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Valorization of Agricultural Residues for Hydrogen-Based Electricity Generation towards Circular Bioeconomy

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Abstract

Global crises, notably climate shocks, degraded ecosystems, and growing energy demand, enforce sustainable production and consumption pathways. A circular bioeconomy offers the opportunities to actualize resource and eco-efficiency enhancement, valorization of waste streams, reduction of fossil energy and greenhouse gas (GHG) emissions. Albeit biomass resources are a potential feedstock for bio-hydrogen (bio-H_2) production, Ghana's agricultural residues are not fully utilized. This paper examines the economic and environmental impact of bio-H_2 electricity generation using agricultural residues in Ghana. The bio-H_2 potential was determined based on biogas steam reforming (BSR). The research highlights that BSR could generate 2617 kt of bio-H_2, corresponding to 2.78% of the global hydrogen demand. Yam and maize residues contribute 50.47% of the bio-H_2 produced, while millet residues have the most negligible share. A tonne of residues could produce 16.59 kg of bio-H_2 and 29.83 kWh of electricity. A total of 4,705.89 GWh of electricity produced could replace the consumption of 21.92% of Ghana's electricity. The economic viability reveals that electricity cost is $0.174/kWh and has a positive net present value of $2135550609.45 with a benefit-to-cost ratio of 1.26. The fossil diesel displaced is 1421.09 ML, and 3862.55 kt CO_2eq of carbon emissions decreased corresponding to an annual reduction potential of 386.26 kt CO_2eq. This accounts for reducing 10.26% of Ghana's GHG emissions. The study demonstrates that hydrogen-based electricity production as an energy transition is a strategic innovation pillar to advance the circular bioeconomy and achieve sustainable development goals.

Keywords

Agricultural Residues, Biogas Steam Reforming, Bio-Hydrogen, Electricity, Circular Bioeconomy

1. Introduction

Energy security and environmental degradation are inherent issues with the linear economy. The United Nations (UN) sustainable development goals (SDGs) were created to spur global economic growth and help countries tackle the most pressing issues affecting society and the environment [1]. Likewise, different concepts have been proposed to boost biomass efficiency and resource utilization to enhance sustainability. The concepts include "green growth", "green economy", "circular economy", and "bioeconomy" [2]. There has been an upsurge in political support for a circular bioeconomy (CBE) in light of the UN SDGs [3], which exploits the use of bioresources to produce high-value products [4]. Instead of relying exclusively on economic considerations to decide how to use a resource, a CBE prioritizes upcycling and cascading to extend the life of bioresources in the technological cycle [5]. The accelerating rates of global warming and environmental degradation have influenced the adaptation of CBE [6], lowering greenhouse gas (GHG) emissions while increasing sustainable consumption and production [7].

Modernization relies heavily on fossil fuels to provide its energy needs. The continuous use of fossil fuel supplies [8] requires sustainable future energy to meet the increasing population growth rate. Bioenergy has the potential to alleviate the climate-related issues caused by fossil fuel consumption in the production of heat, power, and transportation fuels [9]. Given this, to meet the world's growing demand for energy while also reducing hazardous emissions, bio-hydrogen (bio-H_2) is an ideal alternative [10].

Biomass is an appealing renewable energy source and a potential feedstock for hydrogen production [11]. Agricultural residues provide enormous potential for the production of bio-hydrogen [12]. Due to its abundance, affordability, and biodegradability, using agricultural residues to produce hydrogen is highly advantageous [13]. Emerging technologies that support the synthesis of hydrogen could be used to convert residues to attain significant bio-hydrogen production [14]. Biogas steam reforming (BSR) is applied extensively to produce hydrogen. With higher working temperatures and steam-to-carbon ratio, the biogas steam reforming produces more hydrogen [15]. The hydrogen economy is the subject of extensive study and policy development, and hydrogen production could have significant implications for economic growth [11]. Given this, agricultural residue management for hydrogen-electricity generation must be integrated to achieve a circular bioeconomy.

Previous studies evaluated the hydrogen generation capacity of biomass. Asadi *et al.* [16], developed a quantitative framework to evaluate biological hydrogen generation from agricultural wastes whiles, Bundhoo [12] estimated the bio-hydrogen production potential through dark fermentation. The bio-hydrogen potential of untreated residues was higher than treated residues. Likewise, using food waste as feedstock, hydrogen produced from biogas steam reforming to generate power and its environmental benefits was estimated in South-Western Nigeria [17]. Some earlier studies in Ghana assessed the hydrogen generation potential from other renewable sources (solar and wind). Topriska *et al.* [18] researched the feasibility of using a solar hydrogen system as a viable alternative to traditional cooking fuels in Ghana. It was revealed that based on the country's estimated daily cooking demand profile, Ghana could produce 815 kg of hydrogen. The study by Acakpovi *et al.* [19] concentrated on wind resources and the potential for producing hydrogen using water electrolysis. It was determined that the hydrogen fuel cell produced 25,999 kWh annually. Agyekum *et al.* [20] presented an overview of hydrogen from sustainable resources based on water splitting. The economic concerns revealed that water electrolysis utilizing solar or wind energy is not cost-effective.

There are scarce findings on using agricultural residues for bio-hydrogen generation through the biogas steam reforming process. To the best of the authors' knowledge, this paper is the first to conduct preliminary research on agricultural residues' potential to produce bio-hydrogen and electricity and evaluate how they can boost the circular bioeconomy. In Ghana, research into hydrogen synthesis through biogas steam reforming is lacking and has not been actively pursued. There is a scarcity of information on hydrogen production from agricultural residues through BSR. In this regard, agricultural residues were chosen since comprehensively utilizing these biomass resources has received less government attention, although residues can promote circular bioeconomic development. Ghana has witnessed an underdeveloped renewable energy (RE) sector marred with challenges compared to other countries. Likewise, using residues for H_2-power generation needs to be examined to advance the renewable energy sector. The significance of the research is to provide the groundwork for the generation of hydrogen in Ghana from residues as a renewable energy source that may be integrated into Ghana to help the country reach its 10% renewable energy goal by 2030. The study aims to determine the bio-hydrogen electricity potential from agricultural residues and conduct its economic and environmental assessment. Bio-hydrogen production could contribute significantly to global H_2 production to accelerate renewable energy production [17].

2. Materials and Methods

The framework for the study's methodology is shown in **Figure 1**. The trajectories involved bio-hydrogen production and its electricity potential from agricultural residues. Then the economic and environmental potential of the hydrogen energy potential was determined. Under this section, the materials refers to the

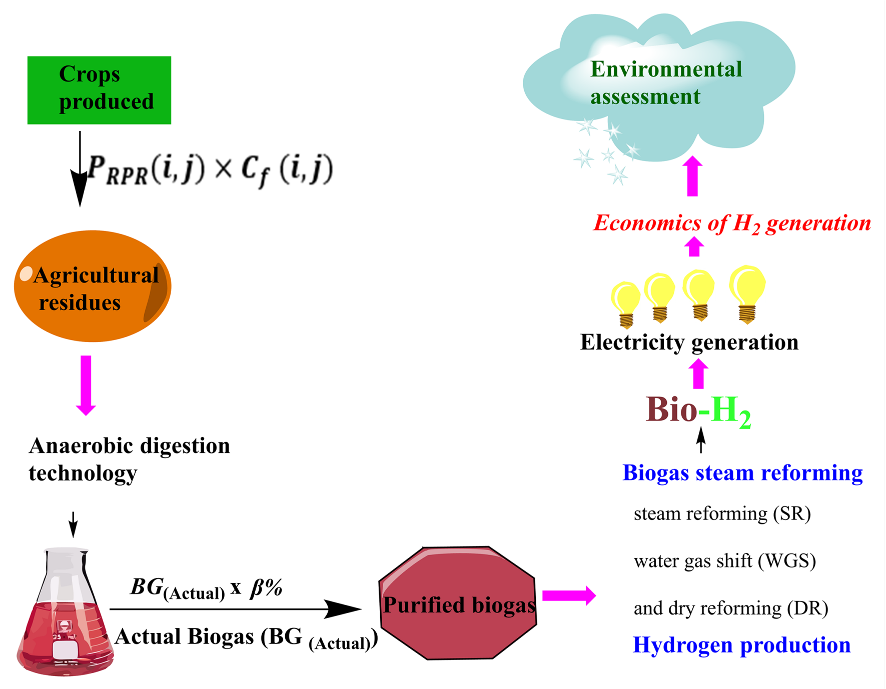

Figure 1. Methodological framework.

feedstock (residues generated from crops), actual biogas and bio methane, hydrogen, electricity and diesel. The methods include determining the residues' potential, anaerobic digestion technology, biogas steam reforming, and methods of assessments for electricity, economic and environmental capacity.

2.1. Determination of the Agricultural Residues' Potential

Agriculture is the backbone of Ghana's economy, predominantly characterized by crop production. Different food and cash crops are cultivated, providing substantial biomass to promote Ghana's circular bioeconomy when comprehensively utilized. The study focused on the selection of major crops cultivated in Ghana. Given this, 12 major crops were selected from 2011 to 2020 from the database of the Food and Agricultural Organization (FAO) [21]. Agricultural residues were traditionally utilized as fertilizer, animal feed, cooking fuels and used in landfills to check erosion [22]. Due to numerous constraints, not all agricultural residues can be collected and reused [23]. This means that only a fraction of residues are converted into bioenergy [24]. In addition, a critical factor that could affect the annual agricultural residue supply is the recoverable proportion [25]. The current study determined the collectible agricultural residue potential based on Equation (1).

$$AR_P(j)=\sum_{i=1}^{n}\left(P_P(i,j)\times P_{RPR}(i,j)\times C_f(i,j)\right) \tag{1}$$

where $AR_P(j)$ is the collectible agricultural residues (tonnes); P_P is the crop produced; P_{RPR} is the residue-to-product ratio and $C_f(i,j)$ is the residue collectible fraction retrieved from Kemausour *et al.* [23].

2.2. Biogas and Biomethane Recovery from Agricultural Residues

Agricultural residues are rich in potassium (K), carbon (C), nitrogen (N) and phosphorus (P) which are used to produce a variety of bioenergy sources [26] [27]. The anaerobic digestion (AD) technology can generate renewable energy in the forms of biogas and bio-methane from residues. When residues are used as a feedstock for biogas production, 25% - 55% carbon dioxide (CO_2) and 40% - 75.7% methane (CH_4) can be produced [28] [29]. Estimating the biogas digester's capacity is critical for designing an efficient biogas steam reforming process. The ability of the digester to produce biogas is determined using a theoretical approach. Buswell's equation was used to determine the potential yield of biogas from the feedstock. The mineral composition of residues was used to determine the stoichiometry of feedstock degradation [17], as shown in Equations (2) and (3).

$$\begin{aligned} &\mathrm{C}_q\mathrm{H}_r\mathrm{O}_s\mathrm{N}_t + \left(q - \frac{r}{4} - \frac{s}{2} + \frac{3t}{4}\right)\mathrm{H_2O} \\ &\Rightarrow \left(\frac{q}{2} - \frac{r}{8} - \frac{s}{4} + \frac{3t}{8}\right)\mathrm{CO_2} + \left(\frac{q}{2} + \frac{r}{8} - \frac{s}{4} - \frac{3t}{8}\right)\mathrm{CH_4} + t\mathrm{NH_3} \end{aligned} \tag{2}$$

$$\mathrm{C}_q\mathrm{H}_r\mathrm{O}_s\mathrm{N}_t + Z_1\mathrm{H_2O} \Rightarrow Z_2\mathrm{CO_2} + Z_3\mathrm{CH_4} + Z_4\mathrm{NH_3} \tag{3}$$

The variables q, t, s, r were the number of carbon (C), nitrogen (N), oxygen (O), and hydrogen (H), atoms, respectively and was estimated using Equation (4).

$$M_{ratio} = \frac{U_A}{M_m} \times \frac{1}{N_{M_r}} \tag{4}$$

U_A is the C, N, O and H of agricultural residues obtained from various literatures; M_m is the molar mass of C, N, O and H [30] and N_{M_r} is the N mole ratio.

Biogas ($BG_{(p)}$) potential was estimated in Equation (5).

$$BG_{(p)} = P_{CO_2} + P_{CH_4} \tag{5}$$

P_{CO_2} and P_{CH_4} are the CO_2 and CH_4 potential of the biogas at a standard temperature (0°C) and pressure (1 atm) expressed in m^3/tonne. The P_{CH_4} and P_{CO_2} were determined based on Equations (6) and (7) [17].

$$T_{CH_4} = 22400 \times \frac{\frac{q}{2} + \frac{r}{8} - \frac{s}{4} - \frac{3t}{8}}{12q + r + 16s + 14t} \tag{6}$$

$$T_{CO_2} = 22400 \times \frac{\frac{q}{2} - \frac{r}{8} + \frac{s}{4} + \frac{3t}{8}}{12q + r + 16s + 14t} \tag{7}$$

During anaerobic digestion technology, about 10% of the feedstock (agri-wastes) fails to decompose in the digester [30] and about 5% to 10% of residues synthesizes the cell tissues of the microorganisms that aid in microbial decomposition [17]. The estimation of the actual biogas ($BG_{(Actual)}$) potential was based on Equation (8).

$$BG_{(Actual)} = AR_P(j) \times BG_{(p)} \times \omega \tag{8}$$

where ω is 85% which represents the portion of residues used for cell tissue synthesis [31].

Before it can be used in the reforming process, the raw biogas must undergo purification and augmentation [32]. Chemically, pure biogas consists of about 93% - 96% CH_4, H_2S (<20 ppm) and 4% - 7% CO_2 [33]. Given this, the study assumed CO_2 is the only pollutant present in purified biogas and the determination of the volume of CH_4 was based on [34], as shown in Equation (9).

$$CH_{4_{(Pure)}} = BG_{(Actual)} \times \beta\% \tag{9}.$$

$\beta\%$ is a biogas upgrading percentage taken as 75.7% [29].

2.3. Hydrogen Production through Biogas Steam Reforming

Steam reforming is a common method for producing hydrogen, which requires operating at high temperatures to get a high hydrogen yield [15]. The steam methane reforming (SMR) process, which has a conversion efficiency of between 74% and 85%, is the most widely used and technologically advanced technique for producing hydrogen [35]. The biogas steam reforming process produces half the hydrogen generated globally [29]. During the steam reforming of biogas, the three significant reactions below occurs (Equation (10) to Equation (12)) [15]:

steam reforming (SR)

$$\mathrm{CH_4 + H_2O \rightleftharpoons CO + 3H_2} \quad \Delta H^0_{298} = +206.2\ \mathrm{kJ/mol} \tag{10}$$

water gas shift (WGS)

$$\mathrm{CO + H_2O \rightleftharpoons CO_2 + H_2} \quad \Delta H^0_{298} = -41\ \mathrm{kJ/mol} \tag{11}$$

and dry reforming (DR)

$$\mathrm{CH_4 + CO_2 \rightleftharpoons CO_2 + 4H_2} \quad \Delta H^0_{298} = +247.9\ \mathrm{kJ/mol} \tag{12}$$

Dry reforming can be disregarded when there is a significant concentration of steam during the reforming process [15], and the efficiency of the reform reactors determines how much hydrogen is produced. The potential for producing large amounts of hydrogen was determined analytically using the stoichiometric chemical equations of these reactions. From Equation (12), one kilogram of steam-reformed methane yields 0.5 kg H_2 gas. The study assumed that the reformer derives all of its energy from a biogas-fueled boiler. The H_2 produced depends on the system's reformer and boiler efficiency. Therefore, the Hydrogen ($H_{2_{(Q)}}$) produced from biogas steam reforming was determined based on Equation (13) [17].

$$H_{2_{(Q)}} = CH_{4_{(Pure)}} \times density_{(CH_4)} \times 0.5 \times \eta_{(sys.eff.)} \tag{13}$$

where $density_{(CH_4)}$ is the density of CH_4; $\eta_{(sys.eff.)}$ denotes the efficiency of the reformer and boiler as 80% [29].

2.4. Determining the Hydrogen-Electricity Potential

The measurement of the energy content of hydrogen derived from biogas steam reforming was conducted by assessing its electricity generation capacity. In this study, the energy content of bio-H_2 was determined only by its capacity to generate electricity for various applications. One of the many applications for hydrogen's outstanding energy carrier capabilities is the production of energy [36] which is one of the most environmentally friendly ways to produce electricity [37]. Biomass-based hydrogen production has emerged as a promising electricity potential [38]. In addition, utilizing biomass waste for energy production has significant environmental benefits and achieves an excellent 94.33% ecological efficiency rating. Hydrogen production and its electricity potential positively correlate with steam reforming efficiency and the biomass waste collection rate [17]. The hydrogen-electricity potential ($H_{2_{(Elec.)}}$) was determined based on Equation (14).

$$H_{2_{(Elec.)}} = \delta \times LHV_{(hydrogen)} \times density_{(H_2)} \times H_{2_{(Q)}} \tag{14}$$

where δ represents the fuel cells electricity conversion rate (taken as 60%) from Alves *et al.* [33]; $LHV_{(hydrogen)}$ represents H_2 lower heating value (LHV) which is 33.3 kWh [39] and $density_{(H_2)}$ is the density of hydrogen considered as 0.09 kg/m^3 [17].

2.5. Economics of Hydrogen Generation

The parameters used to determine the H_2 costs are the project's operations and maintenance cost, the initial cost of investing in the biogas steam reformer, boiler and other variables. The estimation of hydrogen cost was based on Equation (15) to Equation (20).

$$Cost_{H_2} = M_{Cost} + \frac{I_{cost} \times F}{hrs \times H_{2_{(Elec.)}}} + Pn_{cost} \tag{15}$$

$$P_{cost} = \frac{Po_{bio} \times Bio_{cost}}{H_{2_{(Elec.)}}} \tag{16}$$

$$Bio_{cost} = M_{bio} \times LHV_{bio} \tag{17}$$

$$M_{Cost} = \frac{I_{cost} \times F}{hrs \times H_{2_{(Elec.)}}} \times 0.03 \tag{18}$$

$$F = \frac{k^n \times (k-1)}{k^n - 1} \tag{19}$$

$$k = 1 + \frac{ir}{100} \tag{20}$$

$Cost_{H_2}$ = cost of hydrogen; Pn_{cost} = operations cost; M_{Cost} = maintenance cost; I_{cost} = initial cost is taken as \$15000 [29]; hrs = hours per year; F = annuity factor; Po_{bio} = power of biogas; Bio_{cost} = cost of biogas taken as \$0.0518/kWh [29]; M_{bio} = mass of biogas (kg); LHV_{bio} = biogas lower heating value taken as 10.514 kWh/kg [34]; n = total project period (10 years); and ir = interest rate.

A project's economic viability is measured by its net present value (NPV); specifically, a positive net present value denotes an economically viable project, while a negative net present value denotes an economically unviable enterprise [40]. The NPV ($P_{j_{NPV}}$) for the project was determined based on Equation (21) to Equation (25).

$$P_{j_{NPV}} = \sum\nolimits_{n=0}^{y} \frac{C_n}{\left(RD_r + 1\right)^n} = I_{cost} + \frac{C_1}{\left(RD_r + 1\right)^1} + \cdots + \frac{C_y}{\left(RD_r + 1\right)^n} \tag{21}$$

$$P_{j_{REV}} = Cost_{H_2} \times H_{2(Q)} \tag{22}$$

$$P_{j_{tax}} = Tax_{(IPG)} \times P_{j_{REV}} \tag{23}$$

$$P_{j_{profit}} = P_{j_{REV}} - P_{j_{tax}} - Pn_{cost} - M_{Cost} \tag{24}$$

$$RD_r = \frac{\propto + 1}{I_{f_{rate}} + 1} - 1 \tag{25}$$

C_n = net cash flows; RD_r = annual real discount; $P_{j_{REV}}$ = revenue generated; $P_{j_{tax}}$ = tax paid by the project; $Tax_{(IPG)}$ = Ghana's tax on incomes, profits and capital [41]; $P_{j_{profit}}$ = project profit; $I_{f_{rate}}$ = inflation rate in Ghana [42]; $\propto$ = nominal discount [34].

The benefit-to-cost ratio (BCR) is an indicator of profitability related to the net present value. It measures the relationship between the system's lifetime investment costs and overall earnings [40]. The benefit-to-cost ratio is estimated based on Equation (26).

$$P_{j_{BCR}} = \frac{P_{j_{NPV}}}{T_{IVC}} + 1 \tag{26}$$

$P_{j_{BCR}}$ = the project BCR, T_{IVC} = is the total investment cost.

2.6. The Environmental Evaluation of Hydrogen-Electricity

2.6.1. Diesel Fuel Displaced

In Ghana, several socioeconomic groups are forced to use generators due to inadequate state energy delivery [43]. These generators commonly supply the electricity in urban and rural areas because the utility sector cannot produce enough power to fulfill the rising electricity demand. The primary fuel source for these generators is fossil diesel, which has potential severe environmental consequences. Hydrogen gas could offset large amounts of diesel, resulting in huge cost savings. The electricity demand-supply mismatch may be resolved by replacing diesel generators with hydrogen-powered fuel cells [17]. Equation (27) was used to calculate the quantity of diesel fuel (DF) that could be offset by hydrogen-electricity produced from residues [34].

$$D_{(fuel)} = \frac{\delta \times LHV_{(hydrogen)} \times density_{(H_2)} \times H_{2(Q)}}{D_{(Den)} \times \dfrac{LHV_{(D)}}{\gamma} * Gen_{(\varepsilon)}} \tag{27}$$

where $D_{(Den)}$ represents diesel density which is 0.84 kg/litre [44]; $LHV_{(D)}$ represents diesel LHV which is 42.5 MJ/kg [45]; γ denotes MJ to kWh conversion factor and $Gen_{(\varepsilon)}$ denotes diesel generator efficiency of 33% [46].

2.6.2. The Estimation of the Global Warming Mitigation Potential

The release of CO_2, CH_4, and nitrous oxide (N_2O) from diesel fuel generators poses severe problems [47]. The energy industry is key to preventing irreversible climate change because it is the main generator of greenhouse gas emissions. If clean, renewable energy replaces fossil fuels, carbon emissions might significantly decrease [48]. Hydrogen-powered fuel cells have proposed a possible solution to the energy-environment gap [17]. Given this, Equation (28) to Equation (30) were used to estimate the global warming mitigation potential (GWP).

$$CO_{2_{eq}}(\varphi) = CO_{2(GW)} \times \breve{\text{Ж}}_{(CO_2)} \times D_{(fuel)} \tag{28}$$

$$CO_{2_{eq}}(\aleph) = N_2O_{(GW)} \times \breve{\text{Ж}}_{(N_2O)} \times D_{(fuel)} \tag{29}$$

$$CO_{2_{eq}}(\vartheta) = CH_{4(GW)} \times \breve{\text{Ж}}_{(CH_4)} \times D_{(fuel)} \tag{30}$$

The total global warming mitigation potential ($GWP_{(T)}$) was estimated as:

$$GWP_{(T)} = CO_{2_{eq}}(\varphi) + CO_{2_{eq}}(\aleph) + CO_{2_{eq}}(\vartheta) \tag{31}$$

where $CO_{2_{eq}}(\aleph)$, $CO_{2_{eq}}(\varphi)$ and $CO_{2_{eq}}(\vartheta)$ are the nitrous oxide, carbon dioxide and methane CO_2 equivalents; $\breve{\text{Ж}}_{(CO_2)}$, $\breve{\text{Ж}}_{(N_2O)}$, $\breve{\text{Ж}}_{(CH_4)}$ are diesel-specific emission factors for CO_2, N_2O and CH_4 taken as 2.7 kg/liters, 2.167×10^{-5} kg/liters and 3.612×10^{-4} kg/liters; $CO_{2(GW)}$, $N_2O_{(GW)}$ and $CH_{4(GW)}$ GWP of CO_2, N_2O, and CH_4 considered as 1 kg $CO_{2_{eq}}$, 32 kg $CO_{2_{eq}}$ and 298 kg $CO_{2_{eq}}$, respectively [49] [50] [51].

3. Results

3.1. Biogas to Bio-Hydrogen Generation from Agricultural Residues

The study evaluated the potential for producing purified biogas in Ghana using anaerobic digestion technology. Biogas steam reforming was used to determine the amount of hydrogen gas that could be generated. **Figure 2** shows the purified biogas and hydrogen gas potential from agricultural residues. The findings indicate that 11406.03 million cubic meters (Mm^3) of purified biogas were obtained within the study's timeframe (2011-2020), with an annual potential of 1140.60 Mm^3. The purified biogas potential increased from 974.80 Mm^3 (2011) to 1402.05 Mm^3 (2020). In addition, the residues from yam had the most purified biogas potential of 2903.12 Mm^3 for the period and an annual potential of 290.31 Mm^3, and maize residues had the second-highest share of 2853.21 Mm^3 (2011-2020) and 285.32 Mm^3 (yearly potential). For the annual share, the other residues with a significant purified biogas yield were plantain residues (196.42 Mm^3),

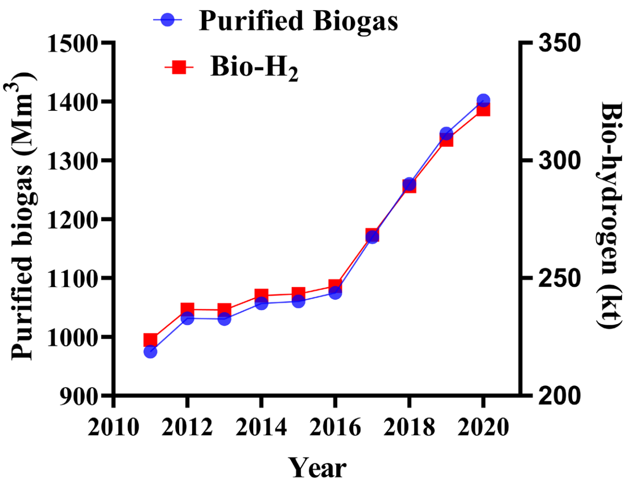

Figure 2. Purified biogas and bio-hydrogen from agricultural residues.

cassava residues (144.02 Mm^3), and cocoa pods (53.07 Mm^3). It was found that the annual purified biogas from oil palm (16.45 Mm^3), groundnuts (13.11 Mm^3), and millet (12.71 Mm^3) residues were not promising.

The findings showed that hydrogen production increased from 223.66 kilotons (kt) (2011) to 321.69 kt (2020). The overall output potential of hydrogen for the project is 2,617 kt. It was also discovered that the average annual production of bio-H$_2$ was 261.70 kt. During the period, the total bio-H$_2$ gas generated for the topmost residues were 666.09 kt (yam residues), 654.64 kt (maize residues), 450.66 kt (plantain residues), 330.44 kt (cassava residues), and 121.75 kt from cocoa pods. These residues contributed 66.61 kt, 65.46 kt, 45.07 kt, 33.04 kt, and 12.18 kt of bio-H$_2$ gas yearly. From the results, yam (25.45%) and maize (25.01%) residues produced 50.47% of the total bio-H$_2$. Plantain residues account for 17.22%, cassava (12.63%), and cocoa had 4.65%. The annual bio-H$_2$ potential for sorghum, rice, cowpea, soybeans, oil palm, and groundnut residues was 8.91 kt, 7.56 kt, 6.95 kt, 6.22 kt, 3.78 kt, and 3.01 kt. Millet residues had the most negligible contribution of 29.17 kt (1.11%) for the period and a lower annual yield of 2.92 kt. The study shows that one tonne (1000 kg) of residues could produce about 16.59 kg of bio-H$_2$. Table 1 shows (see column 2) the bio-H$_2$ gas generation capacity for a tonne of the different types of residues.

3.2. Electricity Potential of Bio-Hydrogen

From the study, hydrogen gas was produced by biogas steam reforming, and its potential for generating energy was measured. The study demonstrated that a tonne (1000 kg) of residues could produce 29.83 kWh of electricity, while the specific energy generation potential per tonne of the residues is depicted in Table 1 (see column 3). The results of the electricity potential of bio-hydrogen are presented in Figure 3. The study reveals that a good amount of electricity can be generated with a total capacity of 4,705.89 GWh for the period. The electricity generation capacity in 2011 was 402.18 GWh which observed a steady increase in production of 578.45 GWh in 2020. In addition, the findings show that Ghana can generate 470.59 GWh annually. Substantial electricity was produced from yam, maize, plantain, and cassava residues, with a total production for the project period of 1197.77 GWh, 1177.17 GWh, 810.38 GWh, and 594.19 GWh.

These residues had an annual electricity potential of 119.78 GWh (yam residues), 117.72 GWh (maize residues), 81.04 GWh (plantain residues), and 59.42 GWh (cassava residues). Yam and maize residues provided a promising energy potential, accounting for 50.47% of the total power. The study highlights that the total energy share of the agro-wastes for cocoa pods was 218.94 GWh, followed by sorghum (160.260 GWh), rice (135.98 GWh), cowpea (124.99 GWh), soybeans (111.79 GWh), oil palm (67.89 GWh) and groundnut (54.08 GWh), whiles millet had the least of 52.45 GWh. The annual electricity from these seven residues had a lower annual power ranging from 21.89 GWh to 5.24 GWh.

Table 1. Hydrogen and electricity generation potential per tonne of residues.

Agricultural residue	H_2 potential (Kg)	Electricity (kWh)
M-R	17.81	32.02
R-R	16.43	29.54
Sg-R	19.84	35.67
Mi-R	11.75	21.13
Sy-R	13.96	25.10
Gn-R	2.67	4.80
Cp-R	18.87	33.92
Y-R	22.44	40.36
Cs-R	18.88	33.94
Pt-R	20.94	37.65
Cc-R	19.31	34.72
Op-R	16.21	29.15

M-R = maize residues, R-R = rice residues, Sg-R = sorghum residues, Mi-R = millet residues, Sy-R = soybean residues, Gn-R = groundnut residues, Cp-R = cowpea residues, Y-R = yam residues, Cs-R = cassava residues, Pt-R = plantain residues, Op-R = oil palm residues and Cc-R = cocoa residues.

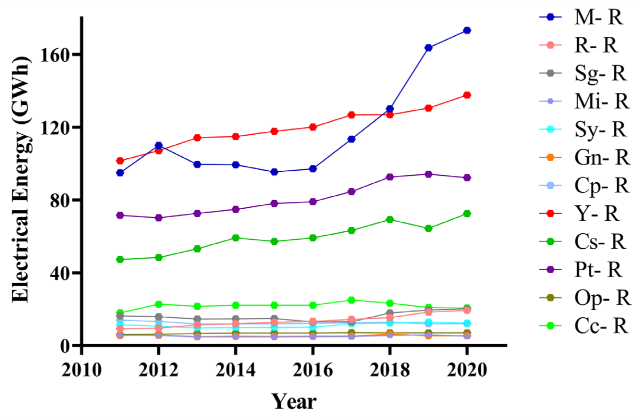

Figure 3. Electricity potential of bio-H_2.

3.3. Economics of the Electricity Potential of Bio-Hydrogen

The economic assessment was based on the total bio-H_2 and electricity generated for the project period. The study shows that the total cost of operations will be \$8206094949.27, with an annual cost of \$820609494.93, corresponding to \$1.744/kWh. The total maintenance cost is \$24501036.03 with a yearly output of \$2450103.60; this corresponds to \$0.005/kWh. The hydrogen production cost was \$816701202.71, which will have a yearly bio-H_2 cost of \$81670120.27. The cost per kWh of electricity was estimated at \$0.174. The project's revenue for the 10 years is \$454177067.46 and could generate a total profit of \$258880926.71, leading to an annual profit margin of \$25888092.67. The sum of net cash flow was estimated at \$234364892.43. The project has an annual positive NPV value of \$213555060.94 corresponding to \$2135550609.45 (2011-2020). The positive NPV values exemplify that using residues for bio-H_2 for power generation is economically viable. Similarly, the study had a BCR value of 1.26, which is encouraging and implies it is worth investing in the project.

3.4. The Diesel Fuel Displacement and Global Warming Mitigation Potential

The diesel displacement capacity of bio-H_2 energy was determined. The results show that 142.11 million liters (ML) of diesel can be displaced annually. The study discovered that 1421.09 ML of fossil diesel consumption could be avoided during the project period, with a diesel displacement capacity of 121.45 ML in 2011 and 174.68 ML in 2020. Table 2 shows the fossil diesel that was displaced for the project period. Yam and maize residues could displace 36.17 ML and 35.55 ML per year, representing 50.47% of the total displaced diesel potential of the project.

The remaining 10 residues contribute to 49.53% of the total diesel avoided. Given this, the amount of diesel that could be displaced per year by plantain residues is 24.47 ML, with cassava residues contributing 17.94 ML. In addition, cocoa, sorghum, rice, cowpea, soybeans, oil palm, groundnut, and millet residues had an annual diesel displacement potential of 6.61 ML, 4.84 ML, 4.11 ML, 3.77 ML, 3.38 ML, 2.05 ML, 1.63 ML, and 1.58 ML. On average, a tonne of residues for H_2-power could displace 9.01 L of fossil diesel, and Figure 4 shows the quantity of diesel displaced per tonne of the specific residues. The study demonstrates that bio-H_2 electricity has environmental co-benefits, with global warming mitigation potential of 24.49 kg CO_2eq per tonne of residue. Figure 4 depicts the global warming reduction potential per tonne for all the crop residues. It was also discovered that 1 kg of H_2 could mitigate 1.48 kg CO_2eq. Within the period, 3862.55 kt CO_2eq could be avoided with an annual reduction potential of 386.26 kt CO_2eq. In addition, from 2011 to 2020, global warming mitigation increased from 330.11 kt CO_2eq to 474.79 kt CO_2eq.

It was also revealed that for the specific residues, the total global warming reduction potential for yam and maize was 983.12 kt CO_2eq and 966.21 kt CO_2eq, demonstrating that these residues could save 98.31 kt CO_2eq and 96.62 kt CO_2eq per year. Similarly, the two residues mentioned above contribute 50.47% of the total CO_2 reduction. **Figure 5** highlights residues' carbon emission reduction potential. The other residues could avoid CO_2 emissions with annual mitigation potential for plantain as 66.52 CO_2eq followed by cassava (48.77 kt CO_2eq), cocoa (17.97 kt CO_2eq), sorghum (13.15 kt CO_2eq), rice (11.16 kt CO_2eq), cowpea (10.26 kt CO_2eq), soybeans (9.18 kt CO_2eq) and oil palm (5.57 kt CO_2eq). Groundnut and millet had a CO_2 reduction potential of less than 5 kt CO_2eq each. Similarly, the total global warming reduction potential for the 10 agricultural residues was from 665.16 kt CO_2eq to 43.05 kt CO_2eq, contributing to 49.53% of the emission reduction.

Table 2. Fossil diesel displacement potential of agricultural residues based on H_2-power (ML).

Year	M-R	R-R	Sg-R	Mi-R	Sy-R	Gn-R	Cp-R	Y-R	Cs-R	Pt-R	Op-R	Cc-R
2011	28.69	2.79	4.92	1.72	3.49	1.70	4.24	30.69	14.31	21.61	1.83	5.46
2012	33.23	2.90	4.80	1.68	3.22	1.73	4.00	32.36	14.61	21.23	1.89	6.86
2013	30.07	3.43	4.40	1.45	2.94	1.49	3.59	34.49	16.06	21.94	2.00	6.52
2014	30.02	3.64	4.44	1.45	3.00	1.56	3.61	34.70	17.88	22.60	2.10	6.70
2015	28.82	3.86	4.50	1.47	3.02	1.52	3.64	35.57	17.29	23.59	2.10	6.70
2016	29.34	4.04	3.94	1.49	3.04	1.55	3.70	36.27	17.88	23.88	2.10	6.70
2017	34.27	4.35	3.94	1.53	3.62	1.58	3.79	38.30	19.10	25.54	2.14	7.56
2018	39.30	4.63	5.42	1.70	3.75	1.90	3.86	38.31	20.94	27.99	2.11	7.06
2019	49.41	5.57	5.92	1.78	3.92	1.64	3.63	39.42	19.46	28.46	2.12	6.33
2020	52.33	5.86	6.10	1.59	3.76	1.64	3.67	41.60	21.91	27.87	2.12	6.24
Total	355.48	41.06	48.40	15.84	33.76	16.33	37.74	361.70	179.44	244.72	20.50	66.12

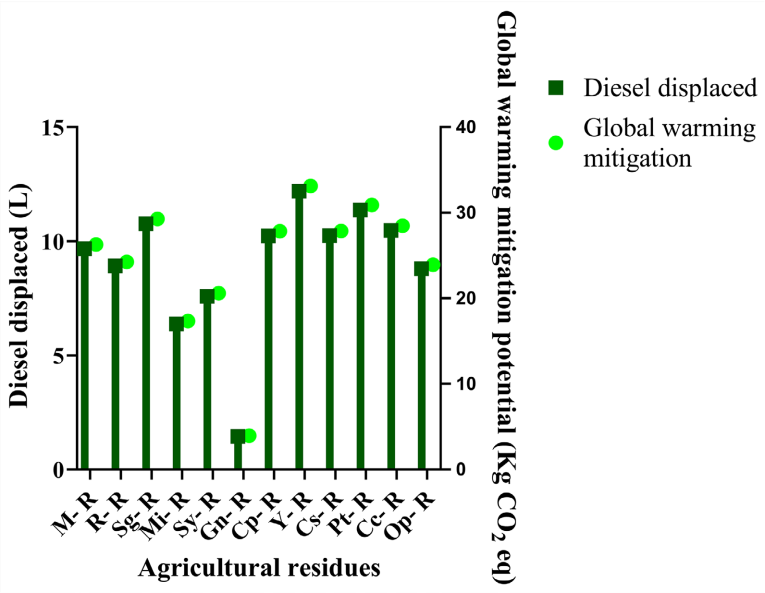

Figure 4. Diesel displaced and global warming mitigation potential per tonne of residues.

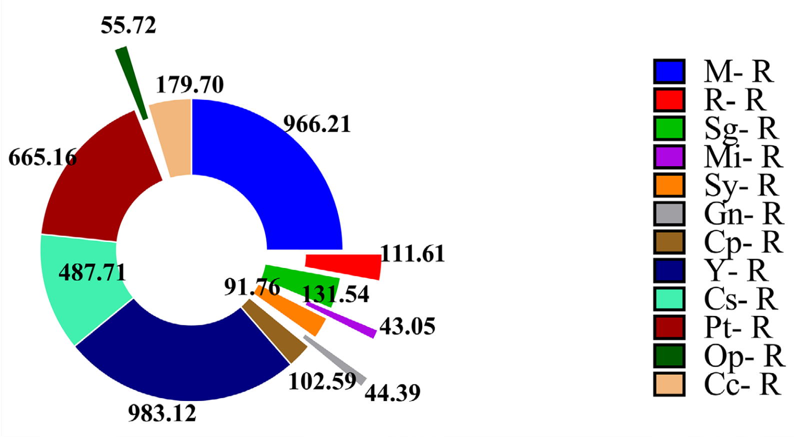

Figure 5. Carbon emission reduction potential of bio-H_2 electricity.

4. Discussions

4.1. Bio-Hydrogen and Electricity Generation

The study highlights that agricultural residues offer a promising alternative for producing sustainable hydrogen. Hydrogen demand from 2020 to 2021 increased by 5%, and global demand for hydrogen in 2021 was 94 Mt [52], indicating that the bio-H_2 produced in this study may meet 2.78% of the global demand for hydrogen. The study reveals that yam, plantain, cassava, and maize residues have a greater potential for bio-H_2. The residues with higher quantities equally had an increased bio-hydrogen generation potential [12].

The annual bio-H_2 production (261.70 kt) from residues is close to the annual H_2 production (284.93 kt) from food waste in Lagos reported by Ayodele *et al.* [17]. The findings partly agree with, Asadi *et al.* [16], where the grain crops residues such as maize had the greatest impact on bio-H_2. Results from the previous authors revealed that a tonne of residues could generate an average of 7.16 kg of H_2, which is lower than the H_2 potential in the current paper of 16.59 kg. This difference is attributable to the fact that the previous paper used a mathematical framework to study bio-hydrogen synthesis, whereas the current study was based on biogas steam reforming. This development proves that biogas steam reforming has higher hydrogen generation potential, and the technology can be adopted in Ghana. According to earlier research, through the biochemical generation of bio-H_2, one tonne of maize residues may generate 9.11 kg of H_2, and one tonne of rice residues can generate 7.69 kg of H_2 [53]. These values are less than the existing values of 17.81 kg H_2 (one tonne of maize residues) and 16.43 kg H_2 (one tonne of rice residues), indicating that biogas steam reforming has a greater hydrogen potential. Also, an assessment from previous research revealed that about 84.87 kg of H_2 could be generated per tonne of food waste. The significant difference is due to food waste's higher carbohydrate and biodegradable content [34]. Based on the lignocellulosic content of residues, the value presented in this research is lower. The results align with previous research where the authors discovered that maize residues provide 20% to 28% hydrogen

[54]. According to Wei *et al.* [55], a low hydrogen yield was found in rice residues which share similarities with this study.

According to the Energy Commission [56], Ghana consumed a total of 21466 GWh of electricity. Given this value, the findings show that the current power potential could displace 21.92% of the energy consumption. Compared to other agro-wastes, yam, maize, plantain, and cassava have impressive electricity generation potential and can be exploited as sustainable renewable energy resources. The results are consistent with Cudjoe *et al.* [34], who confirmed H_2 (221.12 billion kg) from biomass resources (food waste) has a substantial electricity generation potential of 661.97 TWh. In contrast, an assessment of the previous paper showed 1 kg of H_2 from food wastes corresponds to 2.99 kWh, whereas the current paper reveals that 1 kg of H_2 from agricultural residues corresponds to 1.80 kWh. The variances are due to the diverse composition of the feedstocks. Based on fuel cell-hydrogen-wind technology, Acakpovi *et al.* [19] determined that Ghana can produce 25999 kWh annually. The value obtained by Acakpovi *et al.* [19] is less than the yearly power generation potential estimated by the current study, which is 470.59 GWh. This demonstrates that utilizing residues for bio-H_2 synthesis through biogas steam reforming has high electricity potential. Like others in Africa, Ghana's economy has seen energy demand expand faster than supply [57]. Ghana aims for 10% renewable energy by 2030, and hydrogen is considered an alternative to fossil fuels [58]. Using residues to generate hydrogen keeps biomass in the technology cycle longer, forming a closed loop and promoting sustainable energy security to advance the circular bioeconomy.

4.2. Economic and Environmental Context

The results demonstrate that the project is economically viable and will give investors some returns. The electricity cost in the current paper ($0.174/kWh) contrasts with Cudjoe *et al.* [34], in which the authors reported a cost of $0.814/kWh. This could be attributable to the fact that agricultural residues were utilized as feedstock in the current investigation, whereas food wastes were used in the earlier study. This implies that using crop residues for bio-H_2 electricity is cheaper than using food wastes. According to Acakpovi *et al.* [19] the cost of electricity from fuel cell-hydrogen-wind technology per kWh is $0.602. The cost from the earlier research is more expensive than the current price ($0.174/kWh). This means that the technology applied in this study is cost-effective. The positive net present value values imply that investing in residues-H_2 energy generation is worthwhile. The findings concur with Lui *et al.* [59], who verified that using biomass for bio-hydrogen had positive NPV in all scenarios. This shows that using residues as feedstock for biogas steam reforming to produce hydrogen will be profitable. The benefit-to-cost ratio for the study was more than one and the paper partly corresponds to Abdelhady [40], who had a benefit-to-cost ratio greater than one (1.06). The discrepancy between the present number and the earlier value is attributable to the fact that the current study used residues, whereas the earlier paper relied on solar energy. Using crop residues for hydrogen power generation has a higher benefit-to-cost ratio and can yield more profits. When the benefit-to-cost ratio is more than one, it indicates that investment in the project will generate a profit. On the other hand, a $BCR < 1$ will generate a loss, and a $BCR = 1$ implies there will be no profit or loss. The paper reveals that biogas steam reforming is an economically viable technology that can be implemented in Ghana.

The study garnered that large amounts of diesel could be displaced by H_2 electricity, reducing pollution and cutting down costs. The displacement of fossil fuel in Ghana by using hydrogen power will be a relief, as many individuals have voiced concerns about the rising price of fossil diesel. As of 12 September 2022, the price of 1 liter of diesel in Ghana was 14.260 Ghana cedis (GS), equivalent to $1.440 [60]. This implies that for the project period, 20264.743 Ghana cedis (equivalent to $2046.360) could be saved when diesel is displaced. The findings of the fossil diesel displacement of H_2 electricity are consistent with Ayodele *et al.* [17], who emphasized about 7.446 ML of diesel fuel. Similarly, the results agree with previous findings where 15482.26 ML of diesel fuel was replaced with power generated from hydrogen gas [34].

In Ghana, the GHG emissions are estimated at 37650 kt CO_2 [61]. Compared to the CO_2 emission reduction potential of the present study, this could offset 10.26% of the total emissions in Ghana. The study exemplifies that bio-hydrogen has the potential to reduce global warming, which aligns with earlier research. The study is consistent with Alves *et al.* [33], who indicated that generating hydrogen from renewable resources like biogas significantly reduces GHG emissions. Biogas steam reforming as a technology for bio-H_2 production was studied using a life cycle assessment which revealed that 5.59 kg CO_2eq could be obtained from a kg of H_2 [62]. This value is higher than the findings from the current paper because this paper only considered the emission reduction from fossil diesel. The CO_2 savings from bio-H_2 implies that the technology can positively influence the bioeconomy. Using residues for bio-H_2 electricity generation is cheaper, more profitable for investors, and significantly decreases CO_2 emissions, which aligns with the circular bioeconomy concept.

4.3. Circular Bioeconomy and Sustainable Development Goals

The circular bioeconomy movement unites the circular economy and bioeconomy agendas to attain sustainability [63]. Among the 2030 sustainable development goals, 12 goals are linked to the circular bioeconomy [64]. Through the current study, SDG 2 (zero hunger) can be achieved in Ghana. Farmers will benefit from improved crop yields and increased income by using digestate from biogas as fertilizer. This will ensure that food is available all year, and farmers will have enough money to purchase other foodstuffs they do not cultivate to feed their families. Food prices will be affordable when there is an excess of food in the country. Sustainable development goal 3 (good health and wellbeing) can be attained since bio-hydrogen power reduces pollution.

Additionally, the rate of burning agricultural residues will reduce, and humans and other living species will be healthier. Less land and water pollution will result in the achievement of sustainable development goal 6 (clean water and sanitation). Healthy people will not frequently visit hospitals, resulting in a drop in expenses, and people can save more money. Bioelectricity production would ensure people access cheaper, ecologically sustainable electricity, in line with SDG 7 (affordable and clean energy). Establishing bioenergy plants, particularly in regions with significant production of residues from maize, yam, plantain, and cassava will create employment opportunities which will help achieve SDG 8 (decent work and economic growth).

Bio-hydrogen is the innovative fuel of the future that will advance the creation of anaerobic digestion plants and other sectors. Establishing fertilizer and food processing plants could contribute to reaching SDG 9 (industry, innovation and infrastructure). Implementing the project will promote sustainability in the administrative areas. This will result in the sustainable production of food and energy and its consumption. SDG 11 (sustainable cities and communities) and SDG 12 (responsible consumption and production) will be accomplished. Since the project will reduce Ghana's GHG emissions by 10.26%, it will contribute to achieving sustainable development goal 13's carbon neutrality target (climate action). Also, both terrestrial and aquatic organisms will be safeguarded, as neither land nor water will be contaminated. Consequently, SDG 14 (life below water) and SDG 15 (life on land) will be met. In order to accomplish the sustainable development goals, the circular bioeconomy offers a systems approach to the sustainable usage of biological resources for improved production, environment, and quality of life [64]. Utilizing agricultural residues for hydrogen production will ensure the efficient use of resources. This will contribute to Ghana's green development by promoting sustainable development by providing green energy. In light of this, the project will not only serve as a strategy for mitigating the effects of climate change but also create jobs for citizens and improve off-farm agricultural enterprises. The hydrogen market is rapidly increasing and exhibiting features of an integrated industry [7] [65]. A sustainable future can be attained by using bio-hydrogen as an alternative to fossil fuels [66]. This study serves as a strategic innovation pillar to produce electricity from hydrogen using residues which can help Ghana achieve the 2030 Sustainable development goals.

5. Conclusion

Assessing the economic and global warming mitigation potential of residues' hydrogen-electricity potential in Ghana can generate 11406.03 Mm^3 of purified biogas corresponding to 2617 kt of bio-H_2. This bio-hydrogen can meet 2.78% of the global hydrogen demand. The projects' total electricity produced (4705.89 GWh) can replace 21.92% of electricity consumed in Ghana. The generation of hydrogen-electricity from crop residues is a viable option that offers significant environmental and economic advantages. This technology has the potential to contribute to energy security and climate change mitigation in Ghana and other West African nations. However, subsequent investigations could undertake more and comprehensive research on the cost of installation for the conversion process. Using agricultural residues to produce hydrogen will extend biomass's reuse in the technological cycle to help promote circular bioeconomic development. This would promote sustainable energy generation, which has socioeconomic and environmental benefits and assist Ghana in achieving its renewable energy target (10%) and SDGs by 2030.

Authors' Contributions

Patience Afi Seglah: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing: original draft. **Komikouma Apelike Wobuibe Neglo:** Methodology, Writing: review & editing.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Kapoor, R., Ghosh, P., Kumar, M., Sengupta, S., Gupta, A., Kumar, S.S., *et al.* (2020) Valorization of Agricultural Waste for Biogas Based Circular Economy in India: A Research Outlook. *Bioresource Technology*, **304**, Article 123036. https://doi.org/10.1016/j.biortech.2020.123036

[2] Scheiterle, L. and Birner, R. (2020) Considerations on the Role of Institutions and Networks in the Bioeconomy: Three Case Studies from Ghana and Brazil. ZEF Working Paper Series, No. 196.

[3] D'Amato, D., Veijonaho, S. and Toppinen, A. (2020) towards Sustainability? Forest-based Circular Bioeconomy Business Models in Finnish Smes. *Forest Policy and Economics*, **110**, Article 101848. https://doi.org/10.1016/j.forpol.2018.12.004

[4] Klitkou, A. and Bolwig, S. (2019) Adding Value to Side-Streams in the Food and Be-Verage Industry: Lessons for the Circular Bioeconomy. https://nifu.brage.unit.no/nifu-xmlui/bitstream/handle/11250/2600676/2019-12%20Adding_value.pdf?sequence=1&isAllowed=y

[5] Salvador, R., Puglieri, F.N., Halog, A., Andrade, F.G.d., Piekarski, C.M. and De Francisco, A.C. (2021) Key Aspects for Designing Business Models for a Circular Bioeconomy. *Journal of Cleaner Production*, **278**, Article 124341. https://doi.org/10.1016/j.jclepro.2020.124341

[6] Gatto, F. and Re, I. (2021) Circular Bioeconomy Business Models to Overcome the Valley of Death. A Systematic Statistical Analysis of Studies and Projects in Emerging Bio-Based Technologies and Trends Linked to the Sme Instrument Support. *Sustainability*, **13**, Article 1899. https://doi.org/10.3390/su13041899

[7] Mak, T.M.W., Xiong, X., Tsang, D.C.W., Yu, I.K.M. and Poon, C.S. (2020) Sustainable Food Waste Management towards Circular Bioeconomy: Policy Review, Limitations and Opportunities. *Bioresource Technology*, **297**, Article 122497. https://doi.org/10.1016/j.biortech.2019.122497

[8] Hosseini, S.E., Andwari, A.M., Wahid, M.A. and Bagheri, G. (2013) A Review on Green Energy Potentials in Iran. *Renewable and Sustainable Energy Reviews*, **27**,

533-545. https://doi.org/10.1016/j.rser.2013.07.015

[9] Banerjee, A., Schelly, C.L. and Halvorsen, K.E. (2018) Constructing a Sustainable Bioeconomy: Multi-Scalar Perceptions of Sustainability. In: Leal Filho, W., Pociovălişteanu, D., Borges de Brito, P. and Borges de Lima, I., Eds., *Towards a Sustainable Bioeconomy: Principles, Challenges and Perspectives*, World Sustainability Series, 355-374.

[10] Hosseini, S.E. and Wahid, M.A. (2016) Hydrogen Production from Renewable and Sustainable Energy Resources: Promising Green Energy Carrier for Clean Development. *Renewable and Sustainable Energy Reviews*, **57**, 850-866. https://doi.org/10.1016/j.rser.2015.12.112

[11] Wang, Y., Li, G., Liu, Z., Cui, P., Zhu, Z. and Yang, S. (2019) Techno-Economic Analysis of Biomass-to-Hydrogen Process in Comparison with Coal-to-Hydrogen Process. *Energy*, **185**, 1063-1075. https://doi.org/10.1016/j.energy.2019.07.119

[12] Bundhoo, Z.M.A. (2019) Potential of Bio-Hydrogen Production from Dark Fermentation of Crop Residues: A Review. *International Journal of Hydrogen Energy*, **44**, 17346-17362. https://doi.org/10.1016/j.ijhydene.2018.11.098

[13] Urbaniec, K. and Bakker, R.R. (2015) Biomass Residues as Raw Material for Dark Hydrogen Fermentation—A Review. *International Journal of Hydrogen Energy*, **40**, 3648-3658. https://doi.org/10.1016/j.ijhydene.2015.01.073

[14] Levin, D.B., Zhu, H., Beland, M., Cicek, N. and Holbein, B.E. (2007) Potential for Hydrogen and Methane Production from Biomass Residues in Canada. *Bioresource Technology*, **98**, 654-660. https://doi.org/10.1016/j.biortech.2006.02.027

[15] Saebea, D., Authayanun, S., Patcharavorachot, Y. and Arpornwichanop, A. (2014) Thermodynamic Analysis of Hydrogen Production from the Adsorption-Enhanced Steam Reforming of Biogas. *Energy Procedia*, **61**, 2254-2257. https://doi.org/10.1016/j.egypro.2014.12.120

[16] Asadi, N., Karimi Alavijeh, M. and Zilouei, H. (2017) Development of a Mathematical Methodology to Investigate Biohydrogen Production from Regional and National Agricultural Crop Residues: A Case Study of Iran. *International Journal of Hydrogen Energy*, **42**, 1989-2007. https://doi.org/10.1016/j.ijhydene.2016.10.021

[17] Ayodele, T.R., Alao, M.A., Ogunjuyigbe, A.S.O. and Munda, J.L. (2019) Electricity Generation Prospective of Hydrogen Derived from Biogas Using Food Waste in South-Western Nigeria. *Biomass and Bioenergy*, **127**, Article 105291. https://doi.org/10.1016/j.biombioe.2019.105291

[18] Topriska, E., Kolokotroni, M., Dehouche, Z., Novieto, D.T. and Wilson, E.A. (2016) The Potential to Generate Solar Hydrogen for Cooking Applications: Case Studies of Ghana, Jamaica and Indonesia. *Renewable Energy*, **95**, 495-509. https://doi.org/10.1016/j.renene.2016.04.060

[19] Acakpovi, A., Adjei, P., Asabere, N.Y., Sowah, R.A. and Sackey, D.M. (2021) Techno-Economic Evaluation of Hydrogen Fuel Cell Electricity Generation Based on Anloga (Ghana) Wind Regime. *International Journal of Energy Optimization and Engineering*, **10**, 47-69. https://doi.org/10.4018/ijeoe.2021070103

[20] Agyekum, E.B., Nutakor, C., Agwa, A.M. and Kamel, S. (2022) A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-up and Its Role in Future Energy Generation. *Membranes*, **12**, Article 173. https://doi.org/10.3390/membranes12020173

[21] FAOSTAT (2022) Production: Crops and Livestock Products. https://www.fao.org/faostat/en/#data

[22] Ren, J., Yu, P. and Xu, X. (2019) Straw Utilization in China—Status and Recommendations. *Sustainability*, **11**, Article 1762. https://doi.org/10.3390/su11061762

[23] Kemausuor, F., Kamp, A., Thomsen, S.T., Bensah, E.C. and Østergård, H. (2014) Assessment of Biomass Residue Availability and Bioenergy Yields in Ghana. *Resources*, *Conservation and Recycling*, **86**, 28-37. https://doi.org/10.1016/j.resconrec.2014.01.007

[24] Jiang, Y., Havrysh, V., Klymchuk, O., Nitsenko, V., Balezentis, T. and Streimikiene, D. (2019) Utilization of Crop Residue for Power Generation: The Case of Ukraine. *Sustainability*, **11**, Article 7004. https://doi.org/10.3390/su11247004

[25] Kashif, M., Awan, M.B., Nawaz, S., Amjad, M., Talib, B., Farooq, M., *et al.* (2020) Untapped Renewable Energy Potential of Crop Residues in Pakistan: Challenges and Future Directions. *Journal of Environmental Management*, **256**, Article 109924. https://doi.org/10.1016/j.jenvman.2019.109924

[26] Cardoen, D., Joshi, P., Diels, L., Sarma, P.M. and Pant, D. (2015) Agriculture Biomass in India: Part 2. Post-Harvest Losses, Cost and Environmental Impacts. *Resources*, *Conservation and Recycling*, **101**, 143-153. https://doi.org/10.1016/j.resconrec.2015.06.002

[27] Prasad, S., Singh, A., Korres, N.E., Rathore, D., Sevda, S. and Pant, D. (2020) Sustainable Utilization of Crop Residues for Energy Generation: A Life Cycle Assessment (LCA) Perspective. *Bioresource Technology*, **303**, Article 122964. https://doi.org/10.1016/j.biortech.2020.122964

[28] Tayyab, A., Ahmad, Z., Mahmood, T., Khalid, A., Qadeer, S., Mahmood, S., *et al.* (2019) Anaerobic Co-Digestion of Catering Food Waste Utilizing Parthenium Hysterophorus as Co-Substrate for Biogas Production. *Biomass and Bioenergy*, **124**, 74-82. https://doi.org/10.1016/j.biombioe.2019.03.013

[29] Braga, L.B., Silveira, J.L., da Silva, M.E., Tuna, C.E., Machin, E.B. and Pedroso, D.T. (2013) Hydrogen Production by Biogas Steam Reforming: A Technical, Economic and Ecological Analysis. *Renewable and Sustainable Energy Reviews*, **28**, 166-173. https://doi.org/10.1016/j.rser.2013.07.060

[30] Ogunjuyigbe, A.S.O., Ayodele, T.R. and Alao, M.A. (2017) Electricity Generation from Municipal Solid Waste in Some Selected Cities of Nigeria: An Assessment of Feasibility, Potential and Technologies. *Renewable and Sustainable Energy Reviews*, **80**, 149-162. https://doi.org/10.1016/j.rser.2017.05.177

[31] Salami, L., Susu, A.A., Patinvoh, R.J. and Olafadehan, O.A. (2011) Characterisation Study of Solid Wastes: A Case of Lagos State. *International Journal of Applied Science and Technology*, **1**, 47-52.

[32] Rafiee, A., Khalilpour, K.R., Prest, J. and Skryabin, I. (2021) Biogas as an Energy Vector. *Biomass and Bioenergy*, **144**, Article 105935. https://doi.org/10.1016/j.biombioe.2020.105935

[33] Alves, H.J., Bley Junior, C., Niklevicz, R.R., Frigo, E.P., Frigo, M.S. and Coimbra-Araújo, C.H. (2013) Overview of Hydrogen Production Technologies from Biogas and the Applications in Fuel Cells. *International Journal of Hydrogen Energy*, **38**, 5215-5225. https://doi.org/10.1016/j.ijhydene.2013.02.057

[34] Cudjoe, D., Chen, W. and Zhu, B. (2022) Valorization of Food Waste into Hydrogen: Energy Potential, Economic Feasibility and Environmental Impact Analysis. *Fuel*, **324**, Article 124476. https://doi.org/10.1016/j.fuel.2022.124476

[35] Nikolaidis, P. and Poullikkas, A. (2017) A Comparative Overview of Hydrogen Production Processes. *Renewable and Sustainable Energy Reviews*, **67**, 597-611. https://doi.org/10.1016/j.rser.2016.09.044

[36] Sarrias-Mena, R., Fernández-Ramírez, L.M., García-Vázquez, C.A. and Jurado, F. (2015) Electrolyzer Models for Hydrogen Production from Wind Energy Systems. *International Journal of Hydrogen Energy*, **40**, 2927-2938. https://doi.org/10.1016/j.ijhydene.2014.12.125

[37] Ozturk, M. and Dincer, I. (2020) Life Cycle Assessment of Hydrogen-Based Electricity Generation in Place of Conventional Fuels for Residential Buildings. *International Journal of Hydrogen Energy*, **45**, 26536-26544. https://doi.org/10.1016/j.ijhydene.2019.05.150

[38] Wan Ab Karim Ghani, W.A., Moghadam, R.A., Salleh, M.A.M. and Alias, A.B. (2009) Air Gasification of Agricultural Waste in a Fluidized Bed Gasifier: Hydrogen Production Performance. *Energies*, **2**, 258-268. https://doi.org/10.3390/en20200258

[39] Dufo-López, R. and Bernal-Agustín, J.L. (2008) Multi-Objective Design of PV-Wind-Diesel-Hydrogen-Battery Systems. *Renewable Energy*, **33**, 2559-2572. https://doi.org/10.1016/j.renene.2008.02.027

[40] Abdelhady, S. (2021) Performance and Cost Evaluation of Solar Dish Power Plant: Sensitivity Analysis of Levelized Cost of Electricity (LCOE) and Net Present Value (NPV). *Renewable Energy*, **168**, 332-342. https://doi.org/10.1016/j.renene.2020.12.074

[41] Word Bank (2022) Taxes on Income, Profits and Capital Gains (% of Revenue)-Ghana. https://data.worldbank.org/indicator/GC.TAX.YPKG.RV.ZS?locations=GH

[42] Trading Economics (2022) Ghana Inflation Rate. https://tradingeconomics.com/ghana/inflation-cpi

[43] Boamah, F. and Rothfuß, E. (2018) From Technical Innovations towards Social Practices and Socio-Technical Transition? Re-Thinking the Transition to Decentralised Solar PV Electrification in Africa. *Energy Research & Social Science*, **42**, 1-10. https://doi.org/10.1016/j.erss.2018.02.019

[44] Massachusetts Institute of Technology (MIT) (2007) Units & Conversion Fact Sheet.

[45] Demirbas, A., Baluabaid, M.A., Kabli, M. and Ahmad, W. (2014) Diesel Fuel from Waste Lubricating Oil by Pyrolitic Distillation. *Petroleum Science and Technology*, **33**, 129-138. https://doi.org/10.1080/10916466.2014.955921

[46] Nizami, A.S., Shahzad, K., Rehan, M., Ouda, O.K.M., Khan, M.Z., Ismail, I.M.I., *et al.* (2017) Developing Waste Biorefinery in Makkah: A Way Forward to Convert Urban Waste into Renewable Energy. *Applied Energy*, **186**, 189-196. https://doi.org/10.1016/j.apenergy.2016.04.116

[47] Cook, B. (2002) Introduction to Fuel Cells and Hydrogen Technology. *Engineering Science & Education Journal*, **11**, 205-216. https://doi.org/10.1049/esej:20020601

[48] UN Climate Action (2022) For a Livable Climate: Net-Zero Commitments Must Be Backed by Credible Action. https://www.un.org/en/climatechange/net-zero-coalition

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

[50] Ayodele, T.R., Alao, M.A. and Ogunjuyigbe, A.S.O. (2020) Effect of Collection Efficiency and Oxidation Factor on Greenhouse Gas Emission and Life Cycle Cost of Landfill Distributed Energy Generation. *Sustainable Cities and Society*, **52**, Article 101821. https://doi.org/10.1016/j.scs.2019.101821

[51] Cudjoe, D., Wang, H. and zhu, B. (2022) Thermochemical Treatment of Daily COVID-19 Single-Use Facemask Waste: Power Generation Potential and Environmental Impact Analysis. *Energy*, **249**, Article 123707. https://doi.org/10.1016/j.energy.2022.123707

[52] IEA (2022) Hydrogen. https://www.iea.org/reports/hydrogen

[53] Karimi Alavijeh, M. and Yaghmaei, S. (2016) Biochemical Production of Bioenergy from Agricultural Crops and Residue in Iran. *Waste Management*, **52**, 375-394. https://doi.org/10.1016/j.wasman.2016.03.025

[54] Karimi Alavijeh, M., Yaghmaei, S. and Mardanpour, M.M. (2019) Assessment of Global Potential of Biohydrogen Production from Agricultural Residues and Its Application in Nitrogen Fertilizer Production. *BioEnergy Research*, **13**, 463-476. https://doi.org/10.1007/s12155-019-10046-1

[55] Wei, L., Yang, H., Li, B., Wei, X., Chen, L., Shao, J., *et al.* (2014) Absorption-Enhanced Steam Gasification of Biomass for Hydrogen Production: Effect of Calcium Oxide Addition on Steam Gasification of Pyrolytic Volatiles. *International Journal of Hydrogen Energy*, **39**, 15416-15423. https://doi.org/10.1016/j.ijhydene.2014.07.064

[56] Energy Commission (2022) 2022 Energy Outlook for Ghana. Demand and Supply Outlook.

[57] Kuamoah, C. (2020) Renewable Energy Deployment in Ghana: The Hype, Hope and Reality. *Insight on Africa*, **12**, 45-64. https://doi.org/10.1177/0975087819898581

[58] Crabtree, G.W. and Dresselhaus, M.S. (2008) The Hydrogen Fuel Alternative. *MRS Bulletin*, **33**, 421-428. https://doi.org/10.1557/mrs2008.84

[59] Lui, J., Paul, M.C., Sloan, W. and You, S. (2022) Techno-Economic Feasibility of Distributed Waste-to-Hydrogen Systems to Support Green Transport in Glasgow. *International Journal of Hydrogen Energy*, **47**, 13532-13551. https://doi.org/10.1016/j.ijhydene.2022.02.120

[60] GPP (2022) Ghana Diesel Prices, 03-Jun-2024. https://www.globalpetrolprices.com/Ghana/diesel_prices/

[61] World Bank (2022) Total Greenhouse Gas Emissions (kt of CO2 Equivalent)-Ghana. https://www.worldbank.org/en/search?q=Ghana+Greenhouse+Gas+%28GHG%29+Emissions+in+Ghana¤tTab=1&x=21&y=20

[62] Hajjaji, N., Martinez, S., Trably, E., Steyer, J. and Helias, A. (2016) Life Cycle Assessment of Hydrogen Production from Biogas Reforming. *International Journal of Hydrogen Energy*, **41**, 6064-6075. https://doi.org/10.1016/j.ijhydene.2016.03.006

[63] Hadley Kershaw, E., Hartley, S., McLeod, C. and Polson, P. (2021) The Sustainable Path to a Circular Bioeconomy. *Trends in Biotechnology*, **39**, 542-545. https://doi.org/10.1016/j.tibtech.2020.10.015

[64] FAO (2024) Sustainable and Circular Bioeconomy for Food Systems Transformation. https://www.fao.org/in-action/sustainable-and-circular-bioeconomy/overview/en/

[65] Dahiya, S., Kumar, A.N., Shanthi Sravan, J., Chatterjee, S., Sarkar, O. and Mohan, S.V. (2018) Food Waste Biorefinery: Sustainable Strategy for Circular Bioeconomy. *Bioresource Technology*, **248**, 2-12. https://doi.org/10.1016/j.biortech.2017.07.176

[66] Kumar, P., Mehariya, S., Ray, S., Mishra, A. and Kalia, V.C. (2014) Biodiesel Industry Waste: A Potential Source of Bioenergy and Biopolymers. *Indian Journal of Microbiology*, **55**, 1-7. https://doi.org/10.1007/s12088-014-0509-1