Techno-Economic Analysis of Biomass Gasification for Hydrogen Production

Mboneni Charity Mbengwa*, Emmanuel Kweinor Tetteh, Sudesh Rathilal

***Abstract*— This study presents a techno-economic analysis of biomass gasification for hydrogen production, focusing on municipal solid waste (MSW) as the feedstock. With the growing demand for clean energy, renewable hydrogen production has gained significant attention, and MSW gasification offers a promising approach by converting waste into valuable hydrogen. A process model was developed in Aspen Plus to simulate MSW gasification in a RPlug reactor at 800°C and 1 atm, using air and steam as gasification agents. The simulation yielded 110.68 kg/hr of hydrogen from a 1000 kg/hr MSW feed. Key performance indicators, including hydrogen yield, syngas energy and composition, energy efficiency, and environmental impacts, were comprehensively evaluated. Furthermore, an economic assessment was conducted, considering capital costs, operational expenses, investment recovery periods, and hydrogen selling prices. The system achieved a levelized cost of hydrogen (LCOH) of $2.725/kg and an annual revenue potential of $8.85 million, assuming 8000 hours of operation. Over a 20-year project lifespan, the net present value (NPV) reached $1 million at a hydrogen selling price of $10/kg. Additional byproducts, such as nitrogen and water, were repurposed within the plant, further enhancing economic returns and resource efficiency. The results demonstrate that MSW gasification can compete economically with other biomass-based hydrogen production methods, offering a sustainable solution for both hydrogen production and waste management. This aligns with the principles of circular economics, emphasising the value of waste as a resource in the transition to a greener energy future.**

***Keywords*— Gasification, Capital expenses, Operational costs, Aspen plus, municipal solid waste (MSW), levelized cost of hydrogen (LCOH).**

I. Introduction

South Africa is currently moving away from a fossil fuel-based economy to a green economy due to factors affecting the environmental, economic, and social pressures [1]. The country is among the world's top CO_2 emitters, due to its heavy dependence on coal, which accounts for about 77% of greenhouse gases, which affects climate change [2]. Despite being part of global climate agreements, fossil fuel demand has remained high, worsening environmental challenges.

The current atmospheric levels have exceeded the safe threshold, driven by industrial growth, population, and technological challenges [3]. South Africa is investing in renewable energy and the use of clean hydrogen produced using renewable electricity as a key part of its energy transition to reduce emissions and support sustainable development [4, 5]. Although clean hydrogen is currently more expensive than grey hydrogen, studies to reduce renewable energy costs offer potential for price competitiveness.

South Africa has faced an ongoing load shedding issue due to its heavy reliance on ageing coal-fired power plants and increasing electricity demand [6]. The frequent plant breakdowns require constant maintenance, and they are nearing the end of their operational life. In addition, unreliable coal supply and poor coal quality have worsened power shortages [7, 8].

Electricity generated through coal is not only unreliable but also harmful to the climate, prompting the government to work toward decarbonisation. The burning of fossil fuels releases large amounts of CO_2 which is contributing to global warming. [9]. This problem is made worse by population growth, deforestation, pollution, and other human activities that intensify climate change [10]. The country is also a major CO2 emitter, contributing over 50% of Africa's emissions. Notably, the energy sector is responsible for more than 80% of South Africa's greenhouse gas emissions, while less than 40% of the energy produced is efficiently converted into a valuable product [11].

As part of the response, clean hydrogen is attracting significant attention. South Africa's Hydrogen Society Roadmap (HSRM) set the production target of about 500,000 tonnes of clean hydrogen annually by 2030 [12]. This study contributes by evaluating the techno-economic and environmental viability of large-scale clean hydrogen production via biomass gasification while keeping costs lower than those of grey hydrogen alternatives.

Energy scarcity significantly affects companies in developing countries, pushing multiple sectors, including manufacturing, health, education, and agriculture, to seek solutions to reduce their carbon footprints. [13, 14]. Energy is a key driver of economic growth and social development, making it critical to a nation's progress [15].

The rise of CO_2 emissions poses a serious threat to global sustainability, with CO_2 being the main greenhouse gas contributing to climate change [16]. The electricity and heat production sector has seen the highest increase in emissions, accounting for about 45.5% of global emissions growth [17]. However, technological innovation can help reduce emissions by improving production efficiency and resource use. Research by El-Adawy, et al. [18] highlighted the classification of hydrogen types based on their production methods from both

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renewable and non-renewable resources, which helps assess their environmental impact.

Fig. 1 below explains the different types of hydrogen using their colours:

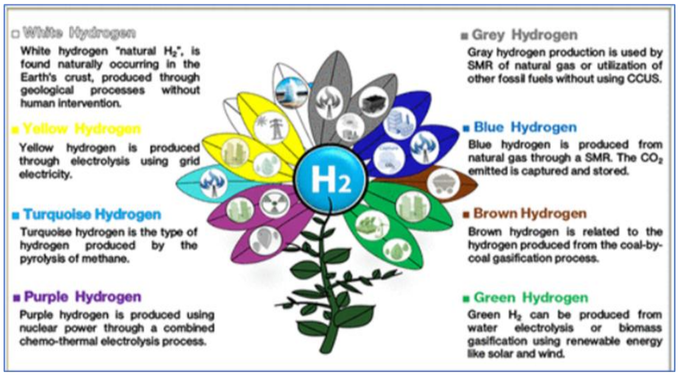

Fig. 1: Types of hydrogen colour-codes adapted from [18]

Incer-Valverde, et al. [19] outlined the most widely recognized hydrogen colour classifications: green, grey, blue, and turquoise. Green hydrogen is generated through water electrolysis powered by renewable energy sources. Grey hydrogen is produced via steam methane reforming (SMR) without carbon capture and storage (CCUS). Blue hydrogen is also produced via SMR, but it uses CCUS to reduce emissions. Turquoise hydrogen is produced through methane pyrolysis, where solid carbon is captured and stored instead of CO_2 gas. South Africa possesses a range of regulations designed to decrease CO_2 emissions and minimise the effects of climate change. The nation's initiatives to safeguard the environment are influenced by domestic legislation and global obligations, especially in accordance with the Paris Agreement.

South Africa's National Climate Change Response Policy outlines the country's approach to tackling climate change, aiming to reduce greenhouse gas emissions and move toward a low-carbon economy. This includes setting emission reduction targets, improving energy efficiency, and promoting renewable energy [20]. Climate change, mainly driven by greenhouse gas emissions, leads to heat being trapped in the atmosphere, causing global warming [21]. Both natural systems and human activities contribute to the rise in emissions, which has increased global temperatures by about 1.1°C above pre-industrial levels [22]. This warming is linked to more frequent extreme weather events, such as wildfires, sea-level rise, heatwaves, and droughts, which carry a significant economic cost worldwide.

South Africa introduced a carbon tax to help reduce greenhouse gas emissions by targeting major emitters like power plants, industrial facilities, and the transport sector [23]. The aim is to push these sectors toward cleaner technologies and lower emissions. It remains the only country in sub-Saharan Africa with a carbon tax and was an early mover globally, beginning discussions as early as 2010 [24]. Due to its energy and carbon-intensive economy, driven mainly by the minerals energy complex, South Africa is the largest emitter in Africa and ranks 14th globally [25].

South Africa's Integrated Resource Plan (IRP) outlines a shift toward a more sustainable energy mix by investing heavily in renewables like solar and wind to reduce reliance on fossil fuels for electricity generation [26, 27].

II. Process Description and Aspen Simulation

ASPEN Plus was chosen for modelling hydrogen production. This simulation software has been used to model gasification in biomass power generation systems in numerous research initiatives. This system uses unit operation blocks that represent specific process operations (such as reactors, heaters, and pumps). [28]. The process converts MSW-derived feed into hydrogen using a staged thermo-chemical treatment and syngas upgrading train. Feed preparation and thermal decomposition remove moisture and separate volatile fractions in a dedicated decomposition and pyrolysis stage, producing char, condensable organics and a volatile gas stream. Volatiles are separated from solids and routed to a mixer, where controlled amounts of steam and air are added to achieve the desired equivalence ratio and steam-to-carbon ratio. The mixed stream enters a two-stage gasification sequence: an oxidation stage (partial combustion) to generate heat and initiate conversion, followed by a reduction stage in which steam reforming and water-gas shift reactions increase the hydrogen content. Solids (ash and residual carbon) are removed downstream in a solid's separator. The hot, raw syngas then pass through tar-removal and heat-recovery/cooling steps before final gas cleanup and hydrogen separation. A low-temperature separator yields purified hydrogen as a product and a byproduct stream containing condensable and unconverted species. The configuration balances robustness against heterogeneous MSW contaminants with opportunities for byproduct valorisation and heat integration to improve overall system economics. The reactions that take place during the oxidation and reduction process are given in **TABLE** .

TABLE I: CHEMICAL REACTIONS

Oxidation reactions:	$CO + \frac{1}{2}O_2 \rightarrow CO_2$	R1
	$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2$	R2
Reduction reactions:	$C + H_2O \rightarrow CO + H_2$	R3
	$CH_4 + H_2O \rightarrow CO + 3H_2$	R4
	$CO + H_2O \rightarrow CO_2 + H_2$	R5
	$C + CO_2 \rightarrow 2CO$	R6

Fig. 2 illustrates the population distribution across seven South African provinces and serves as a foundational indicator of regional waste-generation potential. Gauteng emerges as the most populous province, with approximately 15 million residents, followed by KwaZulu-Natal with approximately 10 million. The Western Cape and Eastern Cape have moderate populations of 6 million each, while the Northwest and Free State each hover near 3 million. The Northern Cape has the smallest population, with fewer than 1 million people. These demographic insights are critical for tailoring waste management strategies to provincial population scales.

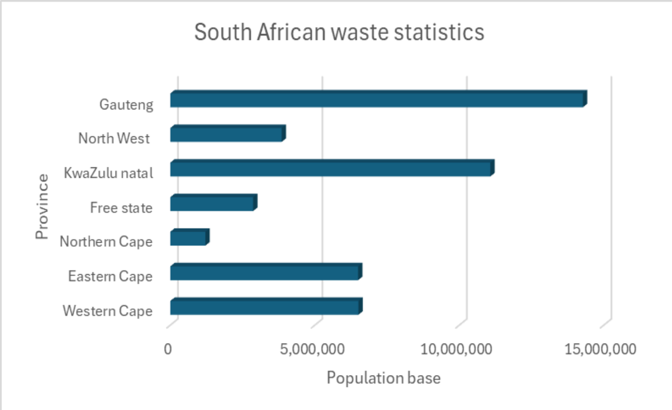

Fig. 2: South African waste statistics adapted from [29]

The composition used was standardised using published waste audits and supplemented with information obtained from the Department of Environmental Affairs and peer-reviewed studies. **Table** Defines the ultimate and proximate analyses used for the elemental composition.

TABLE II: THE MUNICIPAL SOLID WASTE PROPERTIES SPECIFICATION, ADAPTED FROM [30]

Proximate analysis (on dry basis)	
	MSW
Moisture (%)	5.8
Fixed carbon (%)	77.2
Volatile solids (%)	10.0
Ash (%)	7.0
Ultimate analysis (on dry basis)	
Carbon (%)	42.1
Ash(%)	7
Hydrogen (%)	6
Oxygen (%)	44.17
Clorine (%)	0.13
Nitrogen (%)	0.4
Sulfur (%)	0.2
Sulfur analysis data	
Pyritic	0.09
Sulfate	0.02
Ash	0.09
LHV (MJ/kg)	16.71

The values were reported in both the proximate and ultimate analyses, each summing to 100%, ensuring data internal consistency. The ash content must remain consistent across both studies, as it represents a standard parameter. Furthermore, the individual components of the sulfur analysis should collectively correspond to the total sulfur content reported in the ultimate analysis.

To ensure uniformity and achieve the desired particle size for subsequent processing, the feedstock was reduced in size by crushing or grinding. This homogenised material was then introduced into a yield reactor operating at elevated temperatures between 700 °C and 1200 °C. Within this reactor, complex feedstocks were thermally decomposed into fundamental gas-phase molecules and a solid slag by-product. The HCOALGEN and DCOALIGT models were employed to estimate the enthalpy and density of biomass and ash, which are treated as non-conventional, non-reactive solids [31] . The yield of each component was calculated using the following expression:

$$\text{Yield component} = (1 - \text{moisture fraction}) \times \text{component fraction in biomass} \quad (1)$$

This equation was used to determine the required input for the yield reactor. The water yield was assumed to be equivalent to the biomass's moisture content. A portion of the resulting CO_2 and H_2O was subsequently converted into CO and H_2 through interaction with the char produced during pyrolysis. [32].

The output from the yield reactor was then directed to an RGibbs reactor, where pyrolysis occurred at 800 °C in the absence of oxygen. This reactor facilitated the thermal decomposition of organic matter into a mixture of gases and solids. To maintain thermal stability and promote equilibrium, 100 kg/hr of nitrogen was introduced as an inert gas at 25 °C.

Before gasification, solid components were separated using a splitter. The gaseous fraction was then fed into the gasification reactor, where oxidation and reduction reactions further converted the feed into syngas. Parallel homogeneous reactions occur when carbon reacts with gaseous products, indicating that the reactions occur in the gas phase. The kinetic rates used are presented in **Table** III.

TABLE III: KINETIC RATES FOR OXIDATION AND REDUCTION REACTIONS ADAPTED FROM [33]

Reaction no./name	Kinetic rate (Kmol/m3.s)
Methane partial oxidation	$1.58 \times 10^{12} e^{\frac{-2.02 \times 10^4}{RT}}$
CO oxidation	$1.08 \times 10^{7} e^{\frac{-1.8 \times 10^5}{RT}}$
Water gas	$8 \times 10^{-3} e^{\frac{-4.99 \times 10^4}{RT}}$
Methane reformation	$1.2 \times 10^{10} e^{\frac{-318000}{RT}}$
Water-gas shift	$1.35 \times 10^{5} e^{\frac{-102400}{RT}}$
Boundouard – Carbon reaction	$1.05 \times 10^{13} e^{\frac{-1.35 \times 10^5}{RT}}$

The pyrolysis product stream (RG-PROD) is directed into a splitter, where a cyclone is added to separate the gaseous products (SP-OUT) from the solid by-products (SOLID). The solid stream is then routed to a separator, where ash is removed, and a portion of the residual carbon is redirected to a mixer to facilitate complete reaction conversion within the downstream reactors. Meanwhile, the gaseous stream (SP-OUT) proceeds to the mixer, where air and steam are introduced to support further thermochemical processing.

Once the mixing process is complete, the mixer output (MX-OUT) is introduced into the plug-flow reactor, where gasification occurs at 700 °C. The stream from the oxidation reactor is then introduced into the second plug-flow reactor to complete the kinetic model.

The initial reactor sizing diameter used was 15m, and the length was 100 m. **Fig. 3** Shows the MSW gasification simulation process.

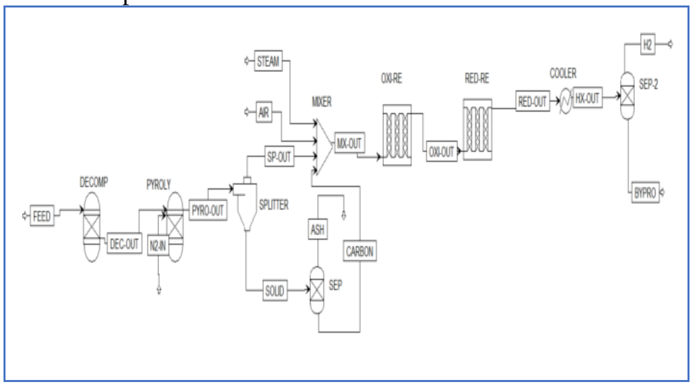

Fig. 3: Aspen simulation flowsheet for the gasification of Municipal Solid Waste to hydrogen production

III. Results and discussion

A. Model results

The results demonstrate how operational parameters affect syngas composition, hydrogen yield, and the overall efficiency of the production process. The simulation was carried out using a steady-state Rplug gasifier model, with air and steam serving as the gasifying agents. Furthermore, the impact of the steam-to-air ratio, gasification temperature, and pressure was analysed to determine the optimal operating conditions.

Under standard operating conditions, dry municipal solid waste (MSW) was fed into the system at a rate of 1000 kg/hr. The process was conducted at 800°C and at atmospheric pressure (1 atm). The feedstock had a moisture content of 5.8%, which significantly influences the system's thermal efficiency and energy balance. These operating parameters are essential for maximising conversion efficiency and ensuring stable reactor performance.

B. The effect of feedstock in the production process

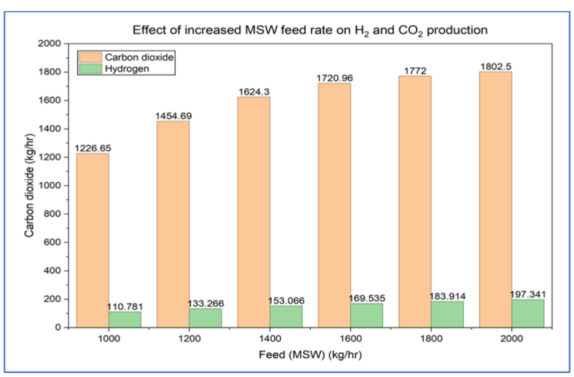

Fig. 4: Effect of varying feed quantity for gasification

te of municipal solid waste (MSW) and the production rates of hydrogen (H_2) and carbon dioxide (CO_2) during gasification. As the MSW feed rate increases from 1000 kg/hr to 2000 kg/hr, both H_2 and CO_2 production rise accordingly. CO_2 production increases from 1226.65 kg/hr to 1802.5 kg/hr. However, the rate of increase begins to taper off at higher feed rates, suggesting a potential saturation effect or limitations in the oxidation reactions. In contrast, H_2 production rises more steadily from 110.78 kg/hr to 197.34 kg/hr, indicating that higher feed rates enhance the availability of hydrogen-rich compounds for conversion. These trends highlight the importance of feed rate optimisation to maximize hydrogen yield while managing CO_2 emissions, which is critical to improving the efficiency and environmental performance of the gasification process.

C. Economic analysis for the gasification of MSW

The economic evaluation of the hydrogen production system via gasification with carbon capture demonstrates strong financial viability. With a municipal solid waste (MSW) feed rate of 1000 kg/hr, the system produced approximately 110.68 kg/hr of hydrogen, translating to an annual output of around 885,440 kg, assuming 8000 operational hours per year. The total annual cost was estimated at $3,165,302.31, resulting in a levelized cost of hydrogen (LCOH) of $2.725/kg. Given current market prices for hydrogen ranging between $3.50 and $10.00 per kg, the projected annual revenue from hydrogen sales alone is approximately $8,854,400.

Over a 20-year project lifespan, with a 10% discount rate and a 2% annual increase in operating costs, the Net Present Value (NPV) reaches $1 million at a hydrogen selling price of $10/kg. The process also captures 1227.54 kg/hr of CO_2, equating to an annual value of $490,816, and 4037.29 kg/year of CO, valued at $242.23. These by-products can be monetised or utilised in downstream applications such as green methanol synthesis. Additionally, nitrogen (N_2) generated during the process contributes to revenue, while the water produced is repurposed for non-critical plant operations, reducing the need for high-purity water.

Overall, the gasification system not only demonstrates efficient hydrogen production but also delivers strong economic performance and environmental benefits, reinforcing its potential as a commercially attractive solution for hydrogen generation.

IV. Conclusion

Municipal solid waste (MSW) gasification presents a highly promising pathway for hydrogen production, offering both environmental and economic advantages. The process demonstrates strong financial viability, with a hydrogen yield of approximately 110.68 kg/hr and an annual revenue potential of $8.85 million at current market prices. Simulation results using Aspen Plus indicate that optimal hydrogen production occurs at 850-900°C and atmospheric pressure, beyond which efficiency gains diminish. Elevated temperatures enhance the formation of CO and CO_2 through intensified gas-phase reactions, while CH_4 declines sharply due to thermal instability and secondary cracking. Hydrogen output increases with temperature, peaking at around 950°C, though energy demands and system complexity also rise. The system captures significant amounts of CO_2 and CO, which can be monetised or utilised in downstream processes such as green methanol synthesis. In contrast, byproducts, such as gasoline and nitrogen, contribute to additional revenue streams. Water produced is repurposed within the plant, reducing the need for high-purity feedstock. Overall, MSW gasification not only supports sustainable waste management but also aligns with strategic goals for clean energy, making it a commercially attractive and environmentally beneficial solution for clean hydrogen production.

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