# Hydrogen Value Chain Analysis: Steam Methane Reforming Coupled with Carbon Capture & Storage


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## Introduction

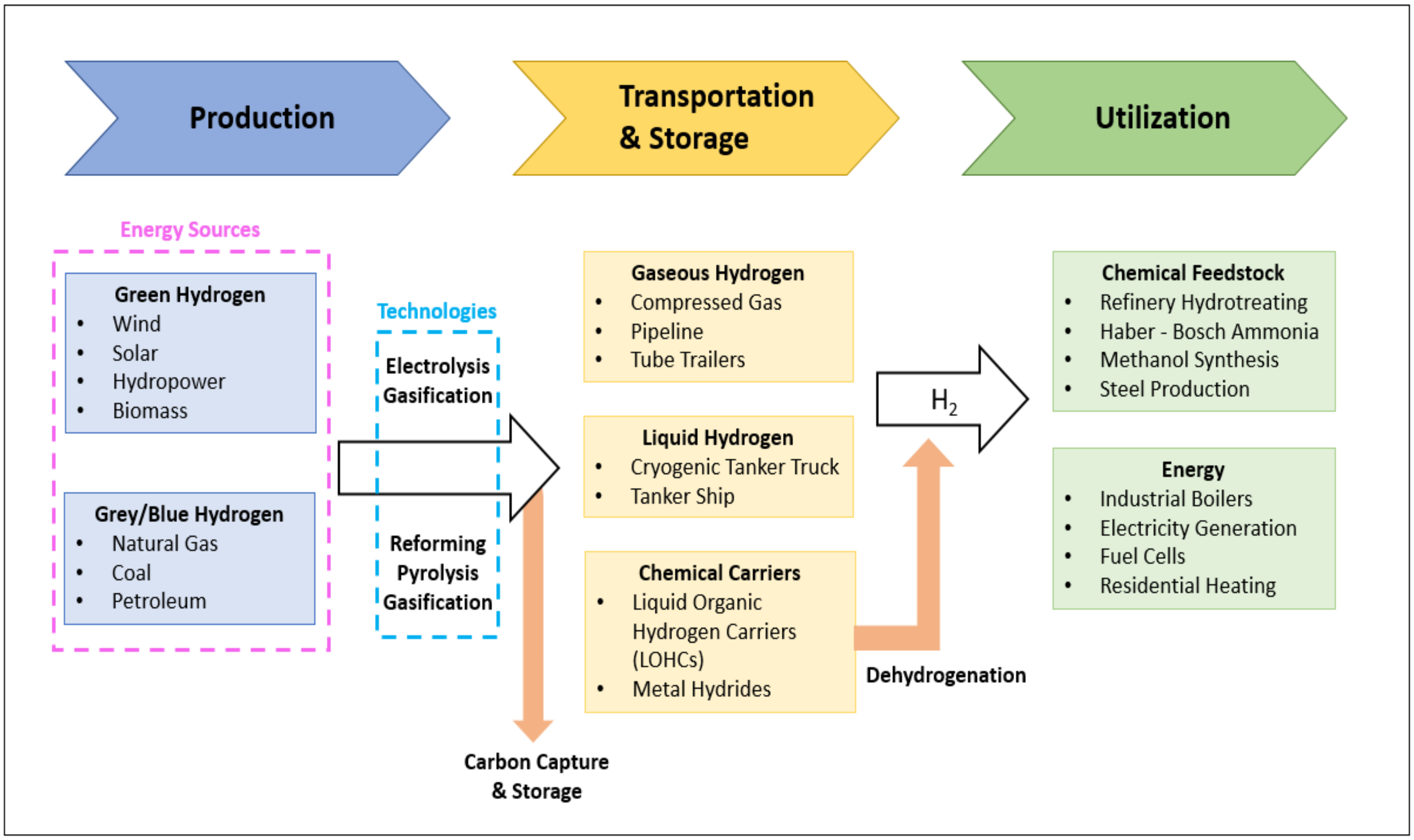
Over the past few decades, employing hydrogen to diversify the world's energy systems has become a major topic of discussion. Elemental hydrogen ($H_2$) does not naturally exist on Earth in large quantities; therefore, it must be produced by some manmade process. It is of great importance to determine the most optimal means of production, transportation and storage, and utilization of this valuable hydrogen resource. Furthermore, it must be noted that hydrogen is an energy carrier, rather than an energy source. The fundamental value of hydrogen as an energy carrier resides in its ability to store electrons and chemical energy in bonds while also being carbon free. It is expected that hydrogen will play a major role in decarbonizing the energy sector as countries around the globe strive to meet the commitments of the 2015 Paris Agreement which calls to limit global warming to below 2$^{o}$C.

This paper aims to provide an overview of the most optimal hydrogen value chain based on an established set of quantitative and qualitative criteria. Those criteria include:

- overall efficiency of production
- ability to leverage thermodynamic properties
- ability to leverage current and future market conditions
- safety and sustainability prospects
- synergies with existing infrastructure

A roadmap of hydrogen value chain activities is pictured below. For this paper, five primary methods of production are analyzed: renewable electrolysis, biomass gasification, steam methane reforming (SMR), SMR with carbon capture and storage (CCS), and coal gasification. Transportation and storage is typically limited to the gaseous phase, liquid phase, or as part of a chemical carrier such as ammonia. Utilization is split into two main categories: use as chemical feedstock or as energy.

**Summary of Hydrogen Value Chains**




Based on a holistic review of the criteria, the steam methane reforming with carbon capture and storage value chain offers the most promise to supplying global hydrogen needs. Hydrogen produced this way is colloquially known as “blue hydrogen.” This paper will analyze the global energy landscape and how blue hydrogen will compete with other existing technologies (e.g. water electrolysis, methane pyrolysis) to supply the world with a more sustainable energy source while also continuing to meet demand as a key feedstock component. Finally, a recommended value chain along with suggestions for future improvement in hydrogen technologies will be given.

## Thermodynamic Analysis of Hydrogen

Hydrogen is the lightest of all elements, containing just one proton and one electron in its most stable form. On Earth, hydrogen primarily exists in the chemical bonds of hydrocarbons, metal hydrides, and most abundantly as pure water. Very little elemental hydrogen exists due to its high chemical reactivity. When evaluating a potentially new energy source or carrier, the thermodynamic properties must be closely analyzed. These properties provide a framework for designing the energy's infrastructure. In the table below, the properties of hydrogen are summarized and compared to methane.

**Key Thermodynamic Properties of Hydrogen and Methane[1]**

| Property | Units | Hydrogen | Methane |
|---|---:|---:|---:|
| Melting Point | °C | -259.2 | -182.5 |
| Boiling Point | °C | -252.9 | -161.5 |
| Adiabatic Flame Temperature (oxygen / air) | °C | 2600 / 2045 | 2810 / 1957 |
| Explosion Limits (Lower / Upper) | % | 4 / 75.6 | 4.4 / 17 |
| Maximum Laminar Flame Speed | $m\ s^{-1}$ | 3.25 | 0.45 |
| Minimum Ignition Energy* | $10^{-4}$ J | 0.2 | 4.7 |
| Minimum Ignition Temperature | °C | 572 | 632 |
| SCF combustion air/ MMBtu fuel** | SCF/MMBtu | 8667 | 10439 |
| SCF flue gas / MMBtu fuel** | SCF/MMBtu | 10488 | 11535 |
| Gravimetric Energy Density | $kWh\ kg^{-1}$ | 33.3 | 13.9 |
| *Gas Phase at STP* | | | |
| Density | $kg\ m^{-3}$ | 0.09 | 0.657 |
| Specific Heat Capacity ($C_p$ / $C_v$) | $kJ\ kg^{-1}K^{-1}$ | 14.32 / 10.17 | 35.8 / 27.4 |
| Volumetric Heating Value (Lower / Higher) | $MJ\ m^{-3}$ | 10.8 / 12.7 | 35.8 / 39.8 |
| Volumetric Energy Density | $kWh\ m^{-3}$ | 0.5 | 1.5 |
| *Liquid Phase at 1 atm* | | | |
| Density | $kg/m^3$ | 70.8 | 422.6 |
| Volumetric Energy Density | $kWh\ m^{-3}$ | 1.2 | 3.3 |

*Stoichiometric fuel/air mixture, **Stoichiometric combustion on Lower Heating Value basis

Methane is the majority component in natural gas, which is a critical component of energy infrastructures around the world. Therefore, the feasibility of utilizing hydrogen as an interchangeable fuel in existing infrastructure can be estimated by comparing its key properties to methane.

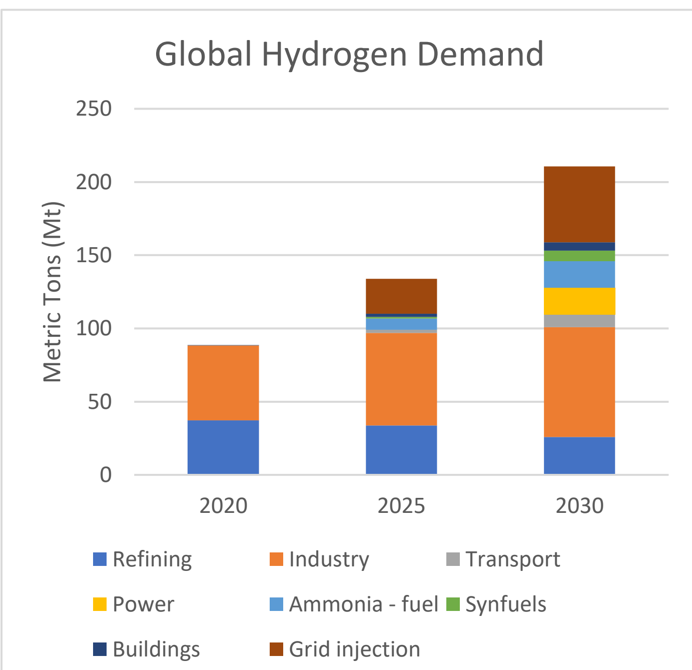
Diatomic hydrogen has several unique thermodynamic properties which can be problematic to design for in engineering applications. It has the second lowest boiling point of all elements, nearly $100^{o}$C lower than methane. At standard temperatures and pressures, it is one of three known elemental gases with a negative Joule Thompson coefficient. This causes hydrogen to heat upon isenthalpic expansion. For example, hydrogen gas temperature will increase when throttled across a valve (pressure decrease).

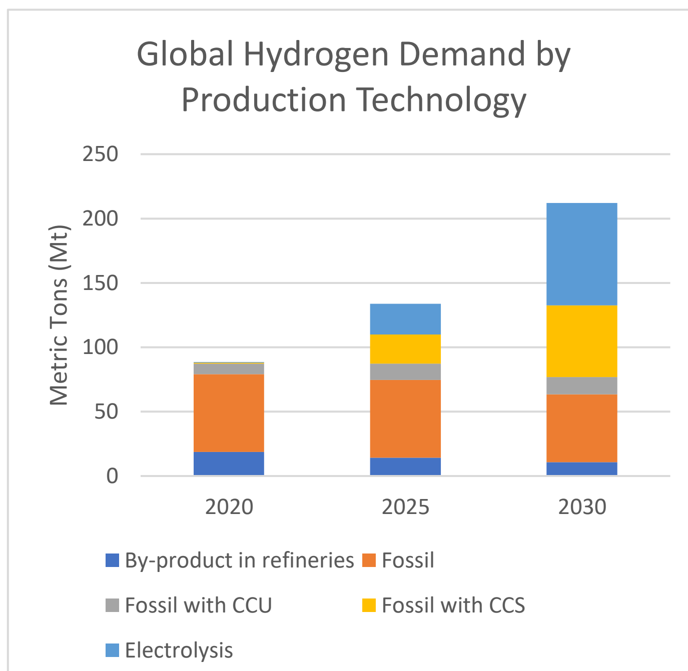
The combustion properties of hydrogen mirror those of methane. Hydrogen has the potential to burn at elevated temperatures with zero carbon dioxide emissions, making it a viable blend component in boiler fuel gas. This is not without serious safety concerns. Gaseous hydrogen combusts in nearly all fuel-air mixtures and at extremely low ignition energies. Flame speeds of pure hydrogen are much higher than that of natural gas and must be accounted for in burner design. When combusted in a furnace, pure hydrogen consumes less air and releases less flue gas than natural gas. This allows for more compact and more efficient heaters to be designed.

Per unit mass, hydrogen has the highest energy density of any known chemical fuel at 33.3 kWh $kg^{-1}$. This makes it the preferred fuel option for space applications. On a volumetric basis, hydrogen has an energy density about one third that of methane in the gaseous and liquid phases.

**Hydrogen Landscape Overview**

Currently, more than 80% of global energy is derived from fossil fuel sources with the remaining 20% coming from nuclear and renewables. As the world continues to search for low-carbon energy solutions, the idea of using of hydrogen has become increasingly popular. In fact, since 1975 the demand for hydrogen has more than tripled and is expected to increase another 44% by 2030. Global hydrogen demand can be broken into two distinct categories: use as chemical feedstock and use as clean energy. On the production side, hydrogen demand is met by either fossil fuel sources or renewable electrolysis methods. The following tables below summarize the hydrogen demand and production methods according to the IEA Net Zero Emissions Scenario. [2]




As seen above, refining and industry demand the largest share of hydrogen, where it is used as a chemical feedstock component. Total global chemicals demand is expected to rise 40% by 2030 due to expanding populations and increased standards of living.[3] Two competing factors contribute to the demand of hydrogen in the refinery sector. On one hand, more electric vehicles (EVs) on the road will decrease the need for hydrotreated fuel, subsequently decreasing demand. On the other, developing countries will continue to require heavy diesel for freighting, causing hydrotreating demand to increase. Overall, refinery hydrogen demand is expected to remain steady in the near term. In the next decade, hydrogen will expand into the energy portfolio of developed countries, as it is burned in mobile fuel cells and injected into natural gas grids. The extent to which this happens is uncertain, and very likely depends on carbon taxes of respective countries.

In the short term, hydrogen demand will primarily be met by fossil fuel resources, particularly steam methane reforming. As carbon capture technology becomes more economical in the next few years, blue hydrogen plants will come online. Electrolysis methods are competitive in regions isolated from natural gas resources and plentiful in renewable energy such as Western Australia. Current hydrogen infrastructure does not allow it to be a globally traded commodity like petroleum, therefore, demand will continue to be met by the most optimal production method in that region of the globe.

With regards to hydrocarbon resources, significant advancements in fracking technology along with large discoveries in shale gas reserves at the turn of the 21$^{st}$ century have put hydrogen production via SMR at the center of attention. These shale gas reserves are comprised of over 95% of methane, a primary feedstock component in the SMR reaction. As of 2021, the world consumes about 3.8 trillion cubic meters (Tcm) of natural gas per year while its proven reserves are estimated to be near 188 Tcm.[4] This allows for nearly 50 years of proven natural gas usage. Unproven reserves are thought to be orders of magnitude more. The implications of these ubiquitous shale gas resources toward short- and medium-term hydrogen production are immense. However, electrolyzers will compete with reformers in the long term as carbon taxes are rolled out across developed countries. Therefore, blue hydrogen can serve as a low-carbon bridge technology to transition the world from fossil fuels to renewable sources of energy.

**Hydrogen Value Chain Overview**

Currently, hydrogen value chains around the world are dictated by the source of energy generating the hydrogen (e.g. hydrocarbons, water) and the end use of the hydrogen. Steam methane reforming with carbon capture and storage can meet global hydrogen needs at the lowest price possible while also reducing carbon dioxide emissions to acceptable levels. This blue hydrogen value chain will be analyzed according to its three key components: production, transportation and storage, and utilization.

*Production*

Hydrogen can be produced a myriad of ways; renewable electrolysis of water (green hydrogen), hydrocarbon reforming, methane pyrolysis, coal gasification, and biomass gasification are amongst the most popular. Today, more than 96% of hydrogen is derived from fossil fuel resources with very little being produced from green energy sources. When considering the best production method, three main factors were considered: cost of production, ratio of carbon dioxide to hydrogen produced, and total energy efficiency of the process. These factors reflect the ability of the process to meet demand in an economical and sustainable manner. As seen in the table below, SMR with CCS provides a balance of inexpensive hydrogen production and high overall energy efficiency with acceptable carbon dioxide emissions.

**Key Hydrogen Production Metrics [5,6]**

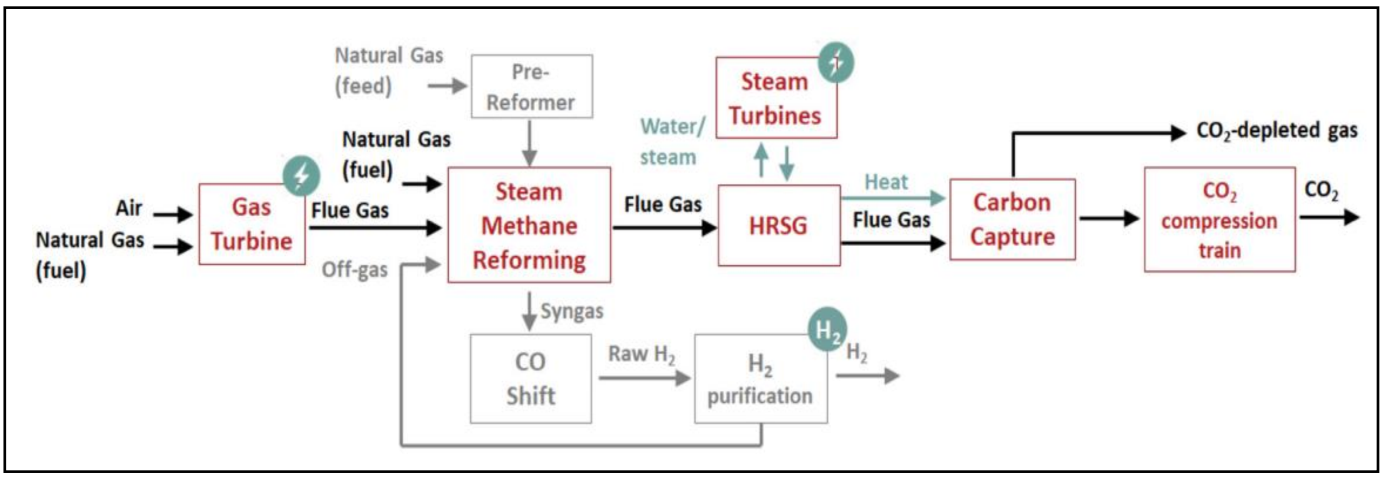
| Method | Approximate Production Cost ($/kg H2) | Ratio kg $CO_2/H_2$ Produced | Energy Efficiency (%) |
|---|---|---|---|
| Electrolysis (wind, solar) | 6.03 , 10.49 | 0.17 | 30 |
| Methane Pyrolysis | 1.70 | 5 | 58 |
| SMR without CCS | 2.08 | 12 | 70-80 |
| SMR with CCS | 2.27 | < 2 | 60 |
| Coal Gasification | 1.80 | 25 | 60 |
| Biomass Gasification | 2.05 | 6 | 35-50 |

Electrolysis of water with renewable energy (wind, solar, hydro) is the lowest emitter of $CO_2$, but suffers from serious process inefficiencies and high capital investments. The intermittency of these resources also raises concerns for matching steady hydrogen demand. Methane pyrolysis produces hydrogen gas and pure solid carbon via the thermal decomposition of methane in an inert atmosphere. In pilot scale plants, hydrogen can be produced at competitive prices with nearly half the emissions of existing processes. However, much research into catalysts and scalability must be done before this technology is proved to be commercially viable. Coal and biomass gasification can provide inexpensive hydrogen in sufficient quantities but suffer from high emissions and process inefficiencies respectively. It is important to note that the economic viability of each of these production processes is highly dependent on the price of carbon taxes placed on $CO_2$ emissions, which vary across the globe.

When considering cost of production and high energy efficiency with low emissions, steam methane reforming is the optimal production pathway. In the absence of carbon taxes, SMR without CCS is currently the most energy efficient technology for producing high volumes of hydrogen, at approximately half to one third of the cost of those created by green electrolysis methods. The reforming process has existed for nearly 80 years and accounts for about 95% of the United States' hydrogen production. Furthermore, reforming integrates into existing petrochemical facilities and takes advantage of the nation's natural gas infrastructure.

SMR coupled with CCS, can reduce $CO_2$ emissions over 90% while also producing inexpensive hydrogen.[7] This low-carbon hydrogen production scheme is expected to be profitable in the short and medium term with carbon taxes of $30-$60 per ton.[8] Low methane feedstock prices driven by immense shale gas supplies in North America will allow reforming in the Gulf Coast region to be especially profitable. In proximity, the Gulf of Mexico offers high capacity for carbon dioxide storage in subsea geologic formations. A sample process flow diagram of an integrated sequential combustion SMR with CCS plant is provided below.[9]

**Block Flow Diagram: SMR Coupled CCS**




<u>Process Description</u>: Natural gas is combusted in the gas turbine to produce electricity for the $CO_2$ compression train, with the flue gas sent to the primary methane reformer furnace. Natural gas is fed to the pre-reformer to convert higher hydrocarbons to methane and reduce coking on the primary reformer catalyst. The methane is fed to the primary reformer where it is reacted with high temperature steam at moderate pressure (1). The hydrogen and carbon monoxide are sent to a water-gas shift reactor (WGSR), where byproduct carbon monoxide is further reacted with steam to produce carbon dioxide and more hydrogen (2).

(1) $CH_4 + H_2O \rightarrow CO + 3H_2$

(2) $CO + H_2O \leftrightarrow CO_2 + H_2$

(Net) $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$

The effluent stream is passed through a pressure swing adsorption (PSA) unit for hydrogen purification according to specification. PSA off-gas is recirculated to the reformer furnace. Reformer furnace flue gas is sent to the heat recovery steam generators (HRSG) to capture both heat and electricity for carbon capture. Carbon dioxide is captured in absorbers and compressed to be pipelined to local sequestration sites. Some low concentration $CO_2$ gas is vented to atmosphere.

This novel cogeneration hydrogen production scheme produces both heat and electricity required for industrial processes with energy efficiencies much higher than that of traditional power plants. Centralizing the carbon capture to the reformer flue gas simplifies the carbon capture unit and allows for greater emissions reductions.

Steam methane reforming has serious tradeoffs to consider. For non-CCS schemes, high volumes of carbon dioxide are emitted via reaction byproduct and furnace flue gas. For CCS schemes, they are only viable when located near carbon sequestration sites. The added carbon capture unit drives down the overall efficiency of the process and requires significant capital investment. Furthermore, due to the high endothermicity of the reaction, tremendous amounts of heat must be input to the reactor. Continued drilling for natural gas will increase methane emissions, which is 25 times more effective at trapping heat than carbon dioxide. Long term prospects of reforming are uncertain as carbon taxes are levied and advancements in electrolyzer technology are made. Nonetheless, blue hydrogen can serve as a low-carbon solution to meet the world's future hydrogen demand.

*Transportation & Storage*

At standard conditions, hydrogen is not thermodynamically stable. This makes it inherently difficult and expensive to transport and store. Today, gaseous hydrogen can be transported in small volumes in compressed gas cylinders, or in large volumes in hydrogen pipelines. Liquid hydrogen can be transported in small volumes on tanker vehicles or stored in large volumes in cryogenic vessels within chemical plants. Large volume mobile deployment of liquefied hydrogen is being explored in hydrogen tanker ships, with the first one being commercialized in early 2022. Transportation, change of phase, and storage all require significant capital and energy investments. With current technology, around 30% of the energy content of hydrogen is consumed during cryogenic liquefaction.[10]

Due to hydrogen's negative Joule-Thompson coefficient, slow filling or a cooling system must be implemented when transferring hydrogen to a high-pressure vessel. Storage vessels must also be heavily insulated to reduce boil off. The high diffusivity of hydrogen causes embrittlement of many metallic and polymeric materials. To account for this, vessel systems typically employ specialized metallic alloys including aluminum or stainless steel. Therefore, it can be argued that the best method for transportation and storage of hydrogen is to use it in-situ and minimizing storage at all costs.

Much of the United States' 1600 miles of hydrogen pipelines are clustered in the Gulf Coast region around refineries and chemical plants.[11] These are also the largest producers and consumers of hydrogen in the country. Most of the hydrogen produced via steam methane reforming is directly used within the refinery as hydrotreating feedstock or pipelined to nearby chemical plants. Therefore, it remains gaseous and does not travel far, keeping costs low. Taking advantage of industrial parks and existing hydrogen pipeline infrastructure is critical to optimizing the SMR produced hydrogen value chain. If hydrogen production continues to match the demand, then there is little need for storage. As hydrogen production is expected to increase, more uses for hydrogen must be discovered. Limiting the need to transport and store hydrogen is a critical component to optimizing the value chain. This can be accomplished by continuing to place the source of production in proximity to the source of consumption.

The table below qualitatively compares performance metrics of the three main methods of transportation and storage: gaseous phase, liquid phase, and chemical carrier. In-situ refers to direct use of hydrogen on the location of production, thus it effectively functions as the most minimal form of transportation and storage.

**Comparison of Hydrogen Transportation & Storage Methods**

| Method | Energy Efficient | Large Volume Capabilities | Minimal Infrastructure | Versatility | Overall Safety |
|---|---|---|---|---|---|
| In-Situ | ● | ● | ● | ◕ | ● |
| Gaseous | ◕ | ● | ◕ | ● | ◕ |
| Liquid | ◑ | ◕ | ◑ | ◔ | ◔ |
| Chemical Carrier | ◑ | ◕ | ◑ | ◔ | ◕ |

Performance Key
- ● Great
- ◕ Good
- ◑ Average
- ◔ Poor
- ○ Very Poor

*Note: Full circles suggest that criteria are well met, while open circles suggest they are not. Note that no weighting is applied to the criteria and is purely qualitative in nature based on the review of literature.

In-situ use of hydrogen inherently performs better because it constricts the need for transportation and storage. Gaseous hydrogen is the most thermodynamically stable, thus infrastructure is easier to design for. Liquid hydrogen and chemical carriers suffer significant energy losses and are not yet well developed.

*Utilization*

Nearly 90% of all hydrogen produced is consumed as chemical feedstock in key industrial processes such as ammonia production (55%), refinery hydrotreating (25%), and methanol production (10%).[12] This will continue to be the case as developing countries experience population growth well into 2050. Growing populations must be fed, thus ammonia production will need to increase to match the demand for more fertilizer. Methanol is a key feedstock component in the production of many chemicals and will continue to increase in demand over time as countries develop higher standards of living. Hydrogen for refinery hydrotreating should be stable in the short and medium term as diesel is expected to be the preferred fuel for heavy freighting. Long term prospects of hydrotreating are expected to decline due to increased usage of EVs. Other small volume uses of hydrogen include mobile fuel cells, rocket fuel, and heating applications.

Locating the source of hydrogen production near the source of consumption allows one to circumvent the difficulties of transportation and storage. Steam methane reforming takes advantage of this idea as it forms many synergies with existing petrochemical facilities. The feedstock is readily available throughout refineries since it is a constituent of the lightest fraction of petroleum. Refineries with excess methane could pass it through the reformer to obtain a higher value hydrogen product which can then be consumed within the plant or sold to nearby customers.

In efforts to decarbonize point emissions of the industrial sector, hydrogen is currently being researched as an alternate fuel to be combusted in fired heaters. It has a similar adiabatic flame temperature and Wobbe index to that of methane, thus making it a suitable blend component for fuel gases. In fact, blending syngas (containing hydrogen) with natural gas has been a commercially viable technique employed within refineries for decades. The unique benefits of burning hydrogen in heaters is twofold: increased burner efficiency over traditional fuels and reduced greenhouse gas emissions. Hydrogen burns hotter than methane in pure air mixtures, and consequently the overall efficiency of heaters has been shown to increase by over 2.2% when hydrogen content is increased from 10% to 90%.[13] But most importantly, hydrogen combusts to pure water without any carbon dioxide emissions. Effectively phasing out hydrocarbon boiler fuels with hydrogen can help reduce Scope 3 emissions of many difficult to decarbonize sectors (e.g. steelmaking). Although $NO_X$ emissions are shown to increase with higher hydrogen content, minor modifications can be made to burner tips to minimize these emissions. Burner technology is very well understood, it is just a matter of retrofitting existing furnaces to accompany the higher percentage blends of hydrogen.

The high energy density of hydrogen suggests that it is a suitable fuel for the transportation sector, particularly in hydrogen fuel cells for heavy duty vehicles. Major safety concerns and high costs have rendered hydrogen powered vehicles uncompetitive in comparison to EVs in the short term. But the long-term prospects of hydrogen fuel cells for mobile sources are intriguing. Compared to today's lithium-ion batteries used in EVs, compressed hydrogen storage systems contain nearly 5 times the amount energy on a per volume basis, and more than 200 times the energy on a gravimetric basis. This lends to greater vehicle range and less frequent fueling. Advancements in safer hydrogen storage along with easier access to hydrogen fueling stations in the future could place hydrogen fuel cells at the forefront of clean transportation.

**Safety & Sustainability Analysis**

Evaluating the safety of an energy carrier or source is often qualitative in nature, but deeply rooted in its thermodynamic properties. High level safety analysis of new energy resources attempts to analyze these properties to determine whether they are capable of being harnessed with existing technologies. The following analysis is based on such and will focus on both process and personal safety. The safety of SMR produced hydrogen will be evaluated at each of the three key stages in its value chain.

Qualitative analysis of various hydrogen production technologies is provided in the table below, ranked from most sustainable to least. Blue hydrogen is ranked second behind renewable electrolysis. Although it can provide the most economical low-carbon hydrogen in near term, it loses out on the long term when considering the finite supply of its feedstock.

**Qualitative Safety & Sustainability Analysis of Hydrogen Production Methods**

| Technology | Availability of Feedstock | Synergies with Existing Infrastructure | Ability to Meet Current Demand | Public Opinion | Process Safety | Energy Savings | Limited Environmental Footprint |
|---|---|---|---|---|---|---|---|
| Electrolysis | ● | ◕ | ◑ | ● | ◑ | ◔ | ◕ |
| SMR with CCS | ◕ | ◕ | ● | ◔ | ● | ◕ | ◑ |
| SMR without CCS | ◑ | ◕ | ● | ○ | ● | ● | ◔ |
| Methane Pyrolysis | ◑ | ◑ | ○ | ◔ | ● | ◕ | ◕ |
| Biomass Gasification | ◕ | ◔ | ◔ | ◕ | ◑ | ◔ | ◕ |
| Coal Gasification | ◕ | ◕ | ● | ○ | ● | ◑ | ○ |

Performance Key

| | |
|---|---|
| ● | Great |
| ◕ | Good |
| ◑ | Average |
| ◔ | Poor |
| ○ | Very Poor |

*Note: Full circles suggest that criteria are well met, while open circles suggest they are not. Note that no weighting is applied to the criteria and is purely qualitative in nature based on the review of literature.

SMR with CCS performs well in all areas except public opinion, partly due to the fact it is derived from fossil fuel sources. Electrolysis suffers from serious thermodynamic limitations, but advancements in technology could make it more competitive.

*Process Safety*

Many of the process safety concerns of hydrogen revolve around its utilization in chemical processes and transportation. The reforming process has existed for nearly a century and its safety hazards are very well understood. Hydrogen production via reforming has continued to be one of the safest methods because the hydrogen is consumed very quickly after it is produced. This minimizes the footprint of hydrogen on the plant site. Additionally, centralizing hydrogen within chemical sites is inherently safer. For instance, the oil and gas sector has been shown to have a recordable injury rate less than one third that of renewable sources.[14]

In-situ utilization of hydrogen allows for fewer hydrogen storage vessels, thus reducing the possibility of a loss of containment event and subsequent explosion. Being able to reduce the need for chemical storage both saves capital and is inherently safer. In fact, the largest chemical disaster in history, the Bhopal disaster, could have been avoided if the toxic methylisocyanate (MIC) was consumed as needed. Furthermore, the storage concerns of hydrogen closely mirror that of MIC. Hydrogen explosively combusts with nearly all air mixtures while MIC exothermically reacts when contacted with water. Both air and water are abundant in chemical processes, leaving significant risk for an incident. Current chemical process safety standards suggest minimizing the need to store chemicals with high reactive indexes. Therefore, this concept should be applied to hydrogen storage.

Like natural gas, hydrogen is most economically and safely transported in large volumes via gas pipelines. Compressed or liquified hydrogen can be trucked to areas outside of the hydrogen pipeline infrastructure. It is estimated that less than 10% of recorded hydrogen incidents occur during the transportation process.[15] Most of these take place during the on and off loading of hydrogen onto vehicles. Safety of hydrogen transportation can be improved by continual reviewal of management systems, enhanced storage design, and reduction of human error.

*Public Safety*

The consequences of putting hydrogen into the hands of the public are more speculative but can be conjectured from historical experiences. Much like nuclear energy, the development of hydrogen as a fuel has been stifled by public perception. For example, in 1937, the airship *Hindenberg* caught fire from ignition of the hydrogen filled envelope. The resulting public reaction was a halt on using hydrogen as a lift gas for all U.S. air ships.[16] More recently, the safety of hydrogen fueled cars has been brought into question. While hydrogen provides better transportation range than EVs, it is unlikely that the public is willing to inherit the associated safety risks. Hydrogen vehicles must be heavily ventilated to avoid explosions in the case of leakage. Mishandling during the fueling process can cause cryogenic burns, odorless leakage, and invisible combustion with air.

Hydrogen storage systems require further development before being placed into the public's hands. Therefore, the most optimal uses of hydrogen are those focused in the industrial sector. As containment systems are better understood, further advancements in technology could prime hydrogen to be used in mobile sources in the long term. It is important to learn from past incidents and consider the thermodynamic limitations of hydrogen when designing infrastructure.

*Sustainability*

The greatest future value hydrogen provides is as a sustainable energy carrier. This is the case when hydrogen is derived from low or zero carbon sources such as SMR coupled CCS or renewable electrolysis. For this analysis, sustainability is defined as the following: meeting the current needs without jeopardizing the ability of future generations to meet their own needs.

Neither clause takes precedence, and both must be mutually obtained. Furthermore, sustainability is never absolute, but instead a relative measure to be gradually revised to meet society's demands. The end uses of hydrogen as a combustible fuel are clearly sustainable as no serious GHG emissions are released into the atmosphere. Choosing a sustainable method of production is at the heart of all hydrogen value chains. SMR produced blue hydrogen provides the highest sustainability index in the short and medium term while renewable electrolysis is the most sustainable in the long term.

One key component of a sustainable hydrogen value chain is the cost of production. A lower cost of production allows society's needs to be met more easily and reflects in a higher quality of life. Expensive production methods may stifle economies due to the higher costs of end use chemicals. SMR is the best option towards meeting current and future hydrogen demand without exorbitant costs. The finite availability of methane feedstock poses a threat to overall sustainability, but only in the long term as sources are expected to last well throughout the 21$^{st}$ century. Furthermore, the carbon capture and storage element of blue hydrogen offers the best short-term decarbonatization solution for hydrogen production. As governments gradually phase out carbon emissions and electrolysis technology progresses, blue hydrogen methods will become obsolete. Nonetheless, SMR and CCS technology holds great potential as a bridge technology as the world transitions from hydrocarbon-based energies to renewables.

**Recommendations**

The recommended hydrogen value chain will focus on SMR produced hydrogen coupled with carbon capture and storage. This will synergize best with large petrochemical hubs located near carbon sequestration sites such as the Gulf Coast region of North America. By leveraging the nearby shale gas resources, this value chain will provide a steady supply of low-carbon hydrogen throughout the short and medium terms.

Hydrogen production will incorporate cogeneration to provide all the necessary heat and electricity to run the process. Any excess electricity generated can be injected into the nearby grid, effectively functioning as low-carbon electricity. Hydrogen production will match the demand so that costly storage and transportation can be circumvented. Once immediate hydrogen demands are met, any excess hydrogen can be blended with fuel gas on site. Utilizing excess hydrogen for combustion to phase out hydrocarbons is a key element of this hydrogen value chain. It takes advantage of hydrogen's value as a clean burning fuel, while harnessing existing natural gas infrastructure.

Research into new hydrogen combustion technologies is essential to unlocking its potential as a sustainable fuel. Currently, gas fired turbines for commercial electricity generation can only take blends of about 5% hydrogen. If pure hydrogen fired turbines could be designed, then low-carbon electricity could be generated. Redesigning industrial furnaces with capability to take higher concentration hydrogen blends could prove pivotal in reducing emissions of the industrial sector.

**Conclusion**

The next 30 years will bring a radical shift in the hydrogen value chain as methods of production centralize around low-carbon and carbon-free sources. The difficulties of transportation and storage will continue to limit its use outside of production hubs. Hydrogen will persist as a feedstock component in chemical processes do to increased standards of living but will also gain traction as a low-carbon energy carrier as countries strive to meet emissions pledges.

Any hydrogen value chain is highly dependent a plethora of factors: location, feedstock availability, emissions taxes, and infrastructure. A holistic review of global hydrogen trends suggests blue hydrogen has the best prospects for supplying low-carbon, inexpensive hydrogen in the decades to come. Based on total energy efficiencies, synergies with existing infrastructure, and ability to leverage markets, SMR with CCS outperforms the alternatives. Although long term hydrogen demand will be met by non-fossil fuel sources as the world wanes its reliance on hydrocarbons, blue hydrogen's role as a bridge technology is nonetheless essential. As such, the next generation of engineers must strive to develop innovative hydrogen value chains around the world.

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