

Electricity Generation Potential from Hydrogen Generated from Municipal Food Waste and Its Environmental Impact in Rajshahi City, Bangladesh

Utsho Saha*, Md. Rezaul Karim, Rezaya Rabbi Rifat and Mim Mashrur Ahmed

Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Rajshahi-6204, Bangladesh

ABSTRACT

With the pressing need for cleaner energy alternatives due to limited fossil fuel resources and environmental concerns, the exploration of renewable energy sources has been perpetual. Despite numerous remarkable discoveries in this field, concern still arises due to the carbon footprints of many proposed solutions. Stating the concern, Hydrogen (H₂) emerges as a promising solution. Unlike other renewable fuels, H₂ doesn't involve any carbon-based emissions. This study explores various prospects of power generation using Hydrogen fuel derived from municipal solid waste's anaerobic digestion (AD). A comprehensive analysis, encompassing quantitative calculation was conducted to determine the potential of utilizing H₂ for power generation and environmental impacts over 20 years in Rajshahi city, Bangladesh. An ecological analysis was conducted to assess the potential environmental benefits associated with the system. It was evaluated that $17.24 \times 10^3 \text{ m}^3$ fossil fuel could be substituted with the produced H₂ per year and the net associated emission of greenhouse gases (GHGs) of 3.565 tons/year could be prevented. When compared with similar studies, RCC outperformed other locations in hydrogen-based power generation. Also, the sensitivity analysis determined the impact of the food waste collection rate on the proposed power generation system. This comprehensive analysis of the entire system will help the researchers and decision-makers make decisions regarding implementing hydrogen fuel-based plants in different cities of Bangladesh alongside Rajshahi.

Keywords: Hydrogen, Electricity, Greenhouse gas, Solid waste, Sustainability.



Copyright @ All authors

This work is licensed under a [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The increasing standards of living and expanding global population are anticipated to drive a continuous increase in global energy consumption over the next few decades. For example, in 2011, around seven billion people used 15 terawatts (TW) energy globally. By 2050, these numbers are expected to increase to 30 trillion and nine billion people, respectively [1]. Approximately fossil fuels provide 80% of the world's energy, followed by renewables at 14% and nuclear power at 6% [2]. Climate change is a result of the continued burning of fossil fuels, which releases greenhouse gases into the atmosphere and creates a severe risk to the ecosystem. Through the use of sustainable energy sources, it is possible to lessen reliance on fossil fuels and reduce emissions that are damaging to the environment. Since hydrogen has a much higher calorific value than fossil fuels (120 MJ/kg), it can be an excellent sustainable energy source. It is becoming apparent that this energy source is flexible and readily available for use in the twenty-first century. However, hydrogen is not easily available in nature like fossil fuels are. It may be generated using any major energy source and used as fuel, either in a fuel cell that produces only water as a byproduct or directly in an internal combustion engine. Depending on the input raw materials, it is possible to create hydrogen gas by conventional and renewable processes. Hydrogen gas is conventionally produced through the application of procedures like gasification, pyrolysis, and hydrocarbon reforming fossil fuels like petroleum, coal, and natural gas. On the other hand, water and biomass are the two renewable resources that may be used to create hydrogen.

However, the process of producing hydrogen via steam methane reforming (SMR) emits about 9 kilograms of CO₂ per kilogram of hydrogen produced [3]. This accounts for nearly 2% of total global CO₂ [4] emissions, largely due to the extensive use of fossil fuels in industrial hydrogen production. By using a water-gas shift reaction-based biogas steam reforming method, each kilogram of hydrogen produced emits 1.5 to 2.5 kilograms of CO₂. This is lower due to the use of renewable methane from biogas. In an anaerobic digester, biogas is produced from the portion of municipal solid waste made up of food that is collected from the Rajshahi City Corporation in Bangladesh. Various studies have demonstrated the potential for generating electricity directly from food waste across the Rajshahi division. However, the challenge lies in efficiently collecting food waste from the entire region. Therefore, we have selected Rajshahi City Corporation as the focus area for this study. Also, several works of literature have highlighted the promising potential of converting food waste into energy. In recent years, numerous studies have been conducted on municipal solid waste (MSW) management in Rajshahi City Corporation (RCC), Bangladesh, highlighting various challenges and strategies for improving waste collection, disposal, and sustainability efforts. In 2021, researchers conducted a study on municipal solid waste (MSW) in RCC, collecting samples from various household groups. Their findings estimate the total MSW generation in RCC to be approximately 358.19 tons per day, with a per capita waste generation rate of 0.4214 kg/person/day. The calorific value of the waste was calculated to be 14.9 MJ/kg, and the potential for electricity generation from the waste was

*Corresponding Author Email Address: utshosaha006@gmail.com

estimated at 159.40 MWh per day [5]. In a separate study, researchers explored energy production from MSW in RCC through anaerobic digestion (AD). The study estimated the daily MSW generation at 420 tons, with an average per capita waste generation of 0.40 kg/person/day, a figure consistent with that of many developing countries. They also estimated that the energy recovery from MSW in RCC could yield approximately 10.2 MW of electrical power, or around 45,300 m³ of biogas, which is equivalent to 11.4 kilotons of LPG. This potential energy generation could play a vital role in addressing the increasing energy demand in RCC [6]. Barun et al. investigated the potential for energy recovery from municipal solid waste (MSW) in Rajshahi City Corporation (RCC) using the landfill technique. Their study estimated that the landfill could produce approximately 7,549 tons of methane (CH₄) annually, with an associated energy potential of around 5.3 MW from the landfill gas [7]. Islam et al. conducted a study to evaluate the power generation potential from municipal waste and sugarcane bagasse. Their findings estimated that approximately 119.8 MWh/day of power could be harnessed from waste, while bagasse had a potential power output of around 544 MWh/day [8].

However, no prior research has explored food waste-to-hydrogen production specifically in this location, making it an area of interest. The present study aims to explore the process of producing hydrogen via the process of biogas steam reforming and to evaluate the electricity generation potential of hydrogen. Although the study is based on Rajshahi city, every region in Bangladesh might use the techniques this study presents.

2. Methodology

The research focuses on Rajshahi city in Bangladesh (latitude 24°22'26"N and longitude 88°36'04"E). 0.984 million people live in this city and the city's rate of waste generation per capita is 0.4214 kg per day [5,9].

2.1 Hydrogen Generation Potential

Anaerobic digestion of organic materials, especially food waste, produces biogas as one of its byproducts. An estimate of the proportion of food waste in municipal solid garbage that will be utilized in the biodigester is crucial for each research site. Food waste is one of the best inputs for a biodigester since it breaks down fast. Utilizing food waste as the feedstock since it breaks down rapidly and is abundant in the approved regions.

How much food waste, or feedstock, should be put into the digester is estimated mathematically using equation (1) because there is a paucity of historical data on the trash created in Rajshahi city.

$$F_{(i)(t)} = MSW_{gen(i)(t)} \times F_{col} \times F_{(i)degradable} \quad (1)$$

where t denotes the time of reference (2017–2036), i indicates the location, and $MSW_{gen(i)(t)}$ represents the total quantity of waste produced by municipalities. This may be determined by using equation (2)[10]. F_{col} denotes the proportion of collected municipal solid trash, which is 0.5667[11], and $F_{(i)degradable}$ represents the constituents of food waste found in the municipal solid garbage collected in Rajshahi, which is 72.29% [5].

$$MSW_{gen} = \frac{(p_{base}(1+r_{base})^t \times W_{base}(1+r_{ec})^t \times 365)}{1000} tons \quad (2)$$

where the base population and base waste generation per capita are represented by p_{base} and W_{base} , respectively. r_{ecn} means the gross domestic product or the growth economic factor; t indicates the anticipated period (2017–2036); and r_{base} is the base population growth rate, which is 2.29% [9]. The value r_{ecn} is positive during periods of economic expansion and negative during periods of economic contraction. Positive economic conditions are anticipated to persist during the estimated period. Here, r_{ecn} equals to 5.7% [12].

The efficiency with which a power plant or energy system runs about its full possible output is measured by its capacity factor (CF). Here, it is the ratio of the energy generated (food waste) over a certain period to the energy that the system would have produced if it had been running at maximum capacity over that same period. The capacity factor, or CF, is stated as 85%[13]. Thus, the following formula is used to calculate the average food waste amount that has to be fed into the digester:

$$F_{AV(i)} = \frac{\sum_{t=1}^{20} (F_{(i)(t)})}{20} \times CF \quad (3)$$

Methane (CH₄) and carbon dioxide (CO₂), two significant greenhouse gases, are present in a mixture known as biogas. About 25–45% of the volume in biogas is made up of CO₂ and 55–75% of the volume is CH₄.

The theoretical generation of methane (B_{CH_4}) at 0 °C at 1 atm may be computed using the following formulae.

$$B_{CH_4} = 22400 \times \left(\frac{\frac{w}{2} + \frac{\alpha}{8} + \frac{\beta}{4} + \frac{3\gamma}{8}}{12w + \alpha + 16\beta + 14\gamma} \right) \quad (4)$$

$$B_{CO_2} = 22400 \times \left(\frac{\frac{w}{2} + \frac{\alpha}{8} + \frac{\beta}{4} + \frac{3\gamma}{8}}{12w + \alpha + 16\beta + 14\gamma} \right) \quad (5)$$

According to Ref. [14], the normalized mole ratio approach is used to derive the constants w , α , β , and γ . The mole ratio is the relationship between an element's molar mass and the mass fraction of each element in the organic substrate. In terms of math,

$$Mole\ Ratio = \frac{K_{Elemental}}{K_{Molarmass}} \times \frac{1}{k} \quad (6)$$

where k denotes the mole ratio of nitrogen, $K_{Molarmass}$ means the molar mass of the relevant elements, and $K_{Elemental}$ is the elemental composition.

The biogas's theoretical volume (V_{Bio}) is

$$V_{Bio} = B_{CH_4} + B_{CO_2} \quad (7)$$

The following relations can be used to determine the percentage content of carbon dioxide and methane in the biogas.

$$\%CH_4 = \frac{B_{CH_4}}{V_{Bio}} \times 100 \quad (8)$$

$$\%CO_2 = \frac{B_{CO_2}}{V_{Bio}} \times 100 \quad (9)$$

Since around 10% of the organic waste in an anaerobic digester does not decompose, the actual biogas output, in reality, is lower than the theoretical amount. Additionally, the

synthesis of an organism's cell tissue requires 5–10% of the organic materials found in garbage, and this has an impact on the microbial breakdown process.

As a result, the real biogas yield may be determined as follows:

$$V_{Bio_actual}(i) = F_C \times V_{Bio} \times F_{AV(i)} \quad (10)$$

where F_C , which is thought to comprise 85% of the organic materials used for the synthesis of cell tissue, is expressed [15].

After purification, biogas contains 93–96% CH_4 , 4–7% CO_2 , and less than 20 parts per million H_2S . But in this case, CO_2 is the sole contaminant taken into account. Consequently, the quantity of methane extracted from the biogas gas that has been filtered is as:

$$V_{CH_4purified}(i) = V_{Bio_actual}(i) \times \%x \quad (11)$$

where the percentage of improved biogas is represented by % x. It should be noticed that % x is in fractional form to execute equation (12).

One m^3 of steam-reformed CH_4 is equal to $(0.5 \times CH_{4density})$ kg of H_2 gas when considering the biogas density, or the density of methane. This research assumes that the reformer uses only energy that comes from a boiler that is fed with biogas. Consequently, the system efficiency—that is, the total efficiency of the reformer and boiler—determines the quantity of H_2 gas generated (kg), which is determined as:

$$A_{H_2(i)} = 0.5 \times CH_{4density} \times V_{CH_4purified}(i) \times \eta_{system} \quad (12)$$

Where $\eta_{system} = \eta_R \times \eta_B$, and $CH_{4density}$ is the methane density. Boiler efficiency (η_B) and reformer efficiency (η_R) are expressed as 80% and 80%, respectively [16].

Practically speaking, hydrogen gas is kept either as a liquid in cryogenic tanks, as metal hydrides, or as high-pressure (compressed) gas cylinders. It is assumed for the sake of the research that compressed gas tanks or cylinders hold the hydrogen gas. Therefore, the following relation is used to calculate the compressed hydrogen gas volume:

$$V_{H_2compressed} = \frac{A_{H_2} \times \eta_{compression}}{H_{2CD}} \quad (13)$$

where H_{2CD} stands for the compressed hydrogen gas density, expressed as 36 kg per m^3 [17], compression efficiency is denoted by $\eta_{compression}$, expressed as 95% [18], and A_{H_2} refers to the total H_2 gas production in kg.

Separately Fuel cells, often known as electrochemical energy devices, are capable of immediately converting chemical energy found in fuels—such as methanol, propane, natural gas, or hydrogen gas—into electrical energy, without the need for combustion. Among the several types of fuel cells are solid oxide fuel cells (SOFC), proton exchange membrane fuel cells (PEMFC), molten carbonate fuel cells (MCFC), and phosphoric acid fuel cells (PAFC) [19]. PEMFC is used in this study because of its benefits. When hydrogen gas is delivered into a PEMFC, the chemical energy it contains is transformed into electrical energy. Consequently, the following may be used to calculate the electrical energy based on the heating value of hydrogen gas:

$$E_{H_2} = V_{H_2Compressed} \times LHV_{H_2} \times \eta_{FC} \times H_{Density} \quad (14)$$

where the electrical conversion efficiency is denoted by η_{FC} , which is estimated to be 60% [20], and the lower heating value of hydrogen gas is LHV_{H_2} , taken as 33.3 kWh per kilogram or 119.9 MJ/kg [18]. Hydrogen density is known as $H_{Density}$.

2.2 Environmental impact

The following formula can be used for calculating the volume of fuel (diesel fuel) displaced yearly in liters based on its heating values (LHV) concerning hydrogen gas:

$$A_{Fuel} = \frac{V_{H_2Compressed} \times LHV_{H_2} \times \eta_{FC} \times H_{Density}}{\left(\frac{LHV_{Fuel}}{3.6}\right) \times D_{Fuel} \times \eta_{Fuel}} \quad (15)$$

where the lower heating value of diesel fuel, calculated as 42.5 MJ per kg, represented by LHV_{Fuel} [21], D_{Fuel} denotes the density of diesel fuel, calculated as 0.837 kg per litre [22], The MJ to kWh conversion factor is 3.6, and η_{Fuel} means the efficiency of the diesel fuel generator, taken as 33% [23].

The energy and environmental sectors are concerned about the emissions of hazardous air pollutants produced by burning fossil fuels, such as diesel fuel, in automobile engines or engine-driven electrical generators for power or transportation (CO_2 , CH_4 , and N_2O). Additionally, the moving components of fossil fuel engines make them loud during operation; heat loss makes them less efficient; and pollution emissions are a common occurrence. One of the most dangerous byproducts of burning fossil fuels is carbon monoxide (CO), which is produced when combustion is incomplete. While there are other greenhouse gasses as well, this research will just focus on CO_2 . This is because it accounts for around 77% of all greenhouse gas emissions worldwide. One proposed remedy that might close the energy-environmental gap is the adoption of FC powered by H_2 . Water is the only output from H_2 -based fuel cells, indicating no environmental risk. By using the formula, the total quantity in kg of CO_2 and CO releases per year might be avoided if H_2 -based fuel cells were used instead of burning diesel fuel:

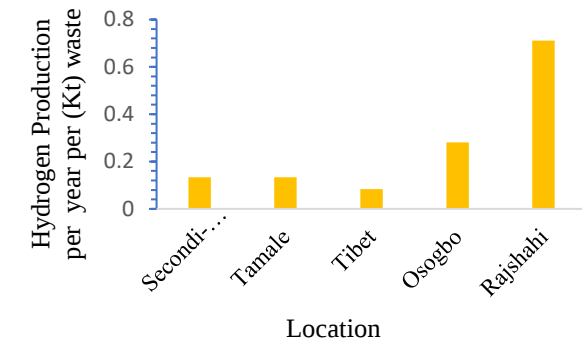
$$E_{CO_2} = A_{Fuel} \times SE_F \quad (16)$$

where SE_F , which might be CO_2 or CO, is the particular air pollutant's emission factor. Diesel fuel's CO_2 emission factor is 2.7 kg per liter, whereas the CO emission factor is 0.00766 kg per liter [24].

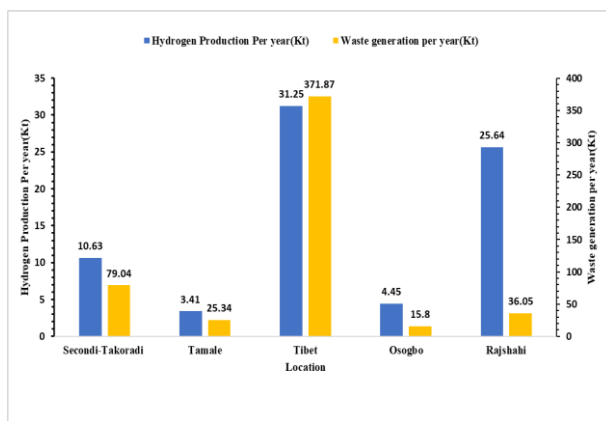
3. Results & Discussion

The waste generation evaluated for Rajshahi City was 36.05 kt/year. The economic growth rate and population growth rate are attributed to the overall waste generation as constant factors. Generated waste was the main feedstock at the bio-digester for biogas production. The biogas generation potential was determined to be 174.28 million liters and the H_2 yield from this biogas per year was calculated at 25.64 kt. For having a lower energy density, storage of H_2 fuel plays a significant role in its production process. For the sake of this study, produced H_2 is assumed to be stored in a gas tank or cylinder. Mathematical relation for compressed H_2 is considered in the methodology for validating the assumption. Then, electricity generation

utilizing the H₂ in fuel cell was evaluated at 1.123 GWh/year, which can also resemble the value for 20 year-period for long-term impact visualization. A summary of the findings is shown in Table 1.



(a)



(b)

Fig.1 (a) Hydrogen Production per year per waste(kt) for different locations. (b) Hydrogen generation and waste generation per year for different locations.

Table 1 Summary of the findings.

Parameters	Value
MSW Generation	36.05 kt/year
Hydrogen Production	25.64 kt/year
Electricity Production	1.123 Gwh/year
Reduction of Carbon Emission	3.565 tons/year

Four different cities were considered for comparison of the potential for the hydrogen economy. Rajshahi was observed to have the lead in hydrogen yield potential per kiloton of waste in a year (Figure 1(a)). Figure 1(b) represents a comparative analysis of effective waste conversion into H₂, where Rajshahi city showed the best performance in terms of H₂ yield for comparatively lower waste. This outcome shows the high potential of Rajshahi City Corporation for practical application of the Hydrogen economy.

This trend of very high efficiency in H₂ production hasn't been seen for other locations in the comparison. Secondly, Takarado [25] showed less effective H₂ production yet had higher waste than Rajshahi followed by Osogbo [26] and tamale [25] at the lowest. On the other hand,

a very noticeable discrepancy or an opposite trend has been seen for Tibet [27], where only 31.25 kt of H₂ was produced per year from 371.87 kt of food waste.

Lower H₂ production or the opposite trend of H₂ production is attributed to variations in some parameters related to the process of H₂ production from food waste such as waste collection rate, waste composition, economic growth factor, population growth factor, and steam reforming efficiency. These factors or parameters varied from location to location and technicalities of the system. Figure 1-b shows how variation in these parameters can affect the H₂ production rate. Afterward, sensitivity analysis (Figure 2) was carried out to determine the sensitivity of H₂ and electricity production to these parameters.

3. Sensitivity analysis

3.1 Food Waste Collection Rate

Food waste's high degradability makes it an excellent fuel for anaerobic digestion. The amount of feedstock supplied into the digester raises the factor of capacity, which raises the amount of biogas generated. Thus, it is necessary to do a sensitivity analysis on how the pace at which food is collected affects the biogas output and, consequently, the generation of hydrogen and energy. It is assumed that the food collection rate would fluctuate between 50% and 90%. The impact of varying food waste collection rates on the potential for producing electricity and hydrogen gas is depicted in Figure 2. The graphic makes it evident that there is a direct relationship between food waste and hydrogen production, which in turn affects the creation of energy. The annual generation of hydrogen varied from 18.32 million kg (0.018 million tons) to 42.22 million kg (0.042 million tons). Likewise, the annual energy output varied between 0.8 and 1.8 million kWh.

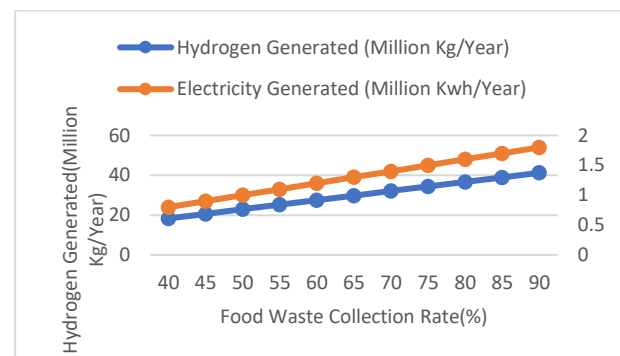


Fig.2 The variance of food waste collecting rate concerning energy and hydrogen generation potentials.

4. Conclusion

Being a densely populated country, every city in Bangladesh holds great potential for utilizing food waste to produce H₂. The present investigation is focused on the aspects of generating electricity from H₂ produced from collected food waste in RCC, Bangladesh. Theoretical evaluation of the entire process has been carried out, from total waste collection to biogas production in the digester and H₂ production to electricity generation, estimating the impact of the H₂ economy for 20 years. Biogas collected from the digester for a particular period was 174.28 million liters, which was later utilized for H₂ fuel generation by steam reforming process. The estimated H₂ generation potential for

RCC was found to be 25.64 kt per year, which well along resulted in 1.123 GWh of electricity. The outcome of this study was validated by comparing it with other similar studies. RCC's potential for H₂ and electricity generation outperformed the others considering that RCC was comparatively smaller economy than all the other locations in the comparison. This study offers some valuable insights such as some factors that work in favor of an area when it comes to converting the waste, particularly for H₂-based power generation. Along with evaluating the potential of the H₂ economy in RCC, this comprehensive analysis of the entire system is assumed to help the researchers and decision-makers to take verdicts regarding the application of hydrogen fuel-based plants in different cities of Bangladesh alongside Rajshahi.

References

- [1] Dincer, "Green methods for hydrogen production," *International Journal of Hydrogen Energy* **37**(2), 1954–1971 (2012).
- [2] A.K. Koshariya, M.S. Krishnan, S. Jaisankar, G.B. Loganathan, T. Sathish, Ü. Ağbulut, R. Saravanan, L.T. Tuan, and N.D.K. Pham, "Waste to energy: An experimental study on hydrogen production from food waste gasification," *International Journal of Hydrogen Energy* **54**, 1–12 (2024).
- [3] K.M. Van Geem, V.V. Galvita, and G.B. Marin, "Making chemicals with electricity," *Science* **364**(6442), 734–735 (2019).
- [4] P. Verma, and S.K. Samanta, "Overview of Biogas Reforming Technologies for Hydrogen Production: Advantages and Challenges," in *Proceedings of the First International Conference on Recent Advances in Bioenergy Research*, edited by S. Kumar, S.K. Khanal, and Y.K. Yadav, (Springer India, New Delhi, 2016), pp. 227–243.
- [5] Md.A. Habib, M.M. Ahmed, M. Aziz, Mohd.R.A. Beg, and Md.E. Hoque, "Municipal Solid Waste Management and Waste-to-Energy Potential from Rajshahi City Corporation in Bangladesh," *Applied Sciences* **11**(9), 3744 (2021).
- [6] P. Das, M.S. Islam, and N. Huda, "Feasibility analysis of municipal solid waste (MSW) for energy production in Rajshahi City Corporation," (Dhaka, Bangladesh, 2019), p. 120004.
- [7] B. Das, M.A. Kader, and S.M.N. Hoque, "Energy recovery potential from municipal solid waste in Rajshahi City by landfill technique," *International Journal of Renewable Energy Research* **4**, 349–354 (2014).
- [8] D. Islam, and A.Z.A. Saifullah, "Solid waste and sugarcane bagasse-a renewable source of energy in rajshahi city, bangladesh.," (2001).
- [9] "Rajshahi, Bangladesh Metro Area Population 1950-2024," (n.d.).
- [10] T.R. Ayodele, M.A. Alao, and A.S.O. Ogunjuyigbe, "Recyclable resources from municipal solid waste: Assessment of its energy, economic and environmental benefits in Nigeria," *Resources, Conservation and Recycling* **134**, 165–173 (2018).
- [11] O. Alam, and X. Qiao, "An in-depth review on municipal solid waste management, treatment and disposal in Bangladesh," *Sustainable Cities and Society* **52**, 101775 (2020).
- [12] "Bangladesh - gross domestic product (GDP) growth rate 2029," Statista, (n.d.).
- [13] "Renewable Energy Cost Analysis - Biomass for Power Generation," (2012).
- [14] Md.S. Rafiq, M.S.H. Apurba, and N.R. Khandaker, "Harnessing Untapped Resources for Sustainable Energy Production from Municipal Solid Waste in Recourse Challenged Economies: A Case Study of Rajshahi City Corporation, Bangladesh," *Journey Sust. Dev. Peace J.* **2**(1), 35–57 (2024).
- [15] "Characterisation study of solid wastes: a case of lagos state | Semantic Scholar," (n.d.).
- [16] L.B. Braga, J.L. Silveira, M.E. Da Silva, C.E. Tuna, E.B. Machin, and D.T. Pedroso, "Hydrogen production by biogas steam reforming: A technical, economic and ecological analysis," *Renewable and Sustainable Energy Reviews* **28**, 166–173 (2013).
- [17] A. Züttel, "Hydrogen storage methods," *Die Naturwissenschaften* **91**, 157–72 (2004).
- [18] J. Lagorse, M.G. Simões, A. Miraoui, and P. Costerg, "Energy cost analysis of a solar-hydrogen hybrid energy system for stand-alone applications," *International Journal of Hydrogen Energy* **33**(12), 2871–2879 (2008).
- [19] P. Bajpai, and V. Dash, "Hybrid renewable energy systems for power generation in stand-alone applications: A review," *Renewable and Sustainable Energy Reviews* **16**(5), 2926–2939 (2012).
- [20] H.J. Alves, C. Bley Junior, R.R. Niklevicz, E.P. Frigo, M.S. Frigo, and C.H. Coimbra-Araújo, "Overview of hydrogen production technologies from biogas and the applications in fuel cells," *International Journal of Hydrogen Energy* **38**(13), 5215–5225 (2013).
- [21] Dincer, and C. Acar, "Review and evaluation of hydrogen production methods for better sustainability," *International Journal of Hydrogen Energy* **40**(34), 11094–11111 (2015).
- [22] Yumpu.com, "Units & Conversions Fact Sheet - MIT Energy Club," Yumpu.Com, (n.d.).
- [23] "Ensyn - Renewable Fuels and Chemicals from Non-Food Biomass.," Ensyn - Renewable Fuels and Chemicals from Non-Food Biomass., (n.d.).
- [24] T.R. Ayodele, and A.S.O. Ogunjuyigbe, "Increasing household solar energy penetration through load partitioning based on quality of life: The case study of Nigeria," *Sustainable Cities and Society* **18**, 21–31 (2015).
- [25] P.A. Seglah, Y. Wang, H. Wang, K.A. Wobuiye Neglo, K. Zhou, N. Sun, J. Shao, J. Xie, Y. Bi, and C. Gao, "Utilization of food waste for hydrogen-based power generation: Evidence from four cities in Ghana," *Heliyon* **9**(3), e14373 (2023).
- [26] T.R. Ayodele, M.A. Alao, A.S.O. Ogunjuyigbe, and J.L. Munda, "Electricity generation prospective of hydrogen derived from biogas using food waste in south-western Nigeria," *Biomass and Bioenergy* **127**, 105291 (2019).
- [27] D. Cudjoe, W. Chen, and B. Zhu, "Valorization of food waste into hydrogen: Energy potential, economic feasibility and environmental impact analysis," *Fuel* **324**, 124476 (2022).