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Nuclear Ammonia as Renewable Energy Source: An Innovative Approach to Advancing Sustainable Fuel Solutions for The Global Energy Crisis

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Abstract:

This paper thoroughly addresses the risks and challenges associated with ammonia as a fuel and asserts that we can effectively harness its potential. We underscore the imperative of implementing safe production, transportation, and utilization frameworks to mitigate any new environmental or safety concerns. The time for action is not in the distant future but now. By ensuring these safe frameworks, we can confidently move forward with ammonia as a fuel alternative. The world is navigating significant challenges, including a growing resource shortage and accelerating environmental degradation. Amid rising global energy demands, ammonia has emerged as a promising yet complex fuel alternative. Its adoption, however, requires careful consideration to ensure safety and sustainability. Liquefied ammonia has emerged as a compelling solution and is already used in the USA. It is produced in ammonia plants through established methods and nuclear reactors. This process requires no new technological breakthroughs; it is already successfully implemented where large quantities of liquefied ammonia are produced and distributed safely. Ammonia condenses into a dense liquid under moderate compression, making transportation straightforward. Furthermore, nuclear ammonia production, particularly when utilizing thorium-fueled molten salt breeder reactors, generates zero greenhouse gas emissions, relying on clean electrical energy, water, and air. These reactors, due to their cost-effectiveness and sustainability, enhance the appeal of ammonia as a fuel alternative.

Key words. Liquid Ammonia, Malthusian Catastrophe, greenhouse gases, thorium-fueled

Abbreviation	:	Definitions
DOE	:	Department of Energy
PCC	:	proton-conducting ceramic
IEA	:	International Energy Association
SSAS	:	Solid State Ammonia Synthesis
GHG	:	Greenhouse gases
MSBR	:	molten salt breeder reactors
H_2S	:	Hydrogen Sulphide
TNPC	:	Thorium Nuclear Power Cycle
LP/HP	:	Low and High Pressure

1 Introduction

The expanding World population is continuously depleting natural resources, clean water, fossil fuels, and food. This is causing severe environmental degradation and will lead to a much lower standard of living. Figure 1 depicts the global challenges, with the human population nearing 8 billion. According to credible scientific sources, this figure is growing at an alarming rate, nearly three times faster than what could be sustained with today's highly energy-intensive food production and distribution technologies. The world's total greenhouse gases and carbon emissions are growing at a rate faster than the population, a stark reflection of the fact that while one segment of society's standards of living have significantly improved, others have deteriorated. This alarming trend underscores the urgent need for action. The USA's economic activities, including accumulating a huge balance of payment deficit and serving as a military police force in the Middle East, have led to an inordinate consumption of oil. This has contributed to a rise of 20 million barrels per day, reaching the peak of the Hubbert curve about 40 years before the rest of the world. This surge in oil consumption occurred during the 1970 World War II economic recession, leading to the 'peak oil' point for the USA and the world. Currently, we are facing an even more severe recession.

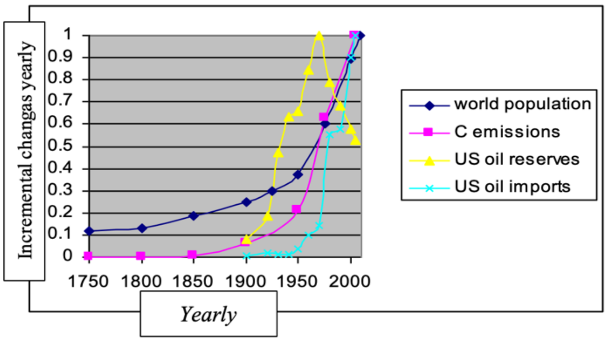


Fig.1 World population, World carbon dioxide emissions-(Source IEA)

Figures 2 and 3 demonstrate the concept of world warming in real-time operations, which will likely cause the world map. We humans don't prefer to live in a dirty way or begin to change. Technically, we should start thinking about greenhouse gases and their impact on global warming in the mid-century. Businesses, as usual, keep growing and push over catastrophic environmental may lead to a "tipping point" by 2040. Recognizing the gravity of these challenges, the Department of Energy (DOE) has taken proactive steps. It has established initiatives to engage contractors in developing comprehensive models for alternative energy scenarios. This strategic approach instills hope and reassurance that we are actively working towards a sustainable future [1],[2].

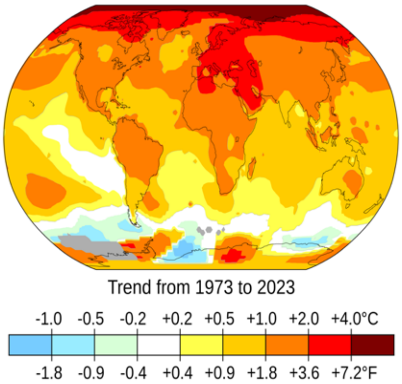


Fig.2 Temperature Anomalies 1995-2023
-(Source IEA)-

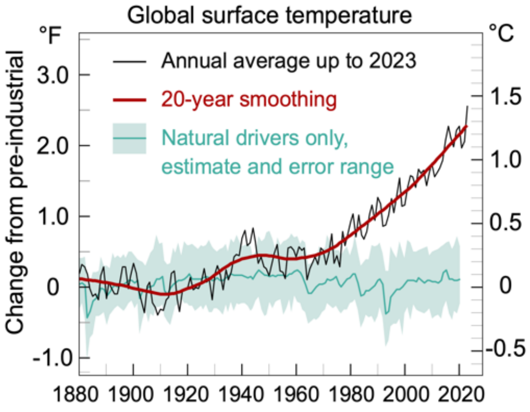


Fig.3 "Business as usual" projection
-(Source IEA)-

A. Problematic area Fuel crises

A significant portion of our energy needs is met by fossil fuels, but a major part of it is also wasted due to the Carnot-law inefficiency of heat engines, gas turbines, steam turbines, cars, trucks, trains, and power utilities. This wastefulness, coupled with the fact that these conventional energy resources produce a huge amount of greenhouse gases, should be a cause for concern and a strong motivation to seek more efficient and sustainable alternatives. Renewable energy resources, including Geothermal, Fuel Cells, Hydrogen (Green and Gray Hydrogen), Nuclear Energy, Wind Power, Biofuels and Biomass, Hydroelectric Power, and Solar Thermal Energy Systems, have the potential to meet a significant portion of our energy needs. Currently, they account for one-third of the energy produced, primarily by 104 nuclear reactors, which is a relatively small fraction of our total energy needs [3],[4].

Over the past three to four decades, the coal industry has played a significant role in meeting our energy needs. It has introduced technologies such as coal fluidized beds to control H_2S contents and coal sequestration to control CO_2. However, these solutions are not without their drawbacks. The industry's vision, along with Madison Avenue's imagination, has led to the Department of Energy's (DOE) extensive efforts to turn large areas of Montana, Wyoming, North Dakota, Illinois, Pennsylvania, and the rest of Appalachia into coal waste tips are not sustainable. This process is not only dirty and water & energy-intensive but also expensive and unsustainable in the long run. As per DOE and EIA reports, the world's total Kerogen reserves are 500 gigatons; this is 3/5th of coal, 843 gigatons. The extracting process of Kerogen will consume many resources, which could be more sustainable. It's crucial to understand the unsustainability of these methods to feel the urgency of finding alternatives.

The Thorium Nuclear Power Cycle, while less expensive, faces political challenges. Therefore, it's crucial to consider non-nuclear renewable energy sources such as Geothermal, Fuel Cells, Hydrogen (Green and Gray Hydrogen), Nuclear Energy, Wind Power, Biofuels and Biomass, Hydroelectric Power, and Solar Thermal Energy Systems. The current energy business model, which provides oil, coal, 235U-burning nuclear reactors, bioethanol, windmills, etc., is not without its drawbacks. Understanding these drawbacks is key to motivating us to seek more sustainable alternatives.

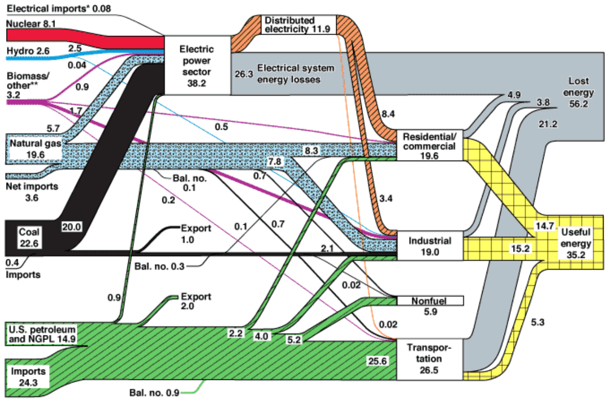


Figure 4 shows how the USA both generates and uses energy
-(Source IEA)-

2 What is Ammonia

The USA imports around two-thirds of its petroleum, totaling 200 billion gallons out of 290 billion gallons annually. The majority of this petroleum is consumed for transportation, making it imperative that we develop viable alternative energy sources. This situation is critical; any disruption could have severe consequences for our society. Optimistically, we can envision our decision-makers adopting a clean and green future, substituting GHG-free electricity for virtually all fossil fuels. This shift could lead to a transformation similar to what France and Japan have already achieved, inspiring and motivating us.

We could inspire and motivate ourselves to build sufficient and efficient railway infrastructure to move goods, fully electrify our homes and industrial processes, and introduce compact battery-powered cars. Even for critical operations, we could significantly reduce our reliance on traditional fuels, although some sectors, like the military and agriculture, may still require them. Since I feel that the bulk of that fuel should be ammonia, the rest of this paper will prove why that makes good sense [5],[6],[7].

A. Ammonia as fuel

Previously, ammonia was efficiently produced from air and steam. The process begins with the precise injection of steam into the primary reformer, where methane is cracked at 850 degrees Celsius in the presence of a crucial nickel catalyst, resulting in an exothermal reaction. The products from the primary reformer, which are rich in carbon monoxide and hydrogen, are directed to the secondary reformer at high temperatures, which is a critical factor. In the next phase, compressed air, consisting of approximately 78% nitrogen (N_2) and 21% oxygen along with other components, is injected into the high-temperature secondary reformer. In the presence of oxygen (O_2), an endothermic reaction occurs, resulting in the production of carbon dioxide.

The third stream then passes through the Absorber to absorb the CO_2 in the presence of a Cata-carb solution. This solution is regenerated, passes through the stripper, and continues through the Low and High shift converters, leading to a high-pressure synthesis compressor. Finally, in the last stage, the stream passes through the reactor to the converter and produces Ammonia in Liquid form. Fig. 5 indicates the University of Michigan's ammonia-powered pickup manufactured in 2007. Fig. 6 Norsk Hydro's ammonia-powered pickup manufactured in 1933. Fig. 7 NASA's X-15 set speed and altitude records burning ammonia, a global achievement. Fig 8 "Converted" Motor busses in German-occupied Belgium manufactured in 1943[6],[7].

Fig. 5 The ammonia-powered pickup 2007

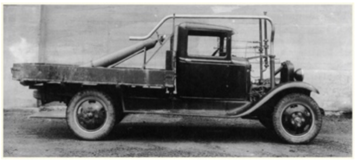


Fig. 6 ammonia-powered pickup 1933

Fig. 7 Altitude records burning ammonia

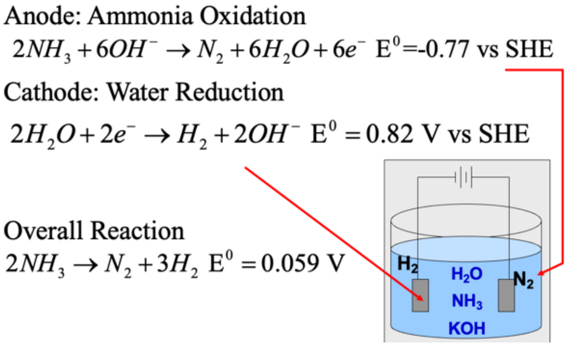
Fig. 8 Ammonia Powered Motor busses, 1943

Ammonia, a practical and valuable fuel, is a powerhouse of energy. It contains dense energy at ambient temperature and moderate pressure of 125 psig, on par with propane. Its energy density matches that of methanol, a fuel favored by Formula One-type racing cars. With 17.6% hydrogen by weight (compared to methanol's 12.5%), ammonia is a potent hydrogen carrier for fuel cells. It even outshines liquid hydrogen, containing 50% more hydrogen. However, its long-term storage is a significant challenge due to its shallow boiling point of -252.87 º C. Another way to prove more practical would be to utilize "Solid Oxide Fuel Cells" as shown in Fig. 9 which will work with uncracked ammonia, equation (1) illustrates ammonia oxidation and equation (2) cathode water reduction, and overall reaction illustrates in equation (3).

$$NH_3 + 6OH^- \rightarrow 6H_2O + 6e^- \tag{1}$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{2}$$

$$2NH_3 \rightarrow N_2 + 3H_2 \tag{3}$$



Anode: Ammonia Oxidation

$2NH_3 + 6OH^- \rightarrow N_2 + 6H_2O + 6e^-$ E^0=-0.77 vs SHE

Cathode: Water Reduction

$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ $E^0 = 0.82$ V vs SHE

Overall Reaction

$2NH_3 \rightarrow N_2 + 3H_2$ $E^0 = 0.059$ V

Fig. 9 Ammonia Oxidation reaction

B. Energy Consumption and Economics[1]

At 27 Deg C

Our analysis indicates that the theoretical conventional energy consumption to produce hydrogen (H_2) is 1.55 W-h/g. One approach to hydrogen production is the cracking process of ammonia (NH_3), which costs $175 per ton for processing. Another option is to utilize solar energy, priced at $0.214 per kW-h. However, it is essential to note that the cost of hydrogen, at $0.899 per kg, must remain below the Department of Energy's (DOE) target of $2 per kg. This highlights the urgency and importance of our task.

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[1] Cost analysis by the Electrochemical Engineering Research Laboratory Ohio University

Table No. 1 provides a comparison with H_2O electrolysis. By using solar energy at a cost of \$0.214 per kW-h, we can achieve a 95.3% reduction in energy consumption and an 87.3% decrease in the cost of hydrogen production.

Table No.1 cost Analysis:

Instances	**Water Electrolysis**	**NH_3 Electrolysis**
Energy (W-h/g H_2)	33	1.55
H_2 Cost (\$/kg H_2)	7.1	0.899

Benefits: We may witness the depreciation of the hydrogen storage problem. Secondly, zero hazardous emissions, fuel flexibility, and low-temperature operation exist. Fertilizer plants and municipal wastewater treatment stations could produce their energy from waste.

C. Making Fuel-Ammonia

The United States uses approximately 30 billion gallons of oil annually in diesel engines, which power trucks, trains, and farm and construction equipment. Additionally, we consume around 140 billion gallons of gasoline primarily for personal transportation, including cars, SUVs, and pickup trucks. In a "Green" USA, we would require far fewer large trucks because an expanded rail system would serve as a replacement. Our new high-speed passenger train system would reduce the need for most commercial airline flights, as all trains, trams, and similar vehicles would run on electricity. For local commuting and shopping trips, we would use compact battery-powered vehicles. \For the sake of estimation, let's assume we would still need the equivalent of today's diesel oil requirements, which is about 30 billion gallons per year, to power essential vehicles such as farm tractors and military trucks. This translates to roughly 60 billion gallons of ammonia [9],[10]. Currently, the USA produces and uses about 20 million tons of ammonia (NH_3) and NH_3-based fertilizers each year, which is one-fifth of what China produces. Energy-wise, this is equivalent to around 3.5 billion gallons of gasoline, indicating that we will need to produce roughly ten times more than we do now. Fortunately, we already have the knowledge to produce ammonia, as well as extensive storage and delivery infrastructure, including pipelines, barges, railroads, and trucks. There are also retail outlets across every state with significant agricultural activity. This existing infrastructure, which features 3,000 miles of ammonia pipelines in the US heartland—800 of which are located in Iowa alone—provides a solid foundation for the increased production and transportation of ammonia.

Most of our ammonia (NH_3) pipelines are constructed from 8 to 10-inch diameter carbon steel pipes, and storage typically occurs in refrigerated, above-ground steel tanks with capacities ranging from 10,000 to 60,000 tons. Currently, ammonia is produced from hydrogen generated by steam-reforming fossil fuels, primarily methane, without carbon sequestration. This method is considered environmentally harmful due to its greenhouse gas (GHG) emissions. Alternatively, ammonia can be produced cleanly using electricity derived from renewable sources such as wind, solar, geothermal, hydro, or nuclear power. Among these, nuclear power, particularly from the thorium cycle, appears to be the most feasible option. For a more detailed explanation of this perspective, I encourage my readers to refer to my companion paper titled **"The Thorium Nuclear Power Cycle - Cleaner** and Less Expensive."

D. Green version of the Haber Bosch process

This version of HB is "green" solely because the hydrogen required is derived from something other than fossil fuel. There is no "rocket science" or great leaps of faith required to produce the amount of ammonia we'll require this way other than the fact that we must first come up with a practical way to produce the huge amount of clean electricity required by its HB reactors, air separation units (ASU), and (especially) the water electrolyzers – in its case, a total of 12,000 kWhr per ton of product. Recently, there has been a great deal of research directed towards reducing the amount of energy required by the Haber Bosch process. Figure 9 depicts a state-of the art synthesis that requires much less power as discussed in section 4 in detail.

a) Primary Reformer Process:
b) Secondary Reformer Process
c) LP/HP Shift converter
d) NH_3 Synthesis Reactor
e) Recovery Unit
f) Appendix A (Ammonia process schematic)
g) Appendix B (carbon content and heating values for different fuels)
h) Appendix C (NH_3 Renewable fuel)
i) Appendix D (NH_3 conversion at each stage)

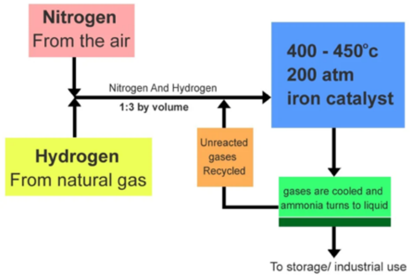

Fig. 9 Haber Bosch process for Green Ammonia

E. Solid State Ammonia Synthesis

SSAS, or Solid-State Electrochemical Synthesis, is a pioneering process that operates like a solid oxide fuel cell in reverse. At 550ºC, steam is efficiently adsorbed and decomposed by an electrocatalyst on the anodic side of a proton-conducting ceramic (PCC) membrane, a key component that facilitates the process. The hydrogen atoms generated in this process are robustly stripped of their electrons using an external voltage, converting them into protons. The remaining oxygen atoms recombine and volatilize, yielding a valuable by-product that is efficiently separated from the steam loop. The resultant protons conduct seamlessly through the PCC "electrolyte" via defect hopping, chemically reacting with adsorbed nitrogen on the cathode side to produce ammonia.

SSAS demonstrates an impressive level of energy efficiency, consuming only 7,500 kWh per ton—far superior to the 12,000-kWh required by the Haber-Bosch process. This significant difference in energy consumption is a clear testament to the superiority of SSAS. Moreover, it is easier to scale and inherently safer. A key advantage of SSAS is eliminating gaseous hydrogen as an intermediate product, removing the need for cumbersome storage and handling. When we say "safer," we highlight the critical difference: the Haber-Bosch process operates at a staggering pressure of 250 atmospheres—similar to that in the core of a light water nuclear reactor—and temperatures 200 degrees higher. In stark contrast, SSAS operates effectively and safely at atmospheric pressure, making it a choice modern industry cannot overlook. This safety aspect of SSAS should provide a sense of reassurance and confidence in its application [10],[11].

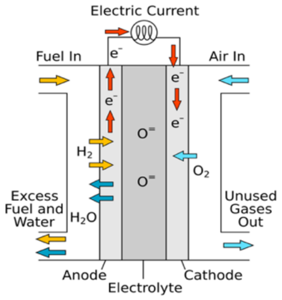

Fig. 10 Solid Oxide Fuel Cell

3 Nuclear Ammonia

During the Vietnam War, the U.S. Army took proactive steps to explore a more cost-effective method of powering its overseas facilities, rather than relying on fuel shipped from thousands of miles away. Harnessing the potential of three portable nuclear reactors, the Army aimed to produce fuel on-site using atomic power. Engine experts recognized that "nuclear ammonia" was the optimal approach, given the abundant availability of air and water in any operational Scenario. They acknowledged that, while it may not be perfect, it would serve as a superior fuel alternative. The initial studies proved successful, but the reactors available at the time simply could not produce enough fuel to make the project viable. Take, for instance, the reactor under consideration, which had a production capacity of about 3 megawatts. When calculated with the 12,000 kWh/ton energy requirement of the Haber-Bosch process, the production rate was limited to roughly 0.25 tons translating to approximately 80 gallons of fuel per hour. This equates to around 40 gallons of gasoline. Given the fuel inefficiency of Army vehicles then, the project encountered significant roadblocks and was ultimately abandoned [11],[12].

Now, let's consider how many reactors would be necessary for the scenario we can propose. With today's more efficient SSAS-type synthesis technique, a single **1GWe** (gigawatt, or one billion watts) civilian reactor can yield an impressive 133 tons of ammonia per hour—approximately 1.17 million tons annually. Since we project that 200 million tons of ammonia per year would fulfill the nation's future "burnable" fuel requirements, we would need around 170 reactors operating at full capacity. Furthermore, to substitute all the "useful" energy that we currently generate from all sources, amounting to about 42.5 quadrillion **BTU/year**, we could require a staggering 1,600 reactors. Today, with only 104 reactors in operation—many nearing the end of their useful life—we face a critical need for innovation and expansion in our nuclear energy capabilities.

4 Discussion

This version of HB is "green" solely because the hydrogen required is derived from something other than fossil fuel. The Primary Reformer Process converts natural gas and steam into synthesis gas (syngas) through steam methane reforming in ammonia production. Operating at high temperatures (700–850°C) and moderate pressures, this endothermic reaction utilizes a nickel-based catalyst to produce hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2). The efficiency of this process is crucial, as it significantly impacts the overall energy consumption of the ammonia plant. Equation (4) illustrates the Zinc oxide and water moisture content as products, equation (5) Carbon Monoxide and Hydrogen products, and equation (6) Carbon dioxide and Hydrogen products. Reformer catalyst is very sensitive to sulfur; hence, before reforming, all sulfurous compounds must be removed from the natural gas to prevent catalyst poisoning. These are removed in desulfurization reactor where sulphur is absorbed in Zn oxide catalytic bed.

Inlet temperature of primary reformer: 500°C
Outlet temperature of primary reformer: 800°C

$$ZnO + H_2S \rightarrow Z_nO + H_2O \tag{4}$$

(Zinc oxide and water moisture content)

$$CH_4 + H_2O \leftrightarrow 3H_2 + CO \qquad H = +ve \tag{5}$$

Carbon Monoxide and Hydrogen contents

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad H = -ve \tag{6}$$

Carbon dioxide and Hydrogen contents

Following the primary reforming, the Secondary Reformer Process introduces air into the syngas to supply the necessary nitrogen (N_2) for ammonia synthesis. This exothermic reaction further reforms residual hydrocarbons, ensuring an optimal H_2: N_2 ratio (typically 3:1) for the subsequent ammonia synthesis. This ratio is crucial as it directly impacts the yield and efficiency of the ammonia synthesis process. The secondary reformer operates at elevated temperatures, completing the conversion of methane and enhancing the efficiency of the process. Equation (7) illustrates the products of Carbon Monoxide and Hydrogen contents, equation (8) product of Carbon Monoxide and Hydrogen contents, equation (9) Moisture contents produce equation (10) Carbon dioxide contents produce.

Inlet temperature: 800°C
Reactions taking place here are:

$$CH_4 + H_2O \leftrightarrow 3H_2 + CO \ldots\ldots H = +ve \tag{7}$$

Carbon Monoxide and Hydrogen contents

$$CH_4 + {}^{1}\!/_{2}\, O_2 \leftrightarrow 2H_2 + CO \ldots\ldots H = -ve \tag{8}$$

(Carbon Monoxide and Hydrogen contents)

$$H_2 + {}^{1}\!/_{2}\, O_2 \leftrightarrow H_2O \ldots\ldots H = -ve \tag{9}$$

Moisture contents produce

$$CO + {}^{1}\!/_{2}\, O_2 \leftrightarrow CO_2 \ldots\ldots H = -ve \tag{10}$$

Carbon dioxide contents produce

The Low-Pressure (LP) and High-Pressure (HP) Shift Converters are pivotal in maximizing hydrogen production by converting CO into additional H_2 via the water-gas shift reaction. These converters, operating at different pressures, efficiently convert CO into CO_2 and H_2, enhancing hydrogen yield and reducing CO concentration. This staged conversion process is a testament to the optimization of the ammonia production process Equation (11) illustrates the product of carbon dioxide and equation (12) carbon dioxide and Hydrogen products [12].

High Temperature Shift Convertor
Inlet temperature 400ºC

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{11}$$

High Temperature Shift Convertor
Inlet temperature 200ºC

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{12}$$

The NH_3 Synthesis Reactor, the core of the ammonia production process, is where H_2 and N_2 are combined under high pressure (100–250 bar) and temperature (400–500°C) in the presence of an iron-based catalyst. This exothermic reaction, the Haber-Bosch process, yields ammonia (NH_3) as the final product. The reactor's design optimizes heat recovery and efficiency, often incorporating cooling systems to maintain ideal reaction conditions and facilitate ammonia condensation. The significance of this step cannot be overstated in the ammonia production process, equation (13) illustrates the product of Ammonia.

Synthesis Reactor Temperature: 400–500°C
High Pressure: 100–250 bar

$$N_2 + 3H_2 \leftrightarrow 2NH_3 \tag{13}$$

Finally, the Recovery Unit is a crucial component in the ammonia production process. It separates ammonia from unreacted gases and purifies it, ensuring high-purity ammonia is suitable for various applications, from fertilizers to fuel production. This unit's unique feature is its ability to recycle unreacted H_2 and N_2 back to the synthesis reactor, thereby enhancing the efficiency of the production process. It achieves this through a series of cooling and condensation steps to liquefy ammonia. Advanced recovery units may also include scrubbers and absorbers to remove impurities, further enhancing the quality of the ammonia produced; equation (14) illustrates the recovery unit, which shows the product of water and methane conversion.

Reaction taking place in methanation:

$$CO_2 + 4H_2 \rightarrow 2H_2O + CH_4 \tag{14}$$

4. Steam Methane Reformer - Specific Hazards, Safety & Environmental

*A. Reformer Combustion hazard*s

Bottom-fired burners deliver exceptional control overheat flux and significantly reduce NOx emissions, making them the perfect choice for applications that demand stringent environmental standards. The top-fired technique stands out for its impressive thermal efficiency, making it ideal for large-scale operations that prioritize both performance and sustainability. Terrace wall firing technology enhances heat distribution and operational flexibility, making it an excellent fit for both medium and large capacity plants. Meanwhile, side-fired systems ensure uniform heat distribution and simplify maintenance, establishing them as a reliable choice for small to medium capacity facilities. Embracing these advanced firing techniques not only optimizes efficiency but also aligns with the growing commitment to environmental responsibility.

B. Balanced Combustion System

The most common type of system, typically found in all large SMRs (Steam Methane Reformer), is the balanced draft configuration. This system includes a forced-draught (FD) fan and an induced-draught (ID) fan, which ensure that the overall system is balanced. The FD fan provides the combustion air charge, while the ID fan removes the flue gas. A balanced draft system usually incorporates an air preheater (APH) to enhance the efficiency of the reformer. APH systems are predominantly used in balanced draft configurations. Complete combustion in this system leads to reduced fuel consumption and increased heat recovery, resulting in lower flue gas temperatures as shown in Figure 11.

On the other hand, incomplete combustion as shown in Figure 12 can cause several issues. It may lead to higher operating temperatures in the radiant section, increased production of nitrogen oxides (NOx) due to elevated flame temperatures, and a greater risk of corrosion for flue-gas wetted components, including the APH exchanger and downstream systems.

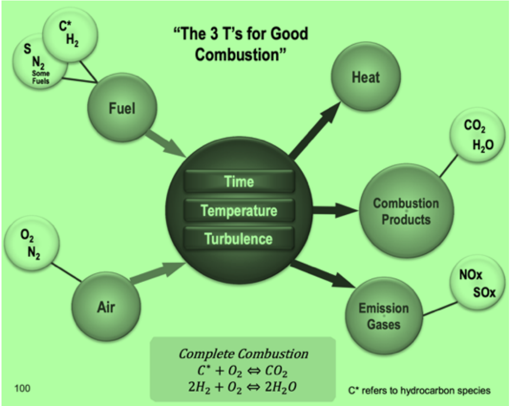

Fig. 11 Complete combustion cycle

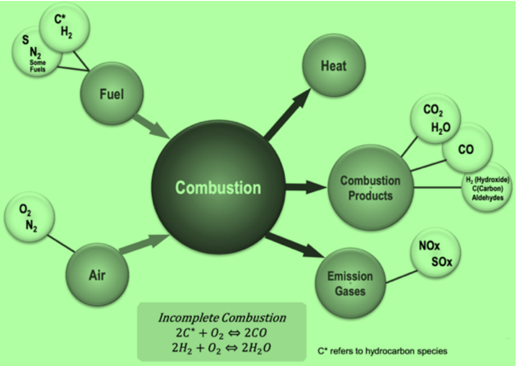

Fig. 12 incomplete combustion cycle

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. 13 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.

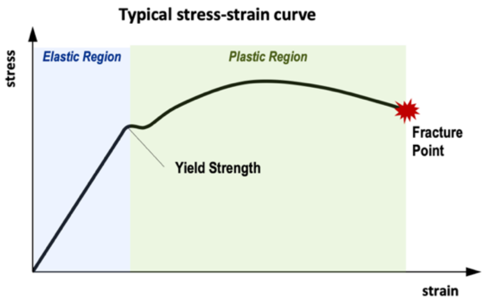

Figure 13 Typical Stress-strain curve

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 14.

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

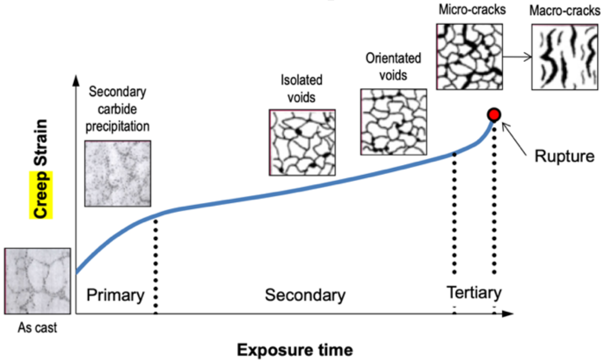

Figure 14 Typical Process **Creep Strain Vs Exposure Time**

5. Conclusion

This paper delves into the vast potential of ammonia as a sustainable fuel, exploring its use as a fuel, energy consumption, economics, comparisons with hydrogen production, advancements in the green Haber-Bosch process, solid-state ammonia synthesis, and nuclear ammonia production. These topics underscore ammonia's promise as a scalable, versatile energy carrier, instilling a sense of optimism about its future applications. Among the reactor technologies discussed, molten salt breeder reactors (MSBRs) using thorium stand out as the most advantageous. MSBRs are projected to be significantly more cost-effective to build and fuel than Generation 3 and Generation 3+ reactors, making them an ideal choice for large-scale, zero-emission ammonia production. This emphasis on their advantages instills confidence in their potential. Despite the challenges such as safety and scalability, ammonia's applications in transportation and industry pave the way for reduced emissions and enhanced energy security. With advanced technologies like MSBRs, ammonia can play a pivotal role in realizing a sustainable energy future, instilling a sense of hope.

In this study, we thoroughly examined the operational dynamics of the SMR reformer, with a keen focus on critical hazards, safety protocols, and environmental considerations. Our analysis emphasized the importance of combustion systems, exploring both the inherent combustion hazards and the effectiveness of balanced combustion systems. Additionally, we investigated the production of NOx and SOx gases and their implications, alongside the significant impact of sustained high temperatures on the creep behavior of reformer tubes. This comprehensive approach underscores the necessity for stringent safety measures and innovative solutions in advancing reformer technology.

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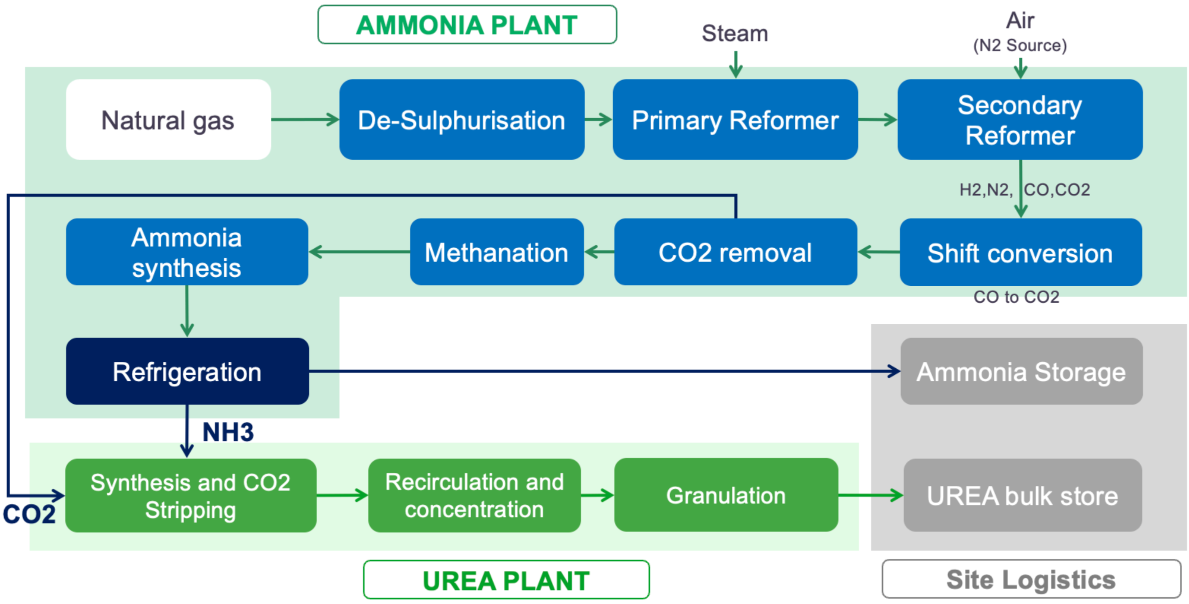
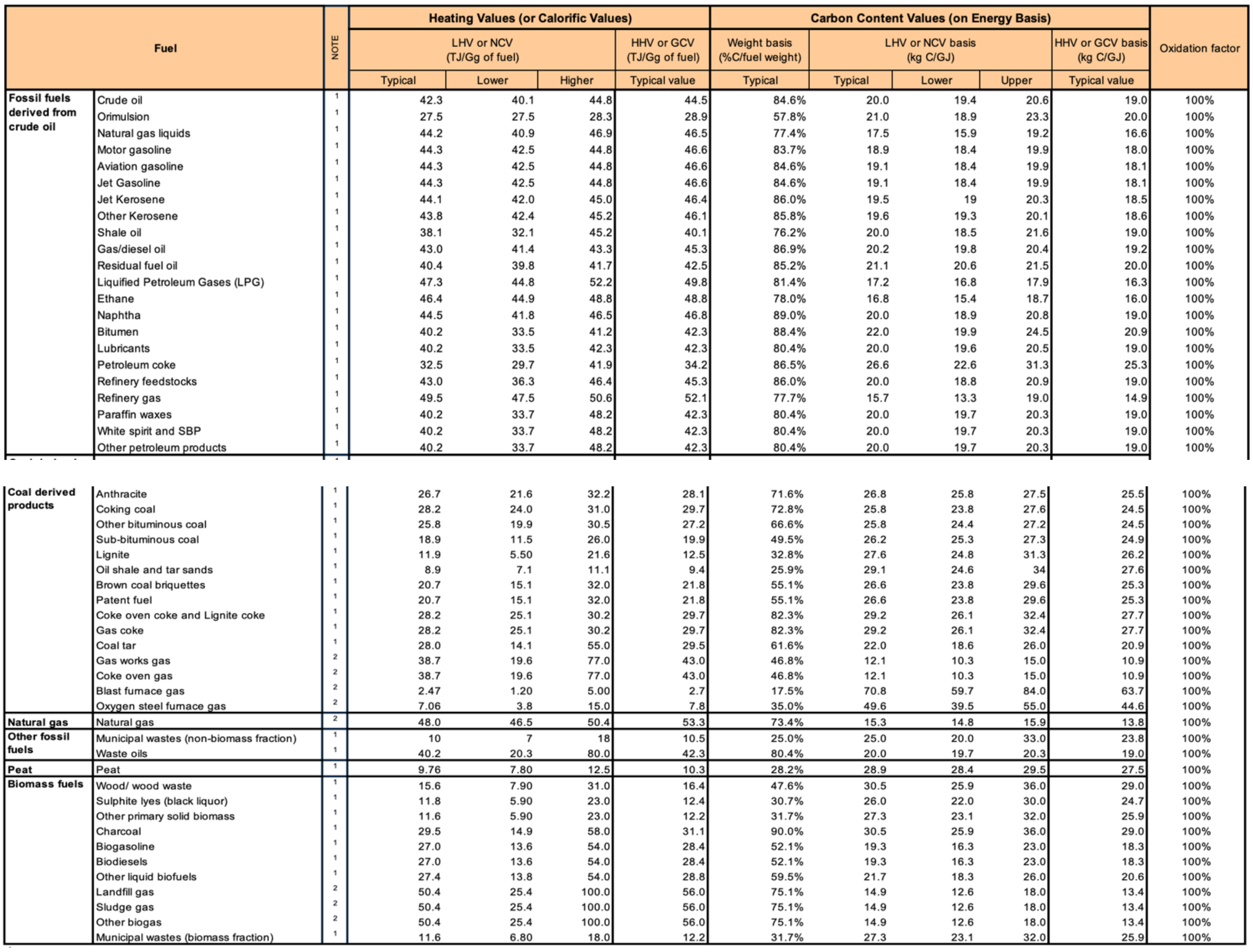
Appendix A



Appendix B

Default carbon content and heating values for different fuels.
HHV = Higher Heating Value or GCV = Gross Calorific Value
LHV = Lower Heating Value or NCV = Net Calorific Value

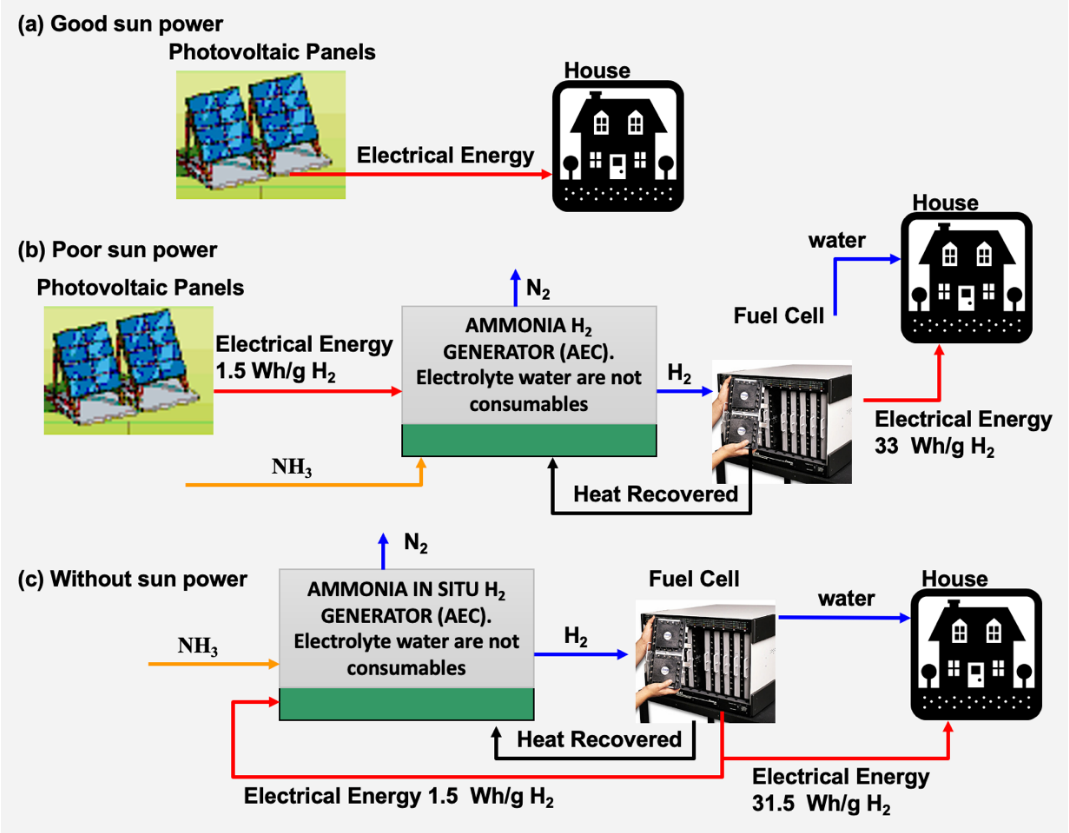


Fuel		NOTE	Heating Values (or Calorific Values)				Carbon Content Values (on Energy Basis)					Oxidation factor
			LHV or NCV (TJ/Gg of fuel)			HHV or GCV (TJ/Gg of fuel)	Weight basis (%C/fuel weight)	LHV or NCV basis (kg C/GJ)			HHV or GCV basis (kg C/GJ)	
			Typical	Lower	Higher	Typical value	Typical	Typical	Lower	Upper	Typical value	
Fossil fuels derived from crude oil	Crude oil	1	42.3	40.1	44.8	44.5	84.6%	20.0	19.4	20.6	19.0	100%
	Orimulsion	1	27.5	27.5	28.3	28.9	57.8%	21.0	18.9	23.3	20.0	100%
	Natural gas liquids	1	44.2	40.9	46.9	46.5	77.4%	17.5	15.9	19.2	16.6	100%
	Motor gasoline	1	44.3	42.5	44.8	46.6	83.7%	18.9	18.4	19.9	18.0	100%
	Aviation gasoline	1	44.3	42.5	44.8	46.6	84.6%	19.1	18.4	19.9	18.1	100%
	Jet Gasoline	1	44.3	42.5	44.8	46.6	84.6%	19.1	18.4	19.9	18.1	100%
	Jet Kerosene	1	44.1	42.0	45.0	46.4	86.0%	19.5	19	20.3	18.5	100%
	Other Kerosene	1	43.8	42.4	45.2	46.1	85.8%	19.6	19.3	20.1	18.6	100%
	Shale oil	1	38.1	32.1	45.2	40.1	76.2%	20.0	18.5	21.6	19.0	100%
	Gas/diesel oil	1	43.0	41.4	43.3	45.3	86.9%	20.2	19.8	20.4	19.2	100%
	Residual fuel oil	1	40.4	39.8	41.7	42.5	85.2%	21.1	20.6	21.5	20.0	100%
	Liquified Petroleum Gases (LPG)	1	47.3	44.8	52.2	49.8	81.4%	17.2	16.8	17.9	16.3	100%
	Ethane	1	46.4	44.9	48.8	48.8	78.0%	16.8	15.4	18.7	16.0	100%
	Naphtha	1	44.5	41.8	46.5	46.8	89.0%	20.0	18.9	20.8	19.0	100%
	Bitumen	1	40.2	33.5	41.2	42.3	88.4%	22.0	19.9	24.5	20.9	100%
	Lubricants	1	40.2	33.5	42.3	42.3	80.4%	20.0	19.6	20.5	19.0	100%
	Petroleum coke	1	32.5	29.7	41.9	34.2	86.5%	26.6	22.6	31.3	25.3	100%
	Refinery feedstocks	1	43.0	36.3	46.4	45.3	86.0%	20.0	18.8	20.9	19.0	100%
	Refinery gas	1	49.5	47.5	50.6	52.1	77.7%	15.7	13.3	19.0	14.9	100%
	Paraffin waxes	1	40.2	33.7	48.2	42.3	80.4%	20.0	19.7	20.3	19.0	100%
	White spirit and SBP	1	40.2	33.7	48.2	42.3	80.4%	20.0	19.7	20.3	19.0	100%
	Other petroleum products	1	40.2	33.7	48.2	42.3	80.4%	20.0	19.7	20.3	19.0	100%
Coal derived products	Anthracite	1	26.7	21.6	32.2	28.1	71.6%	26.8	25.8	27.5	25.5	100%
	Coking coal	1	28.2	24.0	31.0	29.7	72.8%	25.8	23.8	27.6	24.5	100%
	Other bituminous coal	1	25.8	19.9	30.5	27.2	66.6%	25.8	24.4	27.2	24.5	100%
	Sub-bituminous coal	1	18.9	11.5	26.0	19.9	49.5%	26.2	25.3	27.3	24.9	100%
	Lignite	1	11.9	5.50	21.6	12.5	32.8%	27.6	24.8	31.3	26.2	100%
	Oil shale and tar sands	1	8.9	7.1	11.1	9.4	25.9%	29.1	24.6	34	27.6	100%
	Brown coal briquettes	1	20.7	15.1	32.0	21.8	55.1%	26.6	23.8	29.6	25.3	100%
	Patent fuel	1	20.7	15.1	32.0	21.8	55.1%	26.6	23.8	29.6	25.3	100%
	Coke oven coke and Lignite coke	1	28.2	25.1	30.2	29.7	82.3%	29.2	26.1	32.4	27.7	100%
	Gas coke	1	28.2	25.1	30.2	29.7	82.3%	29.2	26.1	32.4	27.7	100%
	Coal tar	1	28.0	14.1	55.0	29.5	61.6%	22.0	18.6	26.0	20.9	100%
	Gas works gas	2	38.7	19.6	77.0	43.0	46.8%	12.1	10.3	15.0	10.9	100%
	Coke oven gas	2	38.7	19.6	77.0	43.0	46.8%	12.1	10.3	15.0	10.9	100%
	Blast furnace gas	2	2.47	1.20	5.00	2.7	17.5%	70.8	59.7	84.0	63.7	100%
	Oxygen steel furnace gas	2	7.06	3.8	15.0	7.8	35.0%	49.6	39.5	55.0	44.6	100%
Natural gas	Natural gas	2	48.0	46.5	50.4	53.3	73.4%	15.3	14.8	15.9	13.8	100%
Other fossil fuels	Municipal wastes (non-biomass fraction)	1	10	7	18	10.5	25.0%	25.0	20.0	33.0	23.8	100%
	Waste oils	1	40.2	20.3	80.0	42.3	80.4%	20.0	19.7	20.3	19.0	100%
Peat	Peat	1	9.76	7.80	12.5	10.3	28.2%	28.9	28.4	29.5	27.5	100%
Biomass fuels	Wood/ wood waste	1	15.6	7.90	31.0	16.4	47.6%	30.5	25.9	36.0	29.0	100%
	Sulphite lyes (black liquor)	1	11.8	5.90	23.0	12.4	30.7%	26.0	22.0	30.0	24.7	100%
	Other primary solid biomass	1	11.6	5.90	23.0	12.2	31.7%	27.3	23.1	32.0	25.9	100%
	Charcoal	1	29.5	14.9	58.0	31.1	90.0%	30.5	25.9	36.0	29.0	100%
	Biogasoline	1	27.0	13.6	54.0	28.4	52.1%	19.3	16.3	23.0	18.3	100%
	Biodiesels	1	27.0	13.6	54.0	28.4	52.1%	19.3	16.3	23.0	18.3	100%
	Other liquid biofuels	1	27.4	13.8	54.0	28.8	59.5%	21.7	18.3	26.0	20.6	100%
	Landfill gas	2	50.4	25.4	100.0	56.0	75.1%	14.9	12.6	18.0	13.4	100%
	Sludge gas	2	50.4	25.4	100.0	56.0	75.1%	14.9	12.6	18.0	13.4	100%
	Other biogas	2	50.4	25.4	100.0	56.0	75.1%	14.9	12.6	18.0	13.4	100%
	Municipal wastes (biomass fraction)	1	11.6	6.80	18.0	12.2	31.7%	27.3	23.1	32.0	25.9	100%

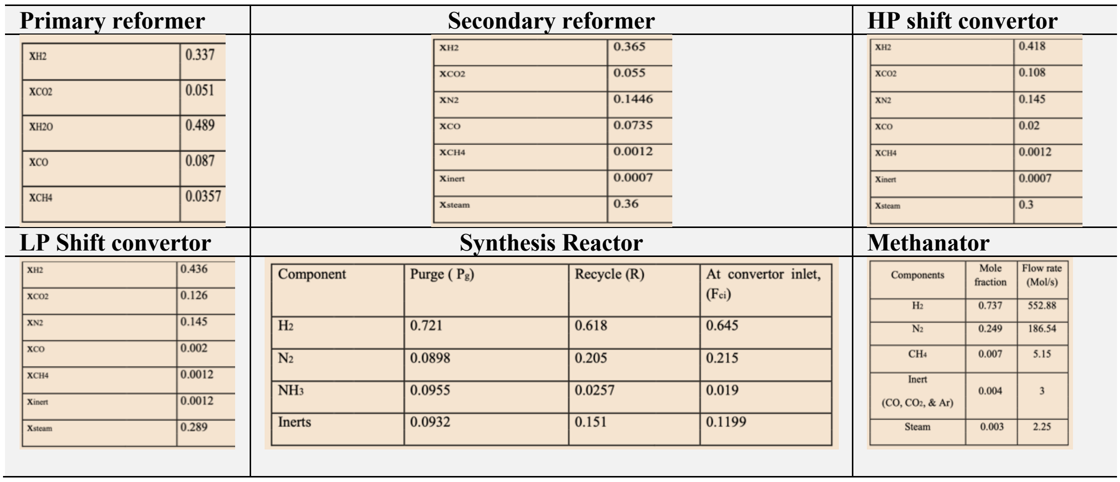
[1] Applies heat content conversion ratio for coal and oil
[2] Applies heat content conversion ratio for natural gas and manufactured gases

Reference: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The default IPCC values, originally published on a NCV (LHV) basis, have been converted to a GCV (HHV) basis using a commonly acceptable approximation. LHV is 95% of HHV for coal and oil, and 90% of HHV for natural gas and manufactured gases. A closer analysis is recommended for organizations that can obtain fuel characterizes (e.g., moisture content, fraction of hydrogen) in order to properly determine the fuel's relationship between net calorific value and gross calorific value as the default approximation adds uncertainty. Gross calorific (higher heating) values are preferred because they are more.

Appendix C



Appendix D



Primary reformer

x_{H_2}	0.337
x_{CO_2}	0.051
x_{H_2O}	0.489
x_{CO}	0.087
x_{CH_4}	0.0357

Secondary reformer

x_{H_2}	0.365
x_{CO_2}	0.055
x_{N_2}	0.1446
x_{CO}	0.0735
x_{CH_4}	0.0012
X_{inert}	0.0007
X_{steam}	0.36

HP shift convertor

x_{H_2}	0.418
x_{CO_2}	0.108
x_{N_2}	0.145
x_{CO}	0.02
x_{CH_4}	0.0012
X_{inert}	0.0007
X_{steam}	0.3

LP Shift convertor

x_{H_2}	0.436
x_{CO_2}	0.126
x_{N_2}	0.145
x_{CO}	0.002
x_{CH_4}	0.0012
X_{inert}	0.0012
X_{steam}	0.289

Synthesis Reactor

Component	Purge (P_g)	Recycle (R)	At convertor inlet, (F_{ci})
H_2	0.721	0.618	0.645
N_2	0.0898	0.205	0.215
NH_3	0.0955	0.0257	0.019
Inerts	0.0932	0.151	0.1199

Methanator

Components	Mole fraction	Flow rate (Mol/s)
H_2	0.737	552.88
N_2	0.249	186.54
CH_4	0.007	5.15
Inert (CO, CO_2, & Ar)	0.004	3
Steam	0.003	2.25