles and challenges in life least to mention my educational sojourn. With all those challenges and hardships, I have been triumphant through all of them because there have always been giants who have sacrificed a lot of things to make sure that I get through them all. I believe that my life will cease to exist if I am not grateful and thankful to the almighty God Jehovah who has shown me undeserved kindness by continuing to keep me alive even though I have many shortcomings. I want to acknowledge the guidance and patient instructions given me throughout the writing of this thesis by my vibrant and hardworking advisor and chairman of the department of Biostatistics at the Near East University, Professor Dr. Ilker Etikan. He is such an excellent professor and mentor. I am happy to have been taught by a statistical genius and a patient instructor whose attitude towards students is worth noting, Associate Prof. Dr. Ozgur Tosun.

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Abstract

The purpose of this study was to estimate the amount of methane that can be recovered and converted to energy from solid waste disposal within the most populated county in the Republic of Liberia, which is Montserrado county. The researcher decided to undertake this study so as to advise government because Liberia for many years has suffered from a lack of electricity thereby contributing to its backwardness. Less than 2% of Liberians have access to electricity. From that report, Liberia's Electricity is one of the lowest as compared to other countries in the world. The grid in Monrovia is mostly powered by high-priced, dirty diesel-fueled electricity. The total installed on-grid capacity in Liberia is less than 23 megawatts (MW). 10 times more than the existing generation capacity is what hotels, restaurants, and office complexes self-generate. (Liberia: Power Africa, May 2016).

The researcher did a quantitative analysis of solid waste disposal by using data obtained from the 1962,1974, 1984 and the 2008 censuses to obtained the population of Montserrado county and obtained the waste generation rate by consulting credible sources and using the waste spreadsheet produced by IPCC to obtain the amount of methane that can be generated from solid waste of Montserrado from 1960 to 2021. SPSS was also used to run correlation and regression analysis to see the relationship between solid waste disposal, methane recovery and energy produce from methane recovered.

The result of the study shows that Solid waste disposal produces methane because there were 1 gigagram of methane produced in 1960 and 8 gigagrams produce in 2021. The Spearman's Correlation coefficient of Solid Waste Disposal and Methane Recovered is 99.6% and it is significant. P-value < 0.001. The Spearman Correlation coefficient of Solid Waste Disposal and Electricity in Kwh is 99.6% and it is significant. P-value < 0.001. The Regression model P-value < 0.001 tell us that the Solid waste deposited has a significant impact on methane recovered. From the coefficient table of the regression model, the P-value < 0.001 tell us that Solid waste deposited has a significant impact on Electricity generated in Kwh. The researchers recommended the need to construct Standardized sanitary landfill in the country for methane recovery so as to ease the electricity problem of the country.

Keywords: Methane ,IPCC, Gigagrams, Sanitary Landfill, Regression.

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List of Abbreviations

CH4	Methane
CHP	combine heat and Power
CO2	carbon dioxide
FOD	First order decay
GWP	global warming potential
IPCC	Intergovernmental panel on climate change
LFG	Landfill gas
LISGIS	Liberia institute of statistics and geoinformation services
MCC	Monrovia City Cooperation
NMOC	Nonmethane organic compounds
RNG	renewable natural gas
SWDS	Solid Waste disposal sites

CHAPTER 1

1.0 Introduction

As an Introductory chapter for this thesis, this chapter focuses on the following: Statement of the Problem that is leading to this research, Objective, research questions or hypotheses, significance, limitations, and definitions of terms that will be used in this research work.

1.1 Statement of the Problem

Liberia, like many countries, is a signatory to the Paris Climate Agreement in which she has committed herself to reduce her greenhouse gas emission. One source of methane emission is solid waste disposal and methane is a greenhouse gas. Methane may be used to generate energy, heat a building, or operate waste collection vehicles. Climate change may be mitigated by capturing methane before it reaches the atmosphere.

United States Agency for International Development (USAID) is credited with leading humanitarian and development initiatives to save lives, decrease poverty, improve democratic government and enable people to advance beyond aid, as reported by Power Africa “Two out of three people in sub-Saharan Africa lack access to electricity”. (https://www.usaid.gov/powerafrica).

Less than 2% of Liberians have access to electricity. From that report, Liberia’s Electricity is one of the lowest as compared to other countries in the world. The grid in Monrovia is mostly powered by high-priced, dirty diesel-fueled electricity. The total installed on-grid capacity in Liberia is less than 23 megawatts (MW). 10 times more than the existing generation capacity is what hotels, restaurants, and office complexes self-generate. (Liberia: Power Africa, May 2016)

Despite having a population of 4.82 million people, the Liberian government is collaborating with development partners to rehabilitate the country's energy infrastructure. As the Liberian civil war ended in 2003, much of Liberia's electrical sector was wiped out. Less than a quarter of the people in Liberia's capital city of Monrovia have access to electricity. Liberia's government hopes to link 70% of Monrovia's population and 35% of the rest of Liberia by 2030, in order to satisfy the country's estimated peak demand of 300 MW and service 1 million consumers. (https://www.usaid.gov/powerafrica/liberia).

According to trends in solid waste, an article published by the world bank "Every year, the globe produces 2.01 billion metric tons of municipal solid trash, of which 33 percent — to put it mildly—is not handled in an ecologically friendly way. The amount of garbage produced by each individual on a daily basis varies greatly, ranging from 0.11 kilos to 4.54 kilograms. More than two times as many people will be living by 2050 if current trends hold, with an estimated 3.40 billion tonnes of trash generated. Developing nations will produce three times as much rubbish as developed ones by the year 2050. Nearly a quarter of the world's garbage is produced in East Asia and the Pacific, whereas just a sixth is produced in the Middle East and North Africa area. By 2050, overall garbage creation is predicted to more than treble in Sub-Saharan Africa, South Asia, the Middle East, and North Africa, mostly in these four areas. There's little doubt that Liberia will be impacted by this forecast since it's located in the Sub-Saharan African area. More than half of the garbage generated in these areas is being disposed of in an open landfill, and the future expansion of this waste will have significant ramifications for the region's ecology, health, and economic well-being." (worldbank.org/what-a-waste/trends in solid waste management.)

Liberia's economic growth is expected to decline as the population continues to grow, making it more difficult for families to make ends meet in the future. This has the potential to be a major environmental issue. Since Liberia's population is expected to grow by 2.5 percent per year through 2030, its total population is expected to rise to 6.4 million. As of 2018, 1.26 million people lived in the country's most populous county, Montserrado, which includes the capital city of Monrovia. (United States Agency for International Development) (2016). The population growth of Montserrado is also generating a huge amount of solid waste as solid waste generation is directly proportional to population growth. The waste generation rate of Paynesville, a city in Monrovia is 0.41 kg/cap/day. (Nyumah et al,2021). Liberia is presently faced with an electricity problem and Montserrado being the highest populated county has a huge potential for solid waste generation which when properly collected can produce significant methane that can be used to produce electricity to help curtail her electricity need.

1.2 Purpose of the Study

Because of its poverty, Liberia is entirely reliant on foreign aid and remittances sent back by Liberians living abroad (World Bank, 2018). A large part of Liberia's economy was devastated by the civil war of the 1990s and 2000s, particularly in Monrovia. Liberia's natural resources were a major factor in the conflict.

Liberia's water, sanitation, and hygiene (WASH) industry are plagued by widespread difficulties with improper waste disposal in the country's urban and rural regions. A lack of attention is paid to the significance of water and sanitation, which are essential for health and dignity in Liberia. The collection and disposal of rubbish in and around Monrovia is still a major issue, according to a recent WASH study. This city's solid trash collection is handled by the Monrovia Municipal Corporation (MCC).

The predominance of sickness in the human world may be seen as a result of a lack of coordination between international agencies, governments, and non-governmental organizations (NGOs). Inadequate management of household waste is one of the causes cited for this deficiency (Fakunle, S. O., Ajani, O. A. 2021). Solid waste management is a long-running global debate, made all the more difficult in developing country cities. Liberia ranks 175th out of 189 nations and territories based on its 2019 HDI score of 0.480, placing it in the "poor human development" category. (http://hdr.undp.org/en/data).

Since Liberia is ranked very low in the human development index due to her inability to meet basic social services for her citizens thereby contributing to reducing life expectancy, implementing this study will help Liberia see how much energy can be generated from solid waste in Montserrado. It will help her see the need to properly collect and manage her solid waste so as to generate more methane which can be used for energy production and reduce many diseases too.

1.3 Research Question/ Hypothesis

The researcher will base his research on the following hypothesis:

H_1: There is a positive relationship between Solid waste disposal and Methane generation

H_2: There is a significant relationship between solid waste disposal and Methane recovery

H_3: There is a relationship between Solid waste disposal and Energy Production.

1.4 Significance of the Study

Less than 2% of Liberians have access to electricity. From that report, Liberia’s Electricity is one of the lowest as compared to other countries in the world. The grid in Monrovia is mostly powered by high-priced, dirty diesel-fueled electricity. The total installed on-grid capacity in Liberia is less than 23 megawatts (MW). 10 times more than the existing generation capacity is what hotels, restaurants, and office complexes self-generate. (Liberia: Power Africa, May 2016).

Liberia's population is expected to grow by 2.5 percent per year through 2030, its total population is expected to rise to 6.4 million. As of 2018, 1.26 million people lived in the country's most populous county, Montserrado, which includes the capital city of Monrovia. (United States Agency for International Development) (2016). This huge population growth place Montserrado on the verge of generating a significant amount of solid waste that when properly collected and manage can generate large amount of methane. This study is important because it will help Liberia accomplish the following:

1. To help Liberia address one of her major problems of Electricity through the capturing of Methane gas from solid waste disposal.
2. To help Liberia and the world at large reduce the effects of climate change by safely capturing Methane gas produced through solid waste disposal.

1.5 Limitations of the study

As in many other studies, this research is limited to Montserrado County in Liberia. Waste generation rate and composition of waste might not perfectly reflect other counties or countries. The estimation of methane emission from solid waste is limited to the first-order decay method that is incorporated into a spreadsheet prepared by IPCC and might not be the same when other methods are used. This research is limited to only solid waste generated from households within Montserrado county in Liberia because the researcher used the waste generation waste of Montserrado county. This research did not take into consideration other sources of solid waste.

1.6 Definition of Terms

Solid Waste - refers to a wide variety of waste products, both animal and human, that are thrown away as undesired and unusable. (An Introduction to Solid Waste Management)

Methane - One of the most dangerous gases on the planet is methane (CH_4). Carbon and hydrogen are the primary constituents. According to the US Environmental Protection Agency, It's also a potent greenhouse gas, which means it's a part of the problem.

IPCC - The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change.

Global Warming Potential (GWPs) - is a measurement that compares the amount of energy that Over a predetermined period of time, the effluence of one ton of a gas will take in the same amount of carbon II oxide as the emissions of one ton of carbon dioxide. This measurement is referred to as a carbon dioxide equivalent (CO_2). When compared to CO_2, a certain gas's Global Warming Potential (GWP) indicates the degree to which it contributes to the overall warming of the planet over a set period of time. The time span of one hundred years is often used for GWPs. (EPA, USA-2022)

Landfill gas (LFG) - The production of landfill gas (also known as LFG) is a natural byproduct that occurs when organic matter is decomposed in landfills. Methane, which is the principal component of natural gas, makes up around half of the composition of LFG, with the other half consisting of carbon dioxide (CO_2) and a trace quantity of non-methane chemical molecules. (EPA, USA- 2022).

Renewable natural gas (RNG) - The term "renewable natural gas" (RNG) refers to a gas that is of pipeline quality and is totally interchangeable with conventional natural gas. As a result, RNG may be used in cars that run on natural gas. RNG is basically biogas, which refers to the gaseous product that results from the breakdown of organic waste, but it has undergone additional purification steps. (U.S department of energy).

CHAPTER TWO

2.1 Literature Review

This chapter is intended to review some pieces of literature by people who have written on the issue of solid waste disposal. It will also provide the framework for this thesis.

2.2 Theoretical Framework

Methane has a global warming potential (GWP) of 28 times that of carbon dioxide over a 100-year time horizon; on a 20-year horizon, carbon dioxide has a GWP of 84 times less than that of methane. IPCC Fifth Assessment Report (AR5). In landfills that are used for the disposal of municipal solid waste (MSW), the breakdown of organic waste results in the production of methane gas. In 2005, the disposal of solid waste in landfills was the third largest source of methane emissions, after enteric fermentation and natural gas and oil systems respectively, according to the US Environmental Protection Agency (EPA). Solid waste disposal is a major source of methane production, as we can see from the US EPA data.

To calculate methane emissions from SWDS in the modified 1996 IPCC Guidelines and IPCC Good Practice Guidance, a mass-balance equation was used. This technique assigns the whole year’s worth of methane emissions from a particular year's trash disposal to that year. As a result, the deterioration profile of wastes over time cannot be accurately modeled using this technique. In actuality, there is a lag period between trash disposal and the onset of methane emissions, and emissions might continue for decades thereafter.

The first few years following deposition are the most productive for SWDS methane production, but when carbon is depleted, production declines. Emission estimations may be inaccurate in cases when waste amount, composition, and conditions vary from year to year, due to assumptions made in the previous default technique. This strategy will overstate emissions as waste disposal increases.

In accordance with IPCC recommendations, the year in which emissions to the atmosphere (or removals from it) occur must be noted. (IPCC 2006 Guidelines). It is highly recommended that the FOD model be used to create more accurate emission estimates that reflect the degradation rate of garbage in a landfill. The IPCC established the Waste Model and revised default settings to help nations who previously assessed SWDS emissions using mass balance and will now provide estimates using the FOD model. The first-order decay model is the most precise of the models that have been required by the IPCC for use in estimating methane emissions from the disposal of solid waste (FOD). This research is intended to address Liberia's electricity problem by helping her to see how much electricity can be generated from methane recovery from solid waste. This study assumes that all garbage is collected and put in a landfill for appropriate methane production.

As a comprehensive report on landfill gas emissions and energy recovery from solid waste disposal, this report covers a wide range of topics related to Liberia's present waste condition, landfill gas composition, Factors Affecting the Production of Landfill Gas, Waste Composition and Generation, and Recovering and Treating Landfill Gas are all discussed here. There are theoretical and empirical data on landfill methane emissions from this work.

2.3 Liberia Waste Condition

A country with more than four million residents, The Liberian economy has grown significantly since the conclusion of the civil war in 2003, thanks in large part to international assistance. It's becoming increasingly difficult to manage trash in Liberia because no complete framework exists, no conventions dictate who is responsible for what types of waste and policymakers are unwilling to develop and put in place a system that is both sustainable and integrated. Montserrado County, where the city of Monrovia is located, is seeing significant growth. Because of the rise in urbanization and economic development, the amount of rubbish being generated has risen as a result of these factors. Based on a review of previous waste density studies and Arup's professional judgment, a baseline value of 261kg/m3 is assumed for greater Monrovia's MSW density (Bunch).

When it comes to environmental sustainability, poor solid waste management is a major hindrance. There are a number of problems with improper solid waste management that endanger the environment and human health, including the use of non-renewable materials in the MSW treatment process. People are exposed to disease organisms and other pollutants when MSW is improperly disposed of and managed, which includes air, soil, and water contamination. Garbage dumping has affected both surface and groundwater systems. Stagnant water for bugs to breed and flooding during the rainy season are the result of MSW clogging the drains. MSW burning and improper incineration are major causes of urban air pollution in Liberia. (Vrijheid M., 2000).

Whein Town landfill is located approximately 13 km northeast of Monrovia and began operation in June 2008 supported under the World Bank International Development Assistance (IDA) financed Emergency Monrovia Urban Sanitation (EMUS) Project. The landfill is approximately 25 acres in size and is surrounded by scattered residential settlements and some agricultural activities. (Environmental and Social Review Summary, May 2011).

The Monrovia City Corporation developed a sanitary landfill at Whein Town and two waste transfer stations, one at Fiamah and the other at Stockton Creek, on the Somalia Drive, as a mean of collecting and disposing of solid waste from the City of Monrovia. The wastes collected from around the City of Monrovia and its environs are temporarily (less than 24 hours) taken to one of the two (2) transfer stations and subsequently taken to the sanitary landfill at Whein Town to be disposed.

In 2010, an Environmental and Social Impact Assessment study (ESIA) was done by POYRY ENVIRONMENTAL, a Liberian-based environmental consultancy firm before the building of the Whein Town Landfill site. It stated in its operation and maintenance manual that "during the operation and post-closure phases, the facility may be associated with negative impacts due mainly to leachate generation with potential surface and/or groundwater contamination, visual/landscape intrusion, biodiversity, air quality, traffic as well as health and safety issues. Other less serious impacts of concern include odorous emissions, soil contamination, Landfill stability/settlement and socio-economics.". (Poyry, ESIA O&M 2010).

Research was conducted on heavy metal contamination of groundwater by taking water samples from a 2km radius and O. T. Oyeku and A. O. Eludoyin who conducted that research concluded that all groundwater within a 2km radius around a landfill is vulnerable to pollution. (O. T. Oyeku and A. O. Eludoyin (2010).

Because of its enormous environmental relevance, the result of landfill on groundwater and surface water resources has recently gained a great deal of attention. Detergents, inorganic compounds, complex organic substances, and metals are all found in the leachate from municipal solid waste (MSW). When rainwater infiltrates the garbage, it causes the leachate to exit the dumping site (landfill) either horizontally or vertically and into the ground water, creating pollution. (Rohit Ahire, et al June 2019).

Groundwater seeps into landfills and open wastes, or precipitation seeps into open dumps. Decomposition products and early interstitial water are progressively released by solid wastes that have been deposited. Leachate is the name given to a liquid that contains a wide variety of organic and inorganic chemicals. The leachate that collects at the bottom of the landfill seeps through the soil and into the surrounding environment. (Suman Mor, et al -2006).

2.4 Composition of Landfill Gas

Distinct gases are what Landfill gas contains. 90 to 98 percent of landfill gas is composed of methane and carbon dioxide. Atmospheric gases like nitrogen and oxygen make up between 2% and 10% of the atmosphere. Bacteria break degrade organic waste in landfills, releasing pollutants into the atmosphere. A landfill's kind of garbage, its age, its oxygen concentration, its moisture content, and its temperature all have an impact on how much gas is produced by decomposition. If the temperature or moisture content rises, for example, gas output will rise. A landfill may continue to create gases for more than 50 years, despite the fact that the generation of these gases typically peaks in five to seven years. (New York state, department of health - 2019).

2.5 How Gas is Generated at Landfill Sites

2.5.1 Major Processes

Gas is produced in a landfill by three distinct processes: degradation by bacteria decomposition, volatilization, and chemical reactions.

Degradation by bacteria - The majority of the gas that is created in landfills is the result of bacterial decomposition. This process takes place when bacteria that are naturally present in the rubbish and in the soil that is used to cover the landfill break down organic waste. This soil also contains bacteria that are responsible for the breakdown of organic waste. Examples of organic waste include things like food, yard trash, rubbish swept up from the street, discarded fabrics, and goods made of wood and paper. There are four stages that bacteria go through as they break down organic waste, and throughout each stage, the makeup of the gas varies. (ATSDR – 2001).

Volatilization - When some types of garbage, especially organic compounds, undergo the phase shift from a liquid or solid state into a vapor state, the resulting gases might be considered to be landfill gases. The term for this kind of process is "volatilization." There is a possibility that the presence of NMOCs in landfill gas is due to certain chemicals having been disposed of in the landfill and then afterward volatilizing. (ATSDR – 2001).

Chemical reactions - Certain chemical reactions that take place in landfills can result in the production of landfill gas and volatile organic compounds (NMOCs). For instance, toxic gas will be created if chlorine bleach and ammonia come into touch with each other inside the waste. (ATSDR – 2001).

During the aerobic (oxygen-rich) breakdown stage of MSW at a landfill, very little methane is produced. A colony of methane-producing bacteria may begin creating methane in as little as a year from the breakdown of garbage. (EPA, USA- 2022)

In four stages, bacteria break down landfill debris. Each step of decomposition has a different gas composition, and the garbage in a landfill may be moving through many stages at once. The length of time it takes for the waste to decompose varies depending on the landfill's conditions.

The following figure shows how the normal LFG composition changes once garbage is placed.

Figure 2.1:

Production Phases of Typical Landfill Gas - (ATSDR 2008.)

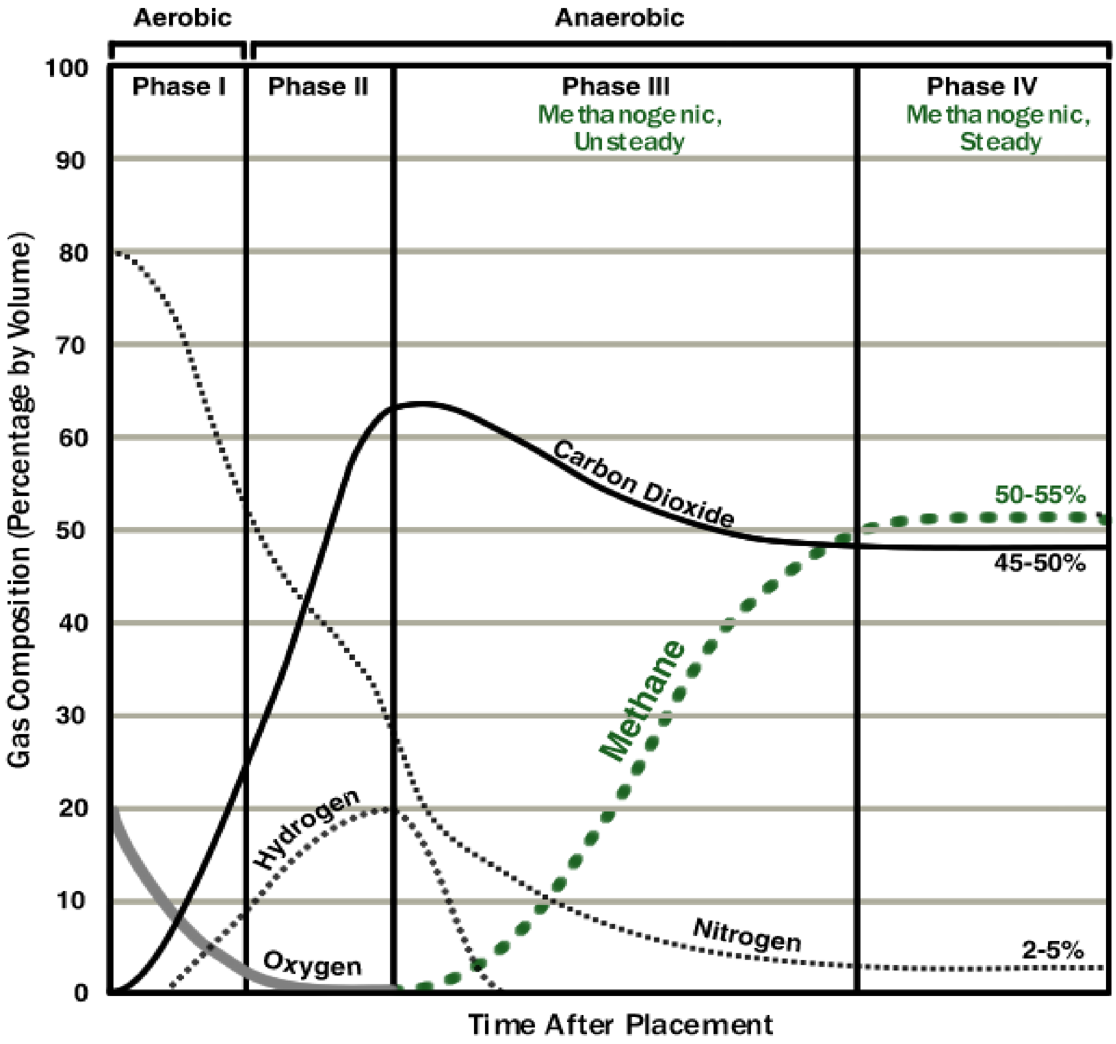


Table 2. 1:

Typical Landfill Gas Components

Component	Percent by Volume	Characteristics
methane	45–60	The gas methane is found in nature. It has no color and no scent.
carbon dioxide	40–60	naturally present is CO2 in the atmosphere at low amounts (0.03 percent). A little acidity

		balances off its lack of color, odor, and flavor.
nitrogen	2–5	Nitrogen makes up a whopping 79% of the air we breathe. It has no flavor, smell, or color.
oxygen	0.1–1	Oxygen makes up around one-fifth of the air we breathe. None of its properties are present in it.
ammonia	0.1–1	A colorless gas is what ammonia is and it has a bad scent.
NMOCs	0.01–0.6	Chemicals can be classified as non-metallic organic compounds (NMOCs) (i.e., compounds that contain carbon). It is an organic compound, although it is not a Nationally Significant Organic Compound (NMOC). NMOCs may be found in nature or created artificially via chemical reactions. A number of common NMOCs are found in landfills, including Trichloroethylene (TCE), vinyl chloride, and hexane, xylene, and acrylonitrile. Carbonyl sulfide, carbonyl methyl ketone,
sulfides	0–1	For example, the landfill gas combination smells rotten because of the naturally occurring sulfides such as mercaptans, dimethyl sulfide, and hydrogen sulfide. Even at low quantities, sulfides may produce disagreeable scents.
hydrogen	0–0.2	No odor and color is hydrogen gas.
carbon monoxide	0–0.2	As a gas, CO has no odor, and color.
[Tchobanoglous, Theisen, and Vigil, 1993] [EPA, 1995]		

2.5.2 Phase One

The process of composting starts with the first stage of decomposition of organic waste by aerobic bacteria. These bacteria make use of oxygen while dismantling the lengthy molecular chains of complex carbohydrates, proteins, and lipids. The main byproduct of this process is carbon dioxide. The nitrogen concentration in the landfill's first phase is greater than in the second, although this will decrease with time. To the point when there is no more oxygen in the system, Phase I continues. For days or months, Phase I decomposition might persist in landfills, whether or if there's enough oxygen. There are varieties of circumstances that determine the oxygen level in the trash, such as how loose or compacted it was before to burial. (ATSDR – 2001).

2.5.3 Phase Two

Phase II decomposition occurs when the landfill's oxygen supply is exhausted. A variety of acids and alcohols may be produced by anaerobic bacteria, including acetic, lactic, and formic acid (a process that does not need oxygen). The landfill turns into a cesspool of acidic waste. Acids in the landfill's moisture break down nitrogen and phosphorus, making them accessible to the landfill's ever-expanding bacterial population. CO_2 and H_2 gas are byproducts of these reactions. Disturbing the dump or introducing oxygen into the rubbish will resume Phase I microbiological activity. (ATSDR – 2001).

2.5.4 Phase Three

Phase III decomposition begins with the consumption of organic acids created in Phase II by specific anaerobic bacteria, resulting in the formation of acetate, an organic acid. As a result of this procedure, the landfill is transformed into a more favorable habitat for the growth of bacteria that produce methane. Bacteria that produce methane and acid have a symbiotic interaction. Compounds produced by acid-producing bacteria are used by methanogenic bacteria. The excessive amounts of carbon dioxide and acetate that are eaten by methanogenic bacteria are toxic to acid-producing bacteria. (ATSDR – 2001).

2.5.5 Phase Four

In order to initiate decomposition in Phase IV, landfill gas composition and production rates must be reasonably stable. There may be 45 to 60 percent methane and 40 to 60 percent carbon dioxide in phase IV landfill gas depending on the landfill. There may be 2 to 9 percent additional gases including sulfur dioxide. At a steady pace for roughly 20 years in Phase IV (usually), Nonetheless, there will be continuous emissions from the landfill for at least fifty years after the waste has been put in it. When there are more organic materials in the garbage, particularly in the case of a landfill that gets more waste from domestic animals than is customary, gas production may continue for a longer period of time. (ATSDR – 2001).

2.6 Landfill Gas Composition Change During the Processes

In landfills, microbial breakdown pathways are quite complex. Based on how quickly waste degradation progresses, (Christensen et al.) developed an eight-phase classification system for the gas composition changes that occur during the processes.

Table 2.2

The Eight Phases of Waste Degradation (Christensen et al)

Phase	**Description**	**Gas(Decreased in Vol.%)**	**Gas (increased in Vol.%)**
I	Composting readily degradable organic matter to CO2 during a brief aerobic phase depletes O2 levels.	O2	CO2

II	Acidogenic and fermentation bacteria create volatile fatty acids, carbon dioxide, and hydrogen gas in anaerobic circumstances. The amount of N_2 in the air is reduced when these gases are present.	N_2	CO_2, H_2
III	Methanogenic bacteria begin generating CH_4 in a second anaerobic phase, CO_2 and H_2 levels decline.	H_2, CO_2	CH_4
IV	50-60% CH_4 and low H_2 concentrations define the stable methanogenic phase. CO2 oxidizes the latter.	CO_2	CH_4
V	The generation of CH_4 is reduced when air enters the outside half of the waste body. Because of the decreased interest rates, there is a greater CH_4.	CO_2, CH_4	N_2
VI	During its journey to the outer reaches of the landfill, the methane created in the waste's core is oxidized to carbon dioxide (CO_2). The gas now contains considerable amounts of N_2.	CH_4	CO_2, N_2
VII	Now, rather than generating methane, the fresh air is oxidizing the solid organic carbon (as well as reduced inorganic species).	CH_4, CO_2	O_2, N_2
VIII	With these increased rates of reaction, landfill gas begins to resemble the air in active soil.	CO_2	O_2

2.7 Landfill Gas Production Affecting Factors

A wide variety of environmental factors, such as the type and age of the garbage (For instance, the amount of oxygen that is present in the waste, the amount of moisture, and the temperature), can have an effect on the amount of produced landfill gas as well as the rate at which it is produced in a particular location. (DoE 1995 EPA 1993 Crawford and Smith 1985)

2.7.1 Waste Composition.

Bacterial decomposition generates more landfill gas when there is a higher volume of organic waste in a landfill. Nutrients including salt, potassium, calcium, and magnesium may be found in organic waste. A higher amount of landfill gas is produced when certain nutrients are present in the waste Some wastes, on the other hand, include substances that damage bacteria and reduce the production of gas. For example, excessive salt concentrations in the trash may suppress methane-producing microbes. (DoE 1995 EPA 1993 Crawford and Smith 1985).

2.7.2 Oxygen in the Landfill

Bacteria begin producing methane only when oxygen is depleted. As landfill oxygen levels rise, aerobic bacteria's ability to digest garbage in Phase I increases. More oxygen is accessible to oxygen-dependent bacteria, allowing them to survive longer and create more carbon dioxide and water vapor. However, methane production will begin sooner if the trash is substantially compacted since anaerobic bacteria that produce methane will replace the aerobic bacteria in Phase III. The anaerobic bacteria begin making methane gas after the aerobic bacteria have used up all of the oxygen in the landfill, thus any remaining oxygen slows down methane production. It's possible that high barometric pressure might change the bacterial activity in waste soils. Once the oxygen is depleted, the waste from Phase IV may momentarily return to Phase I. (DoE 1995 EPA 1993 Crawford and Smith 1985).

2.7.3 Moisture Content

Because bacteria flourish in wet conditions and nutrients and bacteria are carried throughout the garbage, gas generation increases when there is little amount of water in a landfill. Based on the wet weight, most gas may be generated when the waste has a moisture content of 40% or above (e.g., in a capped landfill). Compression reduces methane production by increasing the landfill's density and decreasing the pace at which water can permeate, therefore reducing methane generation. In a landfill, heavy rains and/or permeable landfill cover may enhance the rate of methane production. (DoE 1995 EPA 1993 Crawford and Smith 1985)

2.7.4 Temperature

The rate of landfill gas production rises as a result of increased bacterial activity at higher temperatures. Bacteria are less active at lower temperatures. Bacterial activity often decreases considerably below a temperature of 50 degrees Fahrenheit (F). Shallow landfill gas generation is far more sensitive to variations in weather. This makes them more vulnerable to changes in temperature than deep landfills, which have a thick coating of soil covering the garbage. Deep landfills have a thick layer of dirt covering the rubbish. It is common for a capped landfill to keep a constant temperature, which helps to maximize gas production. While temperatures have been recorded as high as 158 degrees Fahrenheit, the heat released by bacteria in landfills keeps them between 77- and 113 degrees Fahrenheit. Volatilization and chemical processes are also facilitated by rising temperatures. For every 18° F rise in temperature, the emission of NMOCs doubles. (DoE 1995 EPA 1993 Crawford and Smith 1985)

2.7.5 Age of Refuse

More gas will be produced by newly buried garbage than by older rubbish. Within one to three years, significant volumes of gas are often produced by landfills. Five to seven years after garbage is placed, peak gas production normally occurs. Even after a landfill has been closed for 50 years, some gas may still be discharged into the atmosphere for up to 20 years after the garbage has been deposited. Slow decomposition of garbage, on the other hand, is expected to release methane after five years and continue to leak gas for the next 40 years under a low-methane yield scenario. There may be several stages of decomposition may be happening at once based on the time the waste was thrown. When it comes to the duration of gas generation, the volume of organic material in the waste is a critical determinant. (DoE 1995 EPA 1993 Crawford and Smith 1985)

2.8 Factors that affect waste composition and Generation

It is possible to estimate emissions from landfills using garbage generated in various nations and areas, taking into account elements such as public behavior and climate, waste management techniques, and the sorts of energy sources that are accessible. Table 2-3 summarizes factors listed.

Table 2.3

What Affects the Production and Composition of Waste

	Source	
	Eggleston et al., 2006 [a]	*Hoornweg and Bhada-Tata, 2012*
Waste Generation	1) economic situation 2) industrial structure 3) waste management regulations 4) life style	1) economic development 2) the degree of industrialization 3) public habits 4) local climate
Waste Composition		1) culture 2) economic development 3) climate 4) energy sources

a. These variables have an impact on both trash creation and the composition of garbage.

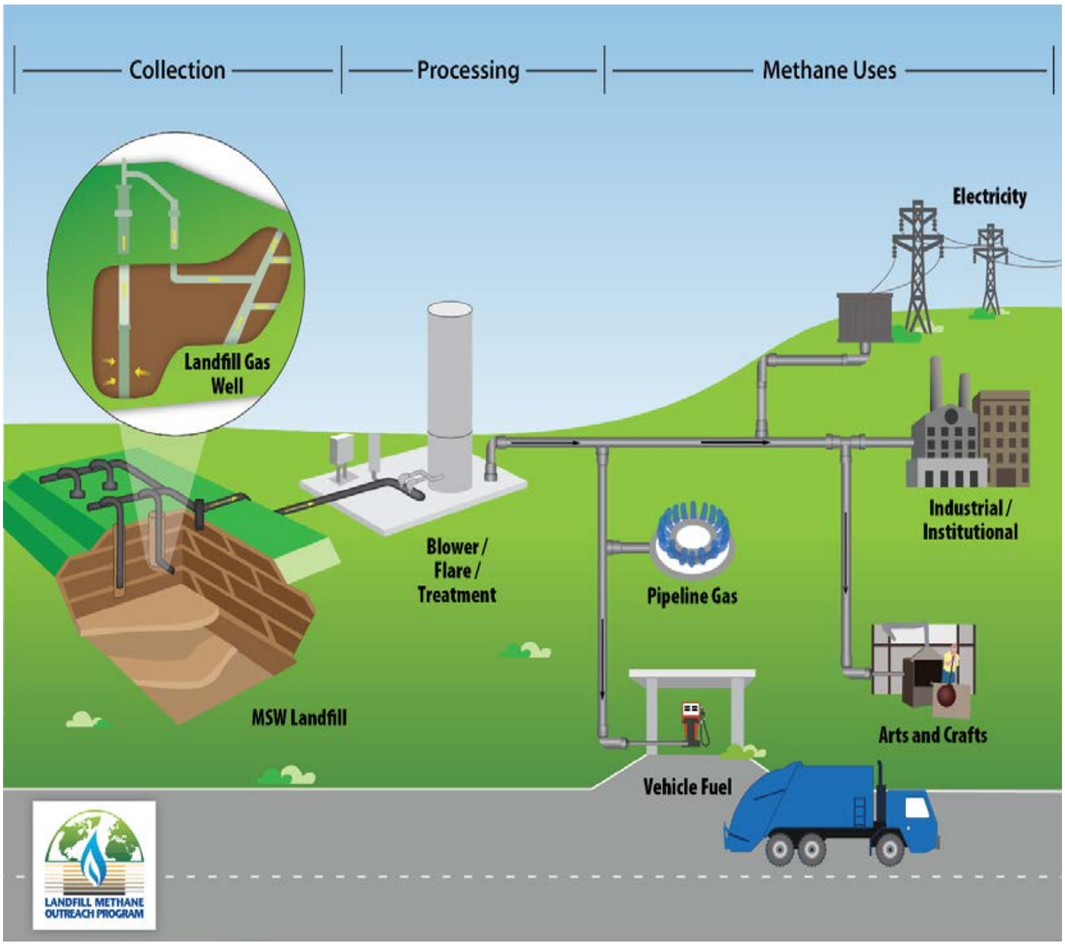
2.9 Treatment and recovery of Landfill Gas

Landfill Gas (LFG) may be utilized as a renewable energy source instead of leaking into the atmosphere. Reduced pollution and global climate change are achieved as a consequence of employing LFG to keep methane from entering the atmosphere. Economic benefits and job opportunities are generated by LFG's energy projects in the surrounding area. (EPA, USA- 2022)

Methane may be used in a variety of ways, and figure 2.2 shows how Landfill Gas is collected and processed. To begin, LFG is gathered using pipework buried in a municipal solid waste (MSW) landfill. It is then prepared for usage by processing and treating the LFG. Among the possible applications of LFG shown in the image are industrial/institutional, artistic/crafts, and pipeline gas/car fuel. (EPA, USA- 2022)

Figure 2.2

Landfill Gas recovery and Uses -(EPA, USA- 2022)

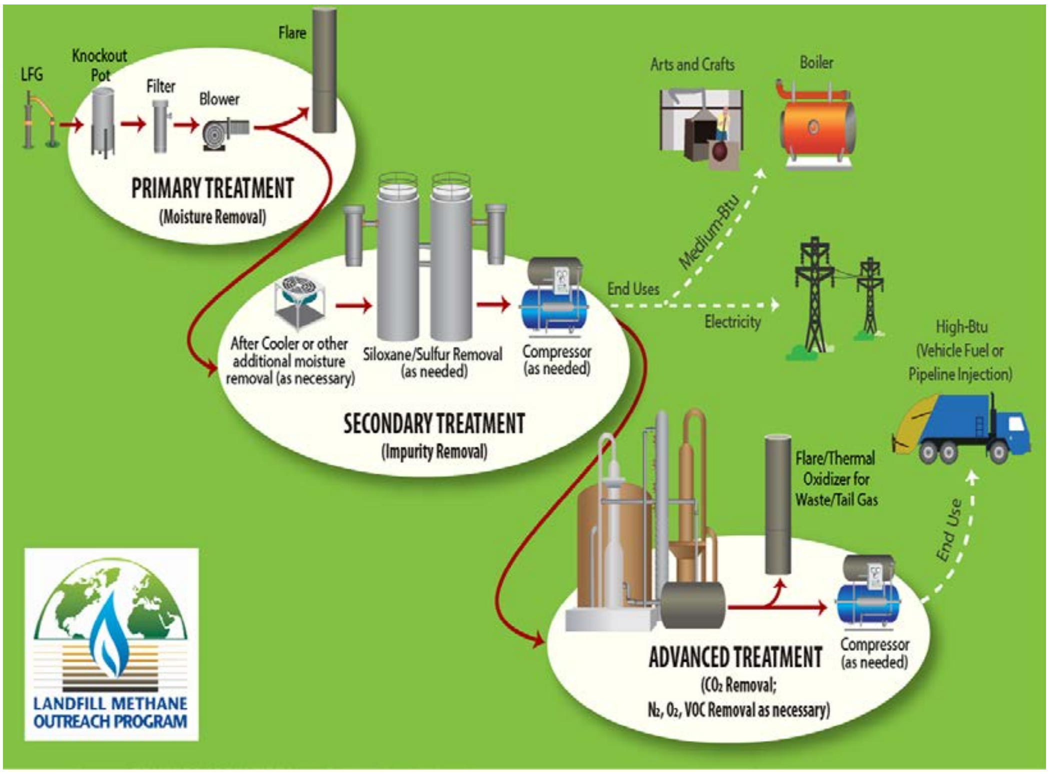


2.9.1 Treatment and recovery of Landfill Gas

Three phases of LFG therapy are shown in figure 2.3. When the gas is sent via a knock-out pot, a filter, and a blower, primary treatment eliminates moisture. After the moisture has been removed from the substance, either using an after cooler or some other method (if required), the secondary treatment will include the removal of siloxane and sulfur, followed by compression (as needed). After the pollutants have been removed during the Secondary Treatment step, LFG may be utilized as a fuel for ships or boilers with a medium BTU output. Compression of the LFG eliminates Co2, N2, and O2 from the LFG and produces a high-Btu gas that may be utilized as fuel for vehicles or delivered into a gas pipeline. Thermal oxidizers, such as flares, are employed to dispose of the waste gas.

Figure 2.3

Treatment of Landfill Gas -(EPA, USA- 2022)



2.10 Energy production From Landfill Gas

In order to turn LFG into energy, there are a variety of approaches. Generation of Electricity, directly using of medium-Btu gas, and natural gas that is renewable are three major categories under which LFG energy projects may be classified. (EPA, USA- 2022)

2.10.1 Energy Generation

Using a variety of different technologies, such as reciprocating internal combustion engines, turbines, fuel cells, and microturbines, it is possible to produce electricity for either on-site consumption or for sale to the grid. Because of its cheap cost, great efficiency, and wide variety of sizes, the reciprocating engine is the technology that is used the most often for applications using LFG energy. Microturbines, on the other hand, are primarily employed in smaller LFG energy projects and in specialist applications. A method by which combined heat and power (CHP) facilities employ liquid fuel gas (LFG) to generate both electrical energy and thermal energy via a process that is known as "cogeneration." Cogeneration using engines or turbines is becoming more and more common in commercial, industrial, and governmental activities alike. This kind of activity may be more profitable if it captures thermal energy as well as generates electricity. (EPA, USA- 2022)

2.10.2 Directly using medium-Btu Gas

More than one-fifth of the world's power plants currently run on LFG as a primary fuel source When it comes to thermal applications, it is possible to make use of LFG in a boiler, dryer, kiln, or greenhouse directly. It's possible that the combustion equipment used in these efforts will be fueled by this alternative fuel, which will then be delivered to a client located nearby. However, certain adjustments to existing combustion equipment may be needed to remove and filter condensate.

Evaporating leachate directly with LFG is also an option. Landfills have the potential to generate revenue from landfill gas in situations in which the disposal of leachate at a water resource recovery plant is either not possible or would be excessively costly. Leachate is evaporated using LFG, which reduces the amount of effluent to a more manageable size.

To name a few, medium-Btu gas may be used to power and heat greenhouses, kiln fire ceramics, and evaporate waste paint. LFG is presently used in many different sectors, such as the manufacture of automobiles, the manufacturing of chemicals, the processing of food and beverages, the manufacturing of medicines, and the creation of cement and bricks. Other industries that use LFG include prisons, hospitals and consumer electronics. (EPA, USA- 2022)

2.10.3 Renewable Natural Gas

High-Btu gas, renewable natural gas (RNG), may be made from LFG by treating it to increase its methane concentration and decrease its CO2, nitrogen, and oxygen contents in the process of upgrading it. There are many ways to utilize renewable natural gas (RNG) as an alternative to traditional fossil fuels (LNG). Around 14% of the LFG power plants currently in operation produce RNG. For example, RNG may be used to heat, generate electricity, and even be utilized as a fuel for vehicles, among other uses. Depending on how it is produced, natural gas may either be used on-site or transported through pipeline. (EPA, USA- 2022).

CHAPTER III

Methodology

3.0 Introduction

Methodology and instrument that will be used in the process of carrying out this investigation are covered in this chapter along with its description. Both of these aspects of the research would be carried out in order to answer the research question. In this chapter, we present the Research Design, the Participants/Population and Sample, the Data Collection Tools/Materials, the Data Analysis Procedures, and the Study Plan.

3.1 Research Design

The secondary quantitative research design was used for this study's data collection and analysis. It is sometimes referred to as research done at a desk. In this kind of study, the researchers make use of the data that has already been collected; this type of data is also known as secondary data. After that, the previously gathered information is condensed and reorganized in order to boost the research's general usefulness. This approach to studying includes gathering information from a variety of sources, including the internet, papers or resources provided by the government, libraries, other research methods, etc. (The ultimate secondary research guide - August 2021). This quantitative study method is to estimate the amount of methane that can be generated from the solid waste disposal of the estimated 1.2 million people that are dwelling in Montserrado, Liberia. It will also make use of past population statistics of Montserrado county. The researcher will use the emission factor produced by the Intergovernmental Panel on climate change (IPCC 2006) and the refine Intergovernmental Panel on Climate (IPCC 2019) coupled with available data from the Monrovia City Corporation (MCC), which include the waste compositions, Liberia Institute of Statistics and Geoinformation services (LISGIS) and consult other international sources like the world bank data for some important parameters that are needed in the estimation of the methane. The amount of methane will then be converted to energy so as to inform the government and others of the importance of solid waste disposal to the energy sector.

3.2 Population

The population of this study comprises the population of Montserrado county from 1960 to 2021. The world bank data contain the population of Liberia from as far back as 1960. There have been four censuses conducted in Liberia since it was founded. The census years are 1962, 1974, 1984, and 2008. According to the National housing and population census that was done in 2008, 32.164714% of the country's population live in Montserrado county; making it the most populated county in Liberia. According to the 1962 census conducted by the Liberia Institute for Statistics and Geoinformation Services (LISGIS), there were 191.1 thousand people living in Montserrado. The census also shows that the annual growth rate of Montserrado was 5.3%. The researcher used that annual growth rate to estimate the population of Liberia from 1960 to 1973. The 1974 census shows that the population of Montserrado is 23. 37% of Liberia's total population. The researcher used that figure to estimate the population of Montserrado from 1974 to 1983. The 1984 population census also shows that Montserrado had a total population of 491,078. The annual growth rate was 3.5%. the researcher uses that figure and the annual growth rate to estimate the population of Liberia from 1984 to 1989. There has been no other census until the 2008 national census. The census shows that 32.164714% of Liberia's population live in Montserrado county. The researcher uses the population of Liberia available from the open repository of the world bank from 1990 to 2021 and applies the 32.164714% that was given by LISGIS in her 2008 census to estimate the population from 1990 to 2021.

3.3 Data Collection Tools

According to what is specified in the study design, the technique of desk research entails gathering data from many sources such as the internet, documents or resources from the government, libraries, and previous research that has been undertaken, etc (The ultimate secondary research guide - August 2021).

The researcher used the Firefox web browser to access the open repository of the world bank to acquire the population of Liberia and apply the 32.164714% from the 2008 census which is also available at www. emansion.gov.lr to obtain the population from 1990 to 2021. The LISGIS censuses were used to get the data from 1960 up till 1989. The excel spreadsheet that contains other parameters needed for the estimation of the methane recovery was also used.

3.4 Data Collection Procedure

Since this study uses secondary data that are available on the internet, and the researcher did not have to consult anyone before assessing this data, the researcher obtains the data from the world bank website at data.worldbank.org and the various census data at www. emansion.gov.lr and put the population from 1960 to 2021.

There have been four censuses conducted in Liberia since it was founded. The census years are 1962, 1974, 1984, and 2008. According to the National housing and population census that was done in 2008, 32.164714% of the country's population live in Montserrado county; making it the most populated county in Liberia. According to the 1962 census conducted by the Liberia Institute for Statistics and Geoinformation Services (LISGIS), there were 191.1 thousand people living in Montserrado. The census also shows that the annual growth rate of Montserrado was 5.3%. The researcher used that annual growth rate to estimate the population of Liberia from 1960 to 1973. The 1974 census shows that the population of Montserrado is 23. 37% of Liberia's total population. The researcher used that figure to estimate the population of Montserrado from 1974 to 1983. The 1984 population census also shows that Montserrado had a total population of 491,078. The annual growth rate was 3.5%. the researcher uses that figure and the annual growth rate to estimate the population of Liberia from 1984 to 1989. There has been no other census until the 2008 national census. The census shows that 32.164714% of Liberia's population live in Montserrado county. The researcher uses the population of Liberia available from the open repository of the world bank from 1990 to 2021 and applies the 32.164714% that was given by LISGIS in her 2008 census to estimate the population from 1990 to 2021.

3.5 Data Analysis Plan

The researcher used the Excel spreadsheet that was developed by The Intergovernmental Panel on Climate Change (IPCC), which is an organization inside the United Nations that is responsible for evaluating the scientific aspects of climate change.

The Spreadsheet contains the formula which uses the First order decay method to estimate methane recovery and emission. The spreadsheet contains other parameters that will be explained in chapter four that are useful for the calculation of methane. The researcher used the default waste composition of the 2006 IPCC waste model sheet for the composition of solid waste of Montserrado county from 1960 to 2000. The researcher then used the composition of Liberia's solid waste that was done as indicated in chapter 4 to distribute the waste from 2001 to 2021. This was done because due to the civil war there was no study available on Liberia's waste composition until after the war ended in 2003. The methane recovery was then converted to energy in kilowatts to see how much energy can be produced in the few years after solid waste is deposited at the landfill. The researcher used SPSS 22 to do the correlation and regression of the data.

CHAPTER IV

4.0 Findings and Discussion

This chapter of the researcher's work is intended to bring you what the researcher has gathered from the analysis of the data.

4.1 Waste generation rate and Composition of Liberia Solid waste

The rates at which garbage is generated are increasing all around the globe. It was projected that by the year 2020, the globe will produce a total of 2.24 billion tonnes of solid garbage, which would equate to a daily waste output of 0.79 kg per individual. It is anticipated that the yearly amount of garbage generated would rise by 73 percent from its levels in 2020 to 3.88 billion tonnes in 2050 as a result of fast population expansion and urbanization. (www.worldbank.org/).

This projection is in line with a recent study conducted in Liberia this is the finding: The Ordinary Least Square Regression (OLS) technique was used to analyze the data, and the results showed that the average amount of garbage generated by households per person on a daily basis was 0.76 kg. (Emery David Jr et al – February 2019).

When the 0.76 is multiplied by 365 days in the year and converted to tonnes, it will equal to 0.2774 or round up to 0.28 Tonnes per household per year. This figure is closely in line with the IPCC default waste generation rate per capital per year which is 0.29 for all African countries.

The composition of the waste in Monrovia is indicated in the table below:

Table- 4.1

Composition of Monrovia Solid Waste

Composition	**Percentage**
Paper	12.2

Plastic	14.2
Glass/Ceramics	10.5
Metal	3.0
Organic Refuge, Vegetables	43
Rubber	10.0
Batteries	7.1
Total	100

Source: Emery David Jr et al – February 2019

This research targeted Montserrado County. The waste generation rate and composition of the Solid waste of Monrovia will be used for the entire Montserrado county because Monrovia is part of Montserrado county and it is the most populated city in Montserrado.

4.2 2006 IPCC Guidelines First-Order Decay (FOD) Method

The First Order Decay (FOD) approach is the methodology that is used in estimating methane emissions from SWDs by the IPCC. This method is based on the concept that part of the waste that can be decomposed by means of bacteria actions (DOC) in the waste would decay gradually over the period of a few decades, which would result in the creation of CH4 and CO2. If all other factors stay the same, the rate at which CH4 is produced is exclusively determined by the quantity of carbon that is still present in the waste. Because of this, the emissions of CH4 from the trash that has been put at a put a trash site are at their highest point in the first few years after the garbage has been dumped, and then they progressively decrease as the bacteria that are responsible for the decay consume the degradable carbon in the waste. During the course of the process, degradable material in the SWDS is transformed to CH4 and CO2 via a succession of chain reactions and parallel reactions that take place in tandem with one another. There is a significant chance that a full model will be exceedingly difficult to understand and will evolve in response to the conditions present in the SWDS. However, studies on data pertaining to CH4 production made in the laboratory as well as in the field show that the complete breakdown process may be roughly approximated using first-order kinetics (Hoeks, 1983), and this idea has been broadly accepted. As a result, the comparatively straightforward FOD model has been selected by the IPCC to serve as the foundation for the calculation of CH4 emissions from SWDS.

As stated from the methodological aspect of this research work, the researcher used the IPCC first order decay method to estimate methane emissions from the amount of solid waste disposal. This is the most accurate method for estimating methane emissions from solid waste.

4.3 METHANE EMISSIONS

CH_4 is produced when organic matter is degraded under anaerobic circumstances. This process takes place in the absence of oxygen. A portion of the CH4 that is produced is either destroyed by the oxidation process that takes place on the front cover of the SWDS, or it might be retrieved from elsewhere and burned off as waste heat. Therefore, the quantity of CH4 that will be really released by the SWDS will be less than what is created. (Riitta Pipatti, et al - 2006)

Equation 4.1 – CH_4 Emission from SWDS

$CH4\ Emission = [\sum_X CH_4\ generated_{XT} – R_T]. (1 – OX_T)$

Where:

CH_4 Emissions = CH_4 emitted in

year *T*, Gg T = inventory year

x = waste

category or type/

R_T = recovered

CH_4 in year *T*, Gg

OX_T = oxidation factor in year *T*, (fraction)

since this research is intended to inform decision-making and it is not actually estimating the present methane at the solid waste disposal site, the amount of methane recovered will be zero and the total methane that will be generated or emitted will be used as the methane recovered and be converted to energy to enable policy maker to see the amount of energy that solid waste disposal from Montserrado can contribute to the energy sector.

Table 4.2 Three Tiers methods to estimate CH4 emissions from SWDs ((Riitta Pipatti, et al- 2006)

Table – 4.2

Methodological Tier

Tier	Method	Activity data	Parameters
Tier 1	IPCC FOD method	Default	Default
Tier 2	IPCC FOD method	data on present and historical waste disposal activities at SWDs that are of high quality and particular to the nation concerned.[a]	Default (some)
Tier 3	IPCC FOD method	data on present and historical waste disposal activities at SWDs that are of high quality and particular to the nation concerned.[a]	Essential parameters [b] defined on a national level, as well as country-specific values parameters [b] generated from measurements

a. Data on the history of waste disposal practices dating back at least ten years should be derived from country-specific statistics, surveys, or other sources of information of a comparable kind. There is a need for data on the quantities that were discarded at the SWDS.

b. Some of the most important characteristics to consider are the half-life, the methane production potential (Lo), the quantity of DOC in trash, and the percentage of DOC that decomposes (DOCf).

There is an equation chain that must be solved in order to determine the amount of CH4 produced, Annex A has the answers to all of these equations. The default values for a wide variety of parameters may be found in the original paper.

This estimation of methane from solid waste was done from the year 1960 to 2021, this is a significant length of time that will make the estimate more accurate since the historical data are needed for 50 years or more. The tier 2 method was used for the estimation of methane for this research work. Some default value was used alone with the data that the researcher gathers from the published materials.

Table 4.3

Methane Generated

Year	**Total**	**Methane recovery**		**Methane emission**
	K	L		M = (K-L)*(1-OX)
	Gg	Gg		Gg
1960	0	0		0
1961	1	0		1
1962	1	0		1
1963	1	0		1
1964	1	0		1
1965	2	0		2
1966	2	0		2
1967	2	0		2
1968	2	0		2
1969	2	0		2
1970	3	0		3
1971	3	0		3
1972	3	0		3
1973	3	0		3
1974	3	0		3

1975	3	0		3
1976	4	0		4
1977	4	0		4
1978	4	0		4
1979	4	0		4
1980	4	0		4
1981	4	0		4
1982	5	0		5
1983	5	0		5
1984	5	0		5
1985	5	0		5
1986	5	0		5
1987	6	0		6
1988	6	0		6
1989	6	0		6
1990	6	0		6
1991	7	0		7
1992	7	0		7
1993	7	0		7
1994	7	0		7
1995	7	0		7
1996	7	0		7
1997	7	0		7
1998	8	0		8
1999	8	0		8
2000	8	0		8
2001	9	0		9
2002	10	0		10
2003	10	0		10
2004	11	0		11
2005	11	0		11
2006	11	0		11
2007	12	0		12

2008	12	0		12
2009	13	0		13
2010	13	0		13
2011	13	0		13
2012	14	0		14
2013	14	0		14
2014	15	0		15
2015	15	0		15
2016	16	0		16
2017	16	0		16
2018	17	0		17
2019	17	0		17
2020	18	0		18
2021	18	0		18

Table 4.3 shows the amount of Methane emission that is generated from the solid waste of Montserrado county using the spreadsheet produced by the IPCC which uses the first order decay Model. The data entered was from 1960 to 2021. The researcher assumes that all of the methane from waste generated is recovered since this research is intended to inform decision-making and not the actual waste deposited in the landfill. This research also supposes that all waste generated in Montserrado is collected and deposited at a managed landfill site for decomposition and the production of methane gas.

From the table above, it shows that in 1960, zero methane gas was emitted or recovered. This is true since the FOD model assumes that waste deposited at a landfill does not begin producing methane since there is a timed lap before the production of methane starts taking place due to the absence of oxygen in the landfill. From the table, the production of methane begins in 1961 with 1 gigagram of methane emission or recovery. There is a continuous increase as Table 4.3 is showing from 1961 up till 2009. The reason for this is seen in Liberia’s economic status during those periods. The rate of decline in Liberia's economy is the highest ever recorded in contemporary times. The real income per capita in Liberia reached an all-time high in 1972 and then plummeted to an all-time low in 1995, a drop of an astounding 93% between those two years. In 1972, when compared to other nations based on their normal buying power, Liberia was placed 107th out of 163 countries, barely ahead of Thailand and Egypt; it was not affluent, but it was also not destitute. It had a GDP per capita that was almost 80 percent larger than China, Indonesia, Vietnam, and India combined. It ranked thirteenth among the nations of sub-Saharan Africa, higher than both Senegal and Botswana. (Eric Werker and Lant Pritchett -2017). There continue to be increase in methane production from 2010 to 2014 and finally, there is a gradual increase from 2015 to 2021. This implies that as the year increases, there is an increase in methane recovered from solid waste. From table 4.3, it can be seen that as the population increases, there is an increase in the amount of methane emitted or recovered.

Table 4.4

Descriptive statistics of Methane Recover or Emitted

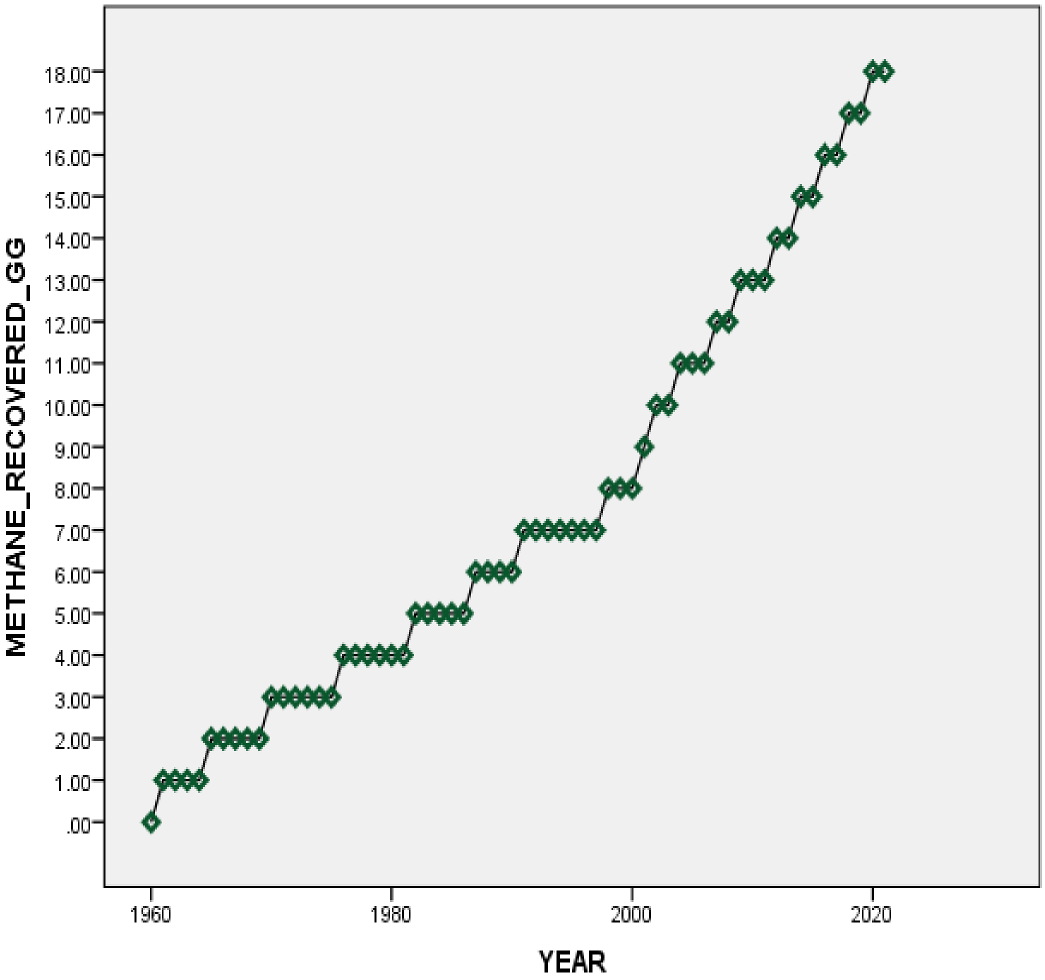
Descriptives				
			Statistic	Std. Error
METHANE_RECOVERED_GG	Mean		7.4677	.63800
	95% Confidence Interval for Mean	Lower Bound	6.1920	
		Upper Bound	8.7435	
	5% Trimmed Mean		7.2796	
	Median		6.5000	
	Variance		25.237	
	Std. Deviation		5.02361	
	Minimum		.00	
	Maximum		18.00	
	Range		18.00	
	Interquartile Range		8.25	
	Skewness		.587	.304
	Kurtosis		-.766	.599

Table 4.4 shows the descriptive statistic of methane recovered from the solid waste of Montserrado county from 1960 to 2021. The mean value of methane recovered is 7.4677 gigagrams. The median methane recovered is 6.500 and the

standard deviation is 5.02361. The minimum amount of methane recovered is 00 gigagrams while the maximum is 18. 00 gigagrams.

Figure 4.1.

The trend in methane Recovered from Montserrado County



From the graph above, there is a steady increase in the recovery trend of methane from solid waste in Montserrado county. There were zero gigagrams of methane recovered in 1960 and 18 gigagrams in 2021. It is plausible to assume that there were zero gigagrams in 1960 due to the fact that the creation of methane does not immediately commence after the dumping of solid waste. After a certain amount of time has passed, the environment will have become anaerobic, which indicates that the oxygen that was originally present in the trash has been consumed. When the oxygen content is depleted, the formation of methane begins. There is a continuous increase as the graph is showing from 1961 up till 2009. There is a continuous increase in methane production from 2010 to 2014 and finally, there is a gradual increase from 2015 to 2021. This implies that as the year increases, there is an increase in methane recovered from solid waste due to the increase in the amount of solid waste generated by increase population.

4.4 From Methane Recovered to Energy Production in Kwh.

As we have seen, the amount of methane generated from solid waste disposal can be converted to energy in Kwh. The amount of Methane produced is in gigagrams. It can be converted from gigagrams to kwh.

1gigagrams = 1,000,000 kg

1kg = 1,000g

1M3 = 1,000,000g

1M3 = 10.55 Kwh

The results of the application of the conversion factors are seen in table 4.4

Table 4.4

Methane Recovered to Energy Production in Kwh

Years	**Methane Recovered in Gigagrams**	**Kwh**	**Years**	**Methane Recovered in Gigagrams**	**Kwh**
1960	0	0	1991	7	73850
1961	1	10550	1992	7	73850
1962	1	10550	1993	7	73850
1963	1	10550	1994	7	73850

1964	1	10550	1995	7	73850
1965	2	21100	1996	7	73850
1966	2	21100	1997	7	73850
1967	2	21100	1998	8	84400
1968	2	21100	1999	8	84400
1969	2	21100	2000	8	84400
1970	3	31650	2001	9	94950
1971	3	31650	2002	10	105500
1972	3	31650	2003	10	105500
1973	3	31650	2004	11	116050
1974	3	31650	2005	11	116050
1975	3	31650	2006	11	116050
1976	4	42200	2007	12	126600
1977	4	42200	2008	12	126600
1978	4	42200	2009	13	137150
1979	4	42200	2010	13	137150
1980	4	42200	2011	13	137150

1981	4	42200	2012	14	147700
1982	5	52750	2013	14	147700
1983	5	52750	2014	15	158250
1984	5	52750	2015	15	158250
1985	5	52750	2016	16	168800
1986	5	52750	2017	16	168800
1987	6	63300	2018	17	179350
1988	6	63300	2019	17	179350
1989	6	63300	2020	18	189900
1990	6	63300	2021	18	189900

Table 4.5

Spearman's Correlation Coefficient Matrix between Solid Waste Disposal, Methane Recovered, and Electricity in Kwh.

Correlations

		Solid Waste Deposited in Gigagrams	Methane recovered in Gigagrams	Electricity Generated in KWH
Spearman's rho Solid Waste Deposited in Gigagrams	Correlation Coefficient	1.000	.996	.996
	Sig. (2-tailed)	.	.000	.000

	N	62	62	62
Methane recovered in Gigagrams	Correlation Coefficient	.996	1.000	1.000
	Sig. (2-tailed)	.000	.	.
	N	62	62	62
Electricity Generated in KWH	Correlation Coefficient	.996	1.000	1.000
	Sig. (2-tailed)	.000	.	.
	N	62	62	62

Spearman's correlation coefficient was used to show the relationships between the various study variables since they are measured on a continuous scale. As seen in Table 4.5 above which is showing the Correlation matrix, Spearman's Correlation coefficient of Solid Waste Disposal and Methane Recovered is 99.6% and it is significant. P-value < 0.001. The Spearman Correlation coefficient of Solid Waste Disposal and Electricity in Kwh is 99.6% and it is significant. P-value < 0.001. From the matrix, it is concluded that there is a significant relationship between Solid Waste Disposal, Methane Recovered and Electricity in Kwh.

4.5 Regression

In this section, hypotheses are tested, and the findings are utilized to make statistical inferences. Hypotheses are put to the test using statistical approaches to the process of testing them. When working with large datasets, inferential statistics employ tiny data samples to make predictions and judgments as well as estimations (Mc Clave, 2000:2).

Simple Linear Regression

The general simple linear regression model formula was used:

$Y= \beta 0 + \beta_1 x_1 + \varepsilon$

Where

Y is the dependent variable

X_1, are the independent variables

$E(y) = \beta 0 + \beta 1.x1$is the deterministic portion of the model

$\beta 1$ – are constant coefficients that determine the contribution of the independent variables X_1

ε_1 represents the random error, which has a mean of 0 and a variation of 1 (Mc Clave 2002: 578).

For this portion of the regression, we will separately take each of the dependent variables which are Methane recovered and Electricity in Kwh, and run it against the independent variable which is Solid Waste disposal.

Methane Recovered

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.996	.992	.992	.46026

Predictors: (Constant), SOLID_WASTE_DEPOSITED_GG

ANOVA[a]

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	1526.725	1	1526.725	7207.057	.000
Residual	12.710	60	.212		
Total	1539.435	61			

Dependent Variable: METHANE_RECOVERED_GG

Predictors: (Constant), SOLID_WASTE_DEPOSITED_GG

Coefficients[a]

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-1.002	.116		-8.668	.000
SOLID_WASTE_DEPOSITED_GG	.041	0.000482	.996	84.894	.000

Dependent Variable: METHANE_RECOVERED_GG

The R^2 value in the model summary table tells us that 99.2 % of the variation in Methane Recovered can be explained by Solid Waste deposited. From the ANOVA table above, the p-value < 0.001. This tells us that the overall model that we developed is significant. From the coefficients table, our p-value < 0.001 tell us that the Solid waste deposited has a significant impact on methane recovered. Reading from the Unstandardized Coefficients beta value shows that if there is a one (1) unit change in Solid waste deposited, there will be a .041 change in Methane recovered.

Hypothesis 1a: Solid Waste deposited has a significant impact on Methane recovered.

As a result of the study, there is a statistically significant positive impact between solid waste deposited and methane recovered because our p-value < 0.001

Electricity in Kwh

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.996	.992	.992	4855.72320

Predictors: (Constant), SOLID_WASTE_DEPOSITED_GG

ANOVA[a]

Model	Sum of	df	Mean Square	F	Sig.

	Squares				
Regression	1699283350 77.879900	1	1699283 35077.880	7207.057	.000
Residual	1414682865.668	60	23578047.761		
Total	1539.435	61			

Dependent Variable: ELECTRICITY_KWH_GENERATED

Predictors: (Constant), SOLID_WASTE_DEPOSITED_GG

Coefficients[a]

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-10574.136	1219.931		-8.668	.000
SOLID_WASTE_DEPOSITED_GG	431.384	5.081	.996	84.894	.000

Dependent Variable: ELECTRICITY_KWH_GENERATED

The R^2 value in the model summary table tells us that 99.2 % of the variation in Electricity in Kwh can be explained by Solid Waste deposited. From the ANOVA table above, the p-value < 0.001 this tells us that the overall model that we developed is significant. From the coefficients table, our p-value < 0.001. tell us that the Solid waste deposited has a significant impact on Electricity generated in Kwh. Reading from the Unstandardized Coefficients beta value shows that if there is a one (1) unit change in Solid waste deposited, there will be a 431.384 change in Electricity generated in Kwh.

Hypothesis 1b: Solid Waste deposited has a positive impact on electricity generated in Kwh.

As a result of the study, there is a statistically significant positive relationship between solid waste deposited and Electricity generated in kWh because our p-value < 0.001.

CHAPTER V

5.1 Discussion

The result of the study shows that Solid waste disposal generates methane. From 1 gigagram in 1960 to 18 gigagrams in 2021. This is actually in line with a study done by the New York state department of health "Distinct gases are what Landfill gas contains. 90 to 98 percent of landfill gas is composed of methane and carbon dioxide. Atmospheric gases like nitrogen and oxygen make up between 2% and 10% of the atmosphere**.** Bacteria break degrade organic waste in landfills, releasing pollutants into the atmosphere. A landfill may continue to create gases for more than 50 years, despite the fact that the generation of these gases typically peaks in five to seven years". (New York state, department of health - 2019). A correlation was run based on the data to show whether there is a relationship between methane produced or recovered and solid waste disposal, Spearman's Correlation coefficient of Solid Waste Disposal and Methane Recovered is 99.6% and it is significant. The P value which is < 0.001. A further regression analysis was done between methane recovered and solid waste disposal. The R^2 value in the model summary table told us that 99.2 % of the variation in Methane Recovered can be explained by Solid Waste deposited. From the ANOVA table above, the p-value < 0.001 this tells us that the overall model that we developed is significant. From the coefficients table, our p-value < 0.001 tell us that the Solid waste deposited has a significant impact on methane recovered. Reading from the Unstandardized Coefficients beta value shows that if there is a one (1) unit change in Solid waste deposited, there will be a .041 change in Methane recovered.

The result of the study also shows that the production of methane does not begin immediately after the deposition of solid waste. There is a time-lapse between deposition and methane generation. Methane is produced under anaerobic conditions.

This will mean that when the waste is deposited, the oxygen content of the waste will have to be depleted for the anaerobic methane production bacteria to begin producing methane through methanogenesis. This was seen from the result of the data analysis during the study. The deposition of solid waste begins at the landfill in 1960 up till 2021. From the result, there was zero methane produced and recovered in 1960. This means that in 1960, was the time taken for the oxygen to be depleted before methane-generating bacteria begins to work. This is proof true from a study conducted according to our literature review, A variety of acids and alcohols may be produced by anaerobic bacteria, including acetic, lactic, and formic acid (a process that does not need oxygen). The landfill turns into a cesspool of acidic waste. Acids in the landfill's moisture break down nitrogen and phosphorus, making them accessible to the landfill's ever-expanding bacterial population. Carbon dioxide and hydrogen gas are byproducts of these reactions. Disturbing the dump or introducing oxygen into the rubbish will resume Phase I microbiological activity. (ATSDR – 2001).

The researcher explained that Methane from solid waste can be used to produce energy. From the literature review, a study was conducted to show that methane from solid waste disposal at the landfill can be used to produce energy. Landfill Gas (LFG) which is predominately methane, may be utilized as a renewable energy source instead of leaking into the atmosphere. Reduced pollution and global climate change are achieved as a consequence of employing LFG to keep methane from entering the atmosphere. Economic benefits and job opportunities are generated by LFG's energy projects in the surrounding area. (EPA, USA- 2022).

Methane can be used to produce electricity. Using a variety of different technologies, such as reciprocating internal combustion engines, turbines, fuel cells, and microturbines, it is possible to produce electricity for either on-site consumption or for sale to the grid. Because of its cheap cost, great efficiency, and a wide variety of sizes, the reciprocating engine is the technology that is used the most often for applications using LFG energy**.** Microturbines, on the other hand, are primarily employed in smaller LFG energy projects and in specialist applications. A method by which combined heat and power (CHP) facilities employ liquid fuel gas (LFG) to generate both electrical energy and thermal energy via a process that is known as "cogeneration."

The researcher converted the amount of methane recovered to energy in Kwh using the conversion factor of a 1-meter cube of methane gas to 10.55 kWh of electricity which is the universal conversion factor and the amount of electricity in kWh was generated from 1961 to 2021.

The researcher ran a Spearman's correlation due to the fact that the data was not normally distributed and the Spearman Correlation coefficient of Solid Waste Disposal and Electricity in Kwh is 99.6% and it is significant. P-value < 0.001. From the matrix, it is concluded that there is a significant relationship between Solid Waste Disposal, Methane Recovered, and Electricity in Kwh.

A regression analysis was done and it shows that the R^2 value in the model summary table tells us that 99.2 % of the variation in Electricity in Kwh can be explained by Solid Waste deposited. From the ANOVA table above, the P-value < 0.001 this tells us that the overall model that we developed is significant. From the coefficients table, our p-value of P-value < 0.001 tell us that the Solid waste deposited has a significant impact on Electricity generated in Kwh. Reading from the Unstandardized Coefficients beta value shows that if there is a one (1) unit change in Solid waste deposited, there will be a 431.384 change in Electricity generated in Kwh.

CHAPTER VI

6.0 Conclusion and Recommendations

This portion of the researcher's work is intended to provide a conclusion based upon the findings of the researcher through the analysis of the data and provide needed recommendations that will pave the way for the implementation of the findings

6.1 Conclusion

The purpose of this study was to estimate the amount of methane that can be recovered and converted to energy from solid waste disposal within the most populated county in the Republic of Liberia, which is Montserrado county. Liberia for many years has suffered from a lack of electricity thereby contributing to its backwardness. Less than 2% of Liberians have access to electricity. From that report, Liberia's Electricity is one of the lowest as compared to other countries in the world. The grid in Monrovia is mostly powered by high-priced, dirty diesel-fueled electricity. The total installed on-grid capacity in Liberia is less than 23 megawatts (MW). 10 times more than the existing generation capacity is what hotels, restaurants, and office complexes self-generate. (Liberia: Power Africa, May 2016).

From the research, It is possible to draw the conclusion that there is a close connection between the creation of methane and the disposal of solid waste. Distinct gases are what Landfill gas contains. 90 to 98 percent of the gases at the disposal site are made up of methane and carbon II Oxide. Atmospheric gases like nitrogen and oxygen make up between 2% and 10% of the atmosphere**.** Bacteria break degrade organic waste in landfills, releasing pollutants into the atmosphere. A landfill may continue to create gases for more than 50 years, despite the fact that the generation of these gases typically peaks in five to seven years". (New York state, department of health - 2019). This report is actually true. From our data, there were 1gigaram or 1000 tons of methane produced from solid waste disposal at the landfill in 1960 and 18 gigagrams or 18000 tons in 2021.

It is also to be concluded that there is a strong relationship between solid waste disposal and methane recovered. Spearman's Correlation coefficient of Solid Waste Disposal and Methane Recovered shows a 99.6% relationship and it is significant. The P-value < 0.001. A further regression analysis was done between methane recovered and solid waste disposal. The R^2 value in the model summary table told us that 99.2 % of the variation in Methane Recovered can be explained by Solid Waste deposited. From the ANOVA table above, the P-value < 0.001 this tells us that the overall model that we developed is significant. From the coefficients table, our P-value < 0.001 tell us that the Solid waste deposited has a significant impact on methane recovered. Reading from the Unstandardized Coefficients beta value shows that if there is a one (1) unit change in Solid waste deposited, there will be a .041 change in Methane recovered. It can definitely be concluded that solid waste disposal at landfill produces methane.

From the research findings, the researcher is concluding that there is a positive relationship between solid waste disposal and energy production. The researcher ran a Spearman's correlation due to the fact that the data was not normally distributed and the Spearman Correlation coefficient of Solid Waste Disposal and Electricity in Kwh is 99.6% and it is significant. P-value < 0.001. From the matrix, it is concluded that there is a significant relationship between Solid Waste Disposal, Methane Recovered, and Electricity in Kwh.

A regression analysis was done and it shows that the R^2 value in the model summary table tells us that 99.2 % of the variation in Electricity in Kwh can be explained by Solid Waste deposited. From the ANOVA table above, the P-value < 0.001 this tells us that the overall model that we developed is significant. From the coefficients table, our P-value < 0.001 tell us that the Solid waste deposited has a significant impact on Electricity generated in Kwh. Reading from the Unstandardized Coefficients beta value shows that if there is a one (1) unit change in Solid waste deposited, there will be a 431.384 change in Electricity generated in Kwh.

6.2 Recommendations

The researcher is delighted to have undertaken a study that is so informative to addressing problems within the country. According to power African" Less than 2% of Liberians have access to electricity. Liberia's Electricity is one of the lowest as compared to other countries in the world. The grid in Monrovia is mostly powered by high-priced, dirty diesel-fueled electricity. The total installed on-grid capacity in Liberia is less than 23 megawatts (MW). 10 times more than the existing generation capacity is what hotels, restaurants, and office complexes self-generate. (Liberia: Power Africa, May 2016).

The following are recommended by the researcher due to the outcome of the study:

1. The government should construct sanitary landfill throughout the country for the purpose of disposing of solid waste and treated hazardous waste. Those landfills should be built with high efficiency that will enable the proper collections of landfill gas which is predominant methane. When this is done, the government will provide enough job opportunities for her citizens that are jobless thereby reducing unemployment and also reducing her emission of greenhouse gases. Those landfills could be built in such a way that 2 or three counties could share a landfill so as to reduce the cost of building one for every county or region.
2. The government should institute a more robust action when it comes to the collection of waste from households and other localities such as markets places so as to avoid the waste being dumped in swamps and other places that will not contribute to the proper decaying of those waste so as to generate landfill gas.

3. The government should carry on adequate awareness informing the citizens of the benefit of properly disposing of their waste at the various pickup points. Highlighting that the cooperation of the citizens will lead to them continually receiving electricity since in fact, it is the waste that is being used to buzz the energy generation of the country.
4. Construct standardized roads that will lead to the smooth collection and deposition of those waste at the various sanitary landfills so as to avoid the waste decaying at the pickup points thereby polluting the environment and losing some biogas due to the waste decaying at the pickup points rather than at the landfill sites.

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APPENDICES

Appendix A

All of the information equations used here are taking directly from the 2006 IPCC guidelines

A. 4A1.2 FIRST ORDER DECAY (FOD) MODEL&SPREADSHEET

The basis for a first order decay reaction is that the reaction rate is proportional to the amount of reactant remaining (Barrow and Gordon, 1996), in this case the mass of degradable organic carbon decomposable under anaerobic conditions (DDOCm). The DDOCm reacted over a period of time *dt* is described by the

EQUATION 4A1.1

DIFFERENTIAL EQUATION FOR FIRST ORDER DECAY

$$d(DDOCm) = -k \bullet DDOCm \bullet dt$$

differential equation 3A.1.1:

Where:

DDOCm = mass of degradable organic carbon (DOC) in the disposal site at time *t*

k = decay rate constant in y^{-1}

The solution to this equation is the basic FOD equation.

EQUATION 4A1.2

FIRST ORDER DECAY EQUATION

$$DDOCm = DDOCm_0 \bullet e^{-kt}$$

Where:

DDOCm = mass of degradable organic carbon that will decompose under anaerobic conditions in disposal site at time *t*

$DDOCm_0$ = mass of DDOC in the disposal site at time 0, when the reaction starts

k = decay rate constant in y^{-1}

t = time in years.

Substituting *t* =1 into Equation 4A1.2 shows that at the end of year 1 (the year after

EQUATION 4A1.3

DDOCM REMAINING AFTER 1 YEAR OF DECAY

At t = 1, $DDOCm = DDOCm_0 \bullet e^{-k}$

disposal), the amount of DDOCm remaining in the disposal site is:

The DDOCm decomposed into CH_4 and CO_2 at the end of year 1 (DDOCm decomp) will then be:

EQUATION 4A1.4

DDOCm DECOMPOSED AFTER 1 YEAR OF DECAY

At t = 1, $DDOCm\,decomp = DDOCm_0 \bullet (1 - e^{-k})$

The equation for the general case, for DDOCm decomposed in period T 8 between time (t□1) and t, will be:

EQUATION 4A1.5 DDOCm

DECOMPOSED IN YEAR T

$$DDOCm\,decomp_T = DDOCm_0 \bullet \left[e^{-k(t-1)} - e^{-kt} \right]$$

Equations 4A1.4 and 4A1.5 are based on the mass balance over the year.

Half-life is the time it takes for the amount of reaction to be reduced by 50 percent. The relationship between half-life time and the reaction rate constant k is found by substituting DDOCm in Equation 4A1.2 with 1/2DDOCm$_0$, and t with $t_{1/2}$:

EQUATION 4A1.6

RELATIONSHIP BETWEEN HALF-LIFE AND REACTION RATE CONSTANT

$$k = \ln(2) / t_{1/2}$$

EQUATION 4A1.7

FOD EQUATION FOR DECAY COMMENCING AFTER 3 MONTHS

$$DDOCm = DDOCm_0 \bullet e^{-k(t+0.25)}$$

4A1.3CHANGING THE TIME DELAY IN THE FOD EQUATION

Then there will be two solutions, one for the year of disposal and one for the rest of the years:

EQUATION 4A1.8

DDOCm DECOMPOSED IN YEAR OF DISPOSAL (3 MONTH DELAY)

$$DDOCm\, decomp_Y = DDOCm_0 \bullet \left(1 - e^{-0.25k}\right)$$

EQUATION 4A1.9

DDOCm DISSIMILATED IN YEAR (T) (3 MONTH DELAY)

$$DDOCm\, decomp_T = DDOCm_0 \bullet \left[e^{-k(T-0.75)} - e^{-k(T+0.25)} \right]$$

8 T denotes the year for which the estimate is done in relation to deposition year.

Where:

DDOCm decomp$_Y$ = DDOCm decomposed in year of disposal

DDOCm decomp$_T$ = DDOCm decomposed in year T (from point t□1 to point t on time axis)

T = year from point t□1 to t on the time axis, where year 1 is the year after disposal.

Y = disposal year

The same can be done to find the equations for reaction start within the year after disposal.

4A1.4 SPREADSHEET FOD MODEL

In order to estimate CH_4 emissions for all solid waste disposal sites in a country, one method is to model the emissions from the waste disposed in each year as a separate row in a spreadsheet. In the *IPCC Waste Model*, CH_4 formation is calculated separately for each year of disposal, and the total amount of CH_4 generated is found by a summation at the end. A typical example, for six years of disposal of 100 units of DDOCm each year, with a decay rate constant of 0.1 (half-life time of 6.9 years), and CH_4 generation beginning in the year after disposal, is shown in the table below. The figures in the table are the DDOCm decomposed from that waste each year, from which the CH_4 emissions can be calculated.

When considered over a period of 50 years, which is necessary for the FOD method, this leads to a rather large calculation matrix. The spreadsheet uses a more compact and elegant approach to the calculations. This is done by adding the DDOCm disposed into the disposal site in one year to the DDOCm left over from the previous years. The CH_4 emission for the next year is then calculated from this 'running total' of the DDOCm remaining in the site. In this way, the full calculation for one year can be done in only three columns, instead of having one column for each year (see Table 4A1.1).

The basis for this approach lies in the first order reaction. With a first order reaction the amount of product (here DDOCm decomposed) is always proportional to the amount of reactant (here DDOCm). This means that the time of disposal of the DDOCm is irrelevant to the amount of CH_4 generated each year - it is just the total DDOCm remaining in the site that matters.

This also means that when we know the amount of DDOCm in the SWDS at the start of the year, every year can be regarded as year number 1 in the estimation method, and all calculation can be done by these two simple equations:

EQUATION 3A1.10

MASS OF DEGRADABLE ORGANIC CARBON ACCUMULATED AT THE END OF YEAR T

$$DDOCma_T = DDOCmd_T + \left(DDOCma_{T-1} \bullet e^{-k} \right)$$

EQUATION 3A1.11

MASS OF DEGRADABLE ORGANIC CARBON DECOMPOSED IN YEAR T

$$DDOCm\,decomp_T = DDOCma_{T-1} \bullet \left(1 - e^{-k}\right)$$

Where:

the decay reaction begins on the 1st of January the year after disposal.

$DDOCma_T$ = DDOCm accumulated in the SWDS at the end of year *T*

$DDOCmd_T$ = mass of DDOC disposed in the SWDS in year *T*

$DDOCma_{T-1}$ = DDOCm accumulated in the SWDS

at the end of year (*T*□1) DDOCm $decomp_T$ =

DDOCm decomposed in year *T*

3A1.4.1 Introducing a different time delay into the spreadsheet model

If the anaerobic decomposition is set to start earlier than this, i.e., in the year of disposal, separate calculations will have to be made for the year of disposal. As the mathematics of every waste category or waste type/fraction is the same, only parameters are different, indexing for different waste categories and types/fractions are omitted in the equations 4A1.12-17, and 4A1.19:

EQUATION 3A1.13

DDOCm DECOMPOSED DURING YEAR OF DISPOSAL

$$DDOCm\,dec_T = DDOCmd_T \bullet \left\lfloor 1 - e^{-k \bullet (13 - M)/12} \right\rfloor$$

(Column G in the CH_4 calculating sheets in the spreadsheet model)

EQUATION 3A1.12

DDOCm REMAINING AT END OF YEAR OF DISPOSAL

$$DDOCm\ rem_T = DDOCmd_T \bullet e^{-k \bullet (13-M)/12}$$

Where:

$DDOCm\ rem_T$ = DDOCm disposed in year *T* which still remains at the end of year *T* (Gg)

$DDOCmd_T$ = DDOCm disposed in year *T* (Gg)

$DDOCm\ dec_T$ = DDOCm disposed in year *T* which has decomposed by the end of year *T* (Gg)

T = year *T* (inventory year)

M = month when reaction is set to start, equal to the average delay time + 7 (month)

k = rate of reaction constant (y^{-1})

Equations 4A1.10 and 4A1.11 will then become:

EQUATION 3A1.14

DDOCm ACCUMULATED AT THE END OF YEAR T

$$DDOCma_T = DDOCm\ rem_T + \left(DDOCma_{T-1} \bullet e^{-k} \right)$$

EQUATION 3A1.15 DDOCm

DECOMPOSED IN YEAR T

$$DDOCm\ decomp_T = DDOCm\ dec_T + DDOCma_{T-1} \bullet \left(1 - e^{-k}\right)$$

Where:

$DDOCma_T$ = DDOCm accumulated in the SWDS at the end of year *T*, Gg

$DDOCma_{T-1}$ = DDOCm accumulated in the SWDS at the end of year (*T*□1), Gg

DDOCm $decomp_T$ = DDOCm decomposed in year *T*, Gg

The spreadsheets are based on Equations 4A1.12 to 4A1.15. If the reaction start is set to the first of January the year after disposal, this is equivalent to an average time delay of 6 months (month 13). Equations 4A1.14 and 4A1.15 will then be identical to Equations 4A1.10 and 4A1.11.

4A1.4.2 Calculating DDOCm from amount of waste disposed

Data on waste disposal is entered into the spreadsheet. The data can be given by waste type (waste composition option) or as bulk waste. In the waste composition option, waste is split by waste type/material (paper and cardboard, food garden and park waste, wood, textiles and other waste). In the bulk waste option, waste is split only by main waste category (MSW and industrial waste). Not all DOCm entering the site will decompose under the anaerobic conditions in the SWDS. The parameter DOC_f is the fraction of DOCm which will actually degrade in the SWDS. The decomposable DOCm (DDOCm) entering the SWDS is calculated as follows:

EQUATION 3A1.16

CALCULATION OF DECOMPOSABLE DOCm FROM WASTE DISPOSAL DATA

$$DDOCmd_T = W_T \bullet DOC \bullet DOC_f \bullet MCF$$

Where:

$DDOCmd_T$ = DDOCm disposed in year *T*, Gg W_T = mass of waste disposed in year *T*, Gg

DOC = Degradable organic carbon in disposal year (fraction), Gg C/Gg waste

DOC_f = fraction of DOC that can decompose in the anaerobic conditions in the SWDS (fraction) MCF = CH_4 correction factor for year of disposal (fraction)

3A1.4.3 Calculating CH_4 generation from DDOCm decomposed

The amount of CH_4 generated from the DDOCm which decomposes is calculated as follows:

EQUATION 3A1.17

CH_4 GENERATED FROM DECOMPOSED DDOCm

$$CH_4\ generated_T = DDOCm\ decomp_T \bullet F \bullet 16/12$$

Where:

CH_4 $generated_T$ = amount of CH_4 generated from the DDOCm which decomposes

DDOCm $decomp_T$ = DDOCm decomposed in year *T*, Gg

F = fraction of CH_4, by volume, in generated landfill gas 16/12 = molecular weight ratio CH_4/C (ratio).

The CH_4 generated by each category of waste disposed is added to get total CH_4 generated in each year. Finally, emissions of CH_4 are calculated by subtracting first the CH_4 gas recovered from the disposal site, and then CH_4 oxidised to carbon dioxide in the cover layer.

EQUATION 3A1.18 CH_4 EMITTED FROM SWDS

$$CH_4\ emitted_T = \left(\sum_x CH_4\ generated_{x,T} - R_T \right) \bullet \left(1 - OX_T\right)$$

(The final result calculating column in the Results sheet)

Where:

CH_4 $emitted_T$ = CH_4 emitted in year *T*, Gg

x = waste type/material or waste category

R_T = CH_4 recovered in

year *T*, Gg

OX_T = Oxidation factor in year *T*, (fraction)