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Original Article

Hydrogen from Biomass for Cogeneration of Heat and Power via High-Temperature Proton Exchange Membrane Fuel Cell and Rankine Cycle: A Case Study for Africa

Saad Saleem Khan[1], Zeshan Abbas[2*], Rabia Khatoon[3], Mohsin Amjad[1], Zeeshan Ali[4], Nuray Alizada[5], Stephen Larkin[6], Hussain Shareef[7*]

[1]*National Transmission and Dispatch Company, Limited, Pakistan*
[2]*School of Mechanical Engineering, Dalian University of Technology, Dalian, China*
[3]*School of Materials Science and Engineering, Zhejiang University, Hangzhou, China*
[4]*Institute of Chemical Sciences, Bahauddin Zakariya University Multan, Pakistan*
[5]*Department of Biology, United Arab Emirates University, UAE*
[6]*Africa New Energies Ltd, United Kingdom*
[7]*Department of Electrical Engineering United Arab Emirates University, UAE*

**Corresponding Author : hopenotout1214@mail.dlut.edu.cn*

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Abstract *- Solar and wind power are unreliable energy sources for underdeveloped countries owing to the expensive infrastructure required for them. Biomass must reckon as a renewable energy source to fix problems with energy storage, seasonality, and intermittency. This paper uses Africa as an example of an impoverished area that fails to fulfill its domestic energy demand. The sustainable utilization of biomass is a concern in this regard, as many African nations have ratified the Paris Agreement on lowering greenhouse gas (GHG) emissions. The production of hydrogen from biomass is a possible means of its clean use. Hence, this study emphasizes the biomass-derived electrification of hydrogen via high-temperature proton-exchange membrane fuel cells (HT-PEMFCs), which are broadly considered to be commercially viable for automotive applications—especially for microgrids and logistics vehicles that require the least hydrogen infrastructure. This effort led to the creation of hydrogen generation infrastructure, its usage, and, thus, power generation for African microgrid systems, with a focus on biomass-derived hydrogen production based on combined cooling, heating, and power (CCHP) systems. Furthermore, energy and exergy studies are performed on power generation based on acost–the benefit evaluation of a hybrid system consisting of the CCHP &HT-PEMFC. This study found that biomass-derived hydrogen, which is used to power the HT-PEMFC system, is more cost-effective than competing technologies in specific off-grid circumstances. This strategy is practical, cost-effective, and ecologically friendly and will be useful for generating heat & power to meet with energy demands of microgrids and the residential sector.*

Keywords *- HT-PEMFC, Biomass, Carbon reduction, Cost–benefit analysis, Hydrogen extraction, Clean environment.*

1. Introduction

Global greenhouse gas emissions and the carbon footprint have increased at an alarming rate in recent periods owing to the excessive fossil fuel consumption for energy [1]. Even though two more barrels of the oil equivalent have been consumed for every barrel of oil that has been used since 1990, global energy demand has risen at a high rate. New energy sources are seldom discovered in areas where this demand is increasing. Abbas et al. have claimed that access to electricity in developing nations is becoming more expensive and complicated [2]. According to some sources, a considerable world population of more than two billion people is still facing a shortage of electricity and clean cooking fuel, among other essential energy services [3]. Renewable energy has begun replacing fossil fuels owing to a lack of dependable supply for them and investment in energy transit that is not economically viable, rather owing to environmental concerns. Renewable materials have the benefit of being ubiquitous and scalable, and this makes them appealing to the developing world, which is expected to face a $13 trillion shortfall in investment in energy infrastructure by 2050 [4]. Renewable energy sources are considered attractive owing to the virtuous circle of demographically driven reduction in interest rates and the levelized cost of energy provision from them. They tend to incur higher costs upfront but lower operating costs in comparison with fossil fuels, where capital costs are lower than operating costs [5]. The positive exogenous shock in oil prices was caused by the decline in interest rates in Western countries from the mid-teens in the 1990s to zero today, but it has been increasing these days. It has successfully enhanced the affordability of and demand for renewable energy. Key economies such as China, the United States, Germany, and Japan have stimulated supply via state incentives, such as guaranteed feed-in tariffs, tax exemptions, concessionary financing, and manufacturing subsidies, so that an equilibrium can be maintained between demand and supply [6]. This combination has had a considerable influence on reducing renewable energy costs. The cost per watt of solar panels decreased from $10 in 2000 to $0.16 in 2020, according to research on the Proton Exchange Membrane Fuel Cell (PEMFC) [7].

Seasonal and intermittent energy sources have recorded the highest growth in recent years owing to their low cost per watt [8]. The global average weighted levelized cost of electricity (LCOE) generation from onshore wind power, offshore wind power, and utility-scale solar photovoltaics (PV) in 2020 decreased by 13%, 9%, and 7%, respectively [9]. Renewable power costs have dropped substantially over the past decade due to technological advances, economies of scale, competitive supply chains, and improved developer expertise [10]. The cost of utility-scale solar PV power dropped by 85% from 2010 to 2020, and solar and wind-generated electricity is cheaper as well. A capacity of 644 GW for renewable power production has been developed at lower prices than that of the lowest fossil fuel-fired alternatives every year since 2010. A supply of 534 GW of renewable energy at lower prices than fossil fuels in emerging nations will cut the cost of power generation by USD 32 billion this year. This has created the need for small-scale renewable energy sources to supply baseload and dispatchable energy [11]. This circumstance necessitates a solution for the energy market that is both environmentally benign and cost-effective. Many researchers have identified the means to replace the prevalent fossil fuel-based energy production with hydrogen generation/storage.

Hydrogen is odorless, tasteless, and colorless. It packs 2.75 times the amount of energy contained in hydrocarbons per gram. Hydrogen-powered cars reduce fuel usage and emissions. Automobiles with hydrogen fuel cells are more efficient than their conventional counterparts. Unmodified conventional internal combustion engines (ICs) can use hydrogen, which is a fast-burning no-emissions automobile fuel. Hydrogen is taken as a chemical feedstock for the electronics, culinary, petrochemicals, and metallurgical industries. It is costly and scarce as fuel. At 15°C temperature and 1 atm pressure, hydrogen requires a larger fuel tank than methane and propane. It has been predicted that hydrogen will supply fuel for 11% and 34% of the global energy demands by 2025 & 2050, respectively. A total of 95% of the world's hydrogen-related needs are fulfilled by fossil fuels, subsequent to water electrolysis (4%) and biomass (1%). Gasifying natural gas (NG), naphtha, heavy oils, and coal are used to generate around 50% of hydrogen. Biomass is not anticipated to be an extensive source of hydrogen despite its abundance. The long-term goal is to derive hydrogen as fuel from carbon-free and lean sources, including biomass. Like many African countries, tropical nations have large sources of renewable biomass that can be utilized to minimize fossil fuel consumption. The availability and capability of regeneration of biomass resources, on one side, and the slow rate of replenishment and a limited amount of non-renewable fuel, on the side, have emphasized the investment need for biomass production [12].

Significant advances have been made in research on hydrogen fuel cells. Each version of such cells is optimized for a certain niche application, where the benefits of the intrinsic design overcome the restrictions of the application [13]. Fuel cells have been considered both environmentally beneficial and cost-competitive among technologies dedicated to producing greener energy over the past 50 years. The primary fuel cell component is a membrane used to separate different ions. A variety of membranes have been used to this end, including inorganic and organic poly-membranes and sulfonated hydrocarbon poly-membranes [14]. The proton-exchange membrane fuel cell (PEMFC) takes hydrogen & oxygen (from the air) as fuel. It creates electricity without emitting carbon dioxide, instead producing water as a by-product. Their continual usage damages the electro-catalyst anode over time, making it difficult for basic PEMFCs to maintain a constant supply of highly pure hydrogen over a long period. Due to the absorption of carbon monoxide in the region of the platinum-side electrodes in the high-temperature PEMFC (HT-PEMFC), contaminants in the hydrogen supply can be tolerated to a greater extent than in a low-temperature (LT-PEMFC)-based system [15]. The ideal range of working temperatures for the HT-PEMFC is 120 to 180°C. To prevent the composition of the electrolyte from percolating into a typical PEMFC at a maximum operating temperature of 80° C, the formation of liquid water must be avoided. The working temperature of HT-PEMFC technology surpasses the boiling point of water to solve this problem [16]. The cathode of the LT-PEMFC has an excess capacity that is too high for its cell voltage. Carbon monoxide (CO) has a specific value for platinum catalysts that are used to enhance the electrochemical process [17]. Hydrogen derived from biomass conversion is an efficient fuel for the HT-PEMFC, the structure of which includes an air-based medium for fuel delivery and a temperature-controlled gas reformation system. The control system consists of feedback, a feed-forward method, and a system to condition the electrical power output. It reduces emissions relative to conventional fuel cells and the cost of producing electricity. Once a feasible solution to durability-related difficulties has been identified, the commercialization of this technology will be facilitated by the creation of supporting infrastructure and the inherent features of the product [18].

Several scientific groups have contributed to the development of means of generating electric power by using a combination of hydrogen and fuel cells through different techniques. Hunter et al. combined a lithium imide–ammonia–hydrogen system to power a 100 W PEMFC. Ammonia was placed on a cracker and filtered to create H_2 and N_2. Clean gas was delivered to the PEMFC with a dead-end anode to power a TV. Solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) are preferred for generating MW-scale power and hydrogen. Luca et al. produced a SOFC that consumed a low fuel volume to generate CO_2-free hydrogen. They sought to replace oil refineries with SOFCs to generate H_2. The system's electric efficiency ranged from 11.6% to 19.5%, and its hydrogen generation efficiency from 47.1% to 60.3%. Mehrpooya et al. created a hybrid multi-generation fuel cell system having a capacity of 6.55 MW to generate gas and power by using a high-temperature fuel cell and the ammonia–water absorption cycle. The fuel cell produced 6 MW of power with a steam cycle of 0.55 MW. The synthesized gas obtained from burning coal generated 90 kmol of hydrogen per hour and captured a substantial 90% of the emitted CO_2 by employing a cryogenic CO_2 collection device. Mohammadi and Mehrpooya integrated a solid oxide electrolyzer dish collector with a compressed air energy storage system to create hydrogen & electricity [19]. This article seeks to predict the amount of hydrogen generated from biomass for combined cooling and heat power (CCHP) and HT-PEMFC-based heat and energy generation.

Hydrogen is a zero-carbon substitute for natural gas and can be specifically useful in countries with wide distribution network systems for natural gas. However, models for the national energy systems of many undeveloped nations, such as those in Africa, do not consider hydrogen or fuel cells for generating heat and electricity. The entire value of the prospective contributions of hydrogen with fuel cells to low-carbon energy systems needs to be considered by policymakers. These technologies need to be incorporated into analyses of scenarios for the future. The objective of this article is to enable industrial producers to visualize the level of technological maturity of each alternative to conventional fossil fuels, highlight the requisite developmental efforts to commercialize them, identify the most viable and competitive pathways, and evaluate the viability of biomass as a feedstock for renewable hydrogen generation. A high-temperature proton-exchange membrane fuel cell (HT-PEMFC) is an innovative substitute for traditional PEMFCs because it can reduce the extent of CO poisoning and alleviate water management issues. The author describes previously developed and prevalent cost-based financial analyses and suggests a special cogeneration system to satisfy the increasing demand for microgrids within the energy market of the African region. This paper also explores the usage of hydrogen produced through biomass as fuel in HT-PEMFCs in combination with CCHP systems for microgrids. The full HT-PEMFC assembly and its application to the microgrid are explained. The technique used for carbon capture and sequestration is investigated to make the process of H_2 extraction environmentally benign and, hence, feasible. The application of biomass-derived hydrogen as a fuel for HT-PEMFC hybrid systems with CCHP for the cogeneration of heat and electricity in microgrids is also explained, along with its cost–benefit analyses and long-term benefits.

2. Power Generation from Combined Heat and Power (CHP) based on Fuel Cell

Fuel cells carry all technologies' highest latent power generation for combined heat & power (CHP) generation. They constitute a versatile plus modular technology that can readily expand from servicing single-family residences to huge office buildings and industrial facilities. While most systems are designed to yield electricity exclusively, the most prevalent stationary applicability is CHP generation, which can deliver an outstandingly high efficiency of up to 95% and reduce reliance on centrally generated power, curtailing carbon emissions and the cost of electricity. Fuel cells are not the solely available technique for heating by using hydrogen, but they are the most protuberant owing to high electrical efficiency [16]. Correspondingly, hydrogen is not just the fuel that may be employed to power fuel cells. A majority of currently used fuel cells generate hydrogen internally by reforming the hydrocarbon provided as fuel. Natural gas, LPG, and biogas are the most popular heat sources for stationary applications.

Unlike traditional power plants, fuel cells do not produce harmful by-products during energy conversion from chemical to electrical. Hydrogen and oxygen are used at opposite ends of the cell, or the electrodes, to produce electricity and water. The benefits of this technology include higher efficiency than traditional thermal machines, the minimal emission of carbon dioxide and sulfur dioxide, and a high power density [20].

Because a fuel cell produces a very low voltage (0.5 to 0.9 V), many cells need to be connected in series to provide a usable voltage. Cells generating electricity ranging from watts to megawatts per module are now commercially available. They typically have efficiencies of 40% to 60% but may attain values of 85% when used in cycles for CHP generation. Fuel cells are currently used in three main applications for electric power generation [21].

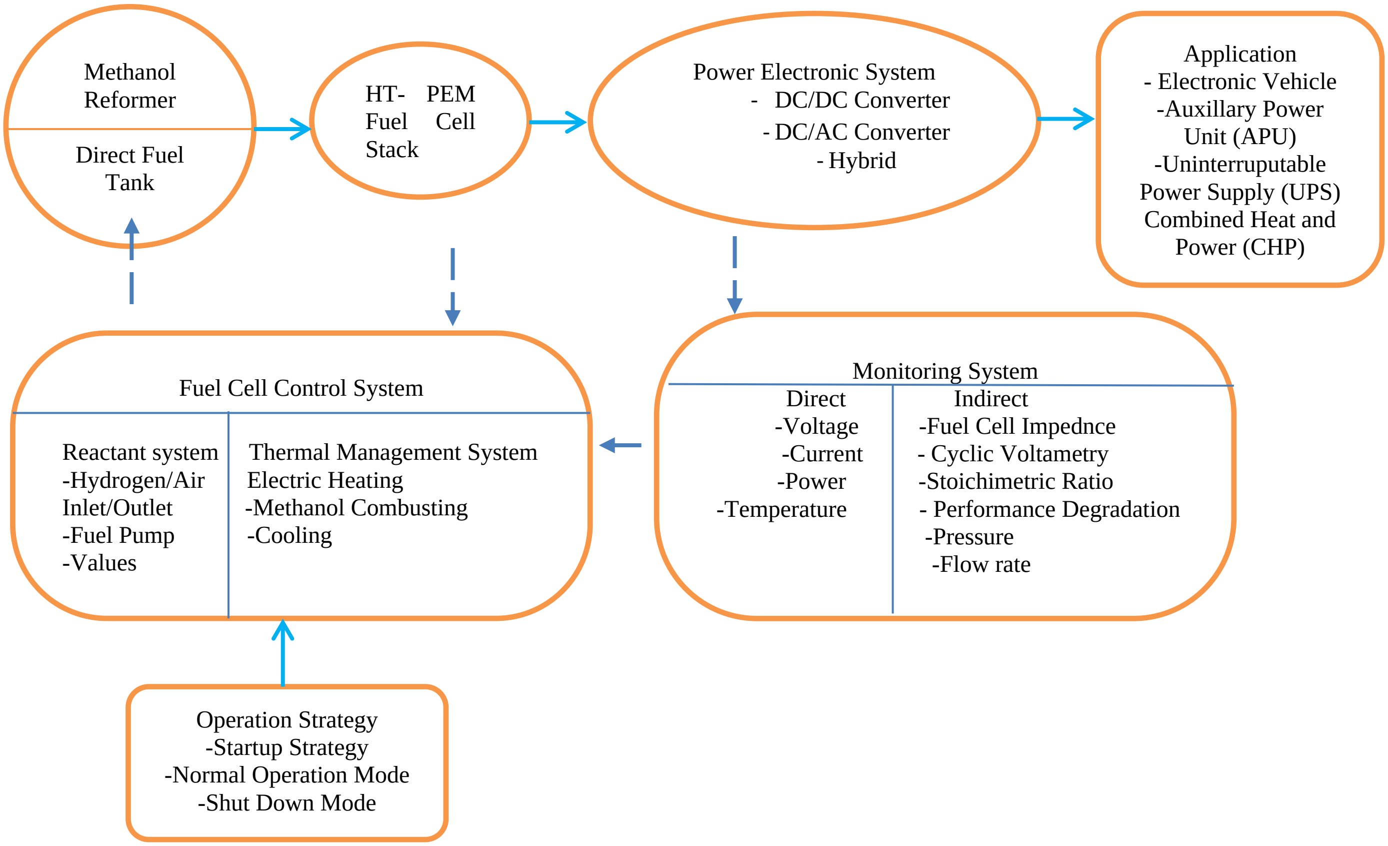


Fig. 1 Components of HT-PEMFC along with their operational positioning [24]

- the portable electrical energy generation in compact devices (power less than 100 watts);
- the generation of electric power in a stationary configuration by using modules with a power output of many megawatts; and
- in automobiles and public vehicles (sometimes as a hybrid configuration).

2.1. Proton-exchange Membrane Fuel Cells

PEMFCs constitute an advanced technology, powering around 90% of heating systems worldwide (1–3 kW thermal power, such as those in the Japanese "ENEFARM" initiative) and are the stack technology applied in fuel-cell automobiles. PEM technology delivers excellent efficiency, durability, dependability, and mass manufacturing and significantly reduces costs. Current research in the area seeks to simplify such systems: Removing platinum might eliminate the requirement for sophisticated technical solutions, and high-temperature PEM cells can function on dry hydrogen at temperatures over 100^{o} C to eliminate the need for humidifiers [22].

The use of cycles for cogeneration increases efficiency and has a significant impact on the range of power for applications of this form of electrical power generation. Many firms are investing in this technology, and fuel cells are expected to play a vital role in power production in forthcoming years. The abilities of the HT-PEMFC to reduce CO poisoning and alleviate water management issues make it a suitable alternative to traditional PEMFCs [14]. Depending on the system design and operating circumstances, the balance-of-plant arrangement proficiency of methanol-fueled HT-PEM fuel cell systems normally ranges between 35% to 45%, reaching as high as the level of 55%. The efficiency of the cells of 63% is attainable. Hence, we focus on the HT-PEMFC in this study.

2.2. Hydrogen-based HT-PEMFC Power Generation Units

A schematic of the fuel cell components and their functional arrangement is depicted in Fig. 1. Owing to the increasing tolerance of contaminants, the hydrogen reformer system for the HT-PEMFC is the ideal source at present. It can reduce the cost of power production.

By serving as a system to generate and streamline fuel processing, the HT-PEMFC improves thermal efficiency. It is important to emphasize that despite these advantages, its widespread commercial adoption is hampered by the lack of a robust infrastructure for producing hydrogen [23].

2.3. Relation between CCHP and HT-PEMFC

Modern technology for CCHP may be described as the simultaneous production of electricity or mechanical power and effective thermal energy (heating and/or cooling) from a single-energy source by using an HT-PEMFC-based system [25]. This system includes heat exchangers, transformers, compressors, and power conditioning devices. The system described below also includes fuel cell stacks, and the volume of the available container determines its desired output. The heat management system is associated with humidity management. Therefore, its design for high-temperature environments is simplified as no water management system is needed due to the absence of water in the stack. The heat/temperature generation rates during the PEMFC operation normally range from 40% to 50%. Therefore, an efficient heat management system is required to eliminate the excessive heat generated during the operation of the cell [26]. The HT-PEMFC works above 120° C, where which reduces heat rejection owing to a high-temperature differential between the environment and the fuel cell. This heat can be transferred to other operations as a by-product or dispersed using an air fan system. Fig. 2 compares the costs of the fuel cell system (FCS) over the past decade to highlight the trend of decline in its cost.

As is typical in the first development phase, Fig. 2 shows that the requisite investment was high. A production capacity of 500,000 units per year was assumed. Dedicated R&D led to a reduction in cost, which reached $49 /kW in 2011. This was an 82% decrease from its $275 /kW cost in 2002. The objective was to attain $40 /kW by 2020. It is expected that the price of the FCS system can eventually be reduced to $23 /kW.

Similarly, Fig. 3 depicts an HT-PEMFC system set-up using tri-generation. It contains a fuel processor and heat exchangers. The acquired heat is used for different purposes, including heating and boiling water [28].

2.4. Power Conditioning Unit of HT-PEMFC

The output voltage level of the fuel cell (FC) can be controlled through the power conditioning unit (PCU). For this reason, a wide range of converters and inverters are used to generate the power needed for the associated load/microgrids. A DC–DC converter is installed with the aim of the DC voltage may be set to an appropriate level. This is similar to how the DC–AC converter transfers electricity from the FC to the AC grid. Furthermore, to provide isolated operation, the transformer serves to convert voltage levels. A battery energy storage system filters and circuit breakers are also integral parts of the overall layout. The primary function of these converters is to standardize the output voltage for safe and efficient use by the end user. Some additional requirements of converters are as follows:

- a long lifespan;
- protecting against electromagnetic interference (EMI);
- the ability to regulate the ripple effect;
- based on a high power density; and
- small size.

Harmonics are kept to a minimum by using converters connected to the FC and a few filters. The dv/dt strains and EMI are reduced by using the LC filter implemented in the sinusoidal filter. Fig. 4 compares different converters and inverters [9, 25, 30]. Hydrogen is the cornerstone of a sustainable energy economy if the relationships among businesses, the government, academia, and non-profits are maintained. The preceding sections demonstrated that fuel cells and other related hydrogen-fueled technologies have the potential to be carbon-efficient alternatives for heat generation. The next section examines certain methods employed to produce hydrogen from biomass.

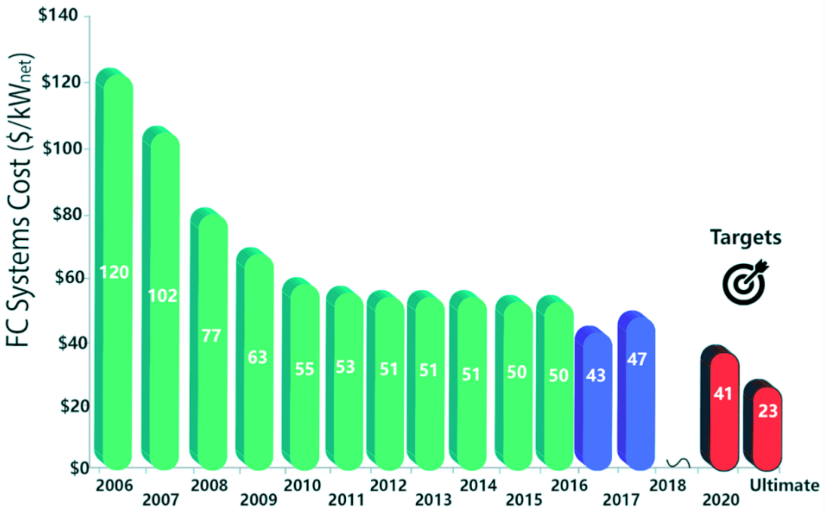


Fig. 2 Cost of the production of 500,000 FCS units per year [27]

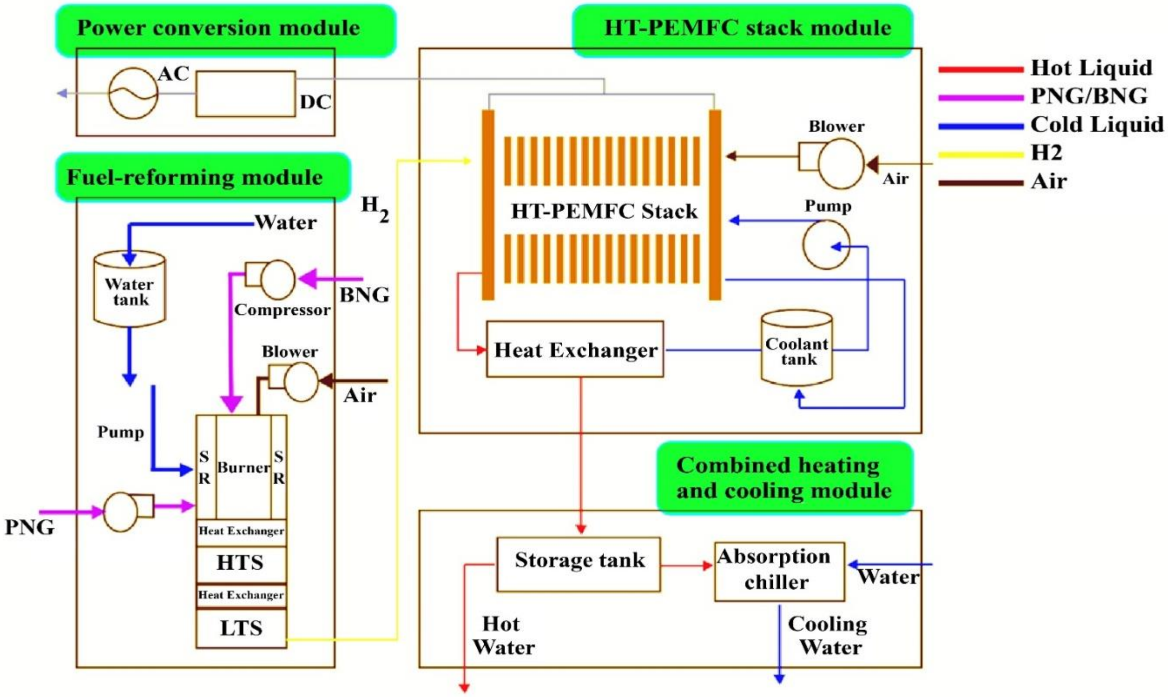


Fig. 3 Configurations of HT-PEMFC system with tri-generation [29]

2.5. Biomass Gasification

Biomass gasification is a recently developed procedure that uses heat, steam, and oxygen. Biomass is transformed into H_2 gas, along with the production of non-combustible by-products. The efficient use of biomass or the storage of CO_2 can improve the sustainability of the ass feedstock. Prevalent strategies for generating H_2 from biomass can be categorized into the two main segments given below [33].

2.5.1. Thermo-Chemical Processes

- Pyrolysis
- Gasification
- Supercritical water gasification (SCWG)

2.5.2. Biological Transformation

- Fermentation of hydrogen
- Photosynthesis
- Biological water–gas shift reaction (BWGS)

2.6. CO_2 Capture Technologies

The most difficult phase in energy production sectors today involves eliminating or capturing CO_2 because of its severe environmental impact and contribution to global warming. Three approaches can be employed to capture carbon or carbon dioxide in the context of this investigation.

- putting a lid on carbon emissions (CCS route);
- sequestration and use of carbon (CCU route); and
- creation of biomass (the BIO way)

- Fig. 5 depicts four techniques for developing carbon-based products that deliver the following social benefits: Business as usual (BAU): Fossil fuels include carbon atoms as part of hydrogen atoms, and product manufacturing necessitates a significant quantity of energy during this contour [34]. Throughout its operation, the plant emits net excess CO_2 into the atmosphere, where this amount is substantially smaller than in any relevant environmental timescale. CCS-DAC: Under this mechanism, emissions from a chain process are compensated for by storing waste underground for a long period, per the direct air capture (DAC) method. This facility can be operated independently of the manufacturing plant and is situated based on the available underground storage capacity. CCU-DAC: It is an independent system that collects CO_2 directly from the atmosphere at a point source using the CCS-DAC combination and converts it into a carbon-based product that complies with the net-zero CO_2 frameworks. Parallel H_2 generation can also yield the hydrogen molecule, which can be used as energy for CO_2 activation and product synthesis. BIOs: The product is made from sustainably grown biomass, such as carbon plus feedstock. During biomass growing, natural processes capture CO_2 directly from the air via photosynthesis, yielding advantageous results like net-zero CO_2 emissions.

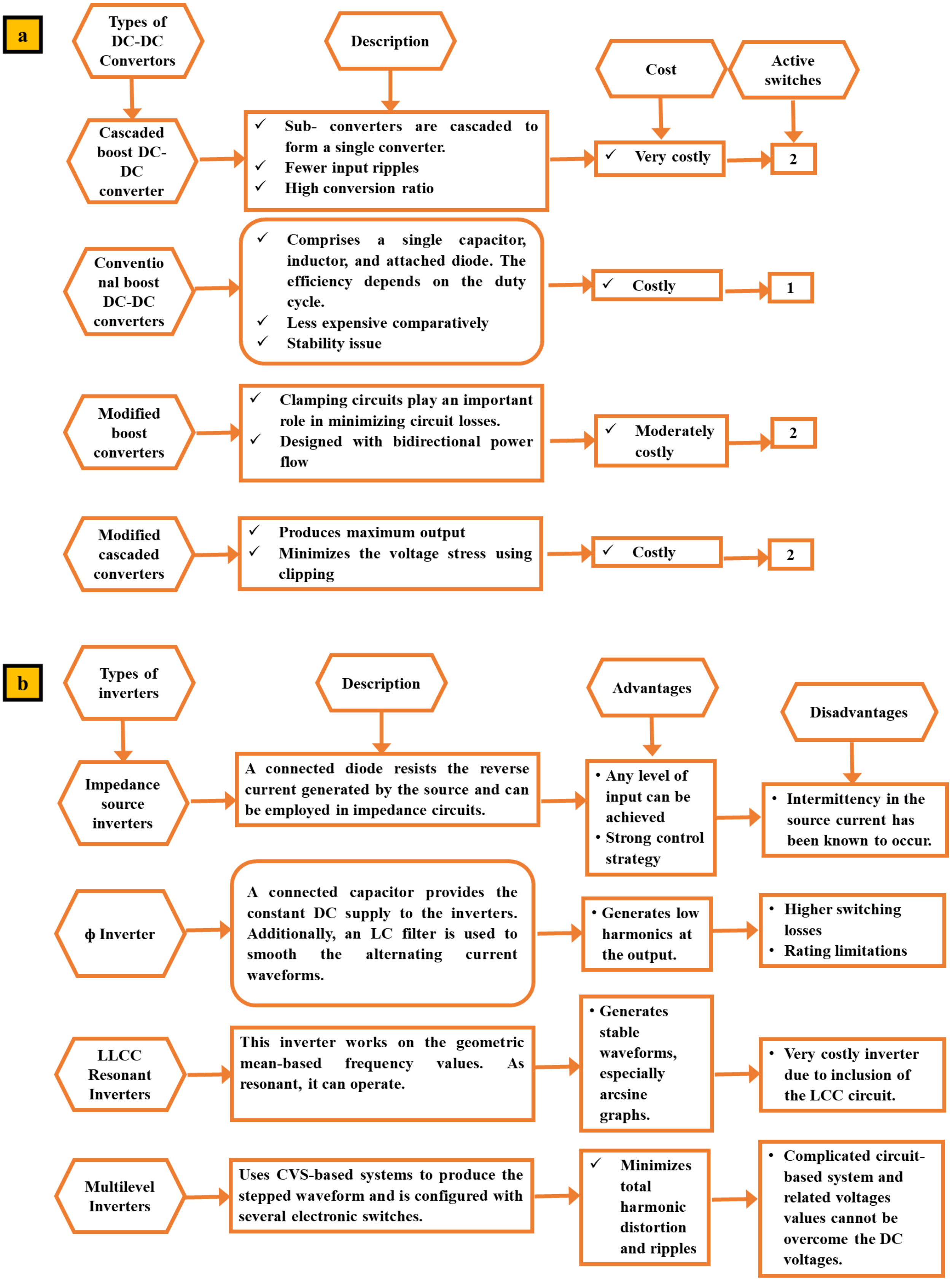


Fig. 4 (a) Overview of DC-DC converters and (b) DC–AC inverters

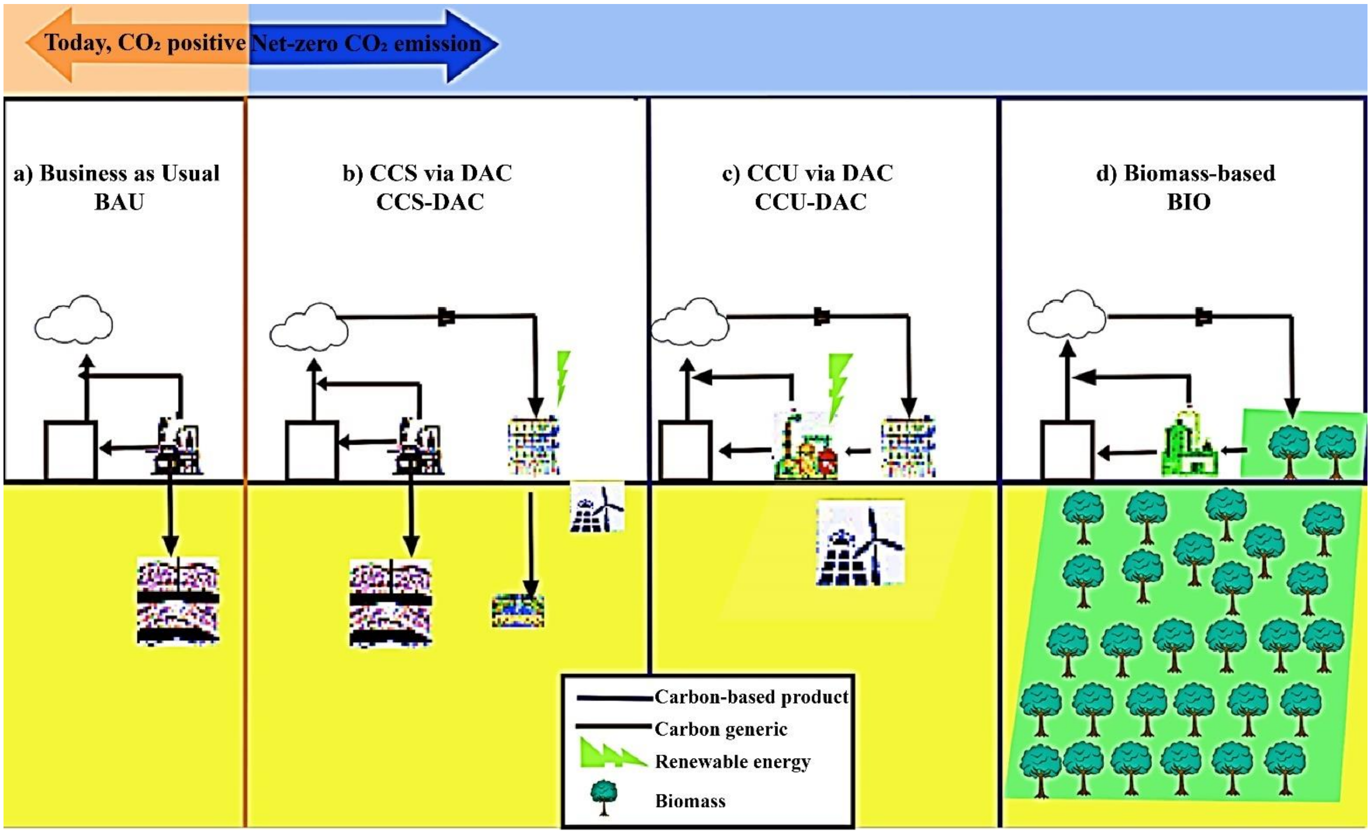


Fig. 5 Different methods for CO_2 capture: (b) CCS-DAC, (c) CCU-DAC, and (d) BIO [25, 30]

3. General Methods to Produce Hydrogen from Biomass

A great deal of energy can be obtained from the calorific value of biological substances like crops, animal waste, municipal garbage, and wood. For thousands of years, humans have used fire as a primary thermal and luminous energy source. Plants store light energy from the sun through photosynthesis by transforming carbon dioxide (CO_2) and water (H_2O) into sugars ($C_6H_{12}O_6$). These organic by-products can be converted into feedstock to synthesize hydrogen gas. Thus, compared with that generated by burning fossil fuels, biomass-derived power from plants generates fewer greenhouse gases [31]. Biomass development has recently lowered the net greenhouse gas levels because, unlike fossil fuels, the CO_2 released by biomass is balanced by the mechanism of capturing it. Agricultural and forestry products, trash and garbage, landfills, biogas, and ethanol, are prevalent sources of biomass utilized for energy production [32].

3.1. Feasibility of Producing Hydrogen in Africa

The viability of hydrogen production in Africa can be evaluated according to several criteria, such as the accessibility of feedstock, the intricacy and reliability of current production technologies, and financial considerations. Biomass feedstock consists of organic wastes, crops, residues, and herbaceous and woody materials. These materials can be burned to create heat to power a thermal turbine, processed into energy products such as bioethanol, biodiesel, and biogas for transportation fuels, or used to generate electricity and heat. Like the rest of the globe, municipal solid waste levels are increasing throughout Africa. A massive maize industry, thousands of kilometers of sugarcane, and paper and pulping industries are located in the region. Thus, biomass may be vital to the continent's transformation from coal to sustainable energy [35]. However, there is a growing realization in the power sector that diverting the use of agricultural land from food crops to energy crops may pose a risk to the food security of rural communities [36]. In addition, Africa is a water-scarce continent on which only 13% of the land is arable, severely limiting the potential for energy generation from agricultural biomass. From the stakeholders' perspectives in this enterprise, the appropriate selection and deployment of suitable technologies are crucial. Maintaining an equilibrium between biomass & food production is vital for bioenergy development. The implemented technologies must utilize various resources, focusing on waste products and minimizing the deterioration of agricultural resources [37]. Fig. 6 presents a schematic of the processing of biomass to generate energy. Based on the available feedstock in Africa, Table 1 lists the final energy outputs available from the respective raw materials. Maize (corn) contributes 36% to the total tonnage of African field crops, and 60% of maize production is consumed as animal feed. Compacted and commoditized corncobs can be compressed for storage. They have a high nutritional value and low sulfur and nitrogen concentrations. The grains of corn are grown for human and livestock consumption, with the remaining portion, such as corncobs and stovers, available for use as biomass to produce hydrogen gas. The corncob contains 77% starch, making it useful as biomass feedstock. The energy value of corncobs as a direct heat source typically ranges from 18.4 to 18.7 MJ/kg. Starch, cellulose, hemicellulose, and lignin contain mainly carbon, hydrogen, and oxygen. As a direct heat source, the energy value of maize cobs normally ranges from 18.4 to 18.7 MJ/kg.

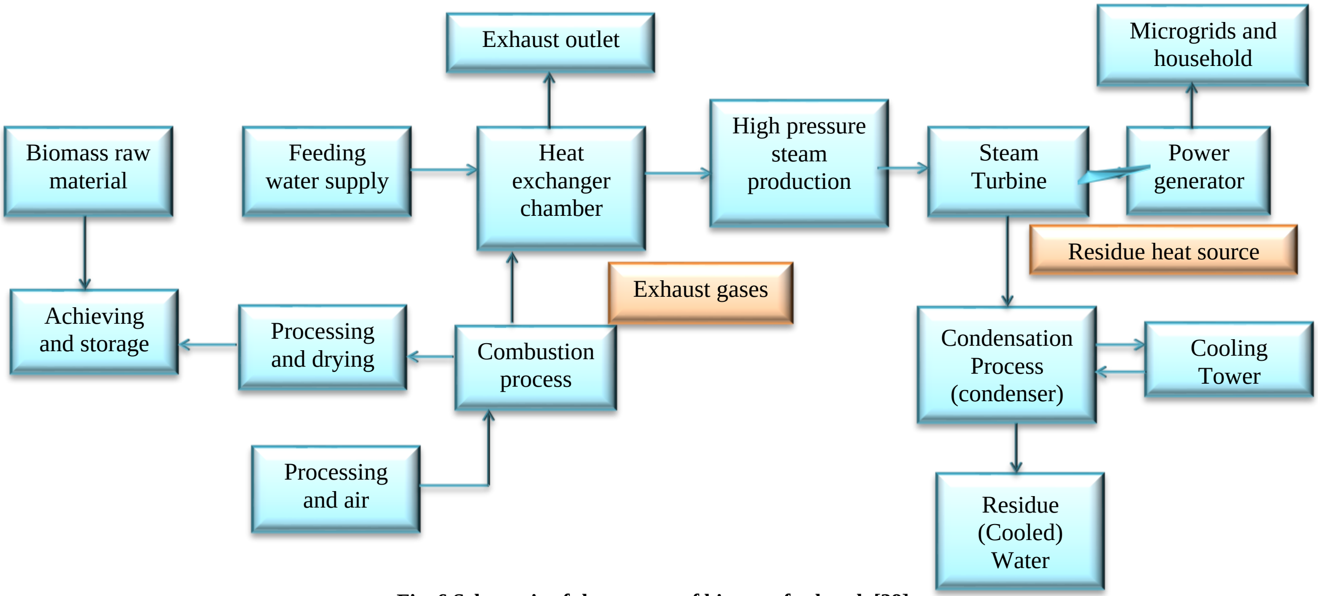


Fig. 6 Schematic of the process of biomass feedstock [38]

Table 1. Biomass resources in Africa for energy applications [37].

S.No.	Sources	Estimated potential		
	Biomass Resource (Dry Mass)	**Current availability**	**Potential additional availability**	**Energy Density**
	UoM	**Million Tons per Anum**	**Million Tons per Anum**	**MPJ per Ton**
1	Agricultural residues	5.80	2.90	10.00
2	Sugarcane residues (filed)	-	2.53	10.00
3	Sugarcane bagasse	0.60	2.34	10.00
4	Plantation residue	1.50	-	12.50
5	Pulp and allied paper mill residues	0.01	0.35	12.50
6	Black liquor	-	0.77	6.30
7	Sawmill waste (including bark)	0.95	1.03	10.40
8	Invasive species	8.07	1.16	14.70
9	Fuelwood	4.00	12.00	14.7
10	Solid waste (organic components)	5.82	-	10.00
11	Sewage sludge (organic residues)	2.28	-	10.00
12	Purposely cultivated crops	9.26	-	14.70
	Total	**38.29**	**23.08**	**-**

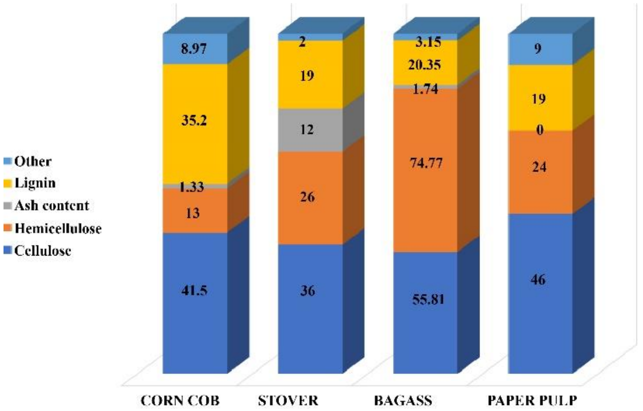


Fig. 7 Percentage compositions of corncob, stover, bagasse, and paper pulp [39]

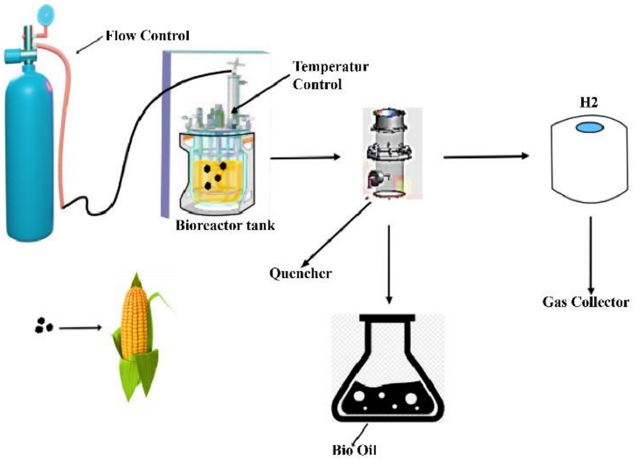


Fig. 8 Schematic diagram of the production of hydrogen gas from corncob [39]

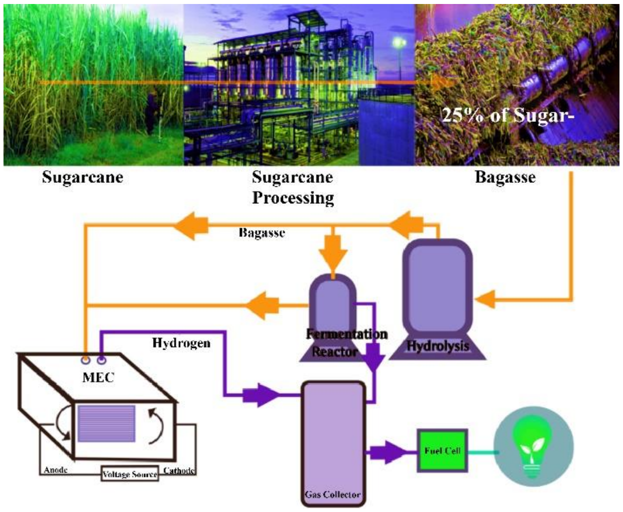


Fig. 9 Schematic diagram of the production of hydrogen gas from bagasse [40]

Fig. 7 shows the composition of a maize cob, stover, bagasse, and paper pulp, and Fig. 8 depicts a schematic for synthesizing hydrogen gas from maize cob [39].

The most common chemical process to produce H_2 gas is the reduction of $C_6H_{12}O_6$ to oxygen, water, and hydrogen, with CO and CO_2 as the most common by-products.

Sugarcane is a potential source of biomass in Africa. Its semi-perennial productive cycle requires re-planting every five years on average. For example, Africa produced about 19.3 million tons of sugarcane in the season 2019-20, about half of the total amount produced in Africa. Bagasse is a fibrous residue and is a by-product of sugarcane milling. It has 45%–50% moisture content, combining hard fiber and smooth & soft parenchymatous (pith) tissue. Bagasse, against annual sugarcane production, has a range of moisture content of 22% to 36%. Fiber present in bagasse also contains cellulose, which can become the chief source of H_2 production. The production of energy from bagasse is an easy, cost-effective, and economical method. A schematic diagram of energy production from bagasse is given in Fig. 9.

Fig. 10 depicts the process of producing hydrogen gas from paper pulp. The system functions as follows: The core component serves as the device's power source. The electricity grid is powered by other energy-consuming devices, such as compressors. A distinct part generates hydrogen gas. After being compressed and stored, hydrogen is transported to the final energy users. The heat exchanger is operated at 40° C.

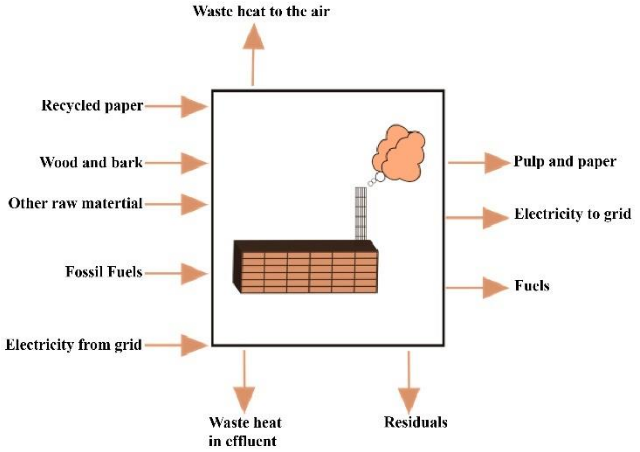


Fig. 10 Schematic diagram of hydrogen gas production from paper pulp

The air-conditioning system can continue to operate by using the condenser fan. The maximum manufacturing capacity of the system is 4 kg/h (hydrogen). Due to maintenance considerations, its actual output capacity is expected to be 3 kg/h. Most municipal waste is dumped on land or burned without being used for other purposes. Improperly dumped or disposed of municipal waste in landfills may cause environmental hazards, such as residual metal elements, dust, polycyclic aromatic hydrocarbons, and malleable compounds. These waste materials are hydrocarbon polymers and include alkene, carbohydrates, lipids, and proteins—substances that can be advantageous for energy production. Only 10% of municipal garbage is recycled, while the other 90% is sent to landfills and may be a significant source of energy [34]. These hydrocarbon-based substances produce an enormous volume of hydrogen gas. The chemical compositions of common waste products are listed in Table 2 [39].

Table 2. Composition of municipal solid waste [39].

Sr. No	Material	% Weight
1	Food	55.86
2	Plastic	11.15
3	Paper	8.52
4	Textile	3.16
5	Wood waste	2.94

A schematic diagram of energy production from municipal waste is shown in Fig. 11 [41], and different sources of biomass and the energy density in Africa are given in Table 3 as an example.

Table 3. Sources of biomass availability and energy density in Africa [42]

Sr. No	Source of Biomass	Availability per year (Million tons)
1	Maize (corncob)	80
2	Sugarcane bagasse	20
3	Paper Pulp waste	1.28
4	Municipal solid waste	54.2

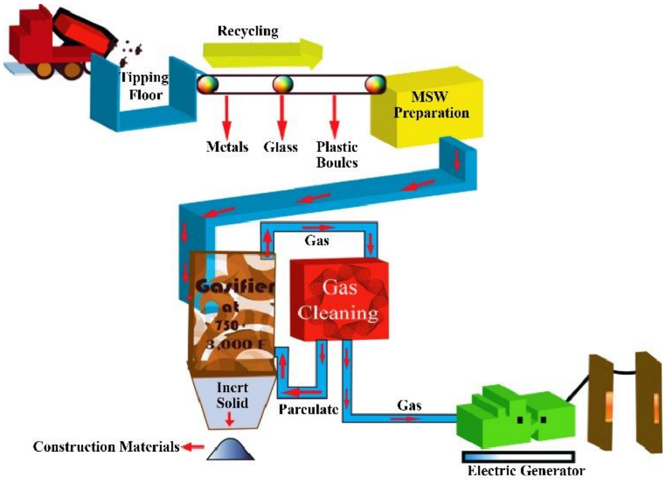


Fig. 11 Schematic diagram of the production of hydrogen gas from municipal waste [41]

It is a requirement of the proposed process that the hydrogen & fuel cell-based heating technologies should be integrated. Policymakers must consider the potential contribution of hydrogen and fuel cell values to establish a low-carbon energy generation system.

4. Case Study in Africa

4.1. Proposed Structure of power generation in Africa

Population growth in Africa has resulted in an increased demand for dependable energy sources. Energy is required to propel the economy forward and allow all Africans to reap its benefits. In the stated policies scenario based on currently implemented and announced plans, Africa's demands for energy will expand at a rate double that of the world average over the next two decades. The stated policies scenario describes the extent of the increase in energy consumption required thru various sources for sustained development [43]. Significant growth in the use of bioenergy is required in Africa within the next two decades. Table 5 (Africa Energy Outlook–Analysis, 2020) illustrates the demand for bioenergy according to the International Energy Agency [10]. The energy demand, in a million tons per annum (Mtoe) of oil, has been converted into petajoules (PJ) here so that it may be compared more easily with the equivalent bioenergy supplied by various methods. In addition, the African policy scenario is detailed in Table 4.

Table 4. Stated policies scenario for Africa [44].

Africa's stated policies projections			
Year	**2018**	**2030**	**2040**
Energy demand (PJ)	293	418	544

The overall primary energy supply in Africa is 5880 PJ. By comparing the bioenergy generation volume from biomass with the supply of energy from various fossil energy sources, it is possible to determine how much of the energy supply can be replaced by bioenergy. Fig. 12 elucidates the total primary supply of energy in Africa and the sources from which they are extracted. As shown, coal is the country's primary energy source [44]. Table 5 lists this information. Biomass provides more than 93.5% of the renewable energy supply. Solar energy, wind power, and hydroelectricity provide for the remaining 6.5%. The overall bioenergy supply is 509 PJ. The overall energy supply has the potential of 5,880 PJ, representing just 8.7% of bioenergy. This indicates that there is a substantial amount of biomass is already being exploited to generate electricity [45].

Hydrogen generation from biomass by gasification is a reliable substitute for natural gas supply. It has the exposure to serve as a power source for the industrial, commercial, agricultural, transportation, and residential sectors. Bio-oil converted into gasoline is a versatile source of biofuel that applies to the above industries. All gasoline used in Africa is imported. If the country uses its biomass to make biofuels, it can reduce its gasoline import and become less reliant on fossil fuel imports.

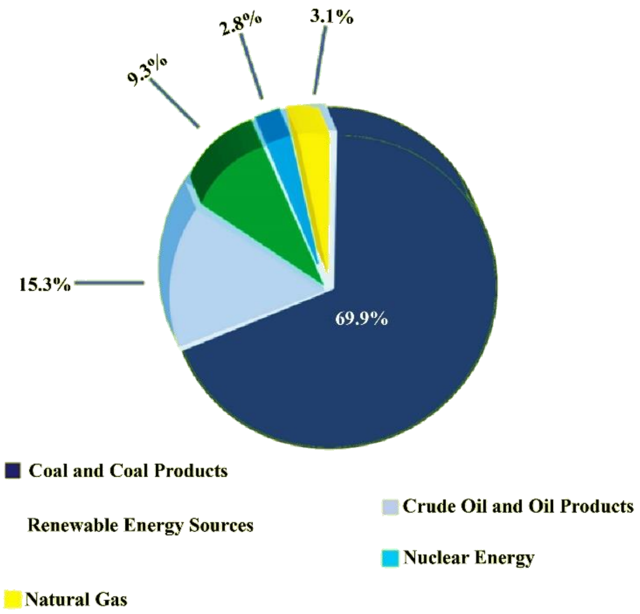


Fig. 12 Total main energy supply in Africa [47]

Fig. 13 depicts the new renewable energy sources in the African region [10]. Energy and exergy energy analysis is based on the heat produced by PEMFC and can be deployed for various collective heating/cooling and power applications solutions. The details are presented in Fig. 14. HT-PEMFCs are fueled by hydrogen generated from biomass and air from the atmosphere. As a result, they directly generate power, called power generation (I), that can be immediately utilized for a microgrid system or domestic usage. Heat is also generated along with power generation (I) by the HT-PEMFC. It can be conceded and re-employed for various combined heating/cooling and power applications, e.g., combined heat & power and cooling & power solutions. The exhaust heat from a fuel cell stack is combined with organic Rankine cycles (ORCT) (consisting of a heat recovery system and a turbine) to generate steam to drive the turbine and to execute thermally regenerative electrochemical cycles for the generation of power called power generation (ii). This can be used for a microgrid or a power generation system. Moreover, heat captured from a fuel cell can be applied to service the system itself. For example, it can be used to increase the rate at which hydrogen is released from the metal hydride canisters (which supply hydrogen towards the stack) or to heat the air & hydrogen going into the fuel cell to make it operate better.

Table 5. Total prime energy supply [46].

Sr. No	Type of energy	PJ
1	Coal and related products	4103
2	Crude oil, related products, and NGL	910
3	Renewable energy resources	546
4	Natural gas	158
5	Nuclear energy	164

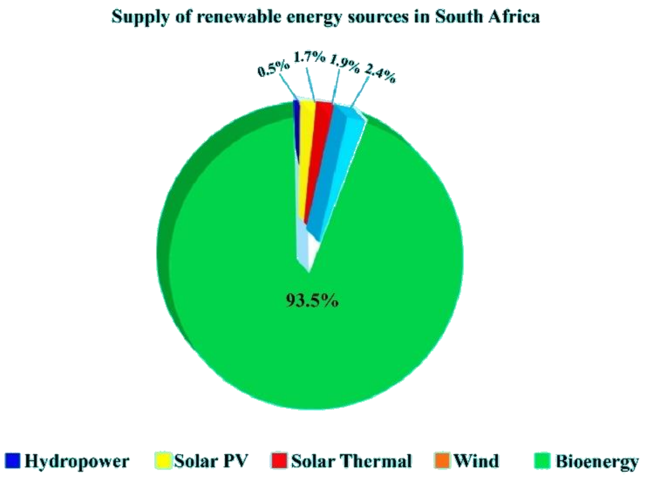


Fig. 13 Illustration of the sources of renewable energy in Africa [48]

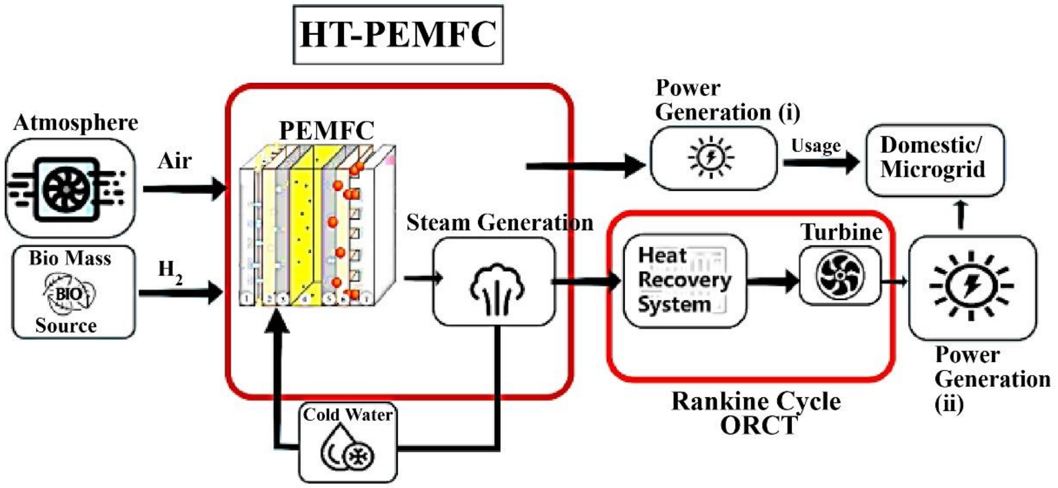


Fig. 14 Schematic of the operation of the HT-PEMFC for the cogeneration of power and heat using biomass-derived hydrogen

The CCHP system comprises the following subsystems: a) the PEMFC subsystem, b) the ORC subsystem, and c) the vapor compression cycle (VCC) subsystem. Typically, 8 kW of electric power, 18 kW of domestic hot waterpower, 12.5 kW of cooling capacity, and 20 kW of heating capacity are required to operate the CCHP system. Six organic working fluids, including C5F12, R36mfc, R601, R601a, R245ca, and cyclopentane, are used in the process. Equation (13) represents the PEMFC subsystem of the CCHP system for the ORC. It is frequently used when the high temperature needed to create steam cannot be obtained. The assumptions below are necessary for analysis.

With small variations in the kinetic and potential energies, steady-state flow conditions exist for all fluid streams. At 101.32 kPa and 25° C, the dead-state scenario obtains. The efficiencies of isentropic exergy of steam and the gasifier are, respectively, 85% and 90%. The unit cost of biomass-based electricity generation is \$115.1/kWh, and its heat energy is 10–15 MJ/Nm^3. The primary equations based on three essential principles are applied to enhance power generation. The mass conservation of mass and the thermodynamics first & second laws of steady-state flow reduce to the form provided by Eqs. (1)–(3), respectively [49].

$$\sum\dot{m}_i = \sum\dot{m}_e \tag{1}$$

$$\dot{Q} - \dot{W} + \sum\dot{m}_i h_i - \sum\dot{m}_e h_e = 0 \tag{2}$$

$$\dot{Ex}_Q - \dot{Ex}_W + \sum\dot{m}_i ex_i - \sum\dot{m}_e ex_e - \dot{Ex}_D = 0 \tag{3}$$

The left side of Eq. (3) consists of exergy transfer due to heat and work, the inlet & outlet of the physical exergy of fluid flow, and the rate of destruction of exergy [4]. The specific flow of physical exergy of the fluid is specified by Eq. (4):

$$ex = (h - h_0) - T_0(s - s_0) \tag{4}$$

Where the subscript "0" refers to the dead-state condition as defined in the assumptions. The performance-related parameters are calculated by using Eqs. (5)–(7):

$$\dot{W}_{net} = \dot{W}_t - (\dot{W}_{cp} + \dot{W}_{fwp} + \dot{W}_{LPHp}) \tag{5}$$

$$EnE = \frac{\dot{W}_{net}}{\dot{Q}_f} \tag{6}$$

$$ExE = \frac{\dot{W}_{net}}{\dot{Ex}_f} \tag{7}$$

$$\dot{W}_t = \dot{m}_{72}(h_{72} - h_{15}) + \dot{m}_{73}(h_{15} - h_{16}) + \dot{m}_{74}(h_{16} - h_{18}) + \dot{m}_{75}(h_{18} - h_{23}) + \dot{m}_{76}(h_{23} - h_{26}) + \dot{m}_{77}(h_{26} - h_{27}) + \dot{m}_{78}(h_{27} - h_{41}) \tag{8}$$

$$\dot{W}_{cp} = \dot{m}_{52} v_{52} \int_{52}^{54} dP \tag{9}$$

$$\dot{W}_{fwp} = \dot{m}_{63} v_{63} \int_{63}^{64} dP \tag{10}$$

$$\dot{W}_{LPHp} = \dot{m}_{35} v_{35} \int_{35}^{37} dP \tag{11}$$

$$\dot{Q}_f = \dot{m}_f \times LHV \tag{12}$$

$$\dot{Ex}_f = \dot{m}_f \times \left[\left(1.0437 + 0.1882 \times \frac{H}{C} + 0.061 \times \frac{O}{C} + 0.0404 \times \frac{N}{C}\right) \times \left\{[LHV_f + \left(h_{fg,water} \times m_{moisture}\right)\right\} + \{m_S(ex_S - LHV_S)]\}\right] \tag{13}$$

4.2. Cogeneration of Power and Heat Using Biomass-derived Hydrogen

A CCHP system is focused on the fuel cell and is connected to an HT-PEMFC to make it more robust than the standard PEMFC [48]. In addition, the powering of ORCs is best accomplished by HT-PEMFCs, which have a range of cell temperature of 120-200° C. The heat generated by this PEMFC may be readily utilized in the process of hydrogen manufacture. The operating temperatures of the prototypical HT-PEMFC vary from 100- 200 °C, allowing for the cogeneration of heat and power as well as making this simpler system highly tolerant to impurities in the fuel.

For a detailed analysis of the energy of the exergy, the variables in the above equations are defined as Q. = net heat transfer (J/s), h = specific enthalpy (kJ/kg), i =intake, o=outlet, P = pressure (kPa), S=specific entropy (kJ/kg.), and T=temperature (ºC). The two components of biomass-based hydrogen generation are energetic and exergetic. A wide range of temperatures of 480 to 1400 ºC, and pressure in the range of 0.1 to 50 MPa could be used in the initial operation of the system. The steam-to-biomass ratio (SBR) ranges from 0.6 to 10, and the equivalency ratio (ER) ranges from 0.1 to 0.4. Compared with the air gasification technique, which yielded values of 3–6 MJ/Nm^3, the gasification of steam obtained 10–15 MJ/Nm3. The efficiency of exergy was 56.8%, with a potential for increases of 670.43 kW and 288.28 kW [49]. In addition, the energetic fuel and comparable components rates of the down-draft gasifier were 1572.08 kW & 901.64 kW, respectively, with a fuel depletion ratio of 43% and a productivity lack ratio of 74.33%. The CCHP coefficients of performance (COP) were 1.19 & 1.42 in the summer and winter, respectively. According to statistics from past work, the hydrogen component ranged from 40% to 80% throughout production. However, with typical operational settings, the average exergy efficiencies were 46% and 47% [50].

4.3. Cost-benefit Analysis of Biomass Power Generation

Based on the calculated values of heat, it can be concluded that gasification is an efficient method for generating electricity by extracting energy from the specified biomasses while maintaining low emissions. However, a variety of technologies depend on the economic viability of H_2 production and its use for large-scale power production relative to the resources of the current generation, as well as an analysis of cost-related variables that can render this technology cost-effective [51]. According to Baratella et al., this techno-economic research with a wide variety of technical choices presents a novel methodology. In addition to the creation of electricity, rejected waste heat is obtained that may be used for other purposes with an integrated mechanism, resulting in a reduction in energy costs. The saving due to this is subtracted from the total cost of generation to obtain its true cost and render it comparable to other sources (Cassir et al., 2012).

4.3.1. Cost-related Components

A major part of the research has been dedicated to techno-economic evaluations and has identified many relevant cost elements. Researchers have broadly characterized the monetary repercussions as follows [52]: Capital spending (CapEx): This includes the costs of plant and machinery, buildings and infrastructure, and other equipment. Operating expenditure (OpEx): It includes employee costs, administrative costs, utilities, waste treatment, depreciation, insurance, and taxes. Feedstock: While the cost of feedstock is included in OpEx, it is typically separately considered for analysis and presentation because of its importance. Tools for economic analysis also contain the other parts of OpEx.

- Tools of Economic Analysis

The economic analysis of a given investment can be conducted using different techniques, such as the one in [53]. The 2004/8/EC-based primary energy savings equation is as follows:

$$PES = 1 - 1/\left[\frac{\eta_{el}-net(cogeneration)}{\eta_{el}-net(ref)} + \frac{\eta_{th}(cogeneration)}{\eta_{th}(ref)}\right] \times 100 \quad (14)$$

PES = primary energy savings.

where, $\eta_{el} - net(ref)\ and\ \eta_{th} - net(ref)$ are the reference efficiencies, which are the efficiencies of the separate production of electricity and heat given in Eq. (14).

Equivalent annual cost (EAC): It depicts the annual cost of an operating plant spread over its useful life. The EAC is the composite of the operating cost and the capital cost that is multiplied by the capital recovery factor (CRF), as shown in Eq.(15):

Equivalent Annual Cost = Annual Operating Cost + (Capital Cost x CRF) (15)

The CRF represents successive cash flows translated into their current value over the plant's useful life and reflects the equivalent value of the net cash flow in a single period. It can be computed by Eq. (16):

$$CRF_{(i,t)} = i\left(\frac{(1+i)}{(1+i)^{t}-1}\right) \quad (16)$$

where i = interest rate and t = useful/operational life of the asset.

Net present value (NPV): the net amount of the difference between two values that are between the current value of cash inflows and cash outflows over the plant's useful/operational life. It is applied to analyze the project's profitability. It can be computed through Eq. (17). At a given rate of return, a positive NPV indicates the favorability of the project, and vice versa [54]. Where Ct = net cash flow (inflow–outflow during a given period), I = interest rate, and t = useful/operational life of the asset. Internal rate of return (IRR): discount rate equates the net present value of inflows and outflows to zero. It provides the output in terms of the percentage instead of the dollar amount. While it can aid in project selection, the absolute value in the form of the NPV is more relevant. The IRR can be computed using the trial-and-error method or by reverse calculation using Eq. (17) by setting the NPV to zero. Levelized cost (LC): Following its computation, the equivalent annual cost is levelized or averaged out at a given production level. The concerned levelized cost is shown in terms of amount and quantity.

$$NPV = Capital\ Cost - \sum_{t=1}^{n} C_t\ x\ (1+i)^{-t} \quad (17)$$

Table 6. Assumptions for the financial analysis of the production of hydrogen using biomass.

Assumptions	Values
Operation Time	8,760 h/year
Capacity Factor	85%
Design Scale	18.9 T H_2/h
Chemical Engineering Plant Cost Index (CEPCI)	574
Internal Rate of Return (IRR)	12%
Loan Interest Rate	9.5%
Debt–Equity Ratio	40:60
Inflation Rate	2.8%
Plant Useful Life	30 years
Loan Period	15 years
Repair and Maintenance	5% of capital cost
Operating Cost	7% of capital cost

For this paper, the cost is shown in H_2 \$/kg and \$/MWh.

Table 7. Comparison of capital costs ($, million) [10].

Capital Cost Components	FBG		EFG	
	Without CC	With CC	Without CC	With CC
Biomass gasifier	236	236	527	527
Boiler and turbines	81	85	48	58
Pressure swing adsorption (PSA)	86	86	70	70
Air separation unit	-	143	157	183
H_2S removal and water gas shift	11	11	20	20
CO_2 removal	233	233	406	406
Carbon capture	-	58	-	75
Total capital cost	**647**	**852**	**1,228**	**1,339**

4.4. Biomass-based Hydrogen Production and Cost of Carbon Capture

The cost of producing hydrogen with and without carbon capture is analyzed for each of the following two methods in terms of H_2 $/kg:

- fluidized bed gasifier (FBG), and
- entrained flow gasifier (EFG).

The assumptions are tabulated in Table 6, and a comparison of the costs of capital is in Table 7.

Cost of H_2 purification: Owing to the high temperature at which the HT-PEMFC operates, H_2 purification is adaptable and does not require additional treatment. The HT-PEMFC system has a lower cost of H_2 purification than the LT-PEMFC, which reduces the cost of H2 generation [55] but increases the requisite equipment, maintenance, and manpower. Further, it increases carbon sequestration in terms of capital and operational expenses at a lower level [56]. By using the AEC and LC, Table 8 shows that hydrogen production cost ($/kg) ranges from $0.87 to $1.79 /kg. One past study estimated the hydrogen production cost through the pyrolysis of biomass to be in the range of $8.86 /GJ to $15.52 /GJ. However, the costs of hydrogen production using wind and PV electrolysis systems are $20.2 and $41.8 /GJ, respectively. Thermodynamic and economic evaluations were performed for the synthesis of hydrogen by using the ammonia–water absorption cycle, and the results showed that the normalized cost of H_2 could be $9.1203 /kg [19]. Similarly, another study calculated the cost of hydrogen production using a coal gasifier as fuel for the PEMFC to be $1.79 /kg [57].

The unit cost for producing electricity from biomass is $115.1 /kWh, and its heating value is 10–15 MJ/Nm^3. Because the HT-PEMFC works at high temperatures, H_2 purification is flexible and does not require additional effort. Even when the cost of cleaning is considered, the HT-PEMFC system is cheaper than most other systems. The production of hydrogen is estimated to cost $1.5 /kg.

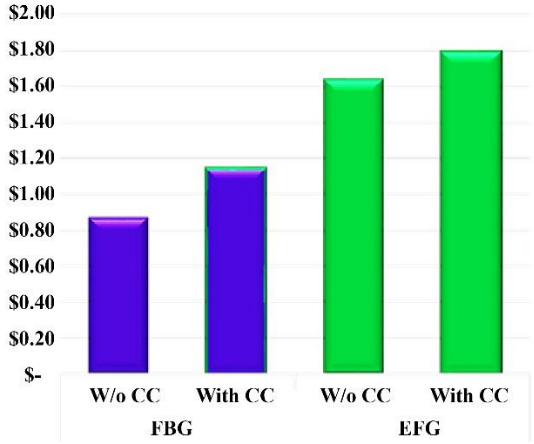


Fig. 15 Comparison of the costs of H_2 production ($/kg) without and with carbon capture using two technologies

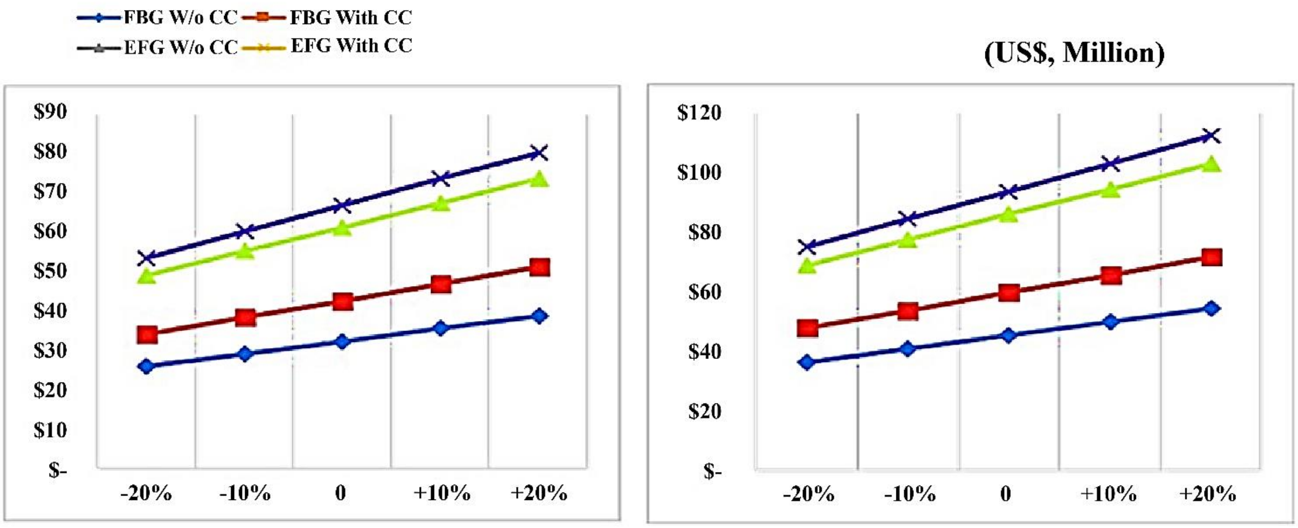
Table 8. Annual equivalent cost and levelized cost ($, million) [69]

Description	FBG		EFG	
	Without CC	With CC	Without CC	With CC
Capital Cost	647.0	852.0	1,228.0	1,339.0
Repair and Maintenance (R&M)	32.4	42.6	61.4	67.0
Operating Expenses	45.3	59.6	86.0	93.7
Total Overnight Cost	724.6	954.2	1,375.4	1,499.7
Annual Equivalent Cost (AEC)	143.4	188.9	272.2	296.8
Levelized Cost (LC) $/kg	0.87	1.14	1.64	1.79

Fig. 15 compares the LC when the same capacity factor and manufacturing output are used. Although the LCt under carbon capture is high, it is compensated for by reducing greenhouse gas emissions over the long term.

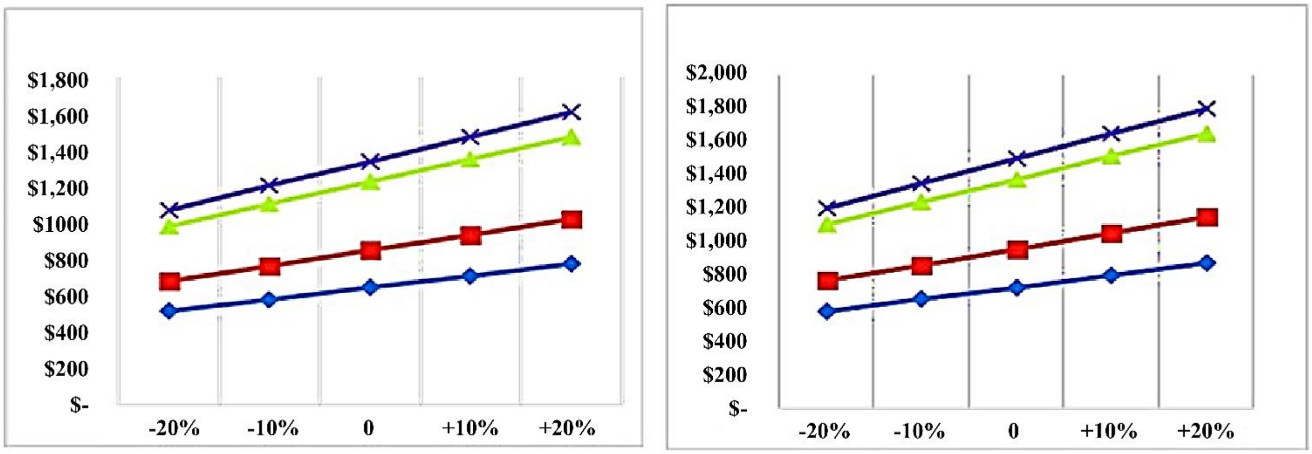
4.5. Sensitivity Analysis of Production Cost

Sensitivity analysis evaluates input variable changes' effect on financial outcomes (output). It depicts a "what-if" scenario based on simulations to support the economic viability of a given enterprise. The scenario in question is dependent on capital cost, which is crucial for determining the effects in terms of the operational cost, capital cost, and overnight cost, as shown in Fig. 16. A sensitivity analysis offers an overall picture of the effects of cost under pessimistic and optimistic scenarios, where this is essential for assessing the financial sustainability of projects. Cost is also determined by the accepted level of sensitivity based on the sensitivities of OpEx and CapEx, which ultimately affect the cost per kilogram of H_2.



Repair and Maintenance (R&M)

Operating Expenses (OpEx)



Capital Cost (CapEx)

Total Overnight Cost

Fig. 16 Sensitivity analysis of cost-related components

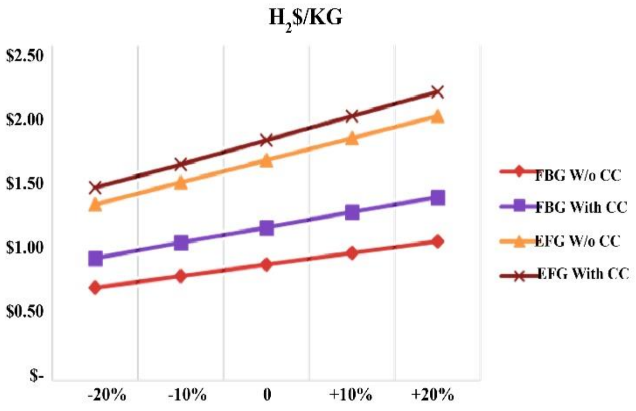


Fig. 17 Impact of sensitivity on per kg cost of H_2

It is indicated in Fig. 17. Sazdovski and Fustik used the lowest and highest expenses to determine and compare the costs of H_2 production with costs incurred by using other sources [59].

Cost of hydrogen production from other sources: A comparison of cost with other sources for hydrogen production is essential for analyzing and ranking the costs associated with producing hydrogen from biomass. Fig. 18 shows this information. The shaded cells represent the cost associated with producing hydrogen from biomass so that it can be readily compared with other sources of hydrogen production. It shows that manufacturing costs can be minimized by using FBG technology and that EFG maintains a competitive position among suppliers in Africa.

Transportation cost: Transport expenses impact the ultimate price of biomass-based fuel generation and vary based on such factors as the weight/distance of the cargo and the mode of transportation. An important factor in determining the impact of the cost of various means of transportation, such as pipelines, ships, trucks, and trains, is the distance between the manufacturing site and the feedstock supply used for power generation. The cheapest mode is used to create a competitive and cost-effective alternative to other sources [61].

Traditional modes of transportation, such as trucks and trains, are used in Africa to carry H_2 converted from biomass to energy generation plants. The actual cost per ton ranges from $3.01 to $14.15. However, it is necessary to develop industrial facilities according to rail and road transit specifications. Research has indicated that railroads are the more cost-effective option, although trucks are the most adaptable [62].

Cost of power generation from different sources: The final product of this process is hydrogen, which has various applications. However, power generation takes up a sizeable portion of the use of the hydrogen produced. The cost of hydrogen is included in the customs tariff. As illustrated in Fig. 19, the cost of power must be examined before the adoption of biomass-based means of energy generation. Its cost of $111.1 /kWh is competitive with those of other sources, which means that it can be feasibly employed as a source of clean energy. Fig. 19 shows a comparison of the costs of electricity generation from different sources [63].

Cost of compliance: According to 2017 data compiled by Lo et al., worldwide carbon emissions totaled around 34.5 billion tons, or 4.8 tons per person [11]. However, Africa's emissions were almost 465 million tons or 10 tons per person.

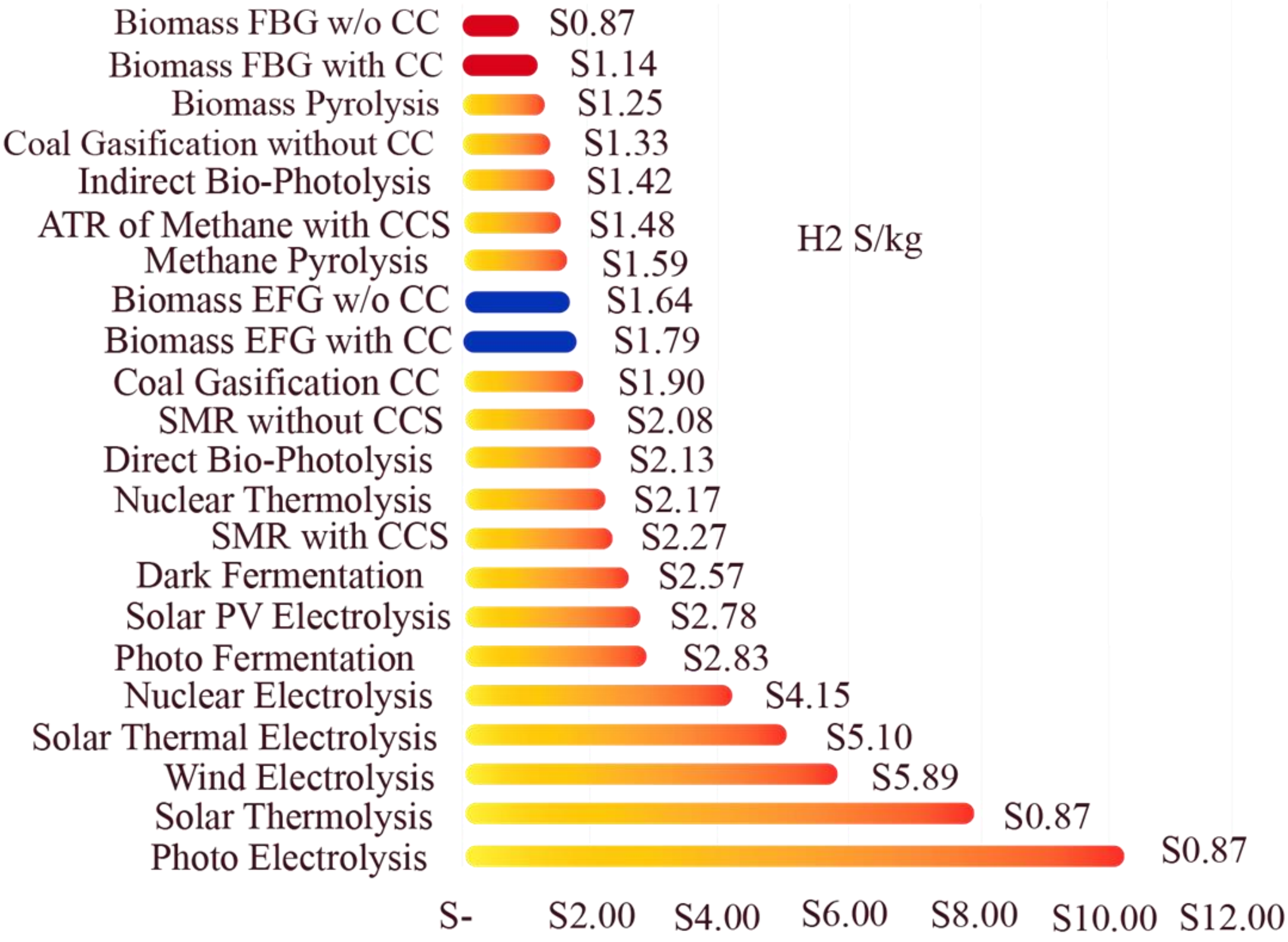


Fig. 18 Costs of hydrogen production from different sources [60]

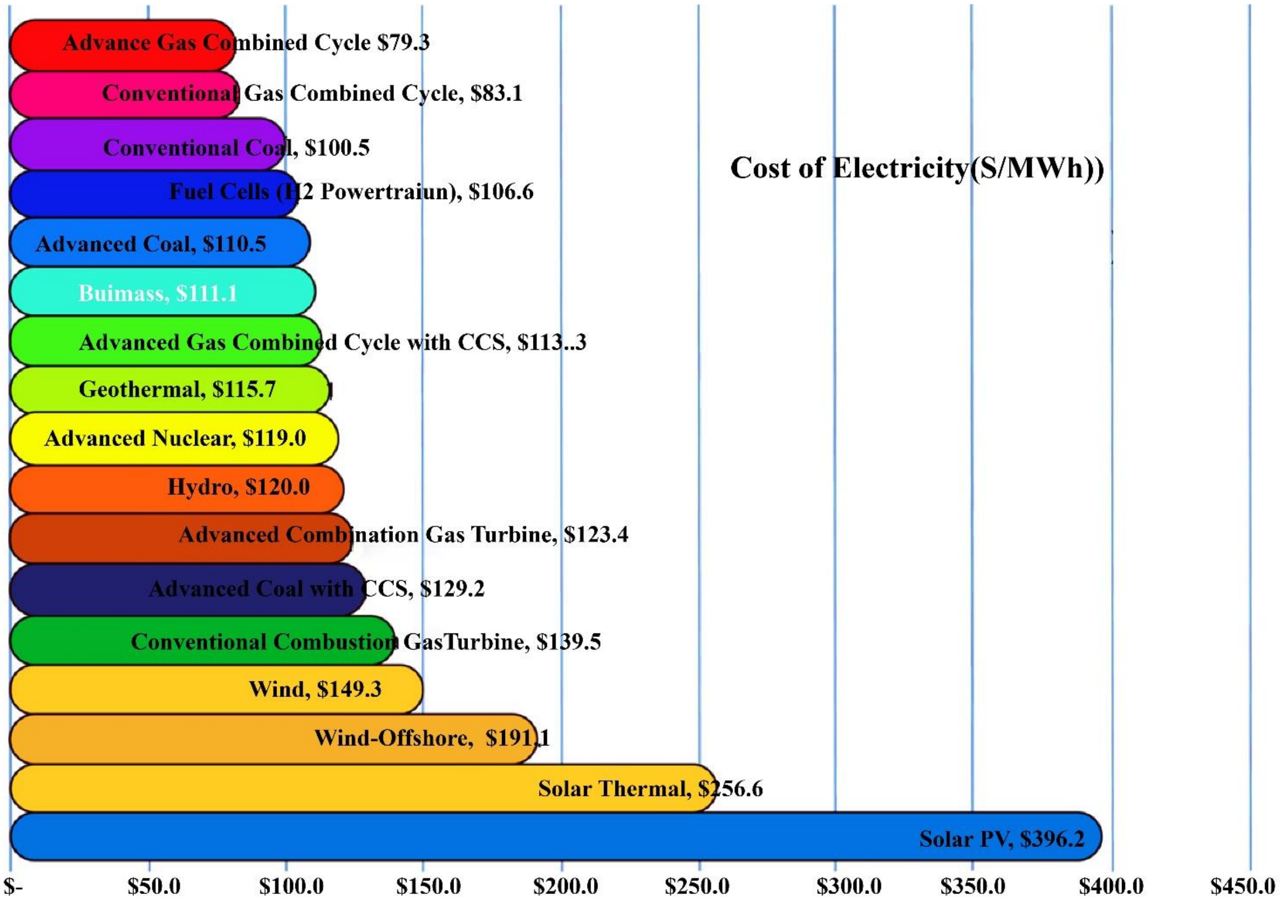


Fig. 19 Comparison of costs of electricity generation from different sources [63]

This enormous component carries a hefty price tag if paired with a $30 /ton emission tax and environmental Sustainability measures. Contextual to hydrogen-based energy economy in the future, it is essential to address the underlying source of carbon emissions. Africa has implemented the R120/tCO_2 carbon emission tax, which is equivalent to $8/kg, to reduce emissions. However, this tax will surge the cost of fossil fuel-based power plants and hinder the application of and support for renewable energy projects, such as biomass-based power generation. Exergy and economic impact: Exergy analysis considers both qualitative and quantitative factors. It helps to provide a useful representation of efficiency and losses by locating and estimating internal invisibility. The flow of exergy drops in the thermodynamic cycle after passing through the source. However, compared with the loss of exergy at the source, its loss at the sink is minor because of internal irreversibility. This difference is called exergy destruction [64]. Both small- and large-scale implementations of the CHP are economically feasible considering using natural gas and other fuels. The large-scale application has superior economic feasibility with a higher NPV and a lower LC.

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On the contrary, operation at a small scale incurs a larger capital cost due to equipment and lower output, making it a more expensive alternative.

Its high output, however, offers benefits at small and large scales, of $0.0222 /kWh and $0.0416 /kWh, respectively, despite the high capital cost at a large scale [64]. Efficiency can thus be improved by investing in biomass technology [65].

5. Future of Sustainable and Environmentally Friendly Energy in Africa: Issues and Concerns

Africa has a sufficient amount of fossil fuel and renewable resources of energy to satisfy its energy demands. Practically all the potential for renewable energy in the continent remains unexplored despite noteworthy efforts over recent years. The African energy mix still relies on renewable energies, such as hydro, geothermal, wind, solar, and non-traditional solid biomass, at less than 2%. The region's energy demand in 2040 is projected to be three times that in 2015 and will be accompanied by a rise in GHG emissions. It will increase the strain not only on local but also on regional energy sources as well as carbon mitigation systems, thus warranting energy conservation and measures for reducing greenhouse gas (GHG) emissions. According to the accelerated energy access (AEA) scenario, the energy consumption and carbon emissions in 2040 will be around 6% greater than the standard scenario, with GHG emissions reaching their peak. This situation involves universal access to energy by 2025. As the continued use of fossil fuels will become dominant in 2040 in the region, GHG emissions are expected to increase.

By contrast, the contributions of oil & coal to global energy demand are expected to decline by 1% because of energy efficiency programs, according to Ouedraogo et al. [65], while the contribution of renewable energy sources will grow by the same amount. Advances in energy-saving policies will help regulate energy in the next few years. The greatest effective strategies for reducing greenhouse gas emissions in the power production industry involve converting current oil and coal facilities into those for generating renewable sources of energy. It will improve energy security while reducing greenhouse gas emissions [66]. A strong, integrated, and sustainable low-carbon plan is needed to enable general access to modern, clean, and dependable energy duly mitigating climate change. The growth in renewable energies and the enhancement in energy efficiency are the two primary portions of any strategic energy policy in Africa [67]. By using native renewable energy resources and efficiently generating energy, Africa can provide the public with widespread access to contemporary energy services. This will be adequate to power continuing socio-economic growth while reducing greenhouse gas emissions. A program for energy efficiency across all energy sectors will result in substantial net energy savings, and the growth in renewable energy will yield not only economical & social benefits but also reap environmental benefits [68]. Reducing health-related problems due to greenhouse gas emissions, enhanced livelihood from services linked to renewable energy businesses and decreased imports of fossil fuels are the primary advantages of this strategy.

5.1. Hydrogen- and Fuel Cell-related Policy Concerns

Despite being a major energy source and greenhouse gas emissions, heat has only recently gained prominence in energy policy debates. The policy related to hydrogen gas has four broad goals: (i) eliminating greenhouse gas and other damaging emissions, (ii) making hydrogen-based energy affordable for individual consumers and businesses, (iii) security & dependability of the supply, and (iv) stimulating the development of export-ready technology. Hydrogen and fuel cell technologies for heating markets are at the crossroads of the heat and energy innovation policies, and various African countries have followed various paths to promote them. Policy-related justifications for supporting hydrogen and fuel cell devices include the following: Market: Current market arrangements may not compensate for the systemic advantages of some technologies, resulting in suboptimal investment and implementation.

5.1.1. Optional

Emerging technologies like hydrogen and fuel cells for heating may require help if not doing so will shut out a long-term alternative or outcome in an intolerable delay. Even if they're the best long-term plan, failing to invest in maintaining options risks losing them in the future. Industrial innovation: Support for hydrogen and fuel cell technologies may lead to a thriving local sector and net economic gains from exports. It also holds for all developing technologies, and substantial technology-specific support based on this rationale may provide limited advantages if industrial growth fails. In the long term, it is evident that decisions will need to be made regarding the distribution of pure hydrogen through the gas network or portions of it. It is impossible to imagine a situation in which market forces (combined with high carbon costs) drive network conversion in the absence of robust government support. This is owing to the coordination-related and regulatory hurdles that need to be overcome to synchronize consumer appliances, infrastructure regulation, and investment in conversion programs. This choice is, therefore, a crucial long-term policy objective that requires substantial developmental work. A transformation of this scope would require the design of appropriate legal frameworks and a well-planned transition. While there may be lessons to be learned regarding the technical elements of conversion from several local gas conversion schemes implemented across the world, most of them have been centrally planned and executed in a completely different regulatory framework that is not analogous to the modern system of several private operators working in many countries [70].

6. Conclusion

This study revealed that Africa's biomass energy sources could be exploited in a clean, efficient, and cost-effective manner. The author investigated the clean exploitation of biomass and the HT-PEMFC and provided a cost–benefit analysis of it. Various aspects of a biomass-derived hydrogen-based HT-PEMFC, with a combined cooling and heating power system to produce electricity and heat, were investigated. The investigation also revealed that power production costs are competitive with other energy sources. Therefore, hydrogen from biomass and hydrogen-based energy generation is expected to reduce carbon emissions and expand the hydrogen economy in developing nations such as Africa in the future. The work here will motivate field engineers and researchers to reconnect Africa to modern technologies in a sustainable, cost-effective, and productive manner. The immediate benefit of this strategy may be enhanced by replacing conventional power plants with hydrogen-based power plants and moving planned expenditure toward hydrogen-based power generation.

With a global emphasis on environmentally friendly strategies for energy generation and net-zero emissions, the HT-PEMFC market is predicted to grow. It reflects a scenario with an ideal microgrid and residential power generation. In some off-grid scenarios, biomass conversion into hydrogen by using an HT-PEMFC system has proved more cost-effective than competing technologies, thus enhancing environmental protection and economic innovation in the energy industry. The academic community must incorporate these technologies into future analyses, and policymakers must consider them when drafting policies to lower GHG emissions from the heat supply sector.

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