Université de Lomé

Universität Rostock

DRP-CCDRM

INTERNATIONAL MASTER PROGRAM IN RENEWABLE ENERGY AND GREEN HYDROGEN

SPECIALITY: Bioenergy/Biofuels and Green Hydrogen Technology

MASTER THESIS

Subject/Topic:

Potential Production of biomethane and green hydrogen from municipal solid waste in Cape-Coast, Ghana, for injection into the Ghana natural Gas Grid

2021-2023

Presented the 26th September 2023

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DECLARATION

I hereby declare that the thesis submitted was prepared and independently by me without any outside assistance. All direct and indirect sources used have been duly acknowledged as references.

DEDICATION

This thesis is dedicated to my family for their support and encouragement.

ACKNOWLEDGEMENTS

I am grateful to Allah for his mercy throughout this academic journey. I would like to express my heartfelt gratitude to all those who have contributed to my academic journey and supported me in achieving my goals. First and foremost, I am deeply thankful to the Funders (BMBF) and WASCAL for providing me with the scholarship that made my education possible. I sincerely appreciate the president of the University of Abdou Moumouni, Niamey, for their unwavering support during both the first and second semesters and for their continuous commitment to the institution's growth. My sincere thanks go to the Vice Chancellor of the University of Lomé, Prof. Kokoroko for providing an enabling environment for studies in my third semester. The research stays in Germany have been very instrumental to my research work and enriched my learning; thanks to the Vice-Chancellor of the University of Rostock for such an opportunity.

I would like to acknowledge Prof. Adamou Rabbani, WASCAL Director, at the University of Abdou Moumouni, Assoc. Prof. Komi Agboka, WASCAL Director and Assoc.Prof. Prosper Begedou, WASCAL Deputy Director (both of the University of Lomé) for their guidance and mentorship, which has been crucial in shaping my academic journey. The support of the Green Hydrogen programme coordinator for the University of Lome, Dr. Damgou Mani Kongnine and the scientific coordinator, Dr Mouhamed Idrissou have been of great importance in my academic pursuit. My Major Supervisor, Prof. Milohum Mikesokpo Dzagli and Co-supervisors, Prof. Styanara Narra, and Ms Zipporah Asiedu (MSc) deserve special recognition for their expert guidance, encouragement, and support throughout my research and studies.

I extend my appreciation to the esteemed jury members for their time and expertise during my defense, which significantly contributed to improving my work. My profound appreciation also goes to the Director and research team of the Department of Waste and Agriculture, University of Rostock, for providing me with a nurturing learning environment and to all the team members from Niger who collaborated with me during the first and second semesters, enhancing my learning experience.

Lastly, I want to express my gratitude to all those who have supported, encouraged and inspired me along the way. Your contributions have been invaluable, and I am truly honoured to have had your support on this journey.Thank you all for being integral to my academic and personal growth.

ABSTRACT

Biomethane and hydrogen have emerged as promising elements in the transition towards sustainable energy, gaining significant attention due to their capacity to mitigate greenhouse gas emissions and foster sustainable development. In Ghana, efforts to promote sustainable waste valorization for energy production are underway; however, the focus on converting organic waste into biomethane for injection into the natural gas grid still needs to be expanded.

This study aims to evaluate the potential of producing biomethane and biohydrogen from the food waste fraction of Municipal Solid Waste in Cape Coast, Ghana for injection of these renewable gases into the national gas grid. The process involves generating biomethane by upgrading biogas produced from anaerobic digestion of food waste. The quantity of biomethane was determined using the modified Buswell equation, incorporating the ultimate analysis of food waste obtained from reliable literature sources. Additionally, hydrogen potential is estimated using the stoichiometric chemical equation for the steam reformation of biomethane. Two scenarios are considered to evaluate the environmental impact: one employing renewable energy-generated hydrogen for methanation and the other using hydrogen derived from steam methane reforming.

The results indicate that Cape Coast produced 6.4 thousand tons of food waste in 2021, with projections to 11 thousand tons by 2050 due to linear population growth of 2% according to the World Bank Group. As a result, Cape Coast possesses significant methane and hydrogen production potential, estimated to be 3.7 million m^3 and 784 thousand kg in 2021 and projected to reach 6.6 million m^3 and 1.4 million kg by 2050. The biomethane potential obtained is equivalent to 0.134 trillion Btu of natural gas as of 2021. This displaces 0.7% of the gas import through the West African Gas Pipeline. Comparing the two scenarios, it is evident that using renewable electricity for methanation leads to lower emissions than employing hydrogen from steam methane reforming. This finding highlights the environmental advantages of integrating renewable energy sources into the biomethane and hydrogen production processes. Converting food waste into biomethane and hydrogen is a viable and eco-friendly method of managing waste in Ghana. This approach not only facilitates the country's transition towards renewable energy but also promotes circular economy principles. Policymakers can leverage these findings to encourage waste-to-energy projects and integrate circular economy strategies into the national energy policy.

Keywords: Biomethane; hydrogen; renewable energy; pollutant emissions; Ghana.

Tire du Mémoire : Production du biohydrogène partir du biomethane genere à base des resius alimentaires solides en provenance des commune de Cape-Coast, au Ghana, en vue de l'injection de ces gaz renouvelables dans le reseau gazier national

RÉSUMÉ

Le biométhane et l'hydrogène sont apparus comme des sources prometteuses dans la transition vers l'énergie durable, et suscitent une grande attention en raison de leur capacité à réduire les émissions de gaz à effet de serre et à favoriser le développement durable. Au Ghana, des efforts sont en cours pour promouvoir la valorisation durable des déchets pour la production d'énergie. Cependant, les actions pour la conversion des déchets organiques en biométhane injectable dans le réseau de gaz naturel doivent être plus développées. Cette étude vise à évaluer le potentiel de production de biométhane et du biohydrogène à partir de la fraction de déchets alimentaires solides municipaux de Cape Coast, au Ghana et l'injection de ces gaz renouvelables dans le réseau gazier national.

Le processus consiste à générer du biométhane en améliorant le biogaz produit par la digestion anaérobie des déchets alimentaires. La quantité de biométhane est déterminée à l'aide de l'équation de Buswell modifiée, en incorporant l'analyse finale des déchets alimentaires obtenus à partir de sources bibliographiques fiables. En outre, le potentiel d'hydrogène est estimé à l'aide de l'équation chimique stœchiométrique pour le reformage à la vapeur du biométhane. Pour évaluer l'impact environnemental, deux scénarios sont envisagés: (i) la méthanisation en utilisant de l'hydrogène produit à partir d'énergies renouvelables et (ii) en utilisant de l'hydrogène dérivé du reformage du méthane à la vapeur. Les résultats indiquent que 6,4 milles tonnes de déchets alimentaires ont été produits à Cape-Coast en 2021, avec des projections à 11 milles tonnes d'ici 2050, en raison de la croissance linéaire de la population avec un taux de croissance annuel de 2%. Par conséquent, Cape Coast possède un important potentiel de production de méthane et d'hydrogène, estimé à 3,7 millions de m^3 et 784 000 kg en 2021. Il devrait atteindre 6,6 millions de m^3 et 1,4 million de kg d'ici 2050. Le potentiel de production du biométhane obtenu est équivalent à 0,134 trillion de Btu de gaz naturel en 2021. Cela représente 0,7% des importations de gaz par le biais du gazoduc ouest-africain. En comparant les deux scénarios, il est évident que l'utilisation d'électricité renouvelable pour la méthanisation entraîne moins d'émissions que l'utilisation d'hydrogène provenant du reformage du méthane à la vapeur. Ce constat met en évidence les avantages environnementaux de l'intégration des sources d'énergie renouvelable dans les processus de production de biométhane et d'hydrogène. La conversion des déchets alimentaires en biométhane et en hydrogène est une méthode viable et écologique de gestion des déchets à promouvoir au Ghana.

Cette approche facilite non seulement la transition du pays vers les énergies renouvelables, mais promeut également les principes de l'économie circulaire. Les décideurs politiques peuvent s'appuyer sur ces résultats pour encourager les projets de valorisation énergétique des déchets et intégrer les stratégies d'économie circulaire dans la politique énergétique nationale.

Mots clé : Biométhane; hydrogène, énergie renouvelable; émissions de polluants, Ghana

ACRONYMS AND ABBREVIATIONS

AD	**:** Anaerobic digestion
ALK	: Alkaline Water Electrolysis
CNG	: Compressed Natural Gas
CEGA	: Center for Effective Global Action
EBA	: European Biogas Association
GIE	: Gas Infrastructure Europe
GHGs	**:** Greenhouse Gases
IPCC	: Intergovernmental Panel on Climate Change
MSW	: Municipal Solid Waste
PtG	: Power to Gas
PtX	: Power to X
PM	: particulate Matter
PEM	: Polymer Membrane Electrolyte
RNG	: Renewable Natural Gas
SOEC	: Solid Oxide Electrolyte Cell
UN-Habitat	: United Nations Human Settlement Programme
VOCs	: Volatile Organic Compounds
WaCT	: Waste Wise Cities Tool
WAGP	: West African Gas Pipeline
WASCAL	: West African Science Service Centre on Climate Change and Adapted Land Use
Btu	: British Thermal Unit

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Introduction

Research background

Biomethane and biohydrogen have recently gained significant attention in the energy transition pathway due to their potential to reduce greenhouse gas emissions and promote sustainable development. Conversing organic solid waste into biomethane and biohydrogen contributes to the renewable energy mix while providing sustainable waste management solutions. Ghana is a West African country endowed with natural gas resources, which could be complemented with biomethane from Municipal Solid Waste (MSW). Using MSW for energy production effectively addresses the challenge of waste management while simultaneously producing renewable energy. According to the International Energy Agency (IEA) (2021), bioenergy is the most significant contributor to renewable energy worldwide, accounting for over 60% of all renewable energy consumed. In addition, hydrogen has been identified as a critical component of a future sustainable energy system. Green hydrogen from renewable sources is a promising alternative to conventional hydrogen production (IPCC, 2021). The potential of bioenergy and green hydrogen production from MSW has been explored in several studies across the globe. According to a study by Figueroa-Escamilla et al., (2021), methane from the Organic Fraction of Municipal Solid Waste (OFMSW) is a potential energy source. A similar study conducted in Spain estimated that around 4499 ktoe could be obtained if all biowaste was converted into biomethane, which would allow 31.6% of the final demand for natural gas to be satisfied in a sustainable way (Sánchez Nocete & Pérez Rodríguez, 2022).

Problem Statement

MSW management is a significant challenge in Ghana particularly in coastal cities such as Takoradi, Cape Coast, and Tema, where the population density is high. The disposal of MSW in landfills results in the emission of methane, a potent greenhouse gas, and other harmful pollutants. However, recent studies have shown that MSW can be a potential feedstock for renewable energy production in Ghana. Ghana generates about 12,710 tonnes of MSW daily, with Accra, Kumasi, and Tamale being the most significant waste generator (Agbefe et al., 2019; Owusu-Ansah et al., 2022). The studies also found that approximately 61% of the solid waste generated is organic, making it suitable for biogas production. Another study by Amo-Asamoah (2020) investigated the potential of MSW for electricity generation in Kumasi. It estimated that 1 m^3 of biogas generated from MSW in Kumasi could generate 36 MJ of energy, equivalent to 10 kW/h (Amo-Asamoah et al., 2020). Biomethane production from MSW involves converting organic matter to methane through anaerobic digestion. The process produces biogas that includes methane (CH_4), carbon dioxide (CO_2), and traces of other gases such as hydrogen sulphide (H_2S) and ammonia (NH_3). The biogas composed mainly of CH_4 and CO_2 is upgraded to biomethane, which has properties similar to natural gas and can be injected into the natural gas grid. Production of MSW biomethane has several advantages, including reducing the dependence on fossil fuels and promoting a circular economy.

Developing a sustainable energy mix is particularly important for Ghana, as the country continues to face significant energy challenges, including high losses in the distribution system (Kumi, 2017). Harnessing the potential of organic solid waste for biomethane and green hydrogen production could play a significant role in achieving Ghana’s target of increasing renewable energy capacity to 10% by 2020 and 20% by 2030 (Ghana Energy Commission, 2019; Ministry of Energy, 2019).

Research Gap and Importance

The potential for biomethane and hydrogen production from MSW has been studied in several countries worldwide, including the European Union and Nigeria, with positive results. However, limited research has been research on the potential for biomethane and green hydrogen production from MSW in Ghana, despite the availability of significant quantities of MSW in the country. The few studies conducted in Ghana have focused mainly on the potential for biogas production from MSW for energy (electricity) production.

Therefore this study aims to fill the research gap by evaluating biomethane and hydrogen production potential from MSW in the Cape Coast municipality for injection into the natural gas grid. This study provides valuable information to policymakers, researchers, and investors in Ghana's gas and energy sectors by evaluating the potential for biomethane and green hydrogen production from MSW in the Cape Coast which can inform the development of policies and strategies to promote its integration into the natural gas grid. Additionally the study can serve as a basis for further research on bioenergy and hydrogen production from MSW in other cities in Ghana and African countries.

Research Questions

The following research questions will be addressed to achieve the research objectives :

1. What is the total MSW potential for biomethane and hydrogen in Cape Coast?
2. How much natural gas equivalent can be produced from MSW-derived biomethane?
3. What is the CO_2 emissions reduction potential of biomethane and green hydrogen production from MSW?

Research Objectives

The main objective of this thesis is to evaluate the production potential of biomethane and green hydrogen from MSW in Cape Coast, Ghana.

The specific objectives are:

1. To estimate the total MSW potential for biomethane and green hydrogen in Cape coast
2. To determine the equivalent natural gas that can be produced from MSW-derived biomethane
3. Investigate the CO_2 emissions reduction potential

CHAPTER 1: Literature Review

Municipal Solid Waste (MSW) management is a significant challenge for many cities in developing countries, including Ghana (Abarca-Guerrero et al., 2013; Gupta et al., 2015; Miezah et al., 2015; Moh & Abd Manaf, 2014). The rise in population and urbanisation in Ghana have led to a significant increase in the amount of MSW generated, which has resulted in environmental pollution, public health issues, and economic challenges (Diao et al., 2019; Lissah et al., 2021). Despite these challenges, MSW can be a valuable resource for producing renewable energy (Ayodele et al., 2017), particularly biomethane and green hydrogen, which can be injected into the Ghana gas grid (Cudjoe et al., 2021; Mohammed et al., 2017).

This literature review aims to evaluate the potential of producing biomethane and green hydrogen from municipal solid waste in cape coast, a coastal city in Ghana. The review will assess the current state of waste management in this city, the potential for biomethane and green hydrogen production, the feasibility of injecting biomethane and green hydrogen into the Ghana gas grid, and the comparative analysis of the potential benefits and challenges of producing biomethane and green hydrogen from municipal solid waste in the chosen location.

1.1. Municipal Solid Waste as a source of energy

MSW is a significant problem in many developing countries, including Ghana. MSW management in Ghana is characterised by inadequate collection, transportation, and disposal facilities (Nartey & Nyarko, 2020). According to Williams et al. (2023), Ghana generates approximately 14000 tons of daily waste with about 48% to 69% organic fraction (Miezah et al., 2015). However only about 20% of the waste is collected, and the remaining 80% is left to open burning of waste, which pollutes the environment and poses health hazards to the population (Williams et al., 2023). Other studies also found that approximately 61% of the waste generated is organic, making it suitable for the production of biogas (Agbefe et al., 2019; Owusu-Ansah et al., 2022). The potential of MSW for energy production is enormous. A study by Amo-Asamoah (2020) investigated the potential of MSW for electricity generation in Kumasi. It estimated that 1 m^3 of biogas generated from municipal solid waste (MSW) in Kumasi could generate 36 MJ of energy, equivalent to 10 kW/h. The idea of "waste-to-energy" offers the chance to find a practical solution for garbage disposal and a greener fuel source to produce power (Afrane et al., 2021; Ofori-Boateng et al., 2013).

The conversion of the Organic Fraction of Municipal Solid Waste (OFMSW) to biogas is an environmentally sustainable alternative for waste management (Ram et al., 2021; Wasewar, 2023). Biogas is a mixture of gases, primarily methane and carbon dioxide, produced by the anaerobic digestion of organic matter. It can be used as fuel for cooking, lighting, and electricity generation or be upgraded (by purification) to biomethane, a renewable natural gas with similar properties to fossil fuel natural gas (Black et al., 2021; Präger et al., 2019). Waste conversion into biogas is much more advanced in developed countries, especially Europe. Across Europe, 52.3 TW h of energy was produced from biogas in 2013, with Germany being the leading producer with about 27 TW h of electricity (Silva Dos Santos et al., 2018). The benefit of these projects included the energy supply to over 5 million households (FACHVERBAND BIOGAS E. V, 2011). The estimated European production of electricity from biogas was expected to reach approximately 65 TW h by 2020 (EUROBSERV'ER, 2014).

Despite a considerable concentration of waste in Ghana cities, only a few projects have been implemented in the waste-to-energy sector. A study conducted by Barnor et al. (2018) showed that Ghana's MSW daily generation rate of 12.3 million kg could generate about 650,206.65 m^3 of methane 1,966.22 MWh of energy every day. This translates into an annual generation of 696,140.191 MWh annually, representing approximately 3.5% of Ghana's total electricity demand as of 2016 and 1.9% of the country's total electricity installed capacity. This gives Ghana quite a good leap towards its 20% renewable energy target by 2030 (Ministry of Energy, 2019).

1.2. Biogas Production and Upgrading to Biomethane

Biogas production from MSW involves a series of processes, including waste collection, sorting, and anaerobic digestion. The anaerobic digestion of MSW consists of the breakdown of organic materials in the waste without oxygen to produce biogas, a mixture of methane and carbon dioxide. The anaerobic digestion process comprises four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Meegoda et al., 2018). In hydrolysis, complex organic matter is broken down into simpler compounds, such as sugars and amino acids. Acidogenesis involves converting these simpler compounds into volatile fatty acids and alcohols. During acetogenesis, volatile fatty acids and alcohols are further converted into acetic acid, hydrogen, and carbon dioxide. Finally, methane is produced in methanogenesis by converting acetic acid and hydrogen. After biogas is produced through anaerobic digestion, it can be upgraded to biomethane to meet the quality standards for utilisation in various applications, such as injection into the gas grid or use as vehicle fuel (Bernardo et al., 2021). The upgraded biogas is renewable natural gas and can be used in similar applications as natural gas (Abanades et al., 2022; Molino et al., 2013). Upgrading processes include pressure swing adsorption, water scrubbing, amine scrubbing, and membrane separation, which remove impurities such as carbon dioxide, hydrogen sulfide, and water vapour (Ahmed et al., 2021). Biogas production chain is represented in Figure 1.

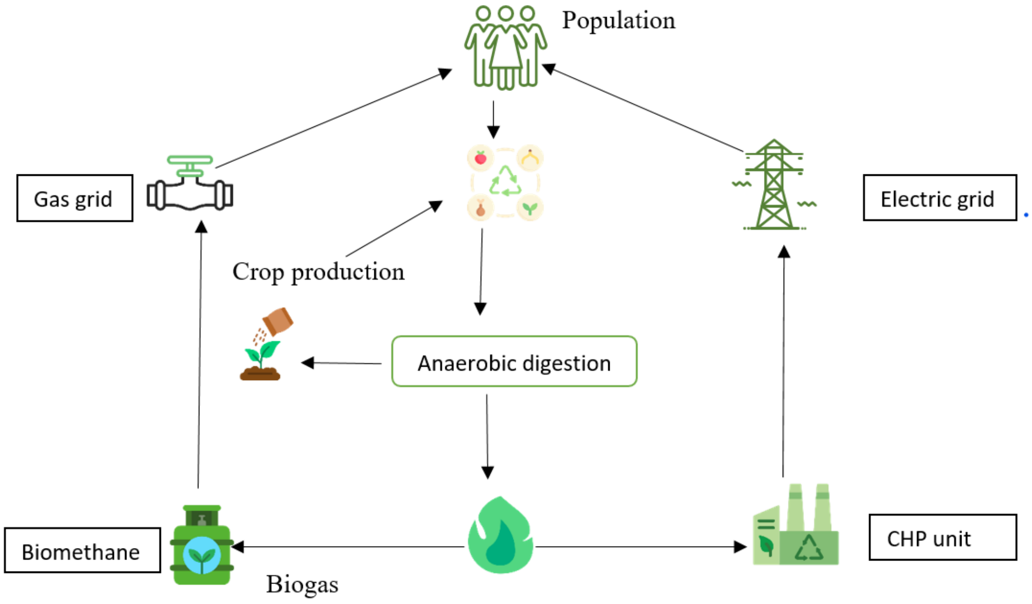


Figure 1 : Organic Waste conversion to biogas (Adopted from Word Biogas Association, 2019)

1.3. Biogas purification technologies

The treatment of biogas is a multistage gas purification process involving the removal of bulk component CO_2, drying of the gas, and removing minor components such as CO, H_2S, and N_2, which are considered biogas pollutants. The two steps of biogas purification are cleaning and upgrading. In “biogas cleaning”, toxic components such as Si, CO, H_2S, siloxanes, volatile organic compounds (VOCs) and NH3 are removed (Angelidaki et al., 2018). The upgraded gas has methane (CH4) content of at least 90% with low content of hazardous pollutants (Kapoor et al., 2019; Niesner J. et al., 2013). Upgrading biogas is essential to remove impurities, particularly carbon dioxide (CO2), to attain natural gas quality and inject it into the gas grid. Currently, four main methods are employed: water absorption, polyethylene glycol scrubbing, carbon molecular sieves, and membrane separation (Ardolino et al., 2021).The choice of biogas upgrading method depends on the required biogas quality, the availability of water, chemicals and equipment and the market and regulations for products and byproducts. A summary of the technical advantages and disadvantages of these methods is shown in Table 1.

(Baker & Lokhandwala, 2008; Patterson et al., 2011; Ryckebosch et al., 2011; Starr et al., 2012; Yang et al., 2014; Yang & Ge, 2016). To efficiently clean biogas and prioritise targeted impurities, specific methods are employed. Pressurised water scrubbing and pressure swing adsorption effectively simultaneously remove multiple impurities, like CO_2 and NH_3. However, these methods could be more effective for reducing H_2S. In some cases, a combination of two methods, such as membrane separation and another technique, enhances purification capacity. Although membrane separation is easy to install and operate, it has a relatively lower CH_4 purification capacity. Amine absorption and cryogenic methods are also employed, producing high-quality CO_2 as a byproduct. However, these methods require high energy inputs for operation. Combining them with other methods, like pressure swing adsorption, could improve energy efficiency.

Table 1: Technical advantages and disadvantages of biogas cleaning methods.

Purifying methods	Advantages	Disadvantages	Sources
Pressurised water scrubbing.	Removes CO_2, NH_3 and dust; high CH4 purity; low CH_4 loss; needs no special chemicals or equipment	With high water demand, H_2S removal efficiency may be low.	(Baker & Lokhandwala, 2008; Patterson et al., 2011; Ryckebosch et al., 2011; Starr et al., 2012; Yang et al., 2014; Yang & Ge, 2016)
Pressure swing adsorption.	Removes CO_2, N_2 and O_2; low power demand; low level of emissions	H_2S and water removal are needed before PSA; needs to regenerate adsorbent periodically	(Baker & Lokhandwala, 2008; Patterson et al., 2011; Ryckebosch et al., 2011; Starr et al., 2012; Yang et al., 2014; Yang & Ge, 2016)

Purifying methods	Advantages	Diasadvantages	Sources
Amine absorption.	Very low methane loss; produces high-quality CO_2 and almost complete H_2S removal.	High energy demands; amines are expensive; corrosion at high temperatures; produce waste chemicals.	(Baker & Lokhandwala, 2008; Patterson et al., 2011; Ryckebosch et al., 2011; Starr et al., 2012; Yang et al., 2014; Yang & Ge, 2016)
Membrane	Compact and light in weight; easy operation and maintenance; low energy requirements.	Relatively low CH_4 purity and high loss rate; membrane can be expensive.	(Baker & Lokhandwala, 2008; Patterson et al., 2011; Ryckebosch et al., 2011; Starr et al., 2012; Yang et al., 2014; Yang & Ge, 2016)
Temperature swing adsorption Cryogenic method	Needs no special chemicals. Produce CO_2 as by product	High energy demands; low CH_4 purity. High energy demands; high capital cost	(Baker & Lokhandwala, 2008; Patterson et al., 2011; Ryckebosch et al., 2011; Starr et al., 2012; Yang et al., 2014; Yang & Ge, 2016)

The biogas upgradation methods discussed, including pressurised water scrubbing, Pressure swing adsorption, Amine absorption, Temperature swing adsorption (Cryogenic process), and membrane purification, are utilised to remove CO_2 and other impurities from biogas. Each method has advantages and suitability depending on the application and specific biogas characteristics. By employing these upgradation methods, biogas can be purified to be injected into the natural gas grid with high methane purity, contributing to a more sustainable energy landscape.

1.4. Recent development in Biomethane in Ghana and other countries

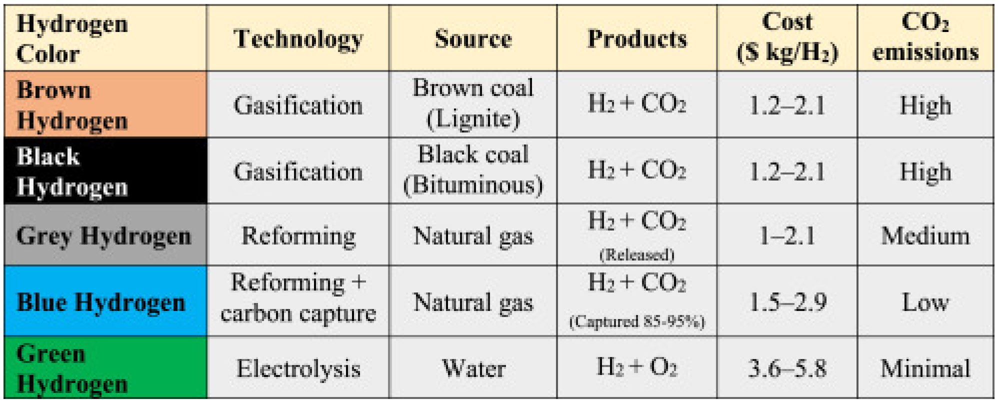
Several studies have been conducted on biomethane production from MSW in Ghana and other countries. A study by Sohoo et al. (2018) estimated the power generation potential alongside the economic and environmental benefits of biochemical methane production from MSW. This study showed that biomethane could generate about 63 MWe of electric power, contributes to a 2.1 % share of daily power supply, and eliminate 0.13 Mt CO_2-eq/annum. In a study conducted in India (Singh and Kalamdhad, 2022), the potential and utilisation of compressed natural gas (bio-CNG) from MSW and wastewater in India can replace 4053.47 tonnes of India's diesel consumption per day, which would have a significant impact on the successful implementation of H_2 energy technology for the country. The European Commission in its vision to end its dependence on Russian fossil fuels has set up an ambitious target of 17 billion cubic metres in 2030 which is to be practically doubled to 35 billion cubic metres of biomethane per year, increasing biomethane production (Abdalla et al., 2022).

In Africa, Ayodele et al. (2019a) study in South-Western Nigeria estimated the electricity generation and environmental potentials of hydrogen produced from the food component of MSW-derived biogas and found that 0.334 Million tons of H_2 gas could be obtained from the selected locations. Shane et al. (2018) assessed the potential of biomethane from MSW in Zambia. The study revealed that MSW in Lusaka has the potential to produce 3 670 000 m^3 of biomethane from MSW with 146 TJ/year of energy. This translated to 10.582 Gg CO_2eq/year of avoided greenhouse gas (GHG) emissions from the transport sector in Lusaka.

Arthur et al. (2020) evaluated the potential biogas production from four primary sources in Ghana in terms of the volume of methane for energy production and the equivalent avoidable carbon dioxide emissions from 2020 through 2030. Their study is based on the projection of methane production from common livestock and poultry manure, landfills, wastewater treatment plants, and palm oil mill effluent. Their results show that 690.7 million m^3 and 848.74 million m^3 of methane could be obtained from all the sources considered in 2020 and 2030 respectively, translating to about 1.84 TWhel and 2.28 TWhel. It also meant that a total carbon dioxide equivalent emission of 12.36 million tCO_2-eq and 15.82 million tCO_2-eq could be avoided in 2020 and 2030, respectively (Arthur et al., 2020). The paper highlights the importance of focusing on these resources by using best practices to achieve the set goal.

1.5. Hydrogen Production Pathways

Hydrogen is an attractive energy carrier due to its high energy content and environmentally friendly nature when used as a fuel, producing only water as a byproduct (Rosen & Koohi-Fayegh, 2016; Sazali, 2020). It is classified into different colour shades: grey, blue, turquoise and green, depending on its production processes (Ajanovic et al., 2022; Bhandari & Shah, 2021; Dawood et al., 2020; Shiva Kumar & Lim, 2022), as shown in Figure 2. The remaining types of hydrogen, except green hydrogen, release CO_2 as a bioproduct, making them not environmentally friendly. As of 2020, 95% of the hydrogen produced was mainly fossil based contributing to about, emitting 830 million tons/year of CO_2 emission and the rest of the hydrogen was made from renewable resources including water electrolysis (International Energy Agency (IEA), 2019; Mosca et al., 2020; Shiva Kumar & Lim, 2022).



Hydrogen Color	Technology	Source	Products	Cost ($ kg/H_2)	CO_2 emissions
Brown Hydrogen	Gasification	Brown coal (Lignite)	$H_2 + CO_2$	1.2–2.1	High
Black Hydrogen	Gasification	Black coal (Bituminous)	$H_2 + CO_2$	1.2–2.1	High
Grey Hydrogen	Reforming	Natural gas	$H_2 + CO_2$ (Released)	1–2.1	Medium
Blue Hydrogen	Reforming + carbon capture	Natural gas	$H_2 + CO_2$ (Captured 85-95%)	1.5–2.9	Low
Green Hydrogen	Electrolysis	Water	$H_2 + O_2$	3.6–5.8	Minimal

Figure 2: Hydrogen colour shades and their Technology, cost, and CO_2 emissions (Shiva Kumar & Lim, 2022)

Green hydrogen, also known as renewable and clean hydrogen, is hydrogen produced through renewable energy sources or processes that do not release greenhouse gases into the atmosphere. It can be produced using various methods, including water electrolysis using renewable electricity, biological processes, and thermochemical processes. One such method of green hydrogen production is the conversion of MSW. MSW has been explored as a potential feedstock for green hydrogen production, aiming to address the waste management and energy challenges many countries face, including Ghana. Some of the mainly used hydrogen production processes have been highlighted below: Figure 3.

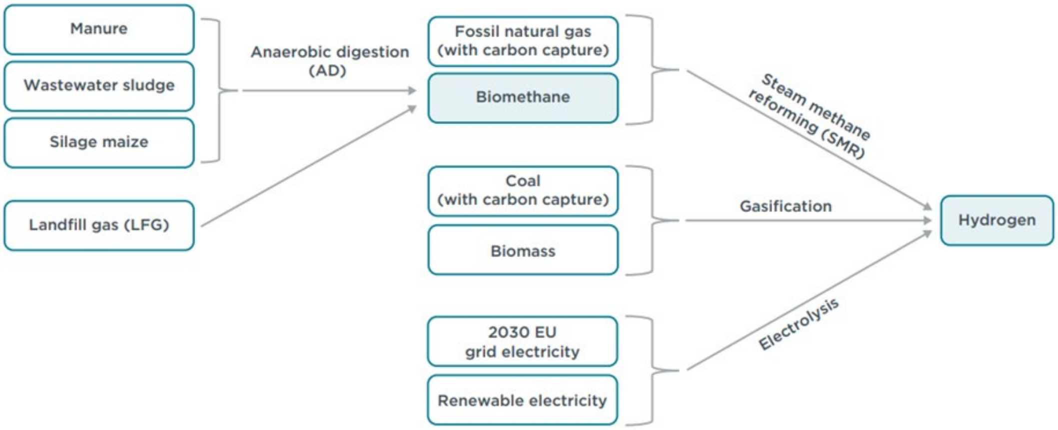


Figure 3: Biomethane and Hydrogen production pathways (Zhou, 2021)

1.5.1 Gasification process

Gasification is a thermochemical process in which carbonaceous materials like coal and municipal solid waste are converted into syngas, a mixture of hydrogen, carbon monoxide, and other gaseous compounds, at high temperatures usually above 650–800°C, and under controlled oxygen conditions (Seo et al., 2018). The syngas can then be purified and converted into hydrogen via a water-gas shift reaction, where carbon monoxide reacts with water to produce hydrogen and carbon dioxide (Kreutz et al., 2008) (Equations 1-4). Alternative to the production of hydrogen, syngas can be used directly or converted into synthetic fuel such as drop-in biomass to liquids or biomethane (Zhou, 2021). A typical gasification process takes place in four stages as shown in Figure 4.

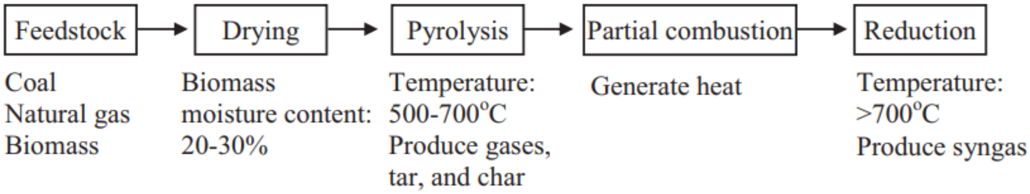


Figure 4: Gasification process using biomass as feedstock. (Yang & Ge, 2016)

Partial oxidation:

$$C(Char) + \frac{1}{2}O_2 \rightarrow CO \qquad \text{(Equation 1)}$$

Boudouard reaction:

$$(Char) + CO_2 \rightarrow 2CO \qquad \text{(Equation 2)}$$

Water-Gas shift reaction:

$$C + CO \rightarrow H_2 \qquad \text{(Equation 3)}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \text{(Equation 4)}$$

1.5.2 Electrolysis of water

Hydrogen production by electrolysis is a clean and sustainable process that involves splitting water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2) gases using electricity from renewable sources. This method emerged as a promising solution for storing excess renewable energy and generating green hydrogen, a clean fuel with various applications. This environmentally friendly process occurs in an electrolyzer with the reaction equation represented in equation 5:

$$2H_2O \rightarrow 2H_2 + O_2 \qquad \text{(Equation 5)}$$

There are three major electrolysis technologies for hydrogen production: alkaline water electrolysis (ALK), polymer electrolyte membrane (PEM) electrolysis, and solid oxide electrolyser cell (SOEC) (Rashid et al., 2015; Shiva Kumar & Himabindu, 2019).

According to the US Department of Energy (2022), ALK electrolysis is the most mature technology dating back to 1920 and holds a market share of approximately 70%. It usually operates in a temperature range of 30–90°C and uses an alkaline KOH/NaOH aqueous solution with a typical concentration of 20–30% as the electrolyte (Wang et al., 2022). ALK benefits from low costs and long operational life. However it requires continuous operation to avoid damage, making it less suitable for variable renewable energy sources. ALK electrolysis also faces challenges with low current densities and corrosive conditions (Ajanovic et al., 2022).

With PEM electrolysis developed by General Electric, a solid sulfonated polystyrene membrane is used as the electrolyte. It operates in a temperature range of (20–80°C) with high current density (Marshall et al., 2007). Some advantages of PEM electrolysis over other technologies are its greater efficiency, low gas permeability, and easy handling and maintenance (Wang et al., 2022). It offers higher efficiency and faster response times, making it suitable for capturing excess renewable electricity. High-pressure PEMs can directly deliver pressurized hydrogen, improving overall efficiency. However, PEM electrolysis is associated with higher capital costs due to expensive electrode catalysts and membrane materials (Minke et al., 2021). Supply problems may arise in a mature PEM market, emphasizing the need for recycling and more efficient PEM technology.

SOEC, a relatively new technology, has gained attention for its low expected capital costs and high efficiency. It has already been installed on the market with a capacity of around 150 kW. SOEC operates at high temperatures (700 °C to 1000 °C)(Motazedi et al., 2021), which improves thermodynamic conditions and allows for the use of less electricity. Heat can also be supplied to the process. However, SOEC faces challenges related to electrode instability, delamination, and safety issues (Shen et al., 2021)

From the literature reviewed, it can be deduced that each electrolysis technology has advantages and disadvantages. Alkaline water electrolysis is the most mature technology with low costs but requires continuous operation. PEM electrolysis is more efficient, and responsive, but has higher capital costs. Solid oxide electrolyzer cell (SOEC) shows promise with low capital costs, high efficiency, and the ability to utilize thermal energy, although it is a newer technology with some operational challenges

1.5.3 Steam methane reforming of biogas

1.5.3.1 Anaerobic digestion

Due to the growing concern for waste disposal and energy security, anaerobic digestion (AD) has attracted more research focus and application. It offers a variety of environmental advantages, such as the generation of renewable energy, the management of organic waste, ecological preservation, the development of a biogas-linked agricultural system, and the reduction of greenhouse gas emissions (Fan et al., 2018). Anaerobic digestion (AD) is a biological process that breaks down organic matter in the absence of oxygen, producing biogas, which mainly contains methane and carbon dioxide (Department for Environment Food and Rural Affairs, 2011; Kumar & Ankaram, 2019).

1.5.3.2 Steam Methane Reformation

After being purified, the methane can be converted to hydrogen through a process called Steam Methane Reforming (SMR) in which methane reacts with steam to produce hydrogen and carbon dioxide (Lee et al., 2021). In addition to the production methods mentioned above, biomethane as well as natural gas can also be used as a feedstock to produce hydrogen as shown in (Equation 6). SMR is a widely used process for hydrogen production from natural gas.

It represents a considerable percentage of the 95% fossil-based hydrogen (Hydrogen Council, 2017; Rodl et al., 2018; Santos, 2015). In the context of green hydrogen from MSW, the methane component of biogas is subjected to SMR. The reaction occurs at high temperatures (700-1100°C) and involves steam, which reacts with methane to produce hydrogen and carbon dioxide (El-Emam et al., 2023). Although SMR has significant CO_2 emissions, using biogas as a feedstock can offset these emissions, making it a green hydrogen production method (Younus et al., 2018). The Steam methane reformation reaction can be represented with the equation 6;

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2 \qquad \Delta H = 165 \text{ kJ/mol} \qquad \text{(Equation 6)}$$

1.6 Overall Challenges and Opportunities

Although hydrogen production from MSW can significantly reduce greenhouse gas emissions, some environmental concerns still need to be addressed. These include air emissions from gasification and the disposal of ash and digestate (Chanthakett et al., 2021). Integrating hydrogen production from MSW into the existing energy system is essential to maximise its benefits. This integration can be achieved by utilising hydrogen in various applications, such as transportation, power generation, and industrial processes (Yue et al., 2021).

Biomethane production from MSW presents a viable solution for sustainable waste management and energy generation in Ghana. While there are several challenges that must be addressed, including the high moisture content of MSW, high capital cost, and the lack of appropriate waste management infrastructure (Amo-Asamoah et al., 2020), there are also significant opportunities that can be harnessed to promote the development of the biomethane industry in Ghana. The already implemented waste-to-energy projects such as the Safisana, which operates in the Ashaiman settlement in Ghana and the hybrid waste-to-energy in Gyankoba in Kumasi (CEGA, 2023; FONA, 2019). These projects provide circular -waste management systems that collect organic waste and produce clean renewable energy and organic fertilizer. Learning from the successes and challenges of these projects could pave a pathway to implementing waste to biomethane for grid injection in the context of Cape Coast. The government of Ghana has set a target of achieving 20% of its energy mix from renewable sources by 2030 (Ghana Energy Commission, 2019), and the increasing interest in sustainable waste management practices and circular economy principles presents significant opportunities for the development of the biomethane industry. As such, the necessary policies and infrastructure must be implemented to promote the development of the biomethane industry in Ghana.

1.7 Natural gas grid and Biomethane Injection

The composition of natural gas varies substantially from source to source. Methane is the major component of birth, typically 75%-90%, but contains significant amounts of other hydrocarbons such as ethane, butane and propane, and some trace impurities, including CO_2 and hydrogen sulfide (Baker & Lokhandwala, 2008; Viswanathan, 2017).

For several years, Ghana has solely depended on the West African Gas pipeline for power generation (Table 2) .

Table 2 Natural gas supply in Ghana (2009 to 2022) (Energy Commissin, 2023)

Year	Import (TBtu)	Export (TBtu)
2009	0.2	-
2010	15.6	-
2011	31.6	-
2012	16	-
2013	11.6	-
2014	22.5	2
2015	20.6	26.4
2016	4	23.5
2017	11.7	33.7
2018	25.3	41.5
2019	25.2	58.8
2020	24.4	95.2
2021	18.7	107.8
2022	19.9	117.9

The West African Gas Pipeline (WAGP) as shown in Figure 5 is a 678 km long regional high-pressure gas transmission system, built to export Niger Delta gas from Itoki, Nigeria to Takoradi, Ghana, via Benin and Togo (The World Bank Group, 2014; WAGP, 2019).

Due to intermittent supply, infrastructure constraints and debts owed by Ghana to Nigeria (N-Gas), this transmission pathway has been described as “unreliable”(Morroco World News, 2019; The Energy Year, 2022).

Figure 3: View of the WAGP project from Nigeria to Ghana with laterals at Cotonou, Lome, Tema and Takoradi (Obanijesu & Macaulay, 2009)

With the advent of indigenous gas supply from the Sankofa, Jubilee and TEN oilfields, Ghana has increased its energy security, and efforts to reduce carbon emissions from power generation

(The Energy Year, 2022). Natural gas transportation and distribution in Ghana is managed and regulated by the Ghana National Gas Company through the natural gas grid. This domestic transportation infrastructure has improved energy security, promoted economic development, and reduced Ghana's reliance on imported fuels (Ghana National Gas, n.d.). As the world shifts towards renewable energy, natural gas infrastructure plays a vital role in supporting the slow electrification process and developing new electricity networks (International Energy Forum, 2021). The EU is positioned to increase the penetration of renewables in its energy mix to at least 42.5% by 2030 (Renewable Energy Targets, n.d.). Renewable gas, such as biomethane is promising and can be quickly blended with natural gas in large quantities without significant modifications to existing gas grids (Fritsche et al., 2022). The number of biomethane plants in Europe has increased from 627 in 2018 to 1,222 in 2023 (European Biogas Association (EBA) & Gas Infrastructure Europe (GIE), 2023; Софія, 2020). Figure 6 The biomethane projects in Europe as of 2020 is shown in Figure 6 ;

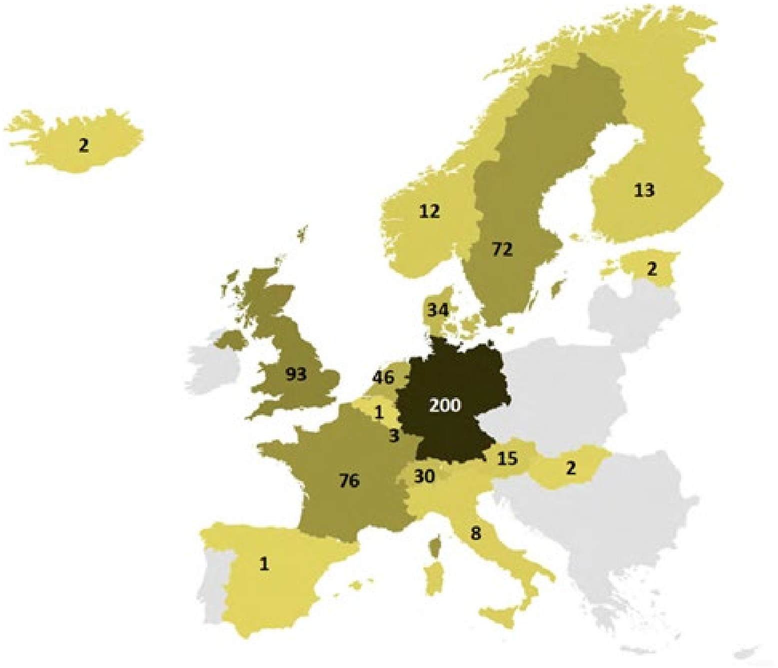


Figure 4: Number of Biomethane plants in European countries (Софія, 2020)

The methane level in biomethane varies among EU member states. Certain countries have higher methane content requirements than others before injecting it into the gas grid. The Netherlands permits biomethane with 85% methane content, while Switzerland and Sweden mandate 96% and 97% methane content, respectively (Aggarangsi et al., 2023; Savickis et al., 2020). Overall, boosting the use of renewable gas, particularly biomethane, in the natural gas sector will enhance the sustainability and carbon neutrality of a country's natural gas infrastructure. Learning from the success of the European Union, Ghana can develop similar projects that suit its geographical context. In 2022, a revelation was made by The Majority Chief Whip, Frank Annoh-Dompreh, about Ghana Gas' plan to construct a 290-kilometre gas pipeline from Aboadze (Western Region) to Tema (Greater Accra Region) (Figure 7). The pipeline will pass through four regions: Western, Central, Eastern, and Greater Accra. Eight stations, including Aboadze, Nsawam, Winneba, Cape Coast, and Tema, will be built to facilitate gas distribution along the pipeline (Ghana Web, 2022; Myjoyonline, 2022). This development allows Ghana to integrate biomethane into natural gas to achieve its energy and climate target.

Figure 5: View of the 290 km project from Aboadze to Tema with distribution station at Cape-Coast

Findings from previous research provides adequate information on the untapped potential of organic waste and how their valorization can contribute the development of renewable energy, especially renewbale gas. Ghana's commitment to increasing the penetration of renewbale energy in the energy mix can be accelerated through the promoting of waste to enegy projects that reduce dependence of fossil fuels.

CHAPTER 2 : Materials and Methods

2.1. Study location

The current study is focused on Cape Coast Municipality. Cape Coast is a coastal city and the capital of the central region of Ghana. It lies along the Atlantic coast of Ghana, approximately 150 kilometres west of the capital city, Accra. It has geographic coordinates of about 5.13151° N latitude and 1.2794744° W longitude. The city has a land area of about 122 square kilometres and is characterised by its proximity to the sea (Figure 8).

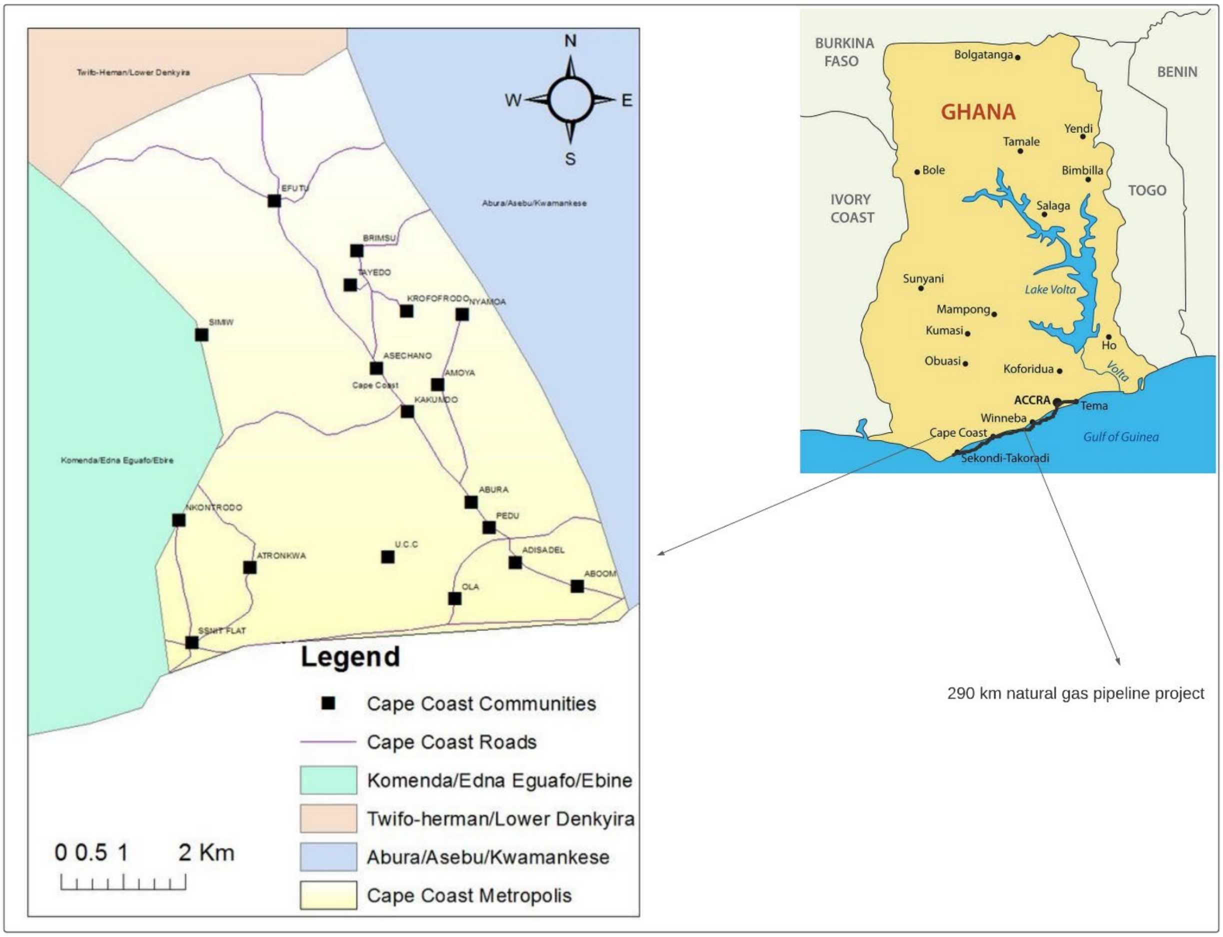


Figure 6: Map of Cape Coast Metropolis and its localization on Ghana map (Adopted from (Kwarteng, 2017)

Cape Coast is the hub of Ghana’s tourism industry and one of the most populated districts in the central region of Ghana with a population of 189,925 inhabitants (Ghana Statistical Service, 2021). Cape Coast's unique geographical location and existing natural gas infrastructure make it an ideal research area for investigating the conversion of waste to biomethane for injection into the Ghana natural gas grid. The construction of a 290-km onshore pipeline from Takoradi to Tema passing through Cape Coast would allow for the transport of natural gas while providing opportunities for studying the integration of biomethane into the existing energy infrastructure (Ghana Web, 2022; Myjoyonline, 2022). Additionally, the district's waste management practices and waste composition can be examined to develop sustainable solutions for waste-to-energy conversion.

2.2. Waste Quantification and Characterization

A comprehensive analysis of waste composition in Cape Coast reveals valuable insights into the types and proportions of waste generated in the area. The study conducted by UN-Habitat, Waste Wise Cities, (2021) indicates that the waste composition in Cape Coast comprises various categories, including organic waste, plastic waste, paper waste, glass waste, and metal waste. The survey highlights that organic waste is the most significant portion of the total waste stream, followed by plastic and paper waste. The study also notes the presence of substantial amounts of glass and metal waste on Cape-Coast. These findings (Table 3; Table 4; Figure 9) provide a better understanding of waste management in the region, which can serve as a basis for developing effective waste management strategies and policies.

Table 3 : Household Municipal Solid Waste Composition

Component	**% composition**
Organics fraction (food waste, garbage, vegetables, etc.)	40
Metals	2
Plastic	22
Glass	1
Textiles	6
Other	19

Table 4 : Municipal Solid Waste Data of Cape Coast , Data Source: UN-Habitat, Wastewise Cities (WaCT) Data Portal (2021)

Component	**Value**
Total MSW generated	166 t/day
MSW generation rate	0.73 kg/capita/day
Household generation	0.44 kg/capita/day
MSW collected	63%
City recovery rate	1 %

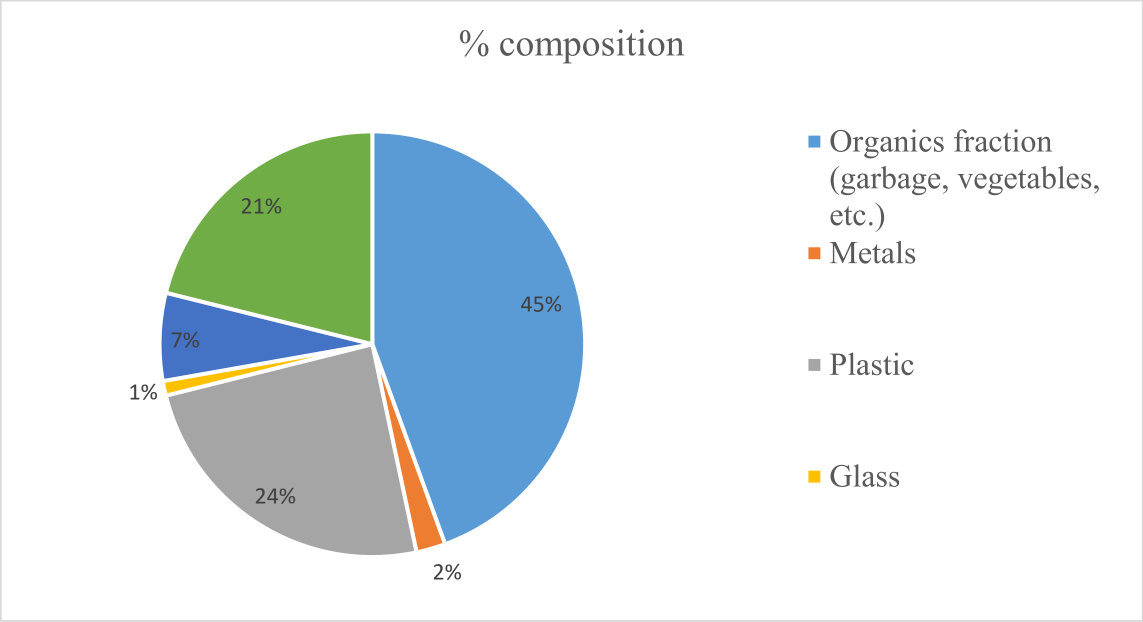


Figure 7: Cape coast Municipal Solid Waste Composition

Data source: United Nations Human Settlements Programme, 2021; World Bank Group, 2018

2.3. Estimation of food waste from selected cities as feedstock for anaerobic digestion

In order to address the lack of historical data on municipal solid waste (MSW) generation in Cape-Coast, a mathematical method was used to estimate the amount of waste produced. This estimation relied on various factors, such as the population in 2021, the average amount of waste generated per person per day, and the recoverable waste fraction. Through the use of these factors, the study was able to calculate the MSW generated in Cape-Coast over some time. To estimate the total amount of MSW generated in Cape-Coast, Equation 7 can be applied.

$$W_{M(i)(t)} = \frac{q \times p(i)(t) \times 365 \times C}{1000} \quad at\ i = Cape\ coast\ and\ t = 2021 \qquad \text{(Equation 7)}$$

Population growth is given by $P_t = P_b(1 + 0.02r)^t$, at a growth rate r of 2 %

where W_M(i)(t) is the annual municipal solid waste generated in Cape-Coast in 2021 in tons; P(i)(t) is the population of Cape-Coast in 2021; C is the recoverable fraction of the municipal solid waste obtained to be 0.63 (UN-Habitat, 2021); q is the average waste generation rate in Cape-Coast as shown in Table 3.

According to a survey by UN-Habitat (2021), food waste represents 20% of the municipal solid waste (MSW) generated in Cape-Coast and forms the majority of the organic waste fraction. Consequently, the separation of the food waste portion of the MSW in Cape Coast at a specific time (W_F(i)(t)) was determined using Equation 8. The equation calculates $W_{F(i)(t)}$ by multiplying the total waste generated in the city in 2021 (W_M(Cape Coast)(2021)) by a factor of 0.20, representing the proportion of food waste within the organic waste fraction (Equation 8).

$$W_{F(i)(t)} = W_{M(i)(t)} \times 0.2 \qquad \text{(Equation 8)}$$

2.4. Estimation of Biomethane Potential from Food Waste Fraction of MSW

The methane production potential methane that may be generated during anaerobic decomposition was obtained by applying the modified Buswell Equation (Equation 9).

Anaerobic digestion (AD) is widely considered to be the most suitable method for effectively managing large quantities of food waste (Dutta et al., 2021). AD processes can harness the energy potential of various food waste materials rich in lipids, proteins, and carbohydrates (Morales-Polo et al., 2018). Typically, AD is carried out in the absence of oxygen to convert food waste into valuable byproducts such as biogas and digestate. Biogas derived from organic biomass presents a significant opportunity to transform substantial bioresources into renewable energy that is environmentally friendly and safe.

When food waste is used as a feedstock, biogas produced through AD typically contains 25-55% CO_2 and 40-75% CH_4, along with other trace gaseous components such as nitrogen (N_2), hydrogen sulfide (H_2S), oxygen (O_2), hydrogen (H_2), ammonia (NH_3), and water vapour (H_2O). However, CO_2 and water vapour are considered contaminants as they do not contribute to thermal power generation and reduce the calorific value of biogas (Ayodele et al., 2019b). Therefore, to upgrade high-grade methane, it is essential to purify the biogas and upgrade its quality using appropriate technologies like water absorption, and pressure swing adsorption (Yousef et al., 2019). The biogas yield is estimated theoretically using the Buswell-Boyle equation (Equation 9).

$$C_aH_bO_cN_d + \left[a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4}\right] H_2O \rightarrow \left[\frac{a}{b} - \frac{b}{8} - \frac{c}{4} + \frac{3d}{4}\right] CO_2 + \left[\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8}\right] CH_4 + dNH_3 \quad \text{(Equation 9)}$$

The constants a, b, c, and d represent the mole of carbon (C), hydrogen(H), oxygen (O), and nitrogen (N) atoms determined mathematically using Equation 10.

$$Mole\ ratio = \frac{U_{elemental}}{M_{mass}} \times \frac{1}{r} \qquad \text{(Equation 10)}$$

Where $U_{elemental}$ is the elemental composition obtained from the ultimate analysis of the organic matter, M_{mass} is the molar mass of the respective elements and r is the nitrogen mole ratio. The ultimate analysis for determining the mole ratio is shown in Table 5 using findings by Anaglate et al. (2007) in Ghana. The data was used due to similarities in food components in Ghana.

Table 5 : Molar mass and Ultimate Analysis of food waste

Elements	Unit	Molar mass (Ayodele et al., 2019b)	Food waste (Anaglate et al., 2007; Seglah et al., 2023)
Carbon (C)	%	12.01	46.7
Nitrogen (N)	%	14.01	2.1
Hydrogen (H)	%	1.01	8.0
Oxygen (O)	%	16.00	38.9

The values of the constants are determined from the mole ratio. For example, the constant

$$a = \frac{46.7}{12.01} \times \frac{1}{r}\ , and\ r = \frac{2.1}{14.01} \qquad \text{(Equation 11)}$$

Other constants are determined similarly as shown in Table 6.

Table 6 : Calculated values of constants in Buswell Equation

Elements	Molar mass	Food waste	Mole ratio
Carbon (C)	12.01	46.7	25.94
Hydrogen (H)	1.01	8	52.84
Oxygen(O)	16	38.9	16.22
Nitrogen(N)	14.01	2.1	1

The methane potential (B_{CH_4}) is calculated at standard temperature and pressure ((0 °C at 1 atm) using the approach by Seglah and Ayodele et al., 2018 as shown in Equation 12.

$$B(CH_4) = \frac{\frac{a}{2}+\frac{b}{8}-\frac{c}{4}-\frac{3d}{8}}{12a+b+16c+14d} \times 22.4 \qquad \text{(Equation 12)}$$

The theoretical CO_2 produced from the process is obtained using Equation 13.

$$B(CO_2) = \frac{\frac{a}{2}-\frac{b}{8}+\frac{c}{4}+\frac{3d}{8}}{12a+b+16c+14d} \times 22.4 \qquad \text{(Equation 13)}$$

Therefore, the total theoretical biogas yield can then be calculated as

$$B_t = B(CH_4) + B(CO_2) \qquad \text{(Equation 14)}$$

The percentage composition of methane and CO_2 in the biogas can be determined from the relations below:

$$\%CH_4 = \frac{B(CH_4)}{B_t} \times 100 \qquad \text{(Equation 15)}$$

$$\%CO_2 = \frac{B(CO_2)}{B_t} \times 100 \qquad \text{(Equation 16)}$$

The actual biogas yields obtained are notably lower than the total biogas potential B_t as indicated in Equation 14. This discrepancy arises from a failure of the digester to decompose approximately 10% of the feedstock, as reported by Ayodele et al., (2019b). Furthermore, as discussed, a certain proportion of the organic waste matter (approximately 5-10%) is utilised for cell tissue production by the organisms that influence microbial degradation. Consequently, Equation 17 was employed to estimate the actual biogas potential B_{ac} expressed in cubic meters per ton, accounting for these factors.

$$B_{ac} = W_{(i)(t)} \times B_t \times \mu \qquad \text{(Equation 17)}$$

Where μ is the fraction of organic matter consumed for cell tissue synthesis and is assumed to be 85% (Salami et al., 2011). Before the reforming process, raw biogas must be cleaned and upgraded (Figure 10). Chemically, purified biogas contains between 93 and 96% CH_4, 4–7% CO_2, and H_2S (<20 ppm) (Alves et al., 2020). Given that CO_2 is the only impurity in purified biogas, the volume of CH_4 (m^3/ton) from the purified biogas is calculated based on (Cudjoe et al., 2021), as shown in Equation 18.

$$CH_4(purified) = B_{ac} \times \delta\% \qquad \text{(Equation 18)}$$

%δ is the proportion of biogas that can be upgraded, which is taken as 75.7% (Bajpai & Dash, 2012; Braga et al., 2013; Seglah et al., 2023).

Figure 8: Schematic diagram of waste-to-Biomethane-to-natural gas grid (own design)

2.5. Estimation of Hydrogen Generation from steam methane reforming

Main reactions as shown by equations 19-21

$CH_4 + H_2O \leftrightarrow CO + 3H_2$ (Steam reforming) (Equation 19)

$CO + H_2O \leftrightarrow CO_2 + H_2$ (Water-gas shift reaction) (Equation 20)

$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$ (Overall reaction) (Equation 21)

From the resulting reaction, it can be obtained that:

- 16 kg of CH_4 when steam reformed produces 8 kg of H_2 gas
- 1 kg of CH_4 (steam reformed) produces 0.5 kg of H_2 gas

Taking into account the biogas density (i.e., the density of methane), 1 m^3 of CH_4 (steam reformed) is equivalent to ($0.5 \times CH_{4density}$) kg of H2 gas (Ayodele et al., 2019b).

According to Bragal et al., (2013), it is assumed that the amount of H_2 gas produced (kg) depends on the system efficiency (i.e., combined efficiencies of the boiler and reformer) and is obtained as in Equation 22.

$$A_{H2} = 0.5 \times CH_4(density) \times \eta_{system} \times VCH_4(purified) \quad \text{(Equation 22)}$$

Where, CH_4 (density) is the density of methane, ($\eta_{system} = \eta_R \times \eta_B$).

η_B is the boiler efficiency, and ηR is the reformer efficiency; each is given as 80% (Braga et al., 2013).

2.6. CO_2 Utilization through Methanation for Power-to-Gas

CO_2 is the primary driver of the greenhouse effect due to its high concentration and long retention time in the atmosphere compared to other greenhouse gases (GHGs) (Tan et al., 2021, 2022). Carbon Capture and Utilisation (CCU) promotes a circular carbon economy where emissions are reduced, reused and recycled (Newman et al., 2023). One promising utilisation of waste CO_2 is to react it with hydrogen in the presence of a catalyst to produce methane. This process is termed Power-to-Gas (PtG) technology, where the power grid is linked with the gas grid by converting excess power into a grid-compatible gas via a two-stage process: H_2 production by water electrolysis and H_2 reaction with an external CO_2 to produce methane (methanation). The high-yield methane produced can be injected into the existing natural gas grid, or used in other applications such as Vehicle fuel. In this study, two scenarios are considered: methanation using hydrogen from electrolysis and hydrogen from steam methane reforming. Scenario 1 is described in Figure 11.

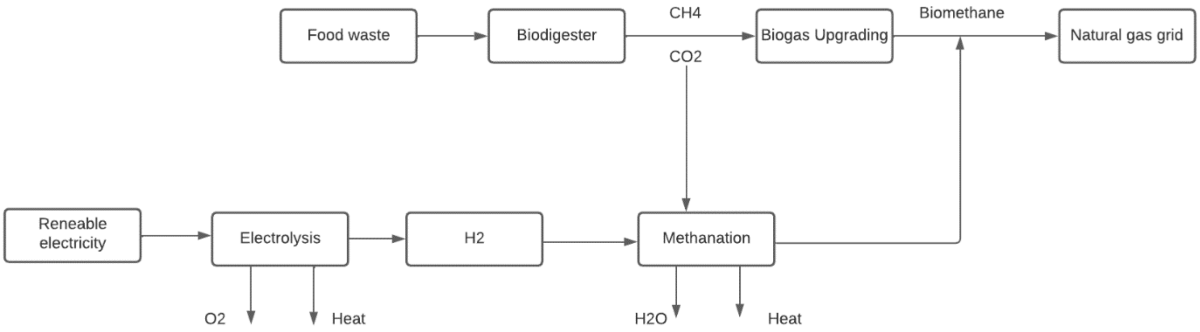


Figure 9: Process flow diagram of methanation with H_2 from renewable electricity (own design)

Methanation Reaction equation

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O + Heat \quad \text{(Equation 23)}$$

In Figure 11 above, the CO_2 utilisation is achieved using hydrogen derived from renewable electricity, termed Power-to-X. The methanation reaction produces more methane increasing the overall Biomethane production in the entire system.

In scenario 2 (Figure 12), the hydrogen is derived from steam methane reforming of biomethane produced (Equation 21).

Scenario 2:

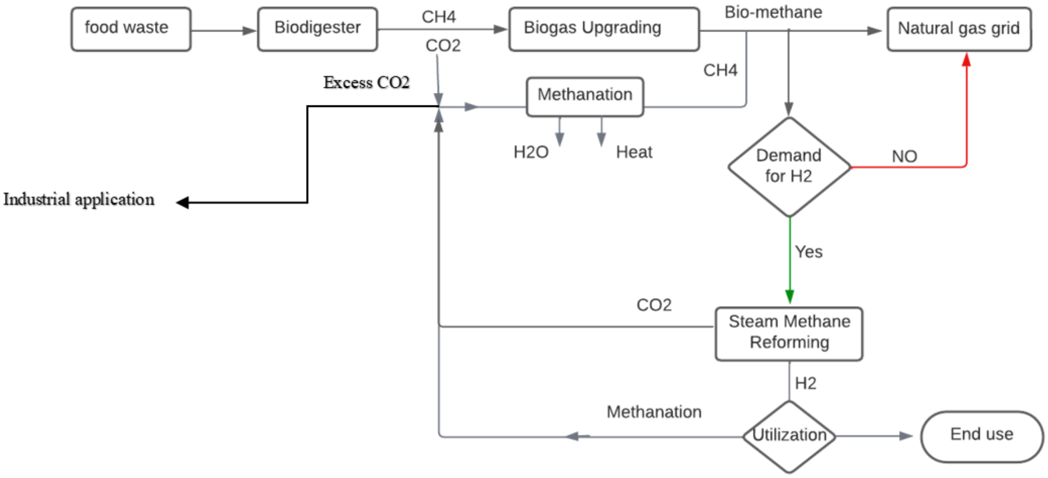


Figure 10 : Process flow diagram of methanation with H_2 from Steam Methane Reforming (own design)

This process is initiated in the demand for hydrogen. However, when the demand for methane is high, or there is no demand for hydrogen for end use application, it utilized for the methantion process. This cycle is repeated to reduce CO_2 emission and increase the overall biomethane production. Many studies have highlighted the effect of H_2: CO_2 ratio on methanation efficiency affecting methane yield (Uçar, 2020; Wahid et al., 2019). As shown in Equation 23, four moles of Hydrogen is required to react with a mole of Carbon dioxide for complete methanation.

2.7. Environmental Analysis

The environmental assessment used in this study is based on the Global Warming Potential of notable gases in the system, such as CO_2 and CH_4. The increasing climate change is due to increasing Greenhouse gas emissions, mainly CO_2 and CH_4 (Kweku et al., 2018; Yoro & Daramola, 2020). To abate this effect, it has been necessary to use renewable energy sources, which are low-carbon. Biomethane and hydrogen have been described as potential energy carriers to reduce the overall emission from the energy sector (European Biogas Association(EBA) & Gas Infrastructure Europe (GIE), 2023; Fritsche et al., 2022). The equation 24 estimates the equivalent CO_2 produce from the process.

The equivalent carbon dioxide $(CO_2)e$ is given by Equation 24.

$$CO_2 = a(CO_2) + b(CH_4) + c(CO) + d(SO_2) + e(NO_x) + f(PM) \qquad \text{(Equation 24)}$$

According to Ayodele et al. (2019a,b) the carbon dioxide released during combustion is considered carbon neutral and does not contribute to global warming. Table 7 provides the emission factors for each pollutant, with x representing the percentage of methane content in the biogas. This study assumes that the biogas has been upgraded to contain 75.7% methane content (Bajpai & Dash, 2012; Braga et al., 2013; Seglah et al., 2023).

This study takes into account the emissions of CO_2 during steam methane reforming, as shown in Equation 24. As a result, the equation 24 is modified to Equation 25.

$$CO_2 = b(CH_4) \qquad \text{(Equation 25)}$$

Where a=1 and b= 25 are the emission coefficients corresponding to the global warming potential of CO_2 and CH_4, respectively.

$$Q_i = LHV(CH_4) \times \%x \qquad \text{(Equation 26)}$$

Q_i is the Low Heating Value of each pollutant.

Table 7: Emission factor of the different pollutants ((Ayodele et al., 2019b)

Pollutants (i)	GWP(i) kgCO$_2$ per kg pollutant (Ayodele et al., 2019b b; EPA, 2020; Ryu, 2010)	Emission factor (lb per scf)	Emission factor (lb per MMBtu) $\beta = \frac{\alpha}{1020}$	Emission factor (kg perMJ) $\gamma = \frac{\beta \times 0.4556}{1055}$	Biogascombustion emissions with respect to carbon dioxide equivalent (kg CO$_2$) $(CO_2)e = Q \times \gamma \times GWP(i)$
CO	1.9	84	8.235×10^{-2}	3.5563×10^{-5}	2.551×10^{-3}
SO_X	80	0.6	3.137×10^{-2}	1.3547×10^{-5}	4.091×10^{-2}
NO_X	50	32	5.882×10^{-4}	2.5401×10^{-7}	4.794×10^{-4}
CH_4	25	7.6	2.255×10^{-3}	9.7382×10^{-8}	9.191×10^{-5}
PM	67	2.3	7.451×10^{-3}	3.2177×10^{-6}	8.138×10^{-3}
Total $(CO_2)e$					52.17×10^{-3}

Lower Heating Value of Methane (LHVCH_4) is taken to be 49.934 MJ per kg.

The theoretical estimatimation of biomethane and biohydrogen potential provide valuable insights for future projections. The linear progression based on population growth is an essential parameter in the approach of this study. It considered how waste generation in Cape-Coast is largely dependent on the population growth, hence on future projections.

CHAPTER 3: Results and Discussion

3.1. Evaluation of food waste potential

In order to determine the potential for producing biomethane and hydrogen from the food waste portion of MSW in Cape-Coast, Ghana, the first step was to determine the overall amount of MSW generated. This was accomplished by calculating waste generation per person, collection efficiency, and the population in 2021. This result served as the basis for further analysis. A detailed evaluation was conducted to determine the potential for food waste from MSW generated in Cape-Coast over a period of 29 years (2021-2050), as shown in Figure 13.

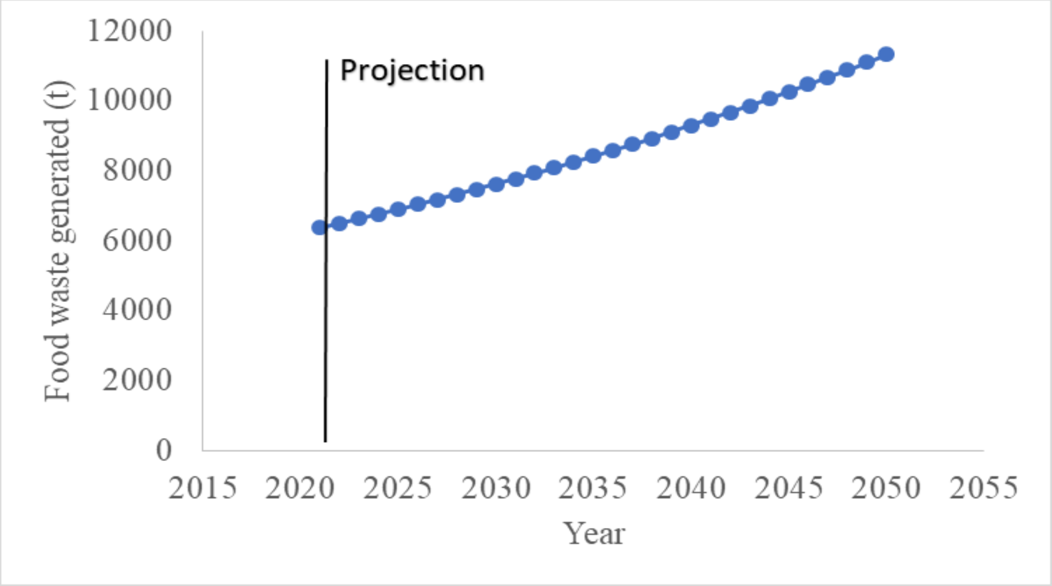


Figure 11: Food waste generated in Cape-Coast from 2021 to 2050

Several factors such as waste composition and waste management practices were considered. 6,376.30 tons of food waste accounting for 20% of the total MSW (31,881 tons) generated in 2021. The estimated biogas potential from foo waste is 4.9 Mm^3. The finding is consistent with Cudjoe et al. (2021) , which found that increasing population in Accra and Kumasi results in high biogas generation potential. The analysis provides a comprehensive overview of the potential for producing biomethane and hydrogen from food waste. An examination of waste generation trends over the 29 years revealed important insights. The result shows that waste generation increased annually, largely due to population growth in the region. Considering Cape-Coast as a tourist hub could impact waste generation potential beyond the projected values. Recovering the food waste fraction of MSW is essential for anaerobic digestion. It's therefore crucial to adopt sustainable waste management approaches to limit the ecological consequences of the increasing waste production.

3.2 Biomethane and Hydrogen production potential in Cape Coast

The biogas composition, calculated using Equations 12 and 13, contains 58.39 % CH_4 and 41.61 % CO_2. After purification, the biogas is upgraded to 75.6 % CH_4 before steam reforming for hydrogen production. Using equation 18, the upgraded biogas (biomethane) is obtained and presented in Table 8.

Table 8: Biomethane and Hydrogen Potential in 2021

Theoretical Biogas (m^3/kg)	Methane percentage	CO_2 percentage	Actual Biogas (m^3/kg)	Upgraded methane (m^3/kg)
0.91	58.39	41.61	0.77	0.58
	Actual Biogas (m^3/ton)	Upgraded methane (m^3/ton)	Hydrogen (kg)	
	774.59	584.82	122.95	

Calculated values for 2021

Food waste (ton)	Actual biogas (m^3)	Upgraded methane (m^3)	Hydrogen (kg)	
6,376.30	4,939,014.92	3,728,956.26	783,975.76	

By purifying the raw biogas and removing some carbon dioxide, the methane concentration increases from 2.88 Mm^3 to 3.7 Mm^3 produced from food waste. Cape-Coast has a high potential for biomethane, producing 3.7 Mm^3 per year in 2021 (Figure 14). The projected potential for biomethane and hydrogen from 2021 to 2050 as shown in appendixes (Table A 1).

The results agree with Seglah et al. (2023) and Ayodele et al. (2019), where hydrogen was produced from food wastes in four cities in Ghana: Kumasi, Accra, Sekondi-Takoradi, and Cape-

Coast and Southern Nigeria, respectively. With the new development in the natural gas pipeline, this potential, when harnessed is capable of complementing the existing natural gas resources in the country and meeting the local methane demand in Cape Coast.

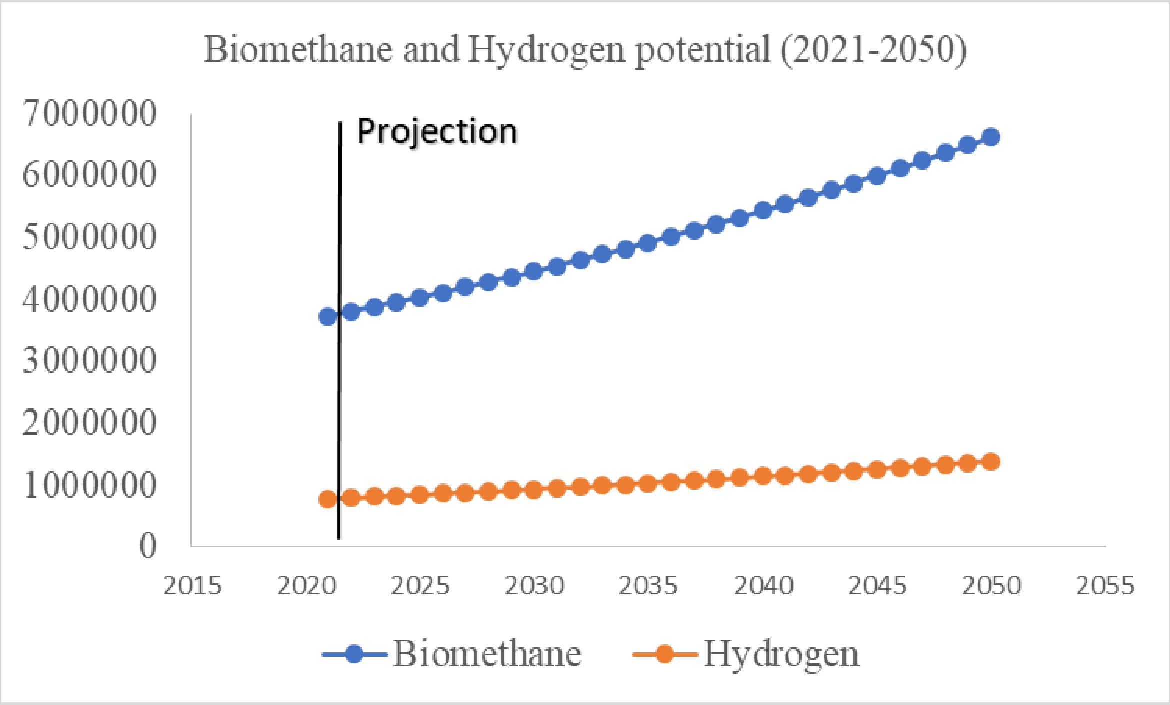


Figure 12: Biomethane and Hydrogen potential in Cape Coast from 2021 to 2050

In 2020, 20.4% of gas supplied to the country was imported from Nigeria through the West African Gas Pipeline. The rest (79.6%) was sourced from within the country through the Atuabo plant. Gas production reached 95.2 tBtu, most of which was used for generating electricity (Energy Commission, 2021). According to calculations, 3.7 million m^3 of biomethane equals 0.132 trillion British thermal units (tBtu) of natural gas. This means that as of 2020, biomethane could replace 0.11% of the fossil-fuel natural gas used in the country. Promoting renewable energy policies is important to encourage the growth of biomethane production (Abdalla et al., 2022). By doing so, it's estimated that by 2050, there would be a potential of 5.34 tBtu of biomethane produced, which can be accelerated with favourable policies. This estimated potential could replace 4.5% of natural gas by 2050.

Hydrogen produced from steam reforming of biomethane is a renewable gas due to its low carbon footprint and contribution to a circular economy. Repsol conclusively demonstrated this fact through their successful industrial test that employed biomethane to create renewable hydrogen to make eco-friendly fuels like gasoline, diesel, and aviation kerosene. 10 tons of hydrogen were produced at the Cartagena Industrial Complex in Spain using 500 MWh (51 thousand m^3) of biomethane (REPSOL, 2021). Repsol's findings confirm this research, which estimated that there is a potential of 783 tons of renewable hydrogen that can be produced through steam reforming of biomethane in 2021. However, unstructured waste management in the municipalities could yield in uncollected food waste needed for anaerobic digestion and impact the biomethane and hydrogen generation potential.

Using Equation 22, the amount of hydrogen produced from the steam reforming process of the biogas is presented in Table 8. The hydrogen gas produced within 29 years (2021-2050) is projected as shown in Table A 1.

3.3 Natural gas displacement

Over the last few years, Ghana has experienced a noteworthy rise in gas production. Production has increased from 2.0 tBtu in 2014 to 117.87 tBtu, which accounts for an annual growth rate of 66.5%, as shown in Table 9. Ghana has also been importing gas from Nigeria through the West African Gas Pipeline (WAGP) to supplement domestic production.

Table 9 : Natural gas supply and equivalent Biomethane potential

Year	Import (TBtu)	Export (TBtu)	Biomethane (TBtu)
2009	0.2	-	-
2010	15.6	-	-
2011	31.6	-	-
2012	16	-	-
2013	11.6	-	-
2014	22.5	2	-
2015	20.6	26.4	-
2016	4	23.5	-
2017	11.7	33.7	-
2018	25.3	41.5	-
2019	25.2	58.8	-
2020	24.4	95.2	-
2021	18.7	107.8	0.132
2022	19.9	117.9	0.134

The total amount of gas imported has been increasing gradually, although slower (Energy Commission, 2023). To reduce Ghana's dependence on imports, it would be essential to develop local production. The biomethane potential for Cape Coast is equivalent to 0.134 tBtu natural as of 2021(Figure 15). This displaces 0.7% of the gas import through the West African Gas pipeline. This shows that a higher displacement is achievable with increasing methane yield influenced by food waste generation and anaerobic digestion.

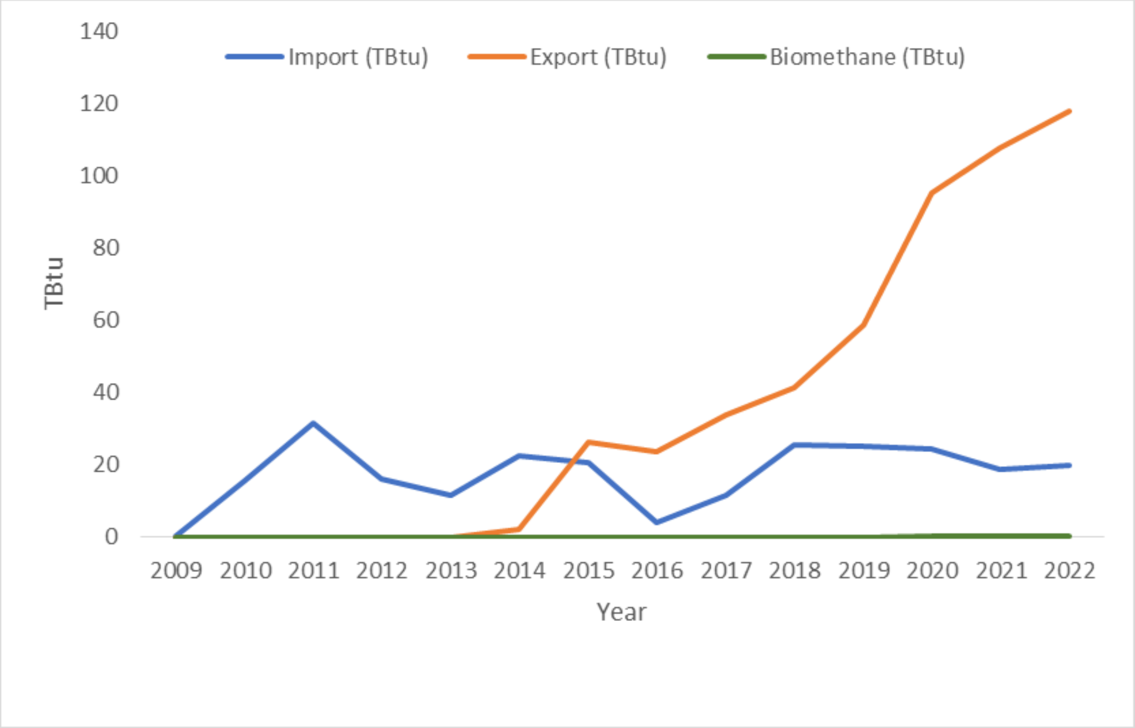


Figure 13 Natural gas supply (2009-2022) and equivalent Biomethane potential

3.4 Environmental Assessment

The biomethane and hydrogen production from food waste releases some CO_2 (David et al., 2019). The estimated emission from biogas combustion in CO_2 equivalent is 81.5 tons. Considering scenario 1, the CO_2 produced from the process is saved and utilised to increase biomethane production. In scenario one (Figure 11), the CO_2 produced from the biogas upgrading is reacted with renewable electricity-generated hydrogen (green hydrogen) to produce more methane (Fraunhofer, 2022). This closes the loops and reduces the CO_2 emissions from the system. The calculated results in Table 8 estimate emissions savings (CO_2)eq in 29 years (2021-2050) (Table A 2).

Table 10: Emission during biogas combustion and steam reforming process

Element	Biogas combustion (kg per kg of biogas)	Biogas steam reforming(kg per kg of biogas (Ayodele et al., 2019b)	Total emission (kg per kg of biogas)
(CO_2)eq	0.052	2.750	2.802

The production of hydrogen is described in scenario 2 (Figure 12) based on the decision process. Hydrogen production from steam methane reforming (see Equation 21) releases CO_2. The CO_2 released is later reutilised for the methanation process.

Scenario 2 shows the emissions produced from hydrogen production and the CO_2 from biogas upgrading are reacted with hydrogen produced as shown in Figure 12. The total emission in CO_2 equivalent is presented in Table A 2 from 2021 to 2050 and shown graphically in Figure 16.

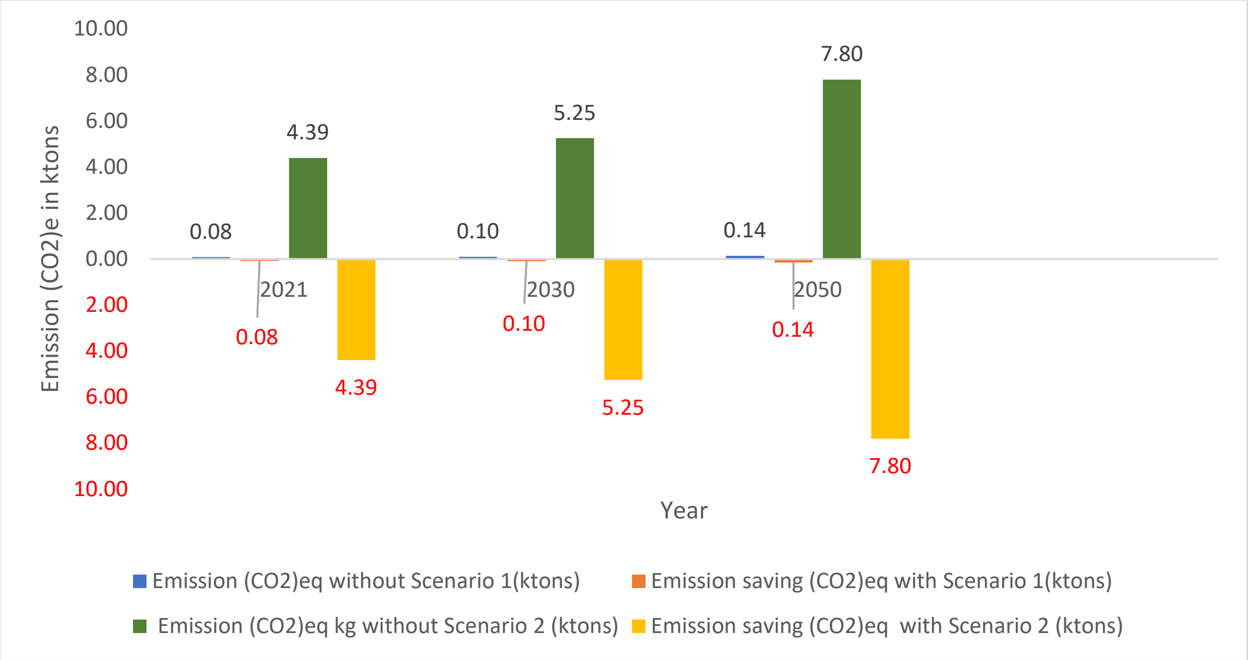


Figure 14: CO_2 emissions saving

The CO_2 emission equivalent of 4.39 ktons obtained in 2021 could reduce 0.12% from 6.34 Mtons CO_2 released from 120 tBtu natural gas consumed in 2020 (U.S. Energy Information Administration - EIA, 2022). This increases to a 2.8% reduction by 2050 from the same volume of natural gas (Table A 1). Comparing the CO_2 reduction potential from the two scenarios, it can be concluded that Scenario 2 offers higher CO_2 emission savings than Scenario 1. This is due to further utilisation of CO_2 released from steam methane reforming of biomethane. Organic waste-derived Renewable Natural Gas (RNG) alone cannot replace fossil fuels enough to meet long-term climate objectives. Nonetheless, RNG can still be helpful in decreasing methane emissions and substituting fossil fuels in economically challenged areas (Cyrs et al., 2020).

Conclusion and Perspectives

The biomethane and hydrogen generation potential from the food waste fraction of municipal solid waste in Cape-Coast has been evaluated. The findings estimate that 31.881 thousand tons of food waste could be generated in 2021 and a projected 258.67 ktons by 2050. This projects the biomethane and hydrogen production potential to 151.28 Mm^3 and 31.8 ktons respectively by 2050. Similarly, this estimated biomethane potential could contribute to replacing 4.5% of natural gas consumption in Ghana by 2050. The projected potential of 31.8 ktons of renewable hydrogen by 2050 could contribute to advancing a hydrogen economy in Ghana by complimenting green hydrogen from electrolysis. Furthermore, these resources stand poised to support Ghana's emergence as a notable hydrogen exporter, with the nation's prospects bolstered by the development of the natural gas pipeline along Cape-Coast.

The research suggests two strategic methods to take advantage of renewable energy sources: integrating biomethane into the natural gas grid and preparing pipelines for hydrogen export. The study also explores innovative scenarios, such as scenario 2, which increase methane yield by utilising O_2 emissions while reducing carbon emissions. This scenario could result in a 2.8% reduction in CO_2 emissions from natural gas consumption by 2050. In order to make cities more environmentally friendly and reduce methane emissions from landfills, sustainable waste management is crucial. However, estimating the potential for biomethane and hydrogen generation in urban areas is difficult, especially wregardingfood waste generation. Municipalities' lack of waste segregation systems creates a challenge for efficient food waste collection for anaerobic processing. To overcome this obstacle, it is essential to promote and implement effective waste management systems in Cape-Coast, which includes prioritising waste segregation at the source.

This research provides valuable guidance for both researchers and policymakers. The study offers a blueprint for utilising food waste to produce hydrogen and injecting biomethane into the natural gas grid. By taking advantage of the renewable and environmental benefits highlighted in this research, Ghana can make significant progress towards achieving its energy and climate goals.

The research conducted has a far-reaching impact beyond academic circles. The advancements in renewable energy production can potentially revolutionise the energy sector and significantly reduce carbon emissions. The key to achieving a sustainable future is through initiatives prioritising environmental consciousness and technological advancement. Further studies could be conducted on the economic feasibility and carbon credits generation from CO_2 emission savings.

Policy Recommendation

Policies that aim at tackling climate change, energy, and waste management can aid in promoting the growth of renewable natural gas. Some key policy areas have been highlighted below;

1. Climate and Energy Mandates for RNG Development: Policies that establish clear mandates for emissions reduction and the adoption of renewable energy sources, including RNG, should be implemented:

    a. Emission Reduction Targets: Set ambitious emissions reduction targets in line with national and international climate goals. Collaborate with the Energy Commission and the Ghana National Gas Company (GNGC) to formulate strategies for reducing greenhouse gas emissions from energy sources and waste management.

    b. Renewable Energy Quotas**:** Establishment of quotas for the share of energy derived from renewable sources, including RNG. Work closely with the GNGC to integrate RNG into the local energy mix.

2. Public Financial Support for RNG Projects: Financial support policies should be introduced for RNG projects. This includes grant programs and collaboration with coastal city authorities to identify and allocate funds. Tax incentives can attract private sector investments in RNG infrastructure.

3. Organic Waste Recycling Mandate: A policy should be put in place mandating the recycling of organic waste in Cape Coast. This should be done in collaboration with the Cape Coast Municipal Assembly and waste collection company like ZOOMLION to facilitate the conversion of organic waste into biogas, which can then be upgraded to RNG. This will reduce waste and provide a sustainable feedstock for RNG production to be injected into the grid.

4. Streamlined Siting and Permitting Rules: The local siting and permitting regulations should be reviewed and updated to provide a more efficient and predictable approval process for RNG production facilities. Working with the GNGC will ensure compliance with safety and environmental standards.

By implementing the recommended policies, Ghana can establish a favourable environment for advancing renewable natural gas.

Limitation

The study was limited to only Cape Coast while other coastal cities along the natural gas pipeline lines where not considered but recommended for future studies. The study only used linear regression to predict values and did not account for other potential scenarios that could affect food waste generation and outcomes. Additionally, the study does not discuss the processing, storage, capture, buand t istead uses on the different points of emission throughout the entire system.

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APPENDIXES

Table A 1Biomethane and Hydrogen potential (2021-2050)

Year	Population	MSW Potential (ton)	Food waste (ton)	Biomethane Potential (m3)	Hydrogen Potential from SMR (kg)
2021	18995	31881	6376	3728956	783976
Projected values					
2022	19374	32519	6504	3803535	799655
2023	19758	33169	6634	3879606	815648
2024	20150	33833	6767	3957198	831961
2025	20551	34510	6902	4036342	848601
2026	20963	35200	7040	4117069	865573
2027	21386	35904	7181	4199410	882884
2028	21814	36622	7324	4283399	900542
2029	22257	37354	7471	4369067	918553
2030	22698	38101	7620	4456448	936924
2031	23158	38863	7773	4545577	955662
2032	23618	39641	7928	4636488	974775
2033	24081	40433	8087	4729218	994271
2034	24568	41242	8248	4823803	1014156
2035	25062	42067	8413	4920279	1034439
2036	25564	42908	8582	5018684	1055128
2037	26076	43766	8753	5119058	1076231
2038	26591	44642	8928	5221439	1097755
2039	27120	45535	9107	5325868	1119710
2040	27665	46445	9289	5432385	1142105
2041	28229	47374	9475	5541033	1164947
2042	28783	48322	9664	5651854	1188246
2043	29360	49288	9858	5764891	1212011
2044	29943	50274	10055	5880188	1236251
2045	30542	51279	10256	5997792	1260976
2046	31152	52305	10461	6117748	1286195
2047	31784	53351	10670	6240103	1311919
2048	32410	54418	10884	6364905	1338158
2049	33064	55506	11101	6492203	1364921
2050	33727	56617	11323	6622047	1392219

Table A 2:CO_2 Emission from the two scenarios considered

Year	Emission (CO2)e without Scenario 1(ton)	Emission saving (CO2)e with Scenario 1(ton)	Emission (CO2) e without Scenario 2 (ton)	Emission saving (CO2)e with Scenario 2 (ton)
2021	81.53	81.53	4393.40	4393.40
2022	83.16	83.16	4481.27	4481.27
2023	84.83	84.83	4570.89	4570.89
2024	86.52	86.52	4662.31	4662.31
2025	88.25	88.25	4755.56	4755.56
2026	90.02	90.02	4850.67	4850.67
2027	91.82	91.82	4947.68	4947.68
2028	93.66	93.66	5046.64	5046.64
2029	95.53	95.53	5147.57	5147.57
2030	97.44	97.44	5250.52	5250.52
2031	99.39	99.39	5355.53	5355.53
2032	101.38	101.38	5462.64	5462.64
2033	103.40	103.40	5571.89	5571.89
2034	105.47	105.47	5683.33	5683.33
2035	107.58	107.58	5797.00	5797.00
2036	109.73	109.73	5912.94	5912.94
2037	111.93	111.93	6031.20	6031.20
2038	114.17	114.17	6151.82	6151.82
2039	116.45	116.45	6274.86	6274.86
2040	118.78	118.78	6400.35	6400.35
2041	121.15	121.15	6528.36	6528.36
2042	123.58	123.58	6658.93	6658.93
2043	126.05	126.05	6792.11	6792.11
2044	128.57	128.57	6927.95	6927.95
2045	131.14	131.14	7066.51	7066.51
2046	133.76	133.76	7207.84	7207.84
2047	136.44	136.44	7352.00	7352.00
2048	139.17	139.17	7499.04	7499.04
2049	141.95	141.95	7649.02	7649.02
2050	144.79	144.79	7802.00	7802.00