23rd International Conference on Renewable Energies and Power Quality (ICREPQ'25)
Tenerife (Spain), 25th to 27th June 2025
ISBN-13: 978-84-09-66511-2

Advancing Sustainable Hydrogen Production: Cost, Environmental, and Technological Innovations in Biomass, Pyrolysis, and SMR

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Abstract. Hydrogen production methods differ significantly in their environmental impact and cost-benefit trade-offs, highlighting the urgent need for sustainable and cost-effective approaches to hydrogen production. In this paper, we focus on studying the optimal production pathway which can balance environmental friendliness, economic feasibility, and long-term sustainability. Currently, approximately 90% of global hydrogen production relies on steam methane reforming (SMR). While methane, the primary component of natural gas, serves as the key feedstock, natural gas also contains 0–20% methane and, occasionally, other hydrocarbons. As a fossil fuel, natural gas is a finite resource, and its eventual depletion is inevitable, even under the most optimistic industry forecasts. The limitations of this production model are becoming increasingly apparent, particularly in the context of volatile natural gas prices, such as the historic price surge in 2008. Although prices have stabilized in recent years due to a combination of global economic slowdowns and the rise of hydraulic fracturing (fracking) in the United States, the environmental consequences of fracking—especially its localized ecological impacts—remain significant.

Keywords: *Municipal solid waste, Steam Methane reformer, Thermo-Chem, Electrohydrogenesis, Pyrolysis*

Abbreviations	:	Definitions
SMR	:	Steam Methane Reforming
ATR	:	Autothermal reactor
MSW	:	municipal solid waste
MEC	:	microbial electrolysis cell
VFA	:	volatile fatty acids
ATP	:	adenosine triphosphate
TCI	:	Total Capital Investment

1. Introduction

Hydrogen is not just a valuable element; it's a lifeline for many industry processes. From the production of ammonia via Haber-Bosch, to the creation of methanol, syngas, and hydrogen peroxide, and as an energy source for fuel cells or combustion engines, hydrogen is a key energy carrier for many facets of society. The urgency of this topic cannot be overstated. With increased investment into new technologies and the refinement of existing ones, hydrogen production through traditional methods like SMR or more novel methods may see a price decrease. On the other hand, diminishing natural gas supplies may cause SMR production prices to increase in the coming years. In contrast, with growing demand, the retail price of H_2 may increase overall, regardless of production method. However, the potential of alternative methods for hydrogen production using biomass is too significant to ignore. These methods, which eliminate the need for natural gas feedstock and offer a sustainable growth path, are still in their early stages. The key to unlocking their complete potential lies in further research and development. Your involvement in this crucial phase of exploration and innovation is vital. With increasing demand and diminishing natural gas supply, optimizing biomass hydrogen production could see it transition from a niche role to a mainstream solution [1],[2].

2. Biomass Sources

There are various methods for producing hydrogen from biomass, a diverse range of sources that, by the definition of 'biomass,' do not involve using natural gas. This is particularly significant given the dwindling supplies and rising demand for natural gas worldwide. Biomass fuel can be derived from several sources, each with its unique characteristics, which can be categorized into four main groups: Firstly, the Energy Crops: This category includes herbaceous, woody, industrial, and aquatic energy crops. Secondly, Agricultural Residues and Waste encompass waste generated from crops and animal byproducts. Thirdly, Forestry Waste and Residues include mill wood waste, logging residues, and leftover materials from trees and shrubs. Lastly, Industrial and Municipal Wastes consist of municipal solid waste (MSW), sewage sludge, and waste from various industries. It's crucial that the biomass source selected for hydrogen production is not only locally available but also sustainably sourced. This responsible approach is key to ensuring a high yield of hydrogen and committing to environmental conservation [3]

3. Biomass Hydrogen Production Methods

Hydrogen production from biomass presents a transformative opportunity, categorized into three compelling methods: thermo-chemical, Electrohydrogenesis, and biological. Each technique offers unique advantages and can be further divided. Electrohydrogenesis, or bio-catalyzed electrolysis, is a testament to the impressive advancements in hydrogen production as illustrated in equation (1). This method, which emerged in 2007 as a breakthrough approach, uses bacteria to decompose organic matter in a specially designed electrochemical cell. When a small voltage is applied, this process achieves an impressive production efficiency of 288%, underscoring its high potential and efficiency. Natural gas is rapidly emerging as an essential pillar of the global energy landscape. Renowned for being one of the cleanest, safest, and most valuable energy sources available, it holds the promise of a more sustainable future. While it is not entirely without risk—burning natural gas can release lower levels of potentially harmful by-products into the atmosphere—its benefits far outweigh the drawbacks. The composition of natural gas can vary, but the chart below provides a clear overview of its typical makeup before it is refined, showcasing its vital role in our energy supply [4].

Finally, biological hydrogen production offers a range of diverse techniques, including direct photolysis, indirect photolysis, photo fermentation, the biological water-gas shift reaction, and dark fermentation. By thoroughly exploring these various methods and understanding their processes, costs, and benefits, we can pave the way for a sustainable hydrogen future.

Table 1 Typical composition of Natural Gas

Methane	CH_4	70-90%
Ethane	C_2H_6	
Propane	C_3H_8	
Butane	C_4H_{10}	0-20%
Carbon Dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulphide	H_2S	0-5%
Rare gases	Ar, He, Ne, Xe	trace

A. Thermo-chemical

1) Biomass Gasification

The biomass gasification process is helpful for sources with less than 35% moisture content. Unlike pyrolysis, the gasification reaction is done in the presence of oxygen. Both are done at high temperatures. The basic gasification reaction appears in equation (1):

$$\boldsymbol{Biomass + H_2O_{(g)} + Heat \rightarrow H_2 + CO + CO_2 + CH_4} \quad (1)$$

The methane can then be steam-methane reformed as illustrated in equation (2) illustrates the carbon monoxide and hydrogen product.

$$\boldsymbol{H_2O_{(g)} + CH_4 \rightarrow CO + 3H_2} \quad (2)$$

Finally, the remaining carbon monoxide can be run through a water-gas shift reaction to yield the maximum hydrogen product, equation (3) illustrates the product of carbon dioxide and hydrogen.

$$\boldsymbol{H_2O_{(g)} + CO \rightarrow CO_2 + H_2} \quad (3)$$

The gasification approach stands out as a highly cost-competitive method in the market, yet there remains significant potential for enhancing efficiency and minimizing wasteful by-products. At elevated temperatures, tar can form complex polymers that impede vital reactions. However, with the right system design, precise controls, and the strategic use of catalysts, we can effectively mitigate tar buildup and maintain control over the process, unlocking the full potential of gasification [4].

*2) SMR (***steam methane reforming)**

This technology, which has been the most predominantly used commercially, involves the catalytic and endothermic conversion of steam and methane to hydrogen and carbon monoxide. After desulphurizing the natural gas feed, the product is mixed with steam (optionally CO2) and then preheated to about 780K before it enters the reformer tubes. The heat for the endothermic reforming reaction is supplied by fuel combustion in the reformer furnace. The hot effluent gas exiting the reformer is used to produce steam. A separator separates water from the syngas by gravitation, and the raw syngas are treated further depending on their use.

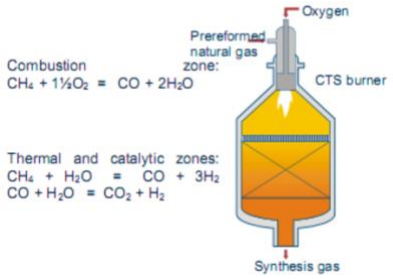

Fig. 1 Thermal reformer

The steam reformer, which demands a substantial amount of heat, is complemented by the autothermic reformer (ATR), which generates heat. An innovative approach utilizes the ATR's heat to meet the steam reformer's heat input requirements, known as heat-exchange or gas-heated reforming as shown in Figure 1. This method significantly reduces investment costs by eliminating the need for an expensive fired reformer and promises substantial cost savings. The trade-off, however, is the generation of only medium-pressure steam and the significant electrical power required to operate the syngas compressor [5].

1. **Appendix-A** (Reactions during methane conversion with steam and/or oxygen)
2. **Appendix-B** (Process schematic- SMR)
3. **Appendix-C** (UNsim Simulation Model-SMR)
4. **Appendix-D** (Catalyst and Reactor Data and Reactor Kinetic and equilibrium data)

3) Pyrolysis

Pyrolysis, a similar thermo-chemical process to gasification, is distinguished primarily by its lack of

oxygen and the high pressures at which it operates. Operating at temperatures of up to 800 K, pyrolysis generates a diverse range of gaseous products that can be further processed through steam methane reforming and the water-gas shift reaction, akin to gasification. It also produces valuable liquid by-products such as acetone, acetic acid, char, and pure carbon solids. This multifaceted process not only showcases the versatility of pyrolysis but also piques interest in its potential as an effective waste-to-energy solution. Equation (4) illustrate the product of bio-oil and gas.

$$Biomass + Energy \rightarrow Bio\text{-}oil + Char + Gas \quad (4)$$

The bio-oil can be reformed in a two-step process using a metal catalyst to produce more hydrogen as illustrate in equation (5).

$$Bio\text{-}oil + H_2O_{(g)} \rightarrow CO + H_2 \quad (5)$$

and then running a water-gas shift reaction, equation (6) illustrates the carbon dioxide and Hydrogen.

$$CO + H_2O_{(g)} \rightarrow CO_2 + H_2 \quad (6)$$

Pyrolysis is favored over gasification if the desired products are also liquids and solids.

4) Electrohydrogenesis

Electrohydrogenesis, a groundbreaking approach that leverages bacteria's natural abilities to break down organic matter in advanced electrochemical cells, is the central theme of the technical paper "Hydrogen Production from Proteins via Electrohydrogenesis in Microbial Electrolysis Cells." This innovative process is sure to intrigue and engage the audience. In recent developments, Electrohydrogenesis has been optimized for hydrogen production from a variety of sources, including carbohydrates, volatile fatty acids (VFAs), and wastewater. Within a microbial electrolysis cell (MEC), Ex-electrogenic bacteria at the anode effectively oxidize organic matter, transferring electrons through an external circuit to the anaerobic cathode. Here, hydrogen gas (H_2) is generated from protons in the solution when an applied voltage of approximately 0.2V or more is utilized. It is crucial to recognize that additional energy input is necessary to render this process thermodynamically favorable, as it is inherently endothermic (indicated by a positive Gibbs free energy) unless hydrogen gas concentrations are kept extremely low. Remarkably, energy recoveries in MECs often surpass 100%, showcasing the efficiency of this method by comparing the heat of combustion of the produced H_2 to the electrical energy invested. This compelling efficiency underscores the potential of Electrohydrogenesis as a sustainable energy source, impressing and convincing the audience of its viability [6], [7].

4. Biological Production of Hydrogen

The production of hydrogen through biological methods is a promising and innovative approach, harnessing the power of specialized enzymes such as hydrogenase and nitrogenase. These vital enzymes are sourced from unique microorganisms, including ***Cyanobacteria, Azotobacter vinelandii, Rhodobacter capsulatus, Anabaena, and Rhodobacter*** **sphaeroides.** It's fascinating to note that these microorganisms, by catalyzing essential reactions, can efficiently generate a diverse array of compounds and elements, with hydrogen at the forefront. Embracing these biological production methods could lead us toward a cleaner and more sustainable energy future.

a) Direct Bio photolysis

Direct bio-photolysis uses solar energy directly to convert water to hydrogen and oxygen. The simplified reaction is as follows, equation (7) illustrates the product of Oxygen and Hydrogen contents.

$$2H_2O_{(l)} + Solar\ Energy \rightarrow O_2 + 2H_2 \quad (7)$$

b) Indirect Bio photolysis

Indirect bio-photolysis is a complex yet fascinating process that surpasses the simplicity of direct bio-photolysis. It typically involves several key steps: (i) the production of biomass through the efficient process of photosynthesis, (ii) concentration of that biomass, (iii) aerobic dark fermentation that transforms the biomass into glucose within algal cells, and (iv) the innovative conversion of acetates into hydrogen.

c) Biological Water-Gas Shift Reaction

Consider the extraordinary microorganism "*Rhodospirillum rubrum"*. This unique organism thrives as a photoheterotroph, meaning it cannot rely on carbon dioxide for its carbon needs but can efficiently utilize carbon monoxide. Remarkably, it can generate adenosine triphosphate (ATP) even in the absence of light by using carbon monoxide. The reaction can be illustrated as follows, equation (8) illustrates the product of carbon dioxide and Hydrogen contents.

$$CO + \tfrac{1}{2}O_2 \leftrightarrow CO_2 + H_2 \quad (8)$$

This reaction establishes a dynamic equilibrium heavily favoring carbon monoxide and hydrogen products, which opens an exciting path for sustainable hydrogen production. Embracing this process could lead us towards cleaner energy solutions and greater environmental sustainability [8].

d) Photo-Fermentation

Photo-fermentation is an innovative process that effectively harnesses solar energy to generate hydrogen from biomass waste, including lactic acid, lactate feedstock, wastewater, and sugar refinery by-products. Utilizing specialized bacteria that employ nitrogenase alongside solar energy, this method can achieve remarkable efficiencies of up to 86% when lactic acid serves as the fuel source. While there are challenges to overcome, such as the need for extensive bioreactor land and the high energy requirements for the enzymes, the potential benefits of this technology make it a promising avenue for sustainable hydrogen production. Embracing photo-fermentation could pave the way for a cleaner energy future [9].

e) Dark Fermentation

Dark fermentation is promising because the process doesn't need sunlight or large swaths of land. Anaerobic bacteria or green algae are used to ferment a carbohydrate-rich substrate like glucose. The pH of the substance dictates what kind and how many products are produced. In the case of glucose, a particular amount of acetic acid, hydrogen, and carbon dioxide are produced in the reaction as follows, equation (9) illustrates the product of carbon dioxide, acetic acid, and Hydrogen contents.

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 4H_2 + 2CO_2 \quad (9)$$

Because this reaction is difficult to control, and other products like acetate and butyrate are produced, the production of hydrogen on a per mole basis is usually less than four.

5. Costs, Benefits & Ethical Issues Discussion

Numerous methods for producing hydrogen from biomass have been explored, yet none rely on natural gas, a proven fossil fuel. This aspect is particularly noteworthy, given the dramatic decline in natural gas supplies and rising global demand. As a result, hydrogen production from biomass is an essential and promising alternative. Utilizing biomass, especially stubble (agricultural waste), as a cost-effective and energy-efficient method is a crucial task for developing countries. The widespread open burning of this biowaste is the leading cause of smog in Indo-Pak, posing a significant threat to air quality and public health. However, with the right strategies and policies, we can prevent this. If biomass is not managed correctly and is left to decay in open dumps or landfills, it releases methane gas through anaerobic biodegradation, further contributing to greenhouse gas emissions.

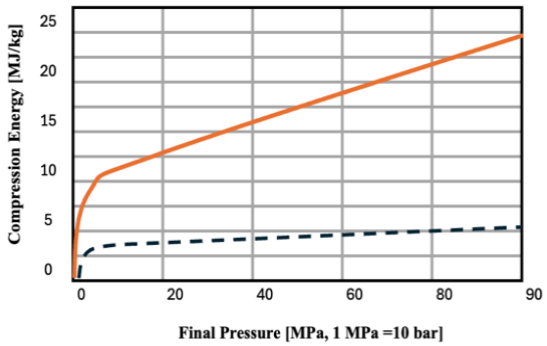

Fig.2: Adiabatic compression work versus Final pressure Hydrogen and Methane

Global natural gas reserves are dwindling at an alarming rate. Some projections indicate that worldwide natural gas production may peak as early as 2030, or even sooner if demand surges. The practice of 'fracking' in the U.S., which consumes millions of gallons of water and chemicals at each site, is a major contributor to this issue. There is considerable evidence that this process contaminates local groundwater and soil, raising serious environmental concerns. Given the significant role of natural gas in power generation, end-use energy, and hydrogen production through steam methane reforming (SMR), the exploration and adoption of alternative hydrogen production methods is not just important, but crucial as shown in figure 1 Adiabatic compression work versus Final pressure Hydrogen and Methane.

Despite the current higher cost, hydrogen production from biomass holds the potential to alleviate the need for practices like fracking. These tactics, which increasingly appear as desperate attempts by fossil fuel corporations to maintain their market share, often come at the expense of both consumers and the environment. Embracing biomass-based hydrogen production is not just a viable alternative but a necessary step toward a more hopeful and sustainable energy future 2. Although hydrogen production will remain essential in the energy industry, a hydrogen-based economy may never become a reality because of cost issues. Hydrogen, by itself, as an energy carrier, is both expensive to store and costly to transport. From a thermodynamic perspective, hydrogen compression for transportation and storage uses much more energy than methane. The work necessary to compress hydrogen is about nine times more per kilogram than methane. The following graph illustrates this problem [10].

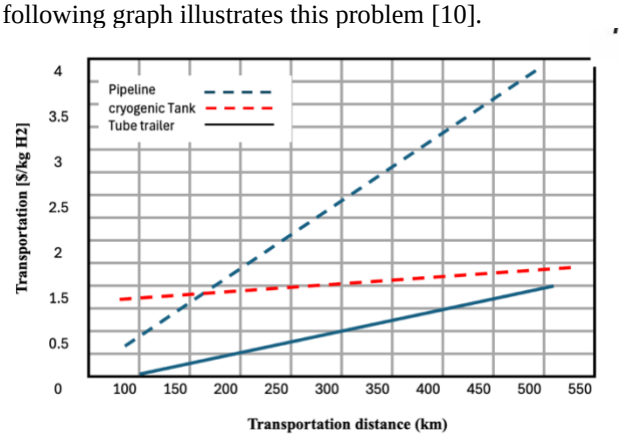

Fig.3: Variation in Hydrogen transportation cost for three transportation modes

Hydrogen transportation is undeniably expensive, and the most cost-effective method currently available is pipelines. While natural gas pipelines have the potential to be adapted for hydrogen transport, they are currently exclusively used for natural gas. Establishing a separate hydrogen pipeline network is likely to be prohibitively costly. The figure 3 illustrates a comparison of three distinct hydrogen transportation methods. Biomass-produced hydrogen represents a promising opportunity to support global agriculture. Its transformation into synthetic fossil fuels and key chemicals like ammonia is crucial.

The Haber-Bosch process, which relies on hydrogen derived from natural gas, will always need a hydrogen source for ammonia production. Biomass-produced hydrogen stands out as a hopeful solution to meet this demand. Moreover, the existing infrastructure for methane, gasoline, and other hydrocarbons is robustly developed. Methane burns efficiently and can be compressed and transported at a low cost, while fuels such as kerosene, butane, and gasoline are established as dense energy carriers with widespread use. As dependence on fossil fuels diminishes, these hydrocarbons can and should be synthesized through the **Fischer-Tropsch** process,

providing a reassuring transition to sustainable energy [11].

$$(2n+1)\ H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O \quad (10)$$

Hydrogen derived from biomass can and should serve as the crucial input for this process, ensuring that any synthetic hydrocarbons produced are carbon neutral. Choosing one biomass source over another must involve a thorough assessment of its local and global environmental impact. This responsibility in decision-making is non-negotiable. Using food crops for biomass fuel can result in heightened food prices—a prime illustration being ethanol production from corn. Diverting corn for fuel rather than food leads to escalating prices both nationally and globally. Although this practice benefits corn growers financially, it ultimately yields negative consequences for the broader economy; importing gasoline may emerge as a more energy-efficient and cost-effective choice compared to domestic ethanol production from corn.

Additionally, the practice of clearing rainforests in countries such as Indonesia for palm oil biodiesel and in Brazil for sugarcane ethanol is not just detrimental, but unequivocally so. These rainforests play a critical role in the Earth's seasonal respiration cycle, and their carbon sequestration capabilities surpass the carbon offsets provided by these biofuels. The potential extinction of numerous plant and animal species, many containing invaluable compounds, is not just a concern, but an urgent one that must be addressed. Exploring alternative biomass sources—such as agricultural waste, forest residues, and municipal waste—is imperative. We must rigorously evaluate the cost-effectiveness and overall environmental impact of their conversion. These sources must be locally available in substantial quantities to ensure economical hydrogen production. Suppose significant fossil fuel consumption is required to transport logging residues, crop waste, or sewage sludge to centralized biomass-to-hydrogen facilities. In that case, the negative environmental ramifications will be considerable, regardless of the perceived economic benefits of the conversion process [11].

The cost of hydrogen production through biomass gasification has decreased due to advancements in catalyst systems and reactor designs. Current estimates place production costs at $8–10 per GJ, contingent on biomass availability and transportation logistics. Decentralized gasification systems utilizing locally available biomass have further reduced logistics-related expenses. Similarly, plasma-assisted pyrolysis has lowered operational costs, making hydrogen production from pyrolysis competitive with steam methane reforming (SMR), particularly in regions with abundant biomass resources. In Electrohydrogenesis, MECs have achieved energy recoveries exceeding 200%, offsetting higher initial costs. The integration of wastewater treatment in these systems provides additional economic benefits by reducing waste disposal costs. Biomass-based hydrogen production methods offer significant environmental advantages, including a reduction in greenhouse gas emissions compared to fossil fuel-based methods. Utilizing waste biomass for hydrogen production decreases landfill usage and supports circular economy principles. Economic opportunities have also emerged, with localized hydrogen production promoting regional energy independence and job creation. Advances in bio-refinery concepts allow for the production of value-added by-products, enhancing the economic viability of biomass hydrogen production. Table 1 and 2 shows the cost comparative analysis.

Table1: Summary of SMR costs[1]

Facility Size (million Nm^3/d)	Reference	Specific TCI ($/GJ)	Hydrogen Price ($/GJ)
Large facilities			
1.34	Lieby1994	14.74	7.46
2.14	Leiby1994	12.61	6.90
2.80	Kirk-othmer1991	9.01	6.26
6.75	Foster-Wheeler1996	10.00	5.44
25.6	Blok et.al1997	10.82	5.97
Small facilities			
0.27	Lieby1994	27.46	11.22

Table 2 Summary of H_2 Production costs for Biomass Gasification and Pyrolysis

Facility Size (million Nm^3/d)	Reference	Specific TCI ($/GJ)	Hydrogen Price ($/GJ)	Biomass Price ($/dry tone)
Biomass Gasification				
2.26	Larson1992	26.91	10.03	46.30
2.16	Larson1992	2060	8.69	46.30
0.720	Mann1995	38.19	13.09	46.30
0.215	Mann1995	42.00	10.65	16.50
0.022	Mann1995	73.85	17.10	16.50
Biomass Pyrolysis All Reformed				
1.014	Mann1995a	14.94	12.42	46.30
0.304	Mann1995a	17.14	12.92	16.50
0.030	Mann1995a	26.05	15.52	16.50
Coproduct				
0.811	Mann1995a	16.74	8.86	46.30
0.243	Mann1995a	19.31	10.11	16.50
0.024	Mann1995a	30.66	12.73	16.50

Land use and food security remain critical concerns in biomass hydrogen production. By prioritizing agricultural residues and industrial waste over food crops, the ethical dilemma of food versus fuel can be mitigated. Policies must ensure that land designated for biomass cultivation does not displace ecosystems or food production. Decentralized hydrogen production systems provide equitable energy access to remote and underserved communities, offering a low-cost alternative to fossil fuel imports. Additionally, advanced biomass methods reduce reliance on environmentally damaging practices like fracking and natural gas extraction. Implementation strategies should prioritize communities disproportionately affected by fossil fuel extraction and use, promoting environmental justice [12].

6. SMR Reformer Specific Hazards, Safety & Environmental

A. Reformer Combustion hazards

Bottom-fired burners offer superior heat flux control and significantly lower NOx emissions, making them ideal for applications with stringent environmental standards. The top-fired technique is renowned for high thermal efficiency, perfect for large-scale operations prioritizing performance and sustainability. Terrace wall firing technology enhances heat distribution and flexibility, ideal for medium and large plants. Side-fired systems ensure

[1] Survey of the Economics of Hydrogen Technologies (https://www.nrel.gov/docs/fy99osti/27079.pdf)

even heat distribution and simplified maintenance, making them reliable for small to medium facilities. By adopting these advanced firing techniques, organizations can boost efficiency and demonstrate their commitment to environmental stewardship.

B. Balanced Combustion System

The balanced draft configuration is the most effective system used in large Steam Methane Reformers (SMRs). It combines a forced-draught (FD) fan to supply combustion air and an induced-draught (ID) fan to expel flue gases. This setup often includes an air preheater (APH), crucial for maximizing efficiency. Achieving complete combustion in this system offers significant advantages: reduced fuel consumption, improved heat recovery, and lower flue gas temperatures, as shown in Figure 11. Conversely, incomplete combustion, illustrated in Figure 12, can lead to high operating temperatures, increased nitrogen oxides (NOx) production, and a greater risk of corrosion in components exposed to flue gas, such as the APH exchanger. Ensuring complete combustion is essential for enhancing system efficiency and reliability.

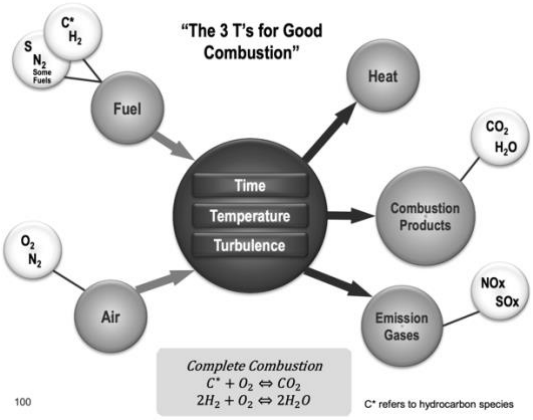

Fig. 4 Complete combustion cycle

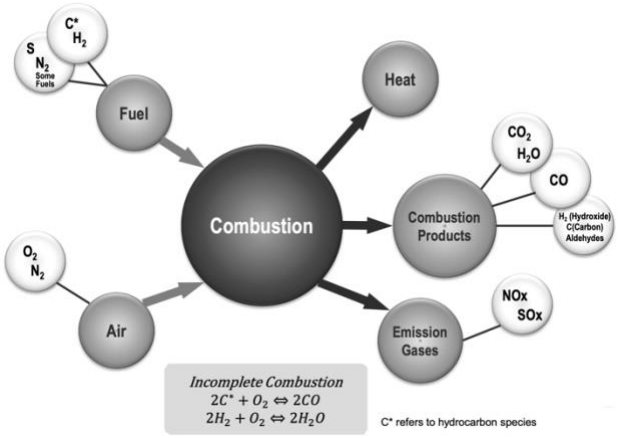

Fig. 5 incomplete combustion cycle

C. Flue gas emissions – NOx Production

There are seven nitrogen oxide species considered in the classification of NOx, which is a regulated pollutant known to cause serious health and environmental effects. NOx is a major precursor to acid deposition (acid rain) and smog in the troposphere.

- NOx is formed during all combustion reactions.
- NOx is produced as a result of fuel combustion.

Nitric oxide (NO) is generated when fuel is burned at high temperatures. Once released into the atmosphere, NO can transform into nitrogen dioxide (NO_2). Combustion systems typically emit NO, NO2, and nitrous oxide (N_2O):

- NO accounts for 90-95% of NOx emissions.
- NO_2 constitutes 5-10% of NOx emissions.

D. Flue gas emissions – SOx Production

SOx are significant contributors to acid deposition (commonly known as acid rain). The production of SOx is influenced by the presence of sulfur, hydrogen sulfide (H_2S), and other sulfur compounds in the fuel. Sulfur dioxide (SO_2) is formed when fuel is burned at high temperatures during combustion. Sulfur trioxide (SO_3) is generated from the conversion of SO_2. Typically, the composition of SOx consists of 94-98% SO_2 and 2-6% SO_3.

E. Reformer Tubes - Creep

Creep is the permanent deformation of a material that results from prolonged mechanical stresses that remain below the yield stress. This ensures that the material stays within its elastic region. Figure No. 6 clearly illustrates the four definitive stages of the creep process: **Elastic Region**: In this initial stage, the material deforms under stress but returns to its original shape as soon as the load is removed. **Yield Strength**: This marks the boundary of the elastic region. Beyond this point, the material will not revert to its original shape. **Plastic Region**: Once the material surpasses the yield strength, it experiences "**plastic deformation**," leading to irreversible changes in its structure. **Fracture Point**: At this crucial final stage, the material reaches its fracture point, resulting in breakage or snapping. Understanding these stages is vital for effectively managing material performance under stress.

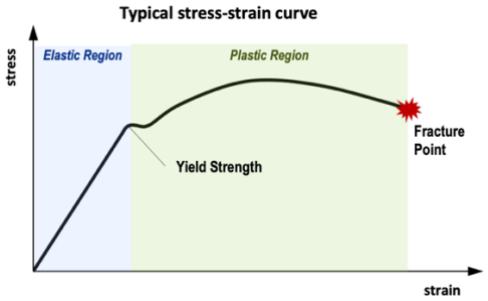

Figure 6 Typical Stress-strain curve

F. Reformer - Process of Creep

Creep occurs at high temperatures and involves three stages. In the primary stage, carbides form at the grain boundaries, while secondary carbides develop within the grain lattice. These secondary carbides are essential for creep resistance during extended high-temperature exposure. As the material enters the tertiary stage, microstructural degradation accelerates, leading to failure as shown in Figure 7.

Resistance to Creep by Metallurgy: The stress to rupture is dependent on the tube wall temperature with modern micro-alloys offering significant benefits over older materials. As a result, the tube wall thickness has been reduced considerably whilst keeping the same design tube lifetime (100,000 hours) 10 years.

Resistance to Creep by Carbides: Stabilized metal carbides in the lattice structure are essential for good creep. Resistance. There are two types of carbides. Primary carbides which form at the grain boundary and Secondary carbides which form within the grain lattice structure during service. In fact, the Secondary carbides are the main contributor to creep resistance

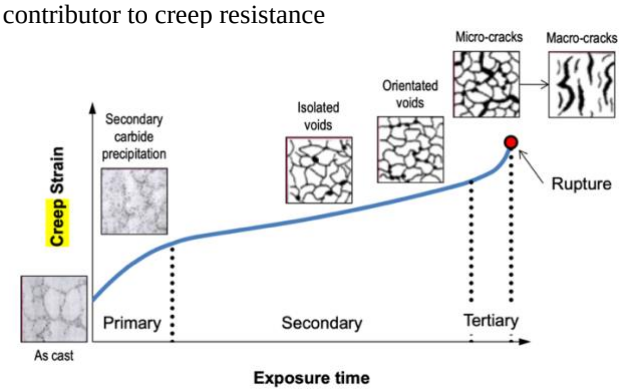

Figure 7 Typical Process **Creep Strain Vs Exposure Time**

7. Conclusion

Hydrogen production methods differ significantly in their environmental impact and cost-benefit trade-offs, emphasizing the urgent need for sustainable and cost-effective approaches to hydrogen production. Currently, approximately 90% of global hydrogen production relies on steam methane reforming (SMR), which depends on natural gas, a finite and environmentally taxing resource. Post-2008 advancements in biomass-based hydrogen production methods offer a transformative solution, mitigating the limitations of traditional methods while addressing critical economic and ethical concerns.

Enhanced gasification, pyrolysis, and Electrohydrogenesis technologies have demonstrated improved efficiency and reduced costs. Artificial intelligence and hybrid systems have further optimized these processes, making biomass hydrogen production increasingly competitive with traditional SMR. The adoption of these methods significantly reduces greenhouse gas emissions and alleviates the environmental consequences of practices like hydraulic fracturing.

The transition to biomass-based hydrogen production is not merely a technical innovation but a necessity for long-term sustainability. As global hydrogen demand grows, these methods offer a pathway to balance environmental friendliness, economic feasibility, and resource sustainability. Future efforts must focus on scaling these technologies, refining cost structures, and ensuring widespread adoption. By integrating ethical considerations and prioritizing sustainable resource use, biomass hydrogen production can play a pivotal role in achieving a cleaner and more equitable energy future.

Lastly, safe and sustainable energy production, the linchpin of achieving UN's SDG 7: Affordable and Clean Energy, is of paramount importance. It allows for the seamless integration of renewable energy sources like Hydrogen and Ammonia production for fuel cells to produce sustainable power production, thereby reducing the carbon footprint of energy production and protecting the environment. By implementing safe production best practices, reliable maintenance strategies, and minimizing operational risks, energy producers can create a working environment that prioritizes the health and safety of employees while reducing environmental impact. This paper is not just about human and ecological resources; it's about ensuring that energy production can continue safely and sustainably, with the promising prospect of a healthier, more sustainable environment.

In this study, we rigorously analyzed the operational dynamics of the SMR reformer, emphasizing critical hazards, safety protocols, and environmental considerations. We firmly established the significance of combustion systems, scrutinizing both their inherent risks and the effectiveness of balanced combustion approaches. Our investigation into the production of NOx and SOx gases and the impact of elevated temperatures on the creep behavior of reformer tubes revealed crucial insights. This comprehensive examination clearly underscores the necessity for stringent safety measures and innovative solutions that will drive the advancement of reformer technology forward.

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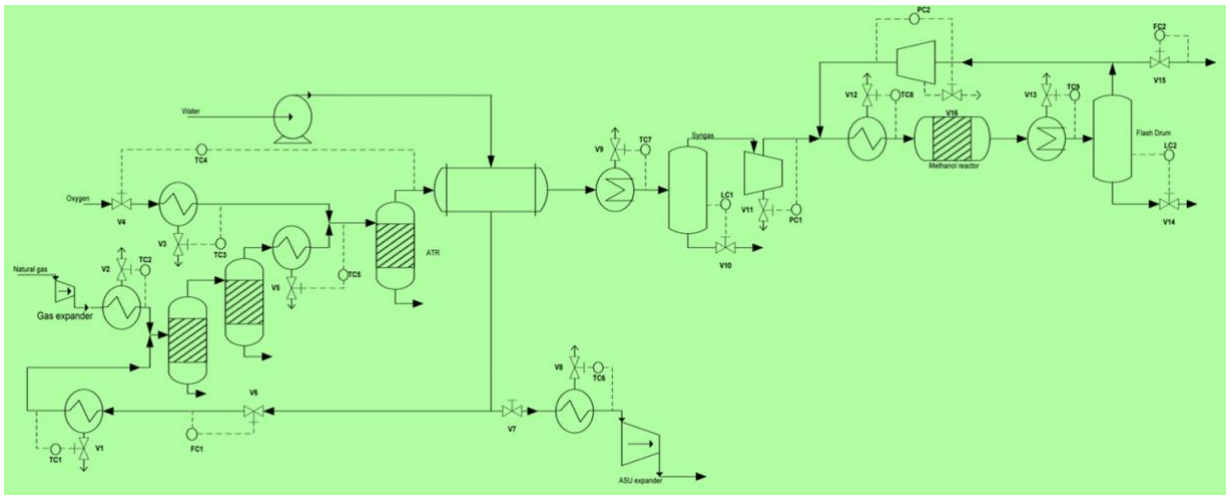
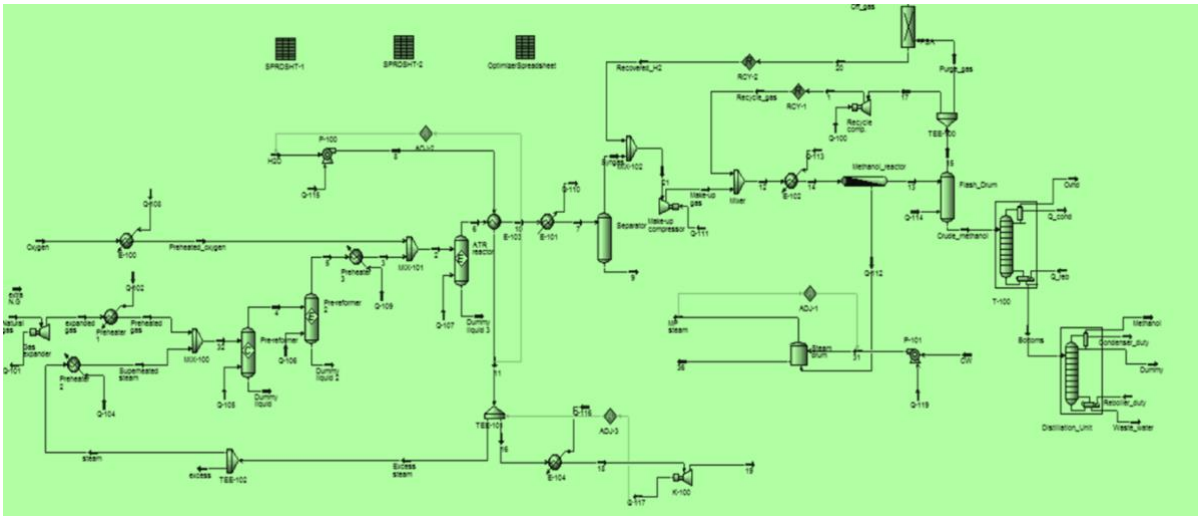
Appendix A: (Reactions during methane conversion with steam and/or oxygen)

Reaction	$\Delta H^0_{298}(\frac{kJ}{mol})$
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	206
$CO + H_2O \leftrightarrow CO_2 + H_2O$	-41
$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$	247
$CH_4 \leftrightarrow C + 2H_2$	75
$2CO \leftrightarrow C + CO_2$	-173
$CH_4 + 1/2O_2 \rightarrow CO + 2H_2$	-36
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	-803
$CO + 1/2O_2 \rightarrow CO_2$	-284
$H_2 + 1/2O_2 \rightarrow H_2O$	-242

Appendix B (Process Schematic, which shows the reformer, compression and recovery Unit)



Appendix C (Simulation Model by using Unism, this also replicate by using HYSYS and ChemCAD)



Appendix D (Catalyst and Reactor Data)

Parameter	Value
Number of tubes	5500
Density (kgm^{-3})	1775
Particle diameter (m)	5.47×10^{-3}
Heat capacity ($kJ\ kg^{-1}\ K^{-1}$)	5
Length of reactor (m)	7.022
Bed void fraction	0.39
Density of catalyst bed (kgm^{-3})	1140
Tube inner diameter (m)	0.038
Tube outer diameter (m)	0.042

Appendix D (Reactor Kinetic and equilibrium data)

$k = A \exp(B/R_gT)$	A	B
k_a ($bar^{-1/2}$)	0.499	17197
k_b (bar^{-1})	6.62×10^{-11}	124119
k_c	3453.38	-
k_d ($mol/kg\ s\ bar^2$)	1.07	36696
k_e ($mol/kg\ s\ bar$)	1.22×10^{10}	-94765
$K^{eq} = 10^{(\frac{A}{T}-B)}$	A	B
$K_1^{eq}(bar^{-2})$	3066	10.592
K_2^{eq}	2073	2.029