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# The Role of Hydrogen in the De-carbonization of the Energy Industry

## Major Impact or Niche Player?

Authored by the Gutierrez Energy Management Institute in collaboration with UH Energy

UH Energy White Paper Series: No. 01.2019

# White Paper Contributors

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Special thanks to Michelle Nnadi, GEMI Graduate Student Assistant , for her support.

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# EXECUTIVE SUMMARY

In April 2019, the Gutierrez Energy Management Institute (GEMI) in the Bauer College of Business at the University of Houston held a symposium and workshop on the potential role of hydrogen in the transition to a low carbon energy industry. The participants identified a number of insights including:

- Hydrogen's abundance and unique capabilities make it potentially a significant part of many segments in the low carbon energy future.
- Hydrogen has advantages over alternatives as a continuous low carbon electricity and heat source, an efficient long distance clean energy carrier, a large scale energy storage medium, and a range/weight-sensitive vehicle fuel among other applications.
- There are significant challenges that will affect the growth of hydrogen and its ultimate role including competitive disadvantages today versus electric vehicles in light duty applications, a requirement for significant new infrastructure investment, and the need for increased consumer awareness/acceptance.
- Key new or emerging investment opportunities include the capture and use of excess wind and solar electricity, low carbon hydrogen production and use via existing infrastructure, ammonia and liquid organic hydrogen carriers for long distance energy transport and storage, hydrogen-fueled fleets, and large scale hydrogen networks in USGC and North West Europe.
- One important area for the use of hydrogen would be for generation of industrial scale heating and electricity demand and the Gulf Coast would provide an excellent test bed for the implementation.

## BACKGROUND

*Abundance and Unique Capabilities - Why Hydrogen?*

"I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable." (Jules Verne 1874)[1]

Hydrogen is the most abundant element in the earth's biosphere as well as the universe. It is the smallest and lightest of all elements. Unfortunately, it is not found "free" in nature but is contained in compounds including water and chemical compounds, most notably hydrocarbons. Hydrogen's potential value in the low carbon economy is driven by three key characteristics. First, as a liquid it has a high specific energy content by weight (three times the energy density of gasoline) which makes it an efficient energy carrier (in parallel with electricity) and storage medium. Second, its combustion produces only heat and water. Third, it can be produced by electrical energy and visa-versa. The electrolysis process can produce hydrogen from water using electrical energy. Conversely, the fuel cell process can convert hydrogen and oxygen into electrical energy and water. Hydrogen use has been limited traditionally by a high cost of production, lack of distribution infrastructure with only 5000 miles of hydrogen pipelines being available globally, economically and technologically effective storage options and limited end uses outside of industrial applications. However, concerns around environmental sustainability and climate change have sparked interest in hydrogen as a clean and sustainable energy option.

*Current Productions and Uses*

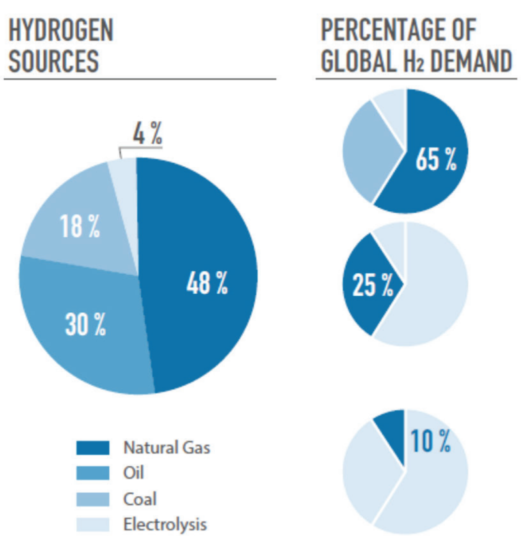
Current global production of hydrogen is approximately 70 million metric tons per year.[2] Almost all hydrogen is produced today from fossil fuels with about half derived from natural gas (Figure 1). In terms of demand, about 65% is used in the chemical industry, mainly to make ammonia and methanol. About 25% is used in the refining of crude oil into petroleum products. The remainder is used in a number of niche industry applications with very small volumes used in forklift fleets, where high uptime and indoor air quality are critical[3] and by the 11,000 global fuel cell vehicle fleet.[4]

*Potential Hydrogen Value Chain in a Low-Carbon World*

Hydrogen can potentially participate in nearly all segments of a low carbon energy value chain. In terms of energy supply, it can add to global energy supply through low-carbon production from fossil fuels. In the short term this involves adding carbon capture to existing natural gas steam methane reforming or coal gasification plants. In the longer term, zero-carbon hydrogen is likely to be available from water electrolysis. In terms of midstream

> "Hydrogen can potentially participate in nearly all segments of a low carbon energy value chain. In terms of energy supply, it can add to global energy supply through low-carbon production from fossil fuels."

**Figure 1: Hydrogen Sources and Uses**




| INDUSTRY SECTOR | KEY APPLICATIONS |
|---|---|
| CHEMICAL | • Ammonia<br>• Polymers<br>• Resins |
| REFINING | • Hydrocracking<br>• Hydrotreating |
| IRON & STEEL | • Annealing<br>• Blanketing gas<br>• Forming gas |
| GENERAL INDUSTRY | • Semiconductor<br>• Propellant fuel<br>• Glass production<br>• Hydrogenation of fats<br>• Cooling of generators |

Source: IRENA Hydrogen from Renewable Sources, September 2018.

segments, hydrogen can also provide energy transportation via hydrogen-derived energy carriers such as ammonia, methanol, and liquid organic hydrogen carriers such as cyclohexane, toluene, formic acid, and borates.[6] Hydrogen can also provide numerous forms of energy storage. A number of potential storage mechanisms are physically-based such as compressed and cryo-compressed gas as well as liquid storage including in nano-porous media.[7] In addition to tankage, hydrogen can be stored in salt caverns and potentially in other geologic formations.[8] One study in Holland estimated that one salt cavern could store 6,000 tons of hydrogen which would be equivalent to 17 million home-sized batteries (14 kWh).[9] Hydrogen can also be stored through material-based systems (including adsorbents, metal hydrides) as well as liquid organic hydrogen carriers.[10] Finally, there are potential hydrogen applications in nearly all end use segments. In transportation, fuel cell systems can potentially be used in specialized applications in automobiles, trucks, trains, shipping, and even small scale aviation. In addition, hydrogen can be combined with captured $CO^2$ to create drop-in liquid synthetic fuels for all transportation applications.[11] In the residential and commercial sector, hydrogen can be used as a source of heat and electricity for buildings. It can also be blended in existing natural gas systems (15-20%) to decarbonize the existing gas grid.[12] Industrial use of hydrogen could include high grade industrial heat for steel-making, cement and chemicals production (replacing fossil fuels).[13] Finally, it can be used to generate electricity from fuel cells at smaller scales and blended with natural gas in gas turbines today with potential for 100% hydrogen or ammonia gas turbines in the future for larger scale generation.[14]

## SYMPOSIUM FOCUS

In April 2019, the Gutierrez Energy Management Institute (GEMI) in the Bauer College of Business at the University of Houston held a symposium and workshop on the potential role of hydrogen given drivers to reduce carbon in energy and developments in hydrogen production, transportation and storage, and end use technologies.The purpose was to deepen understanding of these trends and identify the emerging challenges and opportunities for hydrogen in the energy transition. Participants included high-level executives from the oil, natural gas, renewable energy and power companies as well as representatives from UH colleges, industry research firms, investment banks, and non-profits.

Participants worked in small groups, under Chatham House rules, to exchange ideas and develop insights in a number of areas. Under Chatham House Rules, the free exchange of ideas is facilitated by an agreement not to reveal the names or affiliations of participants and not attribute any statements to individuals.

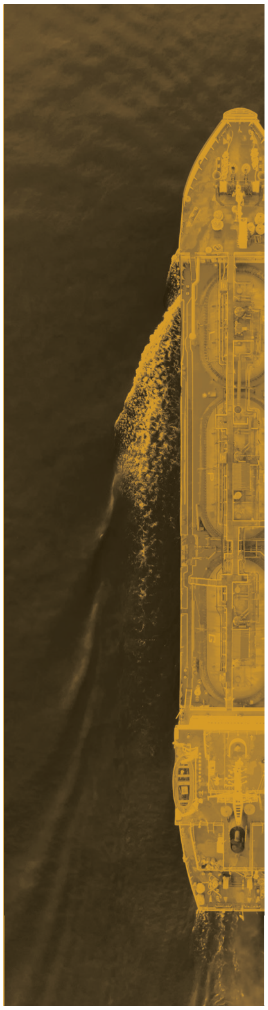
## POTENTIAL ADVANTAGES OF HYDROGEN IN A LOW CARBON WORLD

Hydrogen has advantages over alternatives in many applications in the energy value chain.

*Continuous, Low Carbon Electricity and Heat Source*
Wind and solar powered electricity is now cost competitive with alternative power generation methods and will likely form the backbone of a zero-carbon power sector. However, the intermittency and seasonality impacts on wind and solar electricity production and the difficulty in large scale electricity storage create challenges for deployment of wind and solar as a large component of the power generation mix. Hydrogen, produced from fossil fuels with carbon capture or from electrolysis, can be a source of continuous low carbon electricity, building heat, and industrial heat.

*Efficient Long Distance Clean Energy Carrier*
Currently, the top ten energy importing countries import about 2.5 billion tons of oil equivalent per year or nearly 20% of global energy production. The top ten exporting countries export a similar amount (Figure 2). Given that only one pair of the largest energy importing/exporting countries have common land borders (US and Canada), long distance transportation of significant amounts of energy will be required for the foreseeable future. Replacing current international trade (almost exclusively in oil, coal, and natural gas) with low carbon alternatives will require new energy carriers beyond electricity. Hydrogen and hydrogen-derived energy carriers could potentially fill much of this role efficiently.

*Dense, Large Scale Energy Storage Medium*
The current global energy system requires nearly 25% of global energy demand be held in storage



to cover in-transit, buffer, and seasonal storage needs.[15] Today, this is held in fossil fuels. With an increase of wind and solar energy in the energy portfolio, additional storage will be required to compensate for diurnal and seasonal impacts on renewable production. Hydrogen, with its high energy density and the various physical and material-based storage mechanisms, has significant advantages as a storage medium in a low carbon energy world.

*Range-Sensitive and Weight Sensitive (Heavy Duty/ Long Range) Transportation Fuel*
For light duty vehicles used in situations with limited range concerns, electric vehicles powered by renewable energy are likely to predominate in a low carbon world. However, for transportation of large payloads over long distances or where fast refueling is critical and centralized fueling is possible, hydrogen-fueled vehicles have significant advantages.

Hydrogen's high energy density versus batteries creates advantages in the trade-off of stored energy weight versus range in some transportation applications. There are specific characteristics of Heavy Duty Vehicles (HDVs) that align more appropriately with hydrogen-based technologies than alternatives, such as battery-electric technologies. First, power trains for HDVs require much larger bursts of power than light-duty vehicles; Battery Electric Vehicles (BEVs) struggle to compete on a power density basis. Fuel Cell Electric Vehicles (FCEVs), on the other hand, can combine high power and low emissions. On a specific energy (watt-hour per kilogram) basis, FCEVs provide nearly four times as much power per unit of mass. Simultaneously, in-vehicle hydrogen storage takes up one-half the space as a lithium-ion battery for a given range. This means that the energy density of a 10,000-psi hydrogen storage system combined with a fuel cell (about 400 watt-hours (wh) per liter) is about twice that of lithium-ion battery packs (about 200 wh per liter).[16] Fuel cell powertrains could gain significant market share in medium/heavy duty trucks, buses and trains.[17]

Shipping is potentially a significant opportunity for ammonia derived from low/zero carbon hydrogen. The Energy Transitions Commission (ETC) Illustrative Pathway to a Zero Carbon Economy has ammonia providing 60% of shipping energy consumption by 2050.[18]

*Low Carbon Industrial Fuel and Feedstock*
Fossil fuels have significant industrial uses that result in large GHG emissions today. These include steel, cement, ammonia, and hydrocarbon (ethylene and family of products) production. Decarbonizing these sectors is challenging as 45 percent of $CO_2$ emissions result from feedstocks cannot be abated by a change in fuels, only by changes to processes or carbon capture. Second,

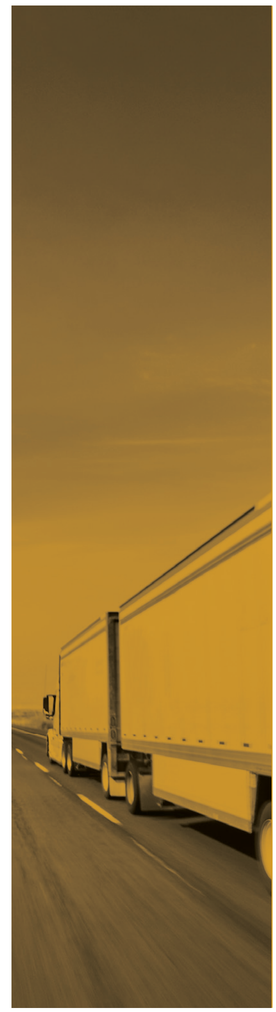


**Figure 2: Largest Energy Net Importers and Exporters**

| Net Importers | Million tonnes oil equivalent |
|---|---|
| China | 559 |
| Japan | 400 |
| India | 315 |
| USA | 265 |
| Korea | 247 |
| Germany | 205 |
| Italy | 121 |
| France | 118 |
| Turkey | 106 |
| Taiwan | 103 |
| | |
| Total | 2,439 |
| World Production | 13,764 |
| % of World Production | 18% |

| Net Exporters | Million tonnes oil equivalent |
|---|---|
| Russia | 624 |
| Saudi Arabia | 447 |
| Australia | 260 |
| Indonesia | 203 |
| Canada | 196 |
| Qatar | 181 |
| Norway | 180 |
| Iraq | 174 |
| Iran | 141 |
| Kuwait | 137 |
| | |
| Total | 2,543 |
| World Production | 13,764 |
| % of World Production | 18% |

Source: IEA Key World Statistics 2018 (data for 2016).

35 percent of emissions come from burning fossil fuels to generate high-temperature heat.[19] Hydrogen can potentially meet those challenges.

Global steel production produces 7% of global GHG emissions and 95% of primary steel production is produced in blast furnaces where $CO_2$ is an inevitable byproduct from using coke as a reducing medium. Steel is the one major industry where a change in process/feedstocks is possible. Several European steel companies are developing steel-making technologies based on the use of hydrogen as a reduction agent, with the hydrogen ($H_2$) being produced through electrolysis of water powered by renewable electricity. These initiatives use hydrogen direct reduction of iron ore combined with an electric arc furnace for further processing into steel. From an environmental standpoint, the most important advantage of this is that the exhaust from this process is water ($H_2O$) instead of $CO_2$, with a consequent reduction in GHG emissions.[20] Emissions from ammonia production, a smaller emitter (0.5% of global GHG emissions), could be significantly reduced by using zero carbon hydrogen as a feedstock.

Cement production generates 8% of global GHG emissions. Sixty percent of $CO_2$ emissions in cement manufacturing originate in the conversion of limestone to calcium oxide and would require changes in cement chemistry/materials or carbon capture to reduce emissions.[21] However, the remaining emissions could be reduced by using hydrogen as the kiln fuel. Similarly, high temperature heat requirements in ethylene production, the smallest of the four industry emitters of GHG, could be met by hydrogen.[22]

In an aggressive de-carbonization scenario, hydrogen could provide 50% of energy consumption in steel production, 30% of consumption in the cement industry, and 25% of chemical industry consumption by 2050.[23]

*Contributor to Captured $CO_2$ Utilization*

Hydrogen will be critical to many potential uses of captured carbon in the fuel and chemical industries. Hydrogen can be combined with captured $CO_2$ to produce basic chemicals like formic acid, methane (Sabatier reaction), methanol, and dimethyl ether (DME) with a positive impact on net GHG emissions according to recent studies.[24] Zero carbon synfuels, hydrocarbon liquid fuels can be produced from electrolysis-produced hydrogen and captured $CO_2$. This is most likely for aviation fuels. In the Energy Transition Commission's' zero carbon pathway, synfuels from all sources capture 30% of the aviation fuels market by 2050.[25]

## KEY CHALLENGES AFFECTING HYDROGEN'S ROLE

While hydrogen has many potential applications in a low carbon energy world, there are significant challenges and uncertainties that will affect the growth of hydrogen and its ultimate role. The symposium teams identified a number of challenges and three were prioritized based on highest potential impact.

*Competitive Disadvantages versus Electric Vehicles in Light Duty Applications*

Light duty hydrogen fueled vehicles (HVs) have significant hurdles to overcome to compete with BEVs. The first is the lack of hydrogen infrastructure versus the near universal availability of electricity infrastructure to homes and businesses. Second, the focus of automobile manufacturers on EVs and the resulting availability of different electric models, has given EVs a significant head start versus HVs in the marketplace. There are currently over twenty EV models available in the US and Europe today[26] versus only three HV models.[27] HVs are also significantly less energy efficient than EVs given current technology. Transport & Environment, a European organization that promotes a transport policy based on the principles of sustainable development, estimates that the current "well to wheels" efficiency of EVs is 73% versus only 22% for HVs.[28] Other estimates concluded current efficiency of 60% for EVs and 30% for HVs.[29]

*Requirement for Significant New Infrastructure Investment*

Significant infrastructure investment will be required for hydrogen to have a significant role in a low carbon energy future. The Hydrogen Council has developed an aggressive vision for 2050 that has hydrogen with an 18% share of total energy consumption which would provide 20% of the reduction in GHG required in the IEA's two-degrees Celsius scenario. This contribution would require annual investments of $20 to 25 billion for a total of about $280 billion until 2030. About 40% ($110 billion) of this investment

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would go into the production of hydrogen, about a third ($80 billion) into storage, transport, and distribution, and about a quarter ($70 billion) into product and series development and scale-up of manufacturing capacity. The remainder, some $20 billion, could go into new business models, such as fuel-cell-powered taxi fleets and car sharing, on-demand transportation of goods, and contracting of combined heat and power units. This compares to $1.7 trillion of global annual energy investment currently. By comparison, current renewable electricity spending is $300 billion. This would require a significant level of scale up of manufacturing capacities so as to achieve competitive costs and mass market acceptance.[30] According to Australia's Commonwealth Scientific and Industrial Research Organization, the authors of the National Hydrogen Roadmap, their analysis shows that the hydrogen value chain is now underpinned by a series of mature technologies that are technically ready but not yet commercially viable. This means that the narrative around hydrogen has now shifted from one of technology development to "market activation".[31]

*Need for Increased Consumer Awareness/Acceptance*
A significant role for hydrogen in the energy landscape will require increased public awareness of hydrogen. The most recent comprehensive research on public opinions was conducted by the University of Queensland in Australia in 2018. The main conclusions were:

- Most attitudes are neutral - In the survey, when Australians first heard the word hydrogen they were most likely (81%) to respond with a neutral response (e.g. gas, energy, water), with only 13% giving negative associations (e.g. bomb, explosion, Hindenburg) and 3% positive (e.g. clean, future).
- There is limited awareness of hydrogen properties and uses - The number of respondents who were aware of five of hydrogen's key properties ranged from 20% to 60%. Similarly, of six potential uses of hydrogen, awareness ranged from 35 to 60%.
- Most are supportive of hydrogen as a possible solution - The majority of participants (52%) were supportive of hydrogen as a possible solution for energy and environmental challenges with another 45% neither supportive nor unsupportive.
- Safety is the main concern - Safety, cost and environmental impacts, particularly concerns around pollution, emissions and water use, were the most frequently cited concerns about the production and use of hydrogen.[32]

More public awareness of hydrogen's benefits is needed to offset the public's greater familiarity with electricity and fossil fuels.

## KEY NEW/EMERGING INVESTMENT OPPORTUNITIES

The symposium groups identified a number of new or emerging investment opportunities with a growing role of hydrogen.

*Capture and Use of Excess Wind and Solar Electricity (Green Hydrogen)*
Combination electrolysis/fuel cell plants with hydrogen storage co-located near wind and solar power plants were viewed as a significant medium/long term opportunity. The groups viewed hydrogen as a key enabler to offset intermittency and seasonality of the two main renewable electricity sources. Investments in similar smaller-scale distributed facilities were also viewed as opportunities to supply micro-grids or provide back-up power for critical uses.

*Low Carbon (Blue) Hydrogen Using Existing Infrastructure*
Carbon capture added to existing and potentially new natural gas steam reforming plants was viewed as significant short/medium term opportunity to produce low carbon hydrogen. The hydrogen could, in limited proportions, be blended into the existing natural gas system or used in existing natural gas power plants to extend the life of that infrastructure. Ideal locations would be close to existing $CO_2$ use (enhanced oil recovery or chemical) or sequestration facilities.

*Ammonia and Liquid Organic Hydrogen Carriers for Long Distance Energy Transport and Storage*
The groups believed that the requirement for significant long distance transportation of clean energy between major importers and exporters results in a significant opportunity for transportation and storage systems using hydrogen-derived energy carriers. Clean ammonia can be produced from low or zero carbon hydrogen in the traditional Haber-Bosch process

"Carbon capture added to existing and potentially new natural gas steam reforming plants was viewed as significant short/medium term opportunity to produce low carbon hydrogen."

or potentially through a number of emerging electrochemical or membrane based synthesis methods. It can then can be transported via existing LPG/ammonia marine carriers and the hydrogen recovered at the point of end use via ammonia cracking. Liquid organic hydrogen carriers are organic liquids that can be loaded with hydrogen, and subsequently dehydrogenated via the application of heat or catalysis. This enables the storage and transport of hydrogen as a liquid at ambient temperature and pressure. After dehydrogenation, the organic liquid can be re-used. Toluene is one such carrier that is being explored for large scale hydrogen storage and transport using established pathways that convert toluene to methylcyclohexane (MCH) or dibenzyltoluene (DBT) for transportation and then conversion back to toluene, releasing the hydrogen in the dehydrogenation process.[33] Hydrogen derived energy carriers also provide potential for large scale, long term storage of hydrogen.

*Hydrogen Fueled Fleets*
Return-to-base vehicle fleets such as local delivery vehicles, taxis, or passenger cars in a future car-sharing economy have high utilization and benefit from central depots with fast refueling. The requirement for less infrastructure and rapid refueling could enable distribution costs for these fleets to fall more rapidly than in the passenger FCEV sector.[34]

*Large Scale Hydrogen Networks and Use in USGC and North West Europe*
There are large existing hydrogen pipeline networks in the industrial areas of the US Gulf Coast (USGC) (2600 km) and Northwest Europe (NWE) (Belgium, Germany, France and Netherlands-1200 km).[35] Today these connect hydrogen producers with petroleum refiners (for desulfurization and hydrocracking) and chemical producers (mainly ammonia and methanol). In the future, hydrogen can provide clean high temperature process heat for these and other industries. Since the USGC and NWE industrial areas are located in/near large urban areas, they would also be natural sites to build out hydrogen distribution and storage for early adopters. These could include hydrogen vehicle fleet fueling that was mentioned previously as well as storage and associated fuel cell/turbine power generation facilities.

## CONCLUSION

Hydrogen has a potentially significant role the low carbon energy future although there is significant uncertainty in the ultimate level of penetration in many applications. There are many new opportunities in the short to medium term as well as long term for investment in different aspects of the future hydrogen value chain.

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# About UH Energy + GEMI

## UH ENERGY

UH Energy is an umbrella for efforts across the University of Houston to position the university as a strategic partner to the energy industry by producing trained workforce, strategic and technical leadership, research and development for needed innovations and new technologies.

That's why UH is the Energy University.

## GUTIERREZ ENERGY MANAGEMENT INSTITUTE

The Gutierrez Energy Management Institute (GEMI) is responsible for the energy education program in the Bauer College of Business at the University of Houston. Our scope includes energy-focused degree and certificate programs for undergraduate and graduate students and energy professionals. We develop student employment, internship and consulting project opportunities in the energy industry. We also conduct research and host events to bring industry executives, faculty and students together to address industry issues.

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