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Biomethane and Green Hydrogen Production Potential from Municipal Solid Waste in Cape Coast, Ghana

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ABSTRACT

Biomethane and hydrogen are promising elements in the transition towards sustainable energy, due to their capacity to mitigate greenhouse gas emissions. In Ghana, efforts to promote sustainable waste valorization for energy production are underway; however, organic waste conversion into biomethane and hydrogen still needs to be expanded. This study aims to evaluate the potential of producing biomethane and hydrogen from the municipal solid waste in Cape Coast, and their injection into the national gas grid. The upgrading biogas obtained from anaerobic digestion of food/organic wastes was used to generate biomethane. The modified Buswell Equation and data from literature were used to estimate the amount of biomethane and hydrogen. The environmental impact was assessed using the CO_2 equivalent emissions. The findings reveal that Cape Coast generated approximately 6,400 tons of food waste in 2021, with a projection to 11,000 tons by 2050. Biomethane and hydrogen quantities were estimated at 3,700,000 m^3 and 784,000 kg in 2021, respectively. Their projection reaches to 6,600,000 m^3 and 1,400,000 kg by 2050. Converting waste into biomethane and hydrogen is an eco-friendly method of their management and use for renewable energy in Ghana. Strategies can be integrated into Ghana national energy policies to encourage waste-to-energy projects.

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إمكانية إنتاج الميثان و الهيدروجين الاخضر من النفايات الصلبة في بلدية كيب كوست، غانا .

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ملخص: يعد الميثان الحيوي والهيدروجين من العناصر الواعدة في التحول نحو الطاقة المستدامة، نظراً لقدرتهما على التخفيف من انبعاثات الغازات الدفيئة. تبذل الجهود في غانا للاستفادة من النفايات لإنتاج الطاقة المستدامة؛ ومع ذلك، فإن تحويل النفايات العضوية إلى الميثان الحيوي والهيدروجين لا يزال بحاجة إلى التوسع. تهدف هذه الدراسة إلى تقييم إمكانية إنتاج الميثان الحيوي والهيدروجين من نفايات البلدية الصلبة في مدينة كيب كوست، تم حقن الميثان والهيدروجين المنتجين في شبكة الغاز الوطنية. تم استخدام طريقة التخمير اللاهوائي للنفايات الغذائية / العضوية لتوليد غاز الميثان الحيوي. كما استخدامت معادلة Buswell المعدلة وبيانات التصميم من المراجع لتقدير كمية الميثان الحيوي والهيدروجين الي يمكن انتاجها من المخلفات العضوية لمخلفات البلدية الصلبة. كما تم تقييم الأثر البيئي من انبعاثات غاز ثاني أكسيد الكربون المكافئ. كشفت النتائج المتحصل عليها؛ أن بلدية كيب كوست جمعت ما يقدر بحوالي6,400 طن من نفايات الطعام في عام 2021، ومن المتوقع أن تصل الكمية إلى 11,000 طن بحلول عام2050 . وقدرت كميات الميثان الحيوي والهيدروجين المنتجة بحوالي 3,700,000 متر مكعب وحوالي784,000 كجم في عام 2021، على التوالي. ومن المتوقع أن تصل الكمية إلى حوالي 6,600,000 متر مكعب من الميثان الحيوي وحوالي 1,400,000 كجم من الهيروجين بحلول عام 2050. ويعتر تحويل النفايات إلى ميثان حيوي وهيدروجين طريقة صديقة للبيئة ومستدامة لإدارة النفايات واستخدامها كمصدر للطاقة المتجددة في غانا. ولتحقيق ذلك يلزم دمج الاستراتيجيات في سياسات الطاقة الوطنية في غانا لتشجيع مشاريع تحويل النفايات إلى طاقة.

الكلمات المفتاحية – الميثان الحيوي، نفايات البلدية الصلبة، إدارة النفايات العضوية، الهيدروجين الأخضر، الانبعاثات الملوثة، الطاقة المتجددة.

1. INTRODUCTION

Biomethane and hydrogen have recently gained significant attention in the energy transition pathway due to their potential to reduce greenhouse gas emissions and promote sustainable development [1-3]. Converting organic solid waste into biomethane and green hydrogen contributes to the renewable energy mix while providing sustainable waste management solutions [2, 4]. 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 [4-5]. According to the International Energy Agency [6], bioenergy is the most significant contributor to renewable energy worldwide, accounting for over 60% of all renewable energy consumed. In addition, hydrogen could be considered as an important element of the sustainable energy system in the future. Green hydrogen from renewable sources is a promising alternative to conventional hydrogen production [7]. The potential of bioenergy and green hydrogen production from MSW has been explored across the globe [8-9]. According to Figueroa-Escamilla et al. [10], methane generated from the organic fraction of MSW is considered as a potential energy source. In similar study conducted in Spain, the ground around 4499 ktoe was estimated if all biowastes were converted into biomethane [11]. This quantity could satisfy almost 31.6% of the final demand for natural gas in a sustainable manner [11].

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 and other harmful pollutants [12]. However, recent studies have shown that MSW can be a potential feedstock for renewable energy production in Ghana [13-15]. Ghana generates about 12,710 tonnes of MSW daily with Accra, Kumasi and Tamale being the most significant waste generators [16, 17]. 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 et al. [18] investigated the potential of MSW for electricity generation in Kumasi. Their findings gave that 36 MJ of energy (10kWh) could be generated from 1 m^3 of biogas yield from MSW in Kumasi [18]. Biomethane production from MSW involves converting the 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 is composed mainly of CH_4 and CO_2 and can be 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 [19]. 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 [20]. 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 2030 [21-22]. The potential for biomethane and hydrogen production from MSW has been studied in several countries worldwide, with positive results [8, 23-24]. Despite the availability of significant quantities of MSW in the country, there is a limited research on the potential for biomethane and green hydrogen production from MSW in Ghana. The few studies conducted in Ghana have focused mainly on the potential for biogas production from MSW for energy or electricity production [12-15]. This study therefore aims to fill the research gap by evaluating biomethane and hydrogen production potential from MSW in Cape Coast municipality to compensate the unavoidable greenhouse gas emissions. The total MSW potential for biomethane and hydrogen in Cape Coast and the quantity of natural gas equivalent to that can be produced from MSW-derived biomethane were investigated and the rate of CO_2 emissions reduction was estimated.

2. CASE-STUDIES PRESENTATION

2.1. Study area

The current study is focused on Cape Coast Municipality. Cape Coast is a coastal city and the capital of the central region of Ghana. This coastal city of the Atlantic ocean is 150 kilometers west far from Accra. It has geographic coordinates of about 5.13151° N latitude and 1.2794744° W longitude, (Figure. 1). 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 [25]. Cape Coast Municipality is covered with two wet seasons and two dry seasons annually.

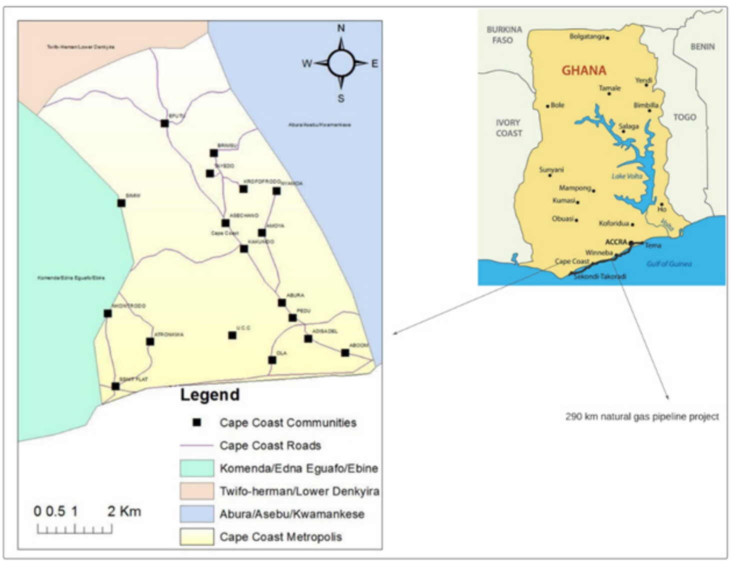

Figure 1. Map of Cape Coast Metropolis and its localization on Ghana map (Adapted from [26]).

The principal wet season occurs from May to July and the rainfall in this area ranges from 750 to 1000 mm [27]. 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 from municipal solid waste 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. It would be an occasion for studying this energy infrastructure in supporting the integration of biomethane [28-29]. Additionally, the district's waste management practices and waste composition can be examined to develop sustainable solutions for waste-to-energy conversion. The city has a land area of about 122 square kilometers and is characterized by its proximity to the sea (13 km along the central coast).

2.2. Waste Quantification and Characterization

A comprehensive analysis of waste composition in Cape Coast has revealed valuable insights into the types and proportions of waste generated in the area. The study conducted by UN-Habitat [30], indicates that the waste composition in Cape Coast comprises various categories, including organic waste, plastic waste, paper waste, glass waste, and metal waste [31-33]. 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 in Cape Coast. From these findings, the total MSW generated and the MSW generation rate were 166 t/day and 0.73 kg/capita/day, respectively. The household generation was 0.44 kg/capita/day while the MSW collected and the city recovery rate were 63% and 1 %, respectively. It provides a better understanding of waste management in the region, which can serve as a basis for developing effective waste management strategies and policies [30].

2.3. Estimation of Food Waste from Cape Coast City as Feedstock for Anaerobic Digestion

To address the lack of historical data on MSW generation in Cape Coast, a mathematical method was used to estimate the amount of waste produced. It takes into account the waste generated per day and the waste fraction that can be recovered. Through the use of these factors, the study was able to calculate the MSW generated in Cape Coast over some time. The total amount of MSW generated in Cape Coast was estimated using the formula (Eq. 1) adapted from reference [34]:

$$W_{M-CC}(t) = \frac{q \times p_{CC}(t) \times 365 \times C}{1000} \qquad .....(1)$$

where W_{M-CC} (t) is the annual MSW generated in Cape Coast at the specific time in tons; C is the recoverable fraction of the MSW considered in the present study to be 0.63 [30]; q is the average waste generation rate in Cape Coast (0.73)[30]. P_{CC} (t) is the population of Cape Coast at the specific time t which growth is given by Eq. 2 [34-35].

$$P_{CC}(t) = P_b(1+r)^t \qquad ....(2)$$

where P_b is the base population of Cape Coast in 2021 and t is the time and the growth rate r is assumed to be 2 % [25].

The separation of the organic waste portion of the MSW in Cape Coast at the specific time in tons (W_{F-CC} (t)) was determined using Eq. 3 [34-35].

$$W_{F-CC}(t) = W_{M-CC}(t) \times 0.2 \qquad ....(3)$$

Where 0.2 is a foctor that corresponds to the proportion of organic waste [30].

2.4. Estimation of Biomethane Potential from Organic Fraction of MSW

The methane production potential that may be generated during anaerobic decomposition was obtained by applying the modified Buswell Equation (Eq. 4). Anaerobic digestion processes can harness the energy potential of various organic waste materials rich in lipids, proteins, and carbohydrates [36].

Typically, anaerobic digestion is carried out in the absence of oxygen to convert food waste into valuable byproducts such as biogas and digestate.

The opportunity of transforming bioresources into renewable energy is significant and environmentally friendly and safe. When organic waste is used as a feedstock, biogas produced through anaerobic digestion 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 [37]. Therefore, to obtain high-grade methane, it is essential to purify the biogas and upgrade its quality using appropriate technologies such water absorption, and pressure swing adsorption [38]. The biogas yield is estimated theoretically using the Buswell-Boyle equation (Eq. 4) [34, 39].

$$C_pH_qO_yN_d + \left[p - \frac{q}{4} - \frac{y}{2} + \frac{3z}{4}\right]H_2O \rightarrow \left[\frac{p}{2} - \frac{q}{8} - \frac{y}{4} + \frac{3z}{4}\right]CO_2 + \left[\frac{p}{2} + \frac{q}{8} - \frac{y}{4} + \frac{3z}{8}\right]CH_2 + zNH_3 \qquad ....(4)$$

The constants p, q, y, and z represent the number of carbon (C), hydrogen(H), oxygen (O), and nitrogen (N) atoms, respectively.

These constants can be determined mathematically using Eq. 5 [34].

$$Mole\ \ ratio = \frac{U_{elemental}}{M_{mass}} \times \frac{1}{N_{mr}} \quad with \quad N_{mr} = \frac{2.1}{14.01} \qquad .....(5)$$

Where $U_{elemental}$ is the elemental composition obtained from the ultimate analysis of the organic matter (C: 46.7; N: 2.1; H: 8.0; O: 38.9) [34,40], M_{mass} is the molar mass of the respective elements (C: 12.01; N: 14.01; H: 1.01 and O: 16.00) [37], and N_{mr} is the nitrogen mole ratio.

The values of the constants are determined from the mole ratio of the elements given as C: 25.94; N: 1; H: 52.84; O: 16.22.

The methane potential (B_{CH4}) in cubic meters per ton (m^3/ton) at standard temperature and pressure (0 °C at 1 atm), the theoretical CO_2 produced from the process and its percentage composition in the biogas are estimated using the approach proposed by Seglah et al. [34] and by Ayodele et al. [37], (Table 1). The actual biogas yields obtained are notably lower than the total biogas potential Bt as indicated in table 1.

This discrepancy arises from a failure of the digester to decompose approximately 10% of the feedstock, as reported by Ayodele et al. [37].

Furthermore, a certain proportion of the organic waste matter (approximately 5-10%) is utilised for cell tissue production by the organisms that influence microbial degradation. Prior to the reforming process, raw biogas must be cleaned and upgraded. The chemical composition of the purified biogas are CH_4 (93- 96%), CO_2 (4-7%), and H_2S (<20 ppm) [41]. Given that, CO_2 is the only impurity in purified biogas, the volume of CH_4 (m^3/ton) from the purified biogas can be calculated, CH_4 (purified) based on reference [12], (Table 1).

Table 1. The methane potential (B_{CH4}) and the theoretical CO_2 calculations [34, 37].

Methane potential (B_{CH4}) (m^3/ton)	$B(CH_4) = \frac{\frac{a}{2}+\frac{b}{8}-\frac{c}{4}-\frac{3d}{8}}{12a+b+16c+14d} \times 22400$
Theoretical CO_2 produced from the process (m3/ton)	$B(CO_2) = \frac{\frac{a}{2}-\frac{b}{8}+\frac{c}{4}+\frac{3d}{8}}{12a+b+16c+14d} \times 22400$
Total theoretical biogas yield	$B_t = B(CH_4) + B(CO_2)$
Methane proportion in the biogas	$\%CH_4 = \frac{B(CH_4)}{B_t} \times 100$
Percentage composition of CO_2 in the biogas	$\%CO_2 = \frac{B(CO_2)}{B_t} \times 100$
Actual biogas potential B_{ac} (m^3/tons)	$B_{ac} = W_{(i)(t)} \times B_t \times \mu$
Amount of CH_4 (m^3/ton) from the purified biogas [42]	$CH_4(purified) = B_{ac} \times \delta\%$

Where, μ is the fraction of organic matter consumed for cell tissue synthesis (85%) [43] and %δ is the proportion of biogas that can be upgraded (75.7%) [34, 43-44].

2.5. Estimation of Hydrogen Generation from Steam Methane Reforming

Main reactions that concerning the steam reforming are shown by Eq. 6 to Eq.8 [45]:
Steam reforming reaction

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad (+206.2\,kJ/mol) \qquad ....(6)$$

Water-gas shift reaction

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad (-41\,kJ/mol) \qquad ....(7)$$

Overall reaction

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \qquad (+247.9\,kJ/mol) \qquad ....(8)$$

From the overall reaction, 1 kg of CH_4 steam reformed produced 0.5 kg of H_2 gas. That means almost ($0.5 \times \rho_{CH4}$) kg of H_2 gas was obtained from 1 m^3 of CH_4 [37], where ρ_{CH4} is the density of methane. It is found that the system efficiency affected the amount of H_2 gas produced which can be expressed as shown in Eq. 9 [43,45].

$$A_{H_2} = 0.5 \times \rho_{CH_4} \times \eta_{system} \times VCH_4(purified) \qquad ....(9)$$

Where, $\eta_{system} = \eta_R \times \eta_B$, with η_B and η_R are the efficiencies of the boiler and reformer, respectively which values are given as 80% [43].

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 [46-47]. Carbon capture and utilization contribute to the circular carbon economy where emissions are reduced, reused and recycled [48]. One promising utilization 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 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). In this study, two scenarios are considered: methanation using hydrogen from electrolysis and hydrogen from steam methane reforming. Figure 2 presents the process flow diagrams of methanation where H_2 is generated from renewable electricity (Figure 2A) and from steam methane reforming (Figure 2B). The high-yield methane produced can be injected into the existing natural gas grid, or used in other applications such as vehicle fuel.

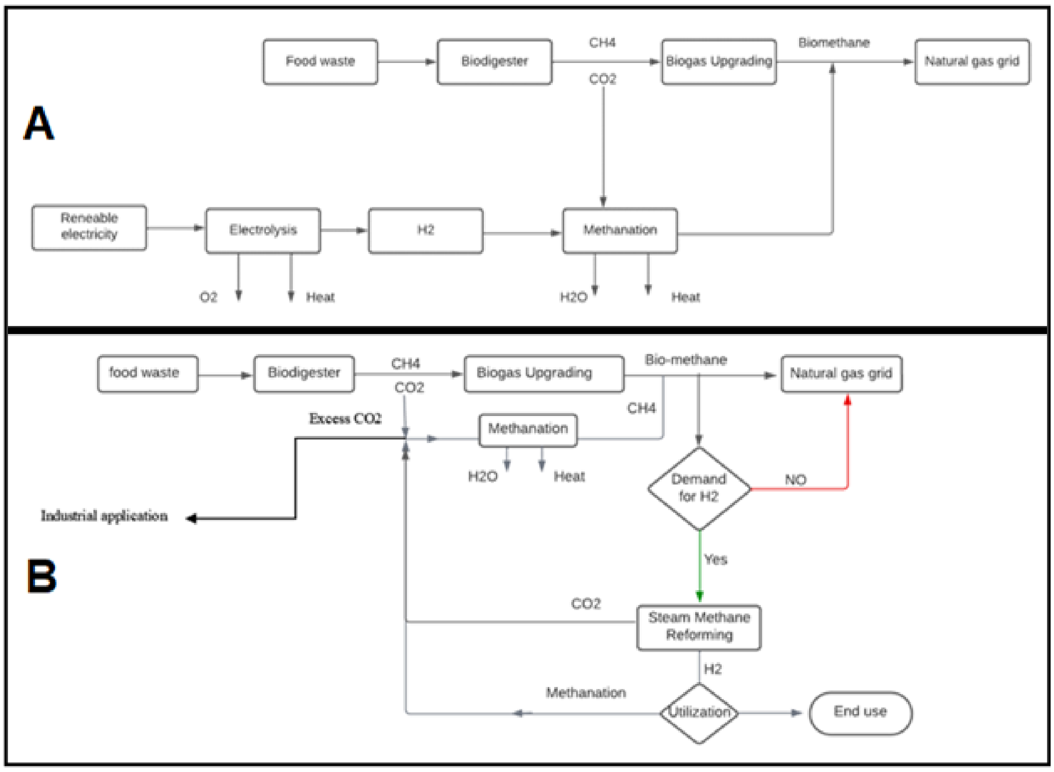

Figure 2. Process flow diagram of methanation with: A-H_2 from renewable electricity and B- H_2 from Steam Methane Reforming.

The methane is produced using Sabatier methanation reaction as given by Eq.10 [49-50]:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O - 165\,kJ/mol \qquad (at\,298\,K) \qquad ......(10)$$

In Figure 2A, the CO_2 utilization 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 2B), the hydrogen is derived from steam methane reforming of biomethane produced. This process is initiated in the demand for hydrogen. However, hydrogen can be used for the methanation process when the demand for methane is high, or there is no demand for hydrogen for end use application. This cycle is repeated to reduce CO_2 emissions and increase the overall biomethane production. It has been stated that the H_2:CO_2 ratio influences the methanation efficiency improving methane yield. The H_2:CO_2 ratio that conducted to the maximum CO_2 conversion, and to a best methane yield was of 4:1 [51-52].

2.7. Environmental Analysis

The environmental assessment performed 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 [53-54]. 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 emissions from the energy sector [55-56]. Eq. 11 estimates the equivalent $(CO_2)e$ produced from the process [37, 57].

$$(CO_2) = a(CO_2) + b(CH_4) + c(CO) + d(SO_2) + e(NO_x) + f(PM) \qquad ....(11)$$

Where a=1, b= 25, c=1.9, d=80, e=50 and f=67, are respectively, the emission coefficients corresponding to the global warming potential of each pollutant [58-59], According to the findings of Ayodele et al. [37], the CO_2 released during combustion is considered carbon neutral and does not contribute to global warming. Table 2 provides the emission factors for each pollutant.

Table 2. Emission factor of some pollutants [37, 58-59].

Pollutants (i)	CO	SOX	NOX	CH_4	PM	$(CO_2)e$
GWP(i) kgCO_2 per kg pollutant	1.9	80	50	25	67	
Emission factor α (lb per scf)	84	0.6	32	7.6	2.3	
Emission factor (lb per MMBtu) ($\times10^{-4}$) $\beta = \alpha/1020$	823.5	313.7	5.882	22.55	74.51	
Emission factor (kg per MJ) ($\times10^{-8}$) $\gamma=(\beta \times 0.4556)/1055$	3556.3	1354.7	25.401	9.7382	321.77	
Biogas combustion emissions with respect to carbon dioxide equivalent (kgCO_2) ($\times10^{-5}$) $(CO_2)e = Q\times\gamma\times GWP(i)$	255.1	4091	47.94	9.191	813.8	5217

In the present study, the biogas has been upgraded to contain 75.7% methane [12, 34,41], and the emissions of CO_2 during steam methane reforming was taken into account in the scenario 2. As a result, Eq.11 is modified to Eq. 12.

$$(CO_2)e = a(CO_2) \qquad ....(12)$$

The fuel low heating value (LHV) of each pollutant as a function of the percentage methane content in the biogas (x) is expressed by Eq.13 [37]:

$$Q_i = LHV(CH_4)\times\%x \qquad ....(13)$$

Lower heating value of methane (LHVCH_4) is taken to be 49.934 MJ per kg [37]. The theoretical estimation of biomethane and hydrogen potential provides valuable insights for future projections. The linear progression based on population growth is an essential parameter in the approach of this study. It considers how waste generation in Cape Coast is largely dependent on the population growth, hence on future projections.

3. RESULTS

3.1. Evaluation of Food Waste Potential

In order to determine the potential for producing biomethane and green 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. Figure 3 shows the correlation between the organic MSW generated, the food waste, and the population in Cape Coast over a period from 2021-2050. This result were used for further analysis. Several factors such as waste composition and waste management practices were considered. Almost 6,376.30 tons of food waste accounting for 20% of the total MSW (31,881 tons) were generated in 2021, (Figure 3). The estimated biogas potential from food waste is 4.9 Mm^3. The findings in this present study are similar to that of Cudjoe et al. [60], where the biogas generation potential is increasing with the population in the studied cities (Accra and Kumasi). 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. A detailed evaluation was conducted to determine the potential for food waste which dominates the organic MSW generated in Cape Coast over a period from 2021-2050, as shown in Figure 3.

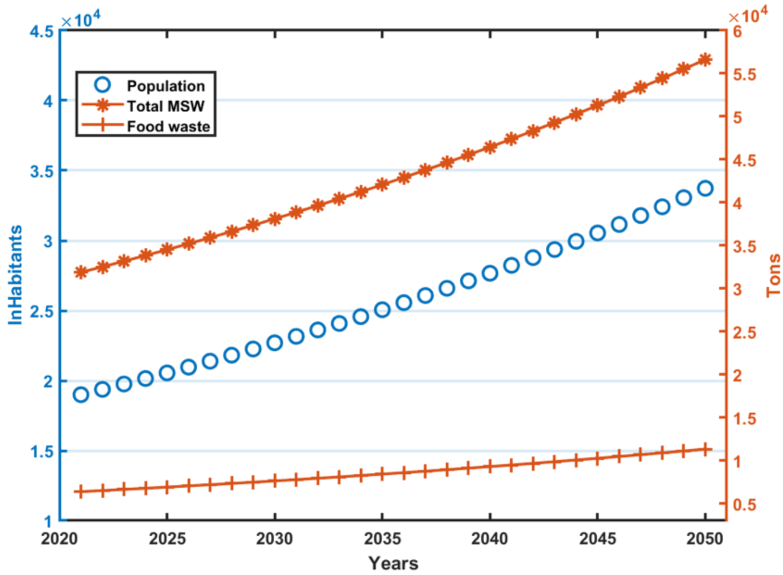

Figure 3. Food waste generated in function of the population growth in Cape Coast from 2021 to 2050.

The result shows that waste generation increased annually, largely due to population growth in the region annually of 3.1% [61]. 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. Therefore, it is crucial to adopt sustainable waste management approaches to limit the ecological consequences of the increasing waste production.

On the left y- axis, the population is represented (empty small circles in blue), while on the right y-axis are the total municipal waste and the food waste fraction generated. The linear graphs show how population affects waste generation in Cape coast.

3.2. Biomethane and Hydrogen Production Potential

Figure 4A presents the projected potential for biomethane and hydrogen in Cape Coast from 2021 to 2050.

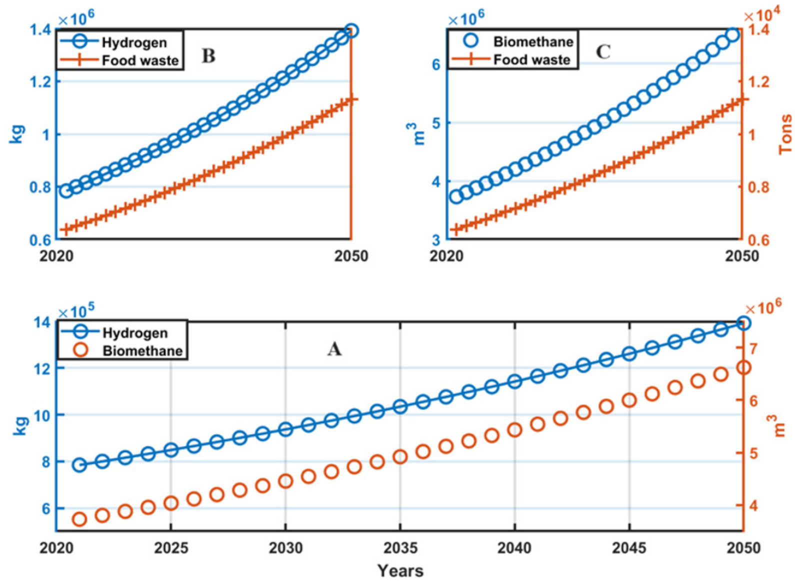

Figure 4. Biomethane and hydrogen potential in Cape Coast from 2021 to 2050.

Figures 4B and 4C show the correlation between biomethane, hydrogen and food waste, respectively. The biogas composition, calculated using equations from Table 1, 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.

The amount of the food waste, the actual biogas, the biomethane, and the green hydrogen for 2021 were 6,376.30 tons, 4,939,014.92 m^3, 3,728,956.26 m^3 and 783,975.76 kg, respectively. 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. Hydrogen generation potential obtained from food wastes in the present study is consistent with that of Seglah et al. [34], obtained in Accra, Kumasi, Sekondi-Takoradi and Tamale, respectively. Ayodele et al. [37] obtained similar findings in Southern Nigeria. With the new development in the natural gas pipeline, this hydrogen generation potential, when harnessed would be capable of complementing the existing natural gas resources in Ghana and meet the local methane demand in Cape Coast. 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 trillion British thermal units (tBtu), most of which was used for generating electricity [62]. According to calculations, 3.7 million m^3 of biomethane equals 0.132 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 [63]. By doing so, it is 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 such as gasoline, diesel, and aviation kerosene [64]. 51 thousand m^3 (500 MWh) of biomethane were used to produce 10 tons of hydrogen at the Cartagena Industrial Complex in Spain [64]. 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 that's needed for anaerobic digestion and impact the biomethane and hydrogen generation potential.

3.3. Natural Gas Displacement

Biomethane offers a potential solution to the achievement of net zero emission due to its several advantages including CO_2 emission reduction, ideal for decentralization of energy production in small-scale units for injection into the distribution systems, and meets natural gas quality for injection into the natural gas grid [65]. Figure 5 shows the equivalent biomethane production and the natural gas supply in Ghana from 2009 to 2022.

Over the last few years, gas production is increasing in Ghana. Production has increased from 2.0 tBtu in 2014 to 117.87 tBtu in 2022, which accounts for an annual growth rate of 66.5%, as shown in Figure 5. Ghana has also been importing gas from Nigeria through the West African Gas Pipeline to supplement domestic production. The total amount of gas imported has been increasing gradually, although slower [66]. 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 gas as of 2022, which displaces 0.7% of the gas imported. This shows that a higher displacement is achievable with increasing methane yield influenced by food waste generation and anaerobic digestion. Ghana's decarbonization strategy includes introducing low-carbon technologies, such as carbon capture utilization and storage, as well as compressed natural gas for road transport by 2070 [67].

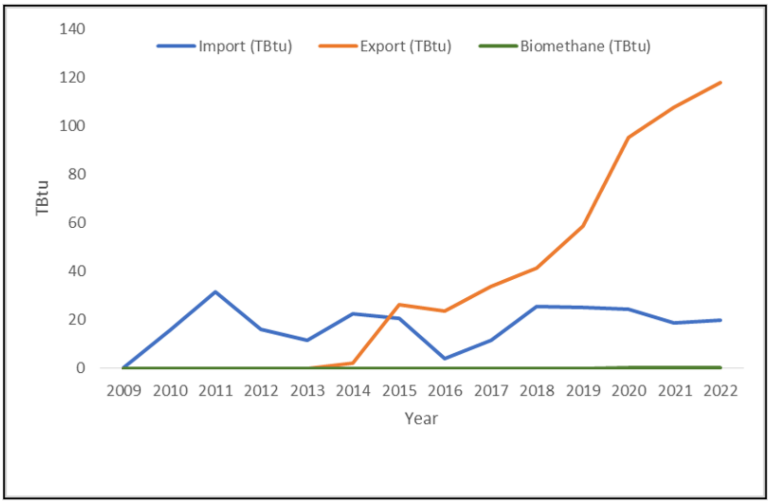

Figure 5. Natural gas supply (2009-2022) and equivalent biomethane potential.

However, no specific analysis or projections were made for biomethane as a complementary solution for the decarbonization of the gas sector. It, therefore, raises a concern about the potential limitations in exploring alternative solutions that could be highly efficient and environmentally beneficial. The biomethane market is growing globally, as countries are encouraging the inclusion of biomethane in their energy mix, and making their targets more achievable through incentives and subsidies [68]. Addressing the challenges in the production of biomethane will be essential in harnessing its full potential sustainable energy source to advance the national economy.

3.4. Environmental Assessment

Figure 6 presents the estimated total emissions in CO_2 equivalent from 2021 to 2050. The biomethane and hydrogen production from food waste releases some CO_2 [69]. The estimated emissions from biogas combustion in CO_2 equivalent is 81.5 tons.

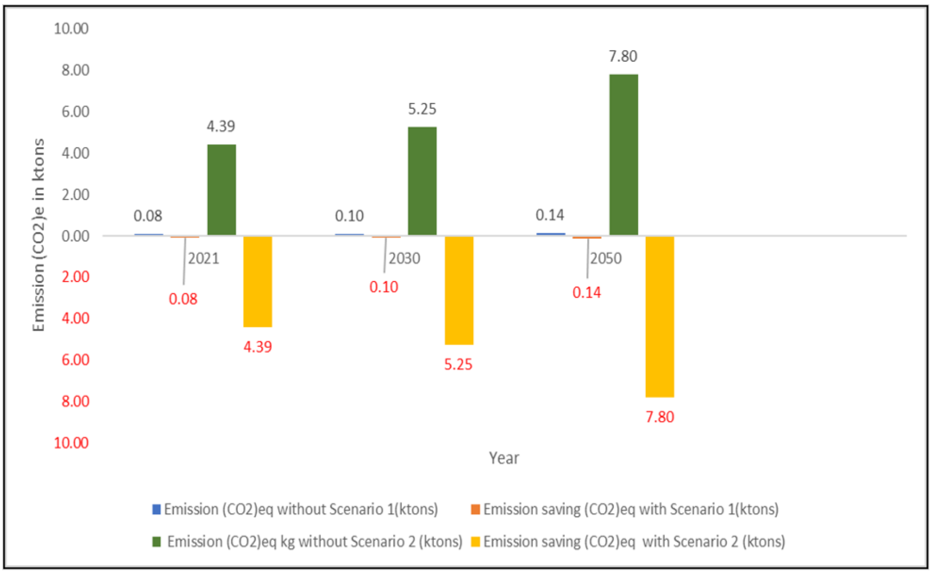

Figure 6. CO_2 emissions saving.

Considering scenario 1, the CO_2 produced from the process is saved and utilized to increase biomethane production. In scenario 1, the CO_2 produced from the biogas upgrading is reacted with renewable electricity-generated hydrogen (green hydrogen) to produce more methane [70]. The loops of the system was closed to reduce the CO_2 emissions. The (CO2)eq. emissions per kg of biogas during biogas combustion and steam reforming process are found to be 0.052 Kg and 2.750 Kg, respectively [37]. Hydrogen production from steam methane reforming releases CO_2 that can be later reutilized for the methanation process in reacting with hydrogen produced.
The CO_2 equivalent emission 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 [71]. This increases to a 2.8% reduction by 2050 from the same volume of natural gas. Comparing the CO_2 reduction potential from the two processes, it can be concluded that scenario 2 offers higher CO_2 emission savings than scenario 1. Hydrogen production from biomethane compared to natural gas as a feedstock has been investigated to be the preferred option to decarbonization as it can lead to negative emissions [72]. Hence, complementing carbon capture to steam methane reforming of biomethane will reinforce resource optimization and emissions reduction of the scenarios, and conforming with bioenergy with carbon capture and storage [73-75]. Organic waste-derived Renewable Natural Gas (RNG) alone cannot replace fossil fuels enough to meet long-term climate objectives. Nonetheless, RNG can still help decrease methane emissions and substitute fossil fuels in economically challenged areas [76].

4. CONCLUSION

The biomethane and hydrogen generation potential from the food waste from the Cape Coast Municipality has been evaluated. The findings estimate that 31,881 tons of food waste could be generated in 2021 and a projected of 258,670 tons by 2050. This projects the biomethane and hydrogen production potential to 151.28 Mm^3 and 31,800 tons, respectively by 2050. The biomethane potential could contribute to replacing 4.5% of natural gas consumption in Ghana by 2050. The projected potential of 31,800 tons 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 study 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 innovative scenarios explored in this study could increase methane yield by utilising CO_2 emissions while reducing carbon emissions at about 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 regarding food waste generation. Municipalities' lack of waste segregation systems creates a challenge for efficient food waste collection for anaerobic processing, so, it is essential to promote and implement effective waste management systems in Cape Coast, which includes prioritizing waste segregation at the source. The advancements in renewable energy production can potentially revolutionize the energy sector and significantly reduce carbon emissions. Further studies could be conducted on the economic feasibility and carbon credits generation from CO_2 emissions savings. This study provides valuable information to policymakers, researchers, and investors in Ghana's gas and energy sectors for the development of policies and strategies to promote the integration of biomethane and green hydrogen 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.

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REFERENCES

[1] S. Chakraborty, S. Dash, R. Madurai Elavarasan, A. Kaur, D. Elangovan, S. Meraj, P. Kasinathan, Z. Said, "Hydrogen Energy as Future of Sustainable Mobility", Frontiers in Energy Research, vol. 10, pp. 1–23, 2022. https://doi.org/10.3389/fenrg.2022.893475.

[2] F. Mneimneh, H. Ghazzawi, M. Hejjeh, M. Manganelli, S. Ramakrishna, (2023), "Roadmap to Achieving Sustainable Development via Green Hydrogen", Energies, vol. 16, no. 3, p. 1368. https://doi.org/10.3390/en16031368.

[3] D. Prato-Garcia, A. Robayo-Avendaño, R. Vasquez-Medrano, "Hydrogen from natural gas and biogas: Building bridges for a sustainable transition to a green economy", Gas Science and Engineering, vol. 111, p. 204918, 2023. https://doi.org/10.1016/j.jgsce.2023.204918.

[4] O. Sarkar, J.A. Modestra, U. Rova, P. Christakopoulos, L. Matsakas, "Waste-Derived Renewable Hydrogen and Methane: Towards a Potential Energy Transition Solution", Fermentation, vol. 9, p. 368, 2023. https://doi.org/10.3390/fermentation9040368.

[5] M. Calero, V. Godoy, C.G. Heras, E. Lozano, S. Arjandas, M.A. Martín-Lara, "Current state of biogas and biomethane production and its implications for Spain", Sustainable Energy and Fuels, vol. 7, pp. 3584–3602, 2023. https://doi.org/10.1039/D3SE00419H.

[6] International Energy Agency, "Renewables 2022 - Analysis and forecast to 2027", OECD Publishing, Paris, 2022, https://doi.org/10.1787/96bc279a-en.

[7] Intergovernmental Panel on Climate Change (IPCC). "Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change". Cambridge University Press; 2023.

[8] G. Basso, L. Pastore, A. Mojtahed, L. Santoli, "From landfill to hydrogen: Techno-economic analysis of hybridized hydrogen production systems integrating biogas reforming and Power-to-Gas technologies", International Journal of Hydrogen Energy, vol. 48, pp. 37607–37624, 2023. https://doi.org/10.1016/j.ijhydene.2023.07.130.

[9] M. Ozturk, I. Dincer, "An integrated system for clean hydrogen production from municipal solid wastes", International Journal of Hydrogen Energy, vol. 46, pp. 6251–6261, 2021. https://doi.org/10.1016/j.ijhydene.2020.11.145.

[10] L. Figueroa-Escamilla, S. Gonzalez-Martinez, R. Campuzano, I. Valdez-Vazquez, "Methane production and bromatological characteristics of the different fractions of organic municipal solid waste", Detritus, vol. 15, pp. 13–23, 2021. https://doi.org/10.31025/2611-4135/2021.15095.

[11] E. Nocete, J. Perez, "A Simple Methodology for Estimating the Potential Biomethane Production in a Region: Application in a Case Study", Sustainability, VOL. 14, p. 15978, 2022. https://doi.org/10.3390/su142315978.

[12] D. Cudjoe, E. Nketiah, B. Zhu, "Evaluation of potential power production and reduction in GHG emissions from bio-compressed natural gas derived from food waste in Africa", Sustainable Production and Consumption, vol. 42, pp. 2–13, 2023. https://doi.org/10.1016/j.spc.2023.09.004.

[13] B. Amponsem, E.C. Bensah, E. Antwi, J.C. Ahiekpor, B. Boahen, I.Mensah, S. Narra, "Electricity generation from biogas as resource recovery potential from solid waste composition in a mixed-income municipality", Clean Waste Systems, vol. 4, p. 100067, 2023. https://doi.org/10.1016/j.clwas.2022.100067.

[14] J. Darmey, J.C. Ahiekpor, S. Narra, O.-W. Achaw, H.F. Ansah, "Municipal Solid Waste Generation Trend and Bioenergy Recovery Potential: A Review", Energies, vol. 16, p. 7753, 2023. https://doi.org/10.3390/en16237753.

[15] N. Nelson, J. Darkwa, J. Calautit, "Prospects of Bioenergy Production for Sustainable Rural Development in Ghana", Journal of Sustainable Bioenergy Systems, vol. 11, pp. 227–259, 2021. https://doi.org/10.4236/jsbs.2021.114015.

[16] L.E. Agbefe, E.T. Lawson, D. Yirenya-Tawiah, "Awareness on waste segregation at source and willingness to pay for collection service in selected markets in Ga West Municipality, Accra, Ghana", Journal of Material Cycles and Waste Management, vol. 21, pp. 905–914, 2019. https://doi.org/10.1007/s10163-019-00849-x.

[17] P. Owusu-Ansah, A.A.Obiri-Yeboah, E.K. Nyantakyi, S.K. Woangbah, S.I.I.K. Yeboah, "Ghanaian inclination towards household waste segregation for sustainable waste management", Scientific African, vol. 17, p. e01335, 2022. https://doi.org/10.1016/j.sciaf.2022.e01335.

[18] E. Amo-Asamoah, D.-G. Owusu-Manu, G. Asumadu, F.A. Ghansah, D.J. Edwards, "Potential for waste to energy generation of municipal solid waste (MSW) in the Kumasi metropolis of Ghana", International Journal of Energy Sector Management, vol. 14, pp. 1315–1331, 2020. https://doi.org/10.1108/IJESM-12-2019-0005.

[19] A. Mertins, M. Heiker, S. Rosenberger, T. Wawer, "Competition in the conversion of the gas grid: Is the future of biogas biomethane or hydrogen?" International Journal of Hydrogen Energy, vol. 48, pp. 32469–32484, 2023. https://doi.org/10.1016/j.ijhydene.2023.04.270.

[20] E. Kumi, "The Electricity Situation in Ghana: Challenges and Opportunities" [Internet], CGD Policy Paper. Washington, DC: Center for Global Development, 2017. Available at: https://www.cgdev.org/publication/electricity-situation-ghana-challenges-and-opportunities. (Accessed: 21 December 2023)

[21] A. Afful-Dadzie, S.K. Mensah, E. Afful-Dadzie, "Ghana renewable energy master plan: The benefits of private sector participation", Scientific African, vol. 17, p. e01353, 2022. https://doi.org/10.1016/j.sciaf.2022.e01353.

[22] Ghana Energy Commission, "Annual Report and Audited Financial Statements for 2019" [Internet]. p126, 2019. Available at: http://www.energycom.gov.gh/about/annual-reports?download=152:annual-report-for-2019.(Accessed: 11 December 2023)

[23] C.C. Ajaero, C.C. Okafor, F.A. Otunomo, N.N. Nduji, J.A. Adedapo, "Energy production potential of organic fraction of municipal solid waste (OFMSW) and its implications for Nigeria", Clean Technologies and Recycling, vol. 3, 44–65, 2023. https://doi.org/10.3934/ctr.2023003.

[24] B. Gungor, I. Dincer, "Development of a sustainable community with an integrated renewable and waste to energy system for multiple useful outputs", Journal of Cleaner Production, vol. 312, p. 127704, 2021. https://doi.org/10.1016/j.jclepro.2021.127704.

[25] Ghana Statistical Service, "Population and Housing Census", Population of Regions and Districts General Report, vol. 3A. p. 128, 2021.

[26] Ghana Meteorological Agency, "Ghana Meteorological Agency's Seasonal Forecast for The Northern Sector and Seasonal Forecast Update for The Southern Sector of Ghana: June-Aug (Jja) And July - Sept (Jas) For The Country". Ref. No: Met. 9.3/207, 2023. [Inernet]. Available at: https://www.meteo.gov.gh/gmet/wp-content/uploads/2022/05/JJA_JAS-Seasonal-Forecast_North-2022.pdf (Accessed: 14 January 2024).

[27] Ghana Web, "Ghana Gas set to construct major 290-kilometre gas pipeline" – MP, 2022. [Internet]. GhanaWeb. Available at: https://www.ghanaweb.com/GhanaHomePage/business/Ghana-Gas-set-to-construct-major-290-kilometre-gas-pipeline-MP-1601444 (Accessed: 11 December 2023).

[28] Ministry of Petroleum, "Gas Master Plan", 2016. [Internet]. Available at: https://uploads-ssl.webflow.com/5a92987328c28c00011db053/5bbf7dca7a04d6da6a45aa82_GMP-Final-Jun16.pdf (Accessed: 14 January 2024).

[29] A. Kwarteng, "Changing face of estate housing development in the Cape Coast Metropolis" [dissertation], 2016. Cape Coast: Univ. of Cape Coast, Ghana.

[30] UN-Habitat, "City waste data collected with the Waste Wise Cities Tool". Step by Step Guide to Assess a City's Municipal Solid Waste Management Performance through SDG indicator 11.6.1 Monitoring. p. 84, 2021. [Internet]. Avaliable at: URL https://unh.rwm.global/Map (Accessed: 06 December 2023).

[31] P. Gyimah, S. Mariwah, K.B. Antwi, K. Ansah-Mensah, "Households' solid waste separation practices in the Cape Coast Metropolitan area, Ghana", GeoJournal, vol. 86, pp. 567–583, 2021. https://doi.org/10.1007/s10708-019-10084-4.

[32] V. Seshie, K. Obiri-Danso, K. Miezah, "Municipal Solid Waste Characterisation and Quantification as a measure towards Effective Waste Management in the Takoradi Sub-Metro, Ghana", Ghana Mining Journal, vol. 20 no 2, pp. 86-98, 2020.

[33] K. Miezah, K. Obiri-Danso, Z. Kádár, B. Fei-Baffoe, M. Y. Mensah, "Municipal solid waste characterization and quantification as a measure towards effective waste management in Ghana", Waste Management, Vol. 46, pp. 15-27, 2015. https://doi.org/10.1016/j.wasman.2015.09.009.

[34] P.A. Seglah, Y. Wang, H. Wang, K.A. Wobuibe Neglo, K. Zhou, N. Sun, J. Shao, J. Xie, Y. Bi, C. Gao, "Utilization of food waste for hydrogen-based power generation: Evidence from four cities in Ghana", Heliyon, vol. 9, p. e14373, 2023. https://doi.org/10.1016/j.heliyon.2023.e14373

[35] A.S.O. Ogunjuyigbe, T.R. Ayodele, M.A. Alao, "Electricity generation from municipal solid waste in some selected cities of Nigeria: an assessment of feasibility, potential and technologies", Renew. Sustain. Energy Rev. Vol 80, pp. 149–162, 2017, https://doi.org/10.1016/j.rser.2017.05.177.

[36] C. Morales-Polo, M. Del Mar Cledera-Castro, B.Y. Moratilla Soria, "Reviewing the Anaerobic Digestion of Food Waste: From Waste Generation and Anaerobic Process to Its Perspectives", Applied Sciences, vol. 8, 1804, 2018. https://doi.org/10.3390/app8101804.

[37] T.R. Ayodele, M.A. Alao, A.S.O. Ogunjuyigbe, J.L. Munda, "Electricity generation prospective of hydrogen derived from biogas using food waste in south-western Nigeria", Biomass and Bioenergy, vol. 127, p. 105291, 2019. https://doi.org/10.1016/j.biombioe.2019.105291.

[38] A.M Yousef., W.M. El-Maghlany, Y.A. Eldrainy, A. Attia, "Upgrading biogas to biomethane and liquid CO_2: A novel cryogenic process", Fuel, vol. 251, pp. 611–628, 2019. https://doi.org/10.1016/j.fuel.2019.03.127

[39] A. Nielfa, R. Cano, M. Fdz-Polanco, "Theoretical methane production generated by the co-

digestion of organic fraction municipal solid waste and biological sludge", Biotechnology Reports, vol. 5, pp. 14–21, 2015. https://doi.org/10.1016/j.btre.2014.10.005.

[40] A. Magrinho, V. Semiao, "Estimation of residual MSW heating value as a function of waste component recycling", Waste Management, vol. 28, pp. 2675–2683, 2008. https://doi.org/10.1016/j.wasman.2007.12.011

[41] J. E Castellanos-Sánchez, F. A. Aguilar-Aguilar, R. Hernández-Altamirano, José Apolonio Venegas Venegas, Deb Raj Aryal. "Biogas Purification Processes: Review and Prospects". Biofuels vol. 15 no. 2, pp. 215–27, 2023. doi:10.1080/17597269.2023.2223801.

[42] L. Salami, A.A Susu., R.J. Patinvoh, O.A. Olafadehan, "Characterization study of solid wastes: a case of Lagos state", International Journal of Applied Science and Technology, vol. 1, no. 3, pp. 47-52, 2011.

[43] L.B. Braga, J.L. Silveira, M.E. Da Silva, C.E. Tuna, E.B. Machin, D.T. Pedroso, "Hydrogen production by biogas steam reforming: A technical, economic and ecological analysis", Renewable and Sustainable Energy Reviews, vol. 28, pp. 166–173, 2013. https://doi.org/10.1016/j.rser.2013.07.060

[44] P. Bajpai, V. Dash, "Hybrid renewable energy systems for power generation in stand-alone applications: A review", Renewable and Sustainable Energy Reviews, vol. 16, pp. 2926–2939, 2012. https://doi.org/10.1016/j.rser.2012.02.009.

[45] D. Cudjoe, W. Chen, B. Zhu, "Valorization of food waste into hydrogen: energy potential, economic feasibility and environmental impact analysis", Fuel, vol. 324, Article 124476, 2022. 10.1016/j.fuel.2022.124476.

[46] C.H. Tan, S. Nomanbhay, A.H. Shamsuddin, Y.-K. Park, H. Hernández-Cocoletzi, P.L. Show, "Current Developments in Catalytic Methanation of Carbon Dioxide—A Review", Frontiers in Energy Research, vol. 9, p. 795423, 2022. https://doi.org/10.3389/fenrg.2021.795423.

[47] C.H. Tan, M.Y. Ong, S.M. Nomanbhay, A.H. Shamsuddin, P.L. Show, "The Influence of COVID-19 on Global CO_2 Emissions and Climate Change: A Perspective from Malaysia", Sustainability, vol. 13, p. 8461, 2021. https://doi.org/10.3390/su13158461.

[48] A.J.K. Newman, G.R.M. Dowson, E.G.Platt, H.J. Handford-Styring, P. Styring, "Custodians of carbon: creating a circular carbon economy", Frontiers in Energy Research, vol. 11, p. 1124072, 2023.https://doi.org/10.3389/fenrg.2023.1124072.

[49] M. Tommasi, S. N. Degerli, G. Ramis, I. Rossetti, "Advancements in CO_2 methanation: comprehensive review of catalysis, reactor design and process optimization", Chemical Engineering Research and Design, Vol. 201, pp. 457-482, 2024, https://doi.org/10.1016/j.cherd.2023.11.060.

[50] T. Schaaf, J. Grünig, M.R. Schuster, T. Rothenfluh, A. Orth, "Methanation of CO_2 - storage of renewable energy in a gas distribution system", Energy, Sustainability and Society, vol. 4, Article number 2, pp. 1-14, 2014, https://doi.org/10.1186/s13705-014-0029-1

[51] R. Wahid, D.G. Mulat, J.C. Gaby, S.J. Horn, "Effects of H_2: CO_2 ratio and H_2 supply fluctuation on methane content and microbial community composition during in-situ biological biogas upgrading", Biotechnology for Biofuels, vol. 12, p. 104, 2019. https://doi.org/10.1186/s13068-019-1443-6.

[52] M.M. Jaffar, M.A. Nahil, P.T. Williams, "Parametric Study of CO_2 Methanation for Synthetic Natural Gas Production", Energy Technology, vol. 7, p.1900795, 2019. https://doi.org/10.1002/ente.201900795

[53] D.W. Kweku, O. Bismark, A. Maxwell, K.A. Desmond, K.B. Danso, E.A. Oti-Mensah, A.T. Quachie, B.B. Adormaa, "Greenhouse Effect: Greenhouse Gases and Their Impact on

Global Warming", Journal of Scientific Research and Reports, vol. 17, pp. 1–9, 2018. https://doi.org/10.9734/JSRR/2017/39630

[54] K.O. Yoro, M.O. Daramola, "CO2 emission sources, greenhouse gases, and the global warming effect, in: Advances in Carbon Capture". Editor(s): M. R. Rahimpour, M. Farsi, M. A. Makarem, Woodhead Publishing, pp. 3–28, 2020. https://doi.org/10.1016/B978-0-12-819657-1.00001-3

[55] S.J. Mandley, B. Wicke, M. Junginger, D.P. Van Vuuren, V. Daioglou, "The implications of geopolitical, socioeconomic, and regulatory constraints on European bioenergy imports and associated greenhouse gas emissions to 2050", Biofuels, Bioproducts and Biorefining, vol. 16, pp. 1551–1567, 2022. https://doi.org/10.1002/bbb.2421.

[56] P. Sulewski, W. Ignaciuk, M. Szymańska, A. Wąs, "Development of the Biomethane Market in Europe", Energies, vol. 16, p. 2001, 2023. https://doi.org/10.3390/en16042001

[57] J.L. Silveira, W.Q. Lamas, C.E. Tuna, I.A.C. Villela, L.S. Miro, "Ecological efficiency and thermoeconomic analysis of a cogeneration system at a hospital", Renewable and Sustainable Energy Reviews, vol. 16, pp. 2894–2906, 2012. https://doi.org/10.1016/j.rser.2012.02.007.

[58] EPA, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021" [Internet]. U.S. Environmental Protection Agency, EPA 430-R-23-002, 2023. Available at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021 (Accessed: 11 December 2023).

[59] C. Ryu, "Potential of Municipal Solid Waste for Renewable Energy Production and Reduction of Greenhouse Gas Emissions in South Korea", Journal of the Air and Waste Management Association, vol. 60, p. 176–183, 2010. https://doi.org/10.3155/1047-3289.60.2.176.

[60] D. Cudjoe, E. Nketiah, B. Obuobi, G. Adu-Gyamfi, M.Adjei, B. Zhu, "Forecasting the potential and economic feasibility of power generation using biogas from food waste in Ghana: Evidence from Accra and Kumasi", Energy, vol. 226, p. 120342, 2021. https://doi.org/10.1016/j.energy.2021.120342.

[61] S.Y. Danso, Y. Ma, Y.D.A. Adjakloe, I.Y. Addo, "Application of an Index-Based Approach in Geospatial Techniques for the Mapping of Flood Hazard Areas: A Case of Cape Coast Metropolis in Ghana", Water, vol. 12, p. 3483, 2020. https://doi.org/10.3390/w12123483.

[62] Energy Commission, "Ghana Key Energy Statistics Handbook", 2021 edition, [Internet].. Available at: https://www.energycom.gov.gh/files/Key%20Energy%20Statistics%20Handbook%2021.pdf. (Accessed: 11 Juin 2024)

[63] N. Abdalla, S. Bürck, H. Fehrenbach, S. Köppen, T. Janosch Staigl, "Biomethane in Europe". ifeu – Institut für Energie- und Umweltforschung Heidelberg gGmbH, 2022, Wilckensstr 3, D-69120 Heidelberg, Germany.

[64] REPSOL, "Repsol produces renewable hydrogen with biomethane for the first time", 2021, [Internet]. REPSOL. Available at: https://www.repsol.com/en/press-room/press-releases/2021/repsol-produces-renewable-hydrogen-with-biomethane-for-the-first-time/index.cshtml (Accessed: 8 August, 2023).

[65] F.S.D. Carvalho, L.C.B.D.S. Reis, P.T. Lacava, F.H.M.D. Araújo, Jr. J.A.D. Carvalho, "Substitution of Natural Gas by Biomethane: Operational Aspects in Industrial Equipment", Energies, vol. 16, p. 839, 2023. https://doi.org/10.3390/en16020839.

[66] Energy Commission, "Energy Statistics and Balances" [Internet]. National Energy Statistical Bulletin, 2023. Available at: http://energycom.gov.gh/newsite/files/2023-energy-Statistics.pdf. (Accessed: 20 December 2023).

[67] C Sefa-Nyarko, "Ghana's National Energy Transition Framework: Domestic aspirations and mistrust in international relations complicate 'justice and equity'", Energy Research & Social Science, Vol. 110, p. 103465, 2024. https://doi.org/10.1016/j.erss.2024.103465.

[68] IEA. "World Energy Outlook (Special Report 2020) Outlook for biogas and Biomethane. Prospects for organic growth". Available at: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane. (Accessed: 10 June 2024).

[69] I. Moreno-Andrade, M.J. Berrocal-Bravo, I. Valdez-Vazquez, "Biohydrogen production from food waste and waste activated sludge in codigestion: influence of organic loading rate and changes in microbial community", Journal of Chemical Technology & Biotechnology, vol. 98, pp. 230–237, 2023. https://doi.org/10.1002/jctb.7238.

[70] M. Farghali, A.I. Osman, K. Umetsu, D.W. Rooney, "Integration of biogas systems into a carbon zero and hydrogen economy: a review", Environmental Chemistry Letters, vol. 20, pp. 2853–2927, 2022. https://doi.org/10.1007/s10311-022-01468-z.

[71] U.S. Energy Information Administration - EIA, "Carbon dioxide Emissions Coefficient", 2022. Available at: https://www.eia.gov/environment/emissions/co2_vol_mass.php (Accessed: 11 December 2023)

[72] C. Antonini, K. Treyer, A. Streb, M. Van Der Spek, C. Bauer, M. Mazzotti, "Hydrogen production from natural gas and biomethane with carbon capture and storage – A techno-environmental analysis", Sustainable Energy and Fuels, vol. 4, pp. 2967–2986, 2020. https://doi.org/10.1039/D0SE00222D.

[73] M. Bui, M. Fajardy, N. Mac Dowell, "Bio-energy with carbon capture and storage (BECCS): Opportunities for performance improvement", Fuel, vol. 213, pp. 164–175, 2018. https://doi.org/10.1016/j.fuel.2017.10.100.

[74] B. Dziejarski, R. Krzyżyńska, K. Andersson, "Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment", Fuel, vol. 342, p. 127776, 2023. https://doi.org/10.1016/j.fuel.2023.127776

[75] P. Gabrielli, M. Gazzani, M. Mazzotti, "The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO_2 Emissions",Chemical Industry, Industrial & Engineering Chemistry Research, vol. 59, pp. 7033–7045, 2020. https://doi.org/10.1021/acs.iecr.9b06579.

[76] T. Cyrs, J. Feldmann, R. Gasper, "Renewable Natural Gas as A Climate Strategy: Guidance for State Policymakers, Working Paper". Washington, DC: World, Resources Institute, 2020. Available online at http://www.wri.org/publication/renewable-natural-gas-guidance. http://dx.doi.org/10.46830/wriwp.19.00006, (Accessed: 04 December 2023).