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Beyond Ammonia: Rethinking The Role For Ammonia Within A Vibrant Hydrogen Economy

Abstract

As the world increasingly seeks sustainable and efficient energy solutions, there is a general consensus that hydrogen will play a significant role, making the question of how this product is best transported not just a technical issue, but also one with profound environmental, economic, and geopolitical implications. A growing number of policymakers and ammonia industry proponents have recently begun to champion ammonia (NH_3) as the best way to transport hydrogen and as a viable alternative to pure hydrogen for various applications, including as a fuel for the maritime industry, an energy storage medium, and feedstock for electricity generation. This perspective touts the potential of “green ammonia” – ammonia produced from hydrogen (H_2) derived from renewable sources like wind, solar or hydropower – as a more practical and economically viable solution than pure hydrogen. This white paper examines this narrative, showing how it arises from two sources. First, from a limited perspective on the emerging opportunities provided by hydrogen; and second, from a lack of awareness of recent advances in transport technologies for both gaseous and liquid hydrogen. Based on an in-depth exploration into the production, storage, utilization, safety, and economic aspects of both hydrogen and ammonia, we show that pure, unadulterated hydrogen is a superior option in all cases except for the indispensable role green ammonia will play as a primary component in fertilizer production and within several niche markets currently served by ammonia derived from non-renewable sources.

Introduction

The global energy landscape is currently undergoing a transformative shift in response to the challenges posed by global warming. For reasons described herein, the success of this shift relies in substantial part on the development of a thriving green hydrogen economy. While electricity produced from renewable sources certainly plays a leading role, hydrogen is also essential to the success of this transition because there exists no other renewable, non-toxic, and carbon-free fuel that can store energy as a chemical battery, generate electricity within both fuel cell and combustion-based systems, sustain ‘hard to abate’ industries such as the production of cement and steel, and enable zero or near-zero emissions in aviation and long-haul trucking.

Green hydrogen, when produced in regions where renewable energy is abundant and inexpensive, presently stands as an economically attractive alternative to fossil fuel. However, these regions are commonly located far from the markets where large quantities of hydrogen is needed. And while additional technological improvements and economies of scale are forecast that will reduce hydrogen production costs even more over the coming decades, there is growing awareness that for hydrogen to be economically competitive, addressing the challenges and high cost associated with hydrogen transport and distribution is essential.

Hydrogen's intrinsic attributes present formidable transport challenges. It has an exceptionally low energy density, effectively making the transport of large quantities of gaseous hydrogen by truck, rail, or ship impractical and far too costly. Compression and liquefaction, while able to boost density, demand additional energy input, thereby requiring complex energy balance considerations to assess whether hydrogen delivery relying on these additional steps represents a viable substitute for fossil fuel products. Moreover, cryogenic storage and transport necessitates maintaining hydrogen at a staggering -253°C (-423°F), merely a few degrees above absolute zero.

In response to these formidable hurdles, attention has turned to the prospect of using "green ammonia" as a green hydrogen carrier notwithstanding ammonia's extreme toxicity. Although hydrogen contains about six times more energy by weight, has a faster rate of combustion, and a higher level of heat generation, ammonia is over 30 times denser than gaseous hydrogen and 8.5 times more dense than liquid hydrogen, making it easier to handle, transport, and store.[1]

Because ammonia is carbon-free, has a higher hydrogen content (17.8% by weight) than other fuels, and has a narrow flammability limit, it is generally considered to be the most popular substance as a green hydrogen carrier. Converting pure hydrogen into ammonia necessitates comparable energy inputs as hydrogen liquefaction, yet it brings intriguing advantages. Ammonia transitions to a liquid state at -33.34°C (-28.01°F) at standard pressure, and it can be stored at 25°C (77°F) rendering it far more manageable than pure hydrogen. Whereas new technologies still must be developed for long distance transport of cryogenic hydrogen, significant experience already exists regarding ammonia storage and distribution. Notwithstanding the additional safety protocols necessitated by ammonia's extreme toxicity, proponents argue that green ammonia presents a practical and economically superior solution to our evolving energy needs.

Some proponents envision ammonia's utility not only as an energy carrier, but also as fuel source in combustion engines and certain types of fuel cell applications. Like hydrogen, they argue that ammonia has no carbon dioxide (CO_2) footprint when burned, although it does result in nitrous oxide (NO_X) emissions that require use of NO_X scrubbing technology. Recently, several major companies within the maritime sector have announced plans to utilize ammonia as a propulsion fuel for newly commissioned ships in conjunction with transporting ammonia by sea.[2]

This paper argues that the current enthusiasm for ammonia as a hydrogen carrier stems from a limited awareness of new technologies designed for hydrogen transport and distribution. The economics and reliability of today's fossil fuel economy relies on an exceptionally efficient network of specialized tankers and port facilities, dedicated pipelines, and trucks. These midstream

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[1] Yousefi Rizi, Hossein Ali, and Donghoon Shin. 2022. "Green Hydrogen Production Technologies from Ammonia Cracking," Energies 15, No. 21: 8246. https://doi.org/10.3390/en15218246

[2] Juliane von Wirén, "*Maersk Tankers to pioneer transportation of clean ammonia*," Maersk Tankers Press Release: November 30, 2023. https://bit.ly/48f0b0L

technologies evolved as the demand for petroleum products surged, and the initially acceptable technical approaches inevitably gave way to much more efficient technologies as the industry expanded. Likewise, the planned escalation of hydrogen production and increasing demand for green hydrogen from end users underscores the need for disruptive transportation innovations in pipeline technology and specially configured vehicles to address the unique requirements associated with hydrogen.

In this regard, we discuss the H2 Clipper airship, which is specially designed for long-distance and trans-oceanic transport of low-cost liquid hydrogen.[3] This innovation enables realization of the full disruptive value of hydrogen and is just one example of the seismic shifts underway in humanity's pursuit of a sustainable energy future. As new technologies continue to be developed, the technological and economic superiority of liquid hydrogen over green ammonia will cause the public to refocus on ammonia's essential, historical role in fertilizer production, and meeting the growing global demand for food and food stocks.

Comparing Hydrogen, Ammonia and Other Fuels

The table below provides a comparison of the properties of gaseous and cryogenic hydrogen with ammonia, natural gas, LNG, and other hydrocarbon fuels.[4] Hydrogen holds a considerable advantage when evaluating its heating value (LHV) per unit weight. However, as noted above, its difficulties in transport and distribution arise from hydrogen's extremely low density in gaseous form and thus, the volume necessary to convey an equivalent amount of energy.

	Gaseous H_2	**Liquid H_2**	**Natural Gas**	**LNG**	**Ammonia**	**Propane**	**Gasoline**	**Methanol**
Formula	H_2	H_2	CH_4	CH_4	NH_3	C_3H_8	C_8H_{18}	CH_3OH
Characteristics:								
Form	Compressed Gas	Cryogenic Liquid	Compressed Gas	Cryogenic Liquid	Liquid	Liquid	Liquid	Liquid
Density (kg/m^3)	17.5	71.1	187.2	450	602.8	492.6	698.3	786.3
LHV (MJ/kg)	120.1	120.1	38.1	38.1	18.8	45.8	42.5	19.7
LHV (MJ/liter)	2.1	8.5	7.1	20.3	11.3	22.6	29.7	15.5
Fuel required to match 10 gallons of gasoline:								
Weight (kg)	9.4	9.4	29.5	29.5	59.8	24.5	26.4	57.0
Volume (liters)	534.4	131.5	157.5	55.5	99.2	49.8	37.9	72.5

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[3] In its role as a think tank and action incubator and in service of its mission to combat climate change and expand corporate consciousness, the World Business Academy incubated the predecessor to H2 Clipper, Inc. between 2008 and 2011, when the private corporation was formed. H2 Clipper is now an independent, Delaware corporation.

[4] *Ibid.*, Yousefi Rizi, et.al. (Table 2, citing references).

Hydrogen is Essential to Reverse Global Warming

The global quest to reverse the perilous course of climate change hinges on the development of sustainable, low-carbon energy solutions. Amid this pursuit, hydrogen, the most abundant element in the universe, has emerged as an essential component. It possesses inherent qualities that make it indispensable in the battle against global warming.

1. Zero-Emissions Energy Production

At the core of hydrogen's value is its capacity to produce energy without generating harmful emissions. When hydrogen reacts with oxygen in Proton Exchange Membrane (PEM) fuel cells, the result is the production of heat and energy with pure water as the only by-product. The fact that this process results in absolutely zero carbon dioxide (CO_2) or nitrous oxide (NO_X) emissions, aligns perfectly with the imperative to decarbonize planetary energy systems.

2. Electrification of Everything

The concept of electrifying all facets of our lives forms the core of any strategy for mitigating climate change. However, some industries such as steel, cement, aviation, and long-distance trucking pose unique challenges for grid-based or battery-electric power. In these cases, hydrogen provides an important solution. It can be harnessed through fuel cells to produce electricity for power, or, alternatively, combusted to generate the extreme temperatures required for cement production and steel manufacturing. Hydrogen's adaptability positions it as a key player in electrifying these ‘hard-to-abate’ sectors.

3. Efficient Energy Storage

As we increasingly harness energy from intermittent clean sources like solar and wind, the need grows for efficient, low cost, and immediately dispatchable energy storage solutions. Hydrogen uniquely provides such a solution. Hydrogen provides long-term storage of energy, in effect representing a lower cost and longer-duration chemical battery. When energy demand surges or renewables wane, hydrogen can be reconverted into electricity either through fuel cells or hydrogen fueled turbines. This capability enhances grid stability and reduces the reliance on fossil fuels during periods of peak demand.

4. A Global Commitment

The significance of hydrogen in the fight against climate change is underscored by its inclusion in major legislative and policy initiatives worldwide – literally from Africa to Australia, Ireland to India, South America to the South Pacific, and the EU to the US. The U.S. government's *Infrastructure Investment and Jobs Act* (2021) and subsequent *Inflation Reduction Act* (2022) allocate substantial funding and tax incentives to advance the hydrogen economy. In response to global energy security concerns, the European Union has prioritized hydrogen in its *REPowerEU* plan and in designating Hy2Tech and Hy2Use initiatives as Important Projects of Common European Interest

(IPCEI). Other nations and multinational corporations are also making substantial investments in hydrogen, reinforcing its pivotal role in a sustainable future.

5. Abundance and Universality

Hydrogen is abundant, comprising approximately 73 percent of the universe's mass. Sixty percent of the atoms in the human body are hydrogen atoms. Positioned at the top of the Periodic Table as the first element, hydrogen is the smallest and lightest atom, making it highly reactive with other elements. While hydrogen primarily exists in bonded form on Earth, recent discoveries of underground reserves of "white" or "gold" hydrogen in northeastern France have added to the potential of even lower cost naturally occurring sources. However, liberating hydrogen from compounds, even from water, currently requires energy. An estimated 70% of the cost of producing a kilogram of hydrogen is the cost of electricity. This is why hydrogen production facilities are strategically placed in or near regions with abundant and therefore low-cost renewable energy sources.[5]

6. The Dawn of "Green Hydrogen"

Historically, hydrogen has been produced primarily through "steam reformation" of natural gas, which releases carbon dioxide (CO_2) and thus the label "gray hydrogen" (or "blue hydrogen" if this carbon is captured at the source). The emergence of "green hydrogen" represents a pivotal shift. Green hydrogen is generated through electrolysis, where an electrical current derived from renewable sources is used to split water into hydrogen and oxygen. The result is a 100% renewable, carbon-free energy carrier. The recent plummeting costs of renewable energy collection and electrolyzer technologies are making green hydrogen competitive, with prices currently around $8 per kilogram (before transportation and distribution costs), and estimated to drop even lower by 2030 as economies of scale are realized in large-size production facilities. This makes green hydrogen a compelling alternative to fossil fuels, with numerous green hydrogen plants poised to enter the market from Canada, Morocco, Scotland, Spain, Chile, Saudi Arabia, the UAE, the USA and 20+ other locations.

7. The Dawn of "Green "Ammonia"

The advent of green hydrogen has also opened the door to the era of "green ammonia." Whereas ammonia production traditionally has been associated with significant carbon emissions due to its reliance on hydrogen derived from fossil fuels, the availability of low-cost, green hydrogen from

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[5] International Renewable Energy Agency (IRENA), "*Renewable Power Generation Costs in 2022*," August 2023, pages 83, 108, 112, and 132. *https://bit.ly/3NpHEqS* (As of 2022, the average global weighted average levelized cost of electricity (LCOE) of utility-scale PV plants is $0.049/kWh ($0.026/kWh in the United Arab Emirates, $0.036/kWh in Saudi Arabia). The global weighted average LCOE of onshore wind was $0.033/kWh; and offshore wind was $0.081/kWh. Like solar energy, specific regions, achieve even lower costs. To ensure the competitiveness of green hydrogen against fossil fuels, hydrogen production must occur in regions with the lowest renewable electricity cost. However, as these examples illustrate, these regions are often considerably far away from major population centers and consumer markets, necessitating long-distance transportation to facilitate the transition to a green hydrogen economy.

renewable sources enables emission-free ammonia production. The implications of green ammonia extend across multiple sectors. Agriculture, where ammonia serves as a vital component in fertilizer production, stands to benefit significantly. By transitioning to green ammonia, the agriculture industry can reduce its carbon footprint, contributing to more sustainable and environmentally responsible food production.

Because of the eternal power of the sun and the abundance of hydrogen, human civilization will never run out of sustainable, non-polluting energy. “Hydrogen could prove to be the missing link to a climate-safe energy future […] with green hydrogen emerging as a game changer for achieving climate neutrality without compromising industrial growth and social development,” says Francesco La Camera, Director-General of the International Renewable Energy Agency.[6]

As we navigate the complexities of combating global warming, these attributes, coupled with emerging technologies and a growing global commitment, position hydrogen as a linchpin in our pursuit of a sustainable, carbon-free energy future. In the following sections, we delve deeper into the nuances of hydrogen's potential and examine why green ammonia, although valuable in specific applications, is not the best option as an energy carrier and/or alternative to pure hydrogen in our battle against climate change.

Hydrogen Transportation Challenges

While hydrogen holds immense promise for energy storage and as a clean energy carrier, its widespread adoption faces significant challenges in the realm of transportation. The efficient and safe transport of hydrogen over long distances from where renewable energy costs are lowest, as well as the efficient and safe distribution of hydrogen from storage facilities to end-users, whether they be industrial plants, fueling stations, or other applications, is a critical aspect of realizing these benefits. This section delves into the complexities and obstacles associated with hydrogen transportation. The major challenges are:

1. Energy Density and Volume

One of the primary challenges of transporting hydrogen is its low energy density in gaseous form. As shown in the foregoing table, gaseous hydrogen is incredibly light, and as a result, it occupies a relatively large volume compared to other fuels like natural gas and gasoline. To overcome this challenge, hydrogen is often compressed or liquefied,[7] which reduces its volume for transport

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[6] International Renewable Energy Agency (IRENA), “*Hydrogen Economy Hints at New Global Power Dynamics*,” IRENA Press Release: January 15, 2022. *https://bit.ly/41kqeS5*

[7] Natural gas has obviously adopted a similar approach for long-distance transport. But while liquefied natural gas (LNG) has been transported globally since the 1960s, liquefied hydrogen presents a distinct challenge due to its requirement for cryogenic temperatures of –253°C, significantly lower than the –161.5°C needed for LNG.

and storage. However, these processes require additional energy, and the need for high-pressure or cryogenic storage systems makes transportation infrastructure more complex and costly.

2. Transport Modes

Hydrogen can be transported by various modes, including pipelines, trucks, ships, and even airships, each with its unique set of challenges. Pipelines are the most efficient, but require right of way acquisition, substantial infrastructure development, a higher initial investment, and as Matthieu Landon of President Macron's Private Office has observed, once a pipeline terminus is constructed, it can't be moved to adjust for changing distribution requirements over time.[8] As natural gas pipes have shown, pipelines are also notorious for leaking; and as the world's smallest molecule, hydrogen will inevitably leak more than methane. Steel pipes are subject to corrosion and hydrogen embrittlement issues; and pipes made with plastic polymers have higher permeation rates. Gaseous hydrogen storage and transportation in trucks is exceedingly expensive and faces safety concerns, especially when dealing with high-pressure hydrogen. Ships are a viable option for long-distance transport, but handling cryogenic liquid hydrogen comes with its own challenges such as boil-off during long voyages across warm ocean waters.

3. Safety Considerations

Safety is a paramount concern in all energy discussions. As noted above, ammonia is highly toxic to the point numerous shipping lines refuse to carry it, and "spills" can send people to the hospital or even kill them. On the other hand, hydrogen is highly flammable, and its properties can pose risks in the event of leaks or accidents. Ensuring the safe containment, handling, and transport of hydrogen is a crucial aspect of any hydrogen distribution system. Implementing robust safety protocols, leak containment and detection systems, and emergency response plans are essential to mitigate these potential risks.

4. Infrastructure Development

Building the necessary infrastructure for hydrogen transportation is a considerable undertaking. The development of pipelines, storage facilities, fueling stations, and distribution networks requires significant investment and planning. Coordinating the expansion of this infrastructure with the growth of hydrogen production facilities and off-takers represents a "chicken and egg" challenge that is essential to creating a seamless supply chain.[9]

5. Energy Efficiency and Losses

During transportation and distribution, energy losses can occur, affecting the overall efficiency of the hydrogen supply chain. Compression, liquefaction, and transportation processes can lead to

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[8] M. Landon is Industry, Research and Innovation Adviser, Private conversation (2021).

[9] Gniewomir Flis and Matthias Deutsch, "*12 Insights on Hydrogen*", Agora Energiewende: January 2022, page 15. *https://bit.ly/3RDVDvx* "The issue boils down to a lack of hydrogen infrastructure for connecting and balancing supply and demand and an underlying failure to integrate industry mapping and energy infrastructure planning."

energy losses, reducing the net energy benefits of hydrogen. Minimizing such losses through technological advancements and optimized logistics is therefore crucial.

6. Geographic Challenges

Hydrogen's promise lies in its ability to transport renewable energy from areas with abundant renewable resources to regions with high energy demand. However, this necessitates the development of an efficient, long-distance transportation infrastructure,[10] which can be geographically challenging. Crossing varied terrains, traversing large bodies of water, and ensuring reliability over extended distances are formidable tasks that require innovative solutions.

7. Cryogenic Transportation Challenges

Transporting liquid hydrogen via ships necessitates extremely heavy storage tanks and massive supplemental cooling systems capable of holding hydrogen at –253 °C (-423°F) for weeks at a time. If this is not done, the volume of liquid hydrogen will inevitably "boil off" during transit, thereby making the voyage uneconomic, as demonstrated by the maiden voyage of Kawasaki Heavy Industry's *Suiso Frontier* ship in January 2023, which lost 37% of its cargo due to boil-off. A recent study calculated that transporting 160 tonnes of liquid hydrogen from Qatar to Japan by ship would result in a loss of 13.77%, or 22 tonnes of hydrogen. In addition to the economic loss this represents, several prominent environmental groups have raised significant concerns about leakage of hydrogen into the atmosphere.

8. Terminal Facility Requirements

Beyond the substantial onboard infrastructure needed to transport hydrogen at cryogenic temperatures, even more extensive facilities are required at terminal sites. These facilities must not only accommodate the volume of liquid hydrogen to be off-loaded during each delivery, but they also must store a sufficient quantity of hydrogen for periods of a month or longer between individual shipments. This presents a considerable challenge, entailing significant investments to construct these highly specialized storage facilities, as well as substantial expenditures related to electricity and land acquisition. Moreover, when ships are used, these facilities must be situated at ports, which are already among the world's most congested and costly real estate due to the demands of routine shipping operations.

9. Economic Viability and Existing Infrastructure

Such terminal facilities for hydrogen distribution need to be built almost from scratch, and will

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[10] *Id.*, page 39. Noting that transporting hydrogen over long distances from regions such as Chile or Australia will be more costly than producing it locally using local renewable energy resources in Germany. Also noting that green hydrogen produced with electricity costs based on Germany's domestic renewable electricity production cost will not compete favorably with fossil fuels, the unavoidable conclusion is that for hydrogen to compete favorably with fossil fuel requires a more efficient means of transport to open markets with very low renewable energy costs per kWh.

require considerable scale-up versus today's largest such facilities. Presently, the world's largest cryogenic hydrogen storage tank, which is dedicated to storing hydrogen for rocket launches, is located at NASA's Kennedy Space Center in Florida.[11] Commercial bunkering facilities for cryogenic hydrogen are limited. Operating commercial service for extended durations while maintaining extremely low temperatures poses both logistical and cost challenges.[12]

Hydrogen distribution over short distances with trucks is already part of the clean energy infrastructure today, with estimated costs at $1.20/kg per 300 km.[13] Long-term, pipelines provide an economical distribution system, such as the European Hydrogen Backbone (EHB), a network of existing and new hydrogen pipelines in the European Union.[14] Hydrogen pipelines can transport ten times the energy at one-eighth the cost associated with long-distance electricity transmission and serve a dual purpose by distributing and storing energy. However, pipelines do not represent a feasible solution to cross thousands of kilometers of open ocean.

Addressing these complexities is crucial to realizing the full potential of hydrogen as a clean energy carrier and combating global warming effectively. Innovative technologies, infrastructure development, and international collaboration surrounding promising alternatives are essential to establishing a robust and efficient hydrogen transportation network. In the subsequent sections, we delve into emerging solutions and advancements that promise to overcome these hurdles and drive the hydrogen economy forward.

The Case for Ammonia

Ammonia is an inorganic chemical compound comprised of nitrogen and hydrogen with the formula NH_3. Its historical significance dates to ancient times when farmers recognized its value as a fertilizer. Before the advent of modern synthesis methods in the early 1900's, ammonia was

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[11] This tank has a volume of 3,800 cubic meters and has been in operation since the 1960's. NASA is presently constructing a larger stationary tank, with a volume of almost 5,700 cubic meters, and which when commissioned will be the world's largest cryogenic hydrogen storage tank.

[12] Currently, there are only two small bunkering facilities for cryogenic hydrogen globally, situated in the ports of Hastings, Australia, and Kobe, Japan. These facilities were constructed to support Kawasaki's Suiso Frontier ship. For commercial operations, cryogenic tanks will need to store quantities of liquid hydrogen as much as 40 times larger than NASA's newest tank, necessitating substantial electricity expenses to maintain the required low temperatures through pressure and cooling mechanisms. Establishing storage facilities this size poses substantial technical issues, high costs, and land availability issues, especially at densely crowded ports.

[13] The Hydrogen Council and McKinsey, *"Hydrogen Insights Report"* (2021).

[14] A group of 33 energy infrastructure operators is actively developing the EHB, aiming to establish a network of hydrogen pipelines. This initiative involves an estimated investment range of €80-143 billion and proposes to construct a 53,000 km hydrogen pipeline network by 2040. Sponsors estimate that of this network, 60% will consist of retrofitted pipelines, and 40% will be new pipeline sections. According to assessments by the Hydrogen Council and McKinsey, the distribution cost for hydrogen gas through onshore retrofitted pipelines is projected to be $0.13/kg/1000 km, while new pipelines are expected to incur a cost of $0.23/kg/1000 km. Offshore pipelines are estimated to be 1.3 to 2.3 times more costly. For further details, visit the EHB website at *https://ehb.eu/*.

primarily sourced from niter deposits and guano on tropical islands. However, as demand grew, these natural reserves became insufficient to meet the world's needs. This scarcity drove scientific exploration into new avenues for ammonia production.

In a significant breakthrough, German chemists Fritz Haber and Carl Bosch developed the 'Haber–Bosch' process. This technology converts atmospheric nitrogen (N_2) into ammonia (NH_3) by a reaction with hydrogen (H_2) using a metal catalyst under high temperature and pressure. This innovation revolutionized ammonia production and allowed it to become a key global commodity.

Today, ammonia plays an important role in various industries worldwide. In 2021, global production of ammonia surpassed 235 million tonnes, approximately 70% of which was used to produce fertilizers, while the balance served as a raw material in the chemical and pharmaceutical industries, mining, textiles, plastics, refrigeration, and in diluted forms, for cleaning products.

As a result, ammonia has a well-established global infrastructure encompassing production, distribution, and storage. Approximately 20 million tonnes of ammonia are traded annually, with more than 80% of this volume being transported by ships to 130 ports worldwide. Due to its attributes, remaining liquid at ambient temperature under its own vapor pressure and having high volumetric and gravimetric energy density, ammonia has gained attention as a potential organic carrier for hydrogen. Proponents suggest that it could offer advantages in terms of known handling techniques and reduced costs compared to transport of liquid hydrogen.

The maritime industry has also recognized the potential of ammonia. In November 2023, Maersk Shipping Lines announced plans to build a fleet of ammonia propelled, ammonia cargo carrying vessels;[15] and Fortescue, one of the leading voices in the green revolution, has announced that it "will use green ammonia to decarbonize [the] company's mining and shipping fleet."[16] However, as Fortescue Executive Chairman, Andrew Forrest, recently noted, "At the moment the regulatory landscape does not allow for ammonia ships to operate."[17] Moreover, according to Wood Makenzie, it's important to note that despite these efforts, it will take decades for such shipbuilding commitments to meet a fraction of the burgeoning demand for green ammonia as a fertilizer, let alone as a source for green hydrogen once at the destination.[18]

Limitations and Disadvantages of Ammonia

While ammonia has important applications in various industries, it is essential to consider its

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[15] Maersk Release, "*Maersk Tankers to pioneer transportation of clean ammonia*," Nov 30, 2023. https://bit.ly/48f0b0L

[16] Fortescue Website, "*Green Ammonia*," Accessed Dec 12, 2023. https://bit.ly/3v5NR4H

[17] Fortescue Release, "*Fortescue's Green Pioneer arrives in Dubai for COP28*," Dec 2, 2023. https://bit.ly/4agdsYX

[18] Mariana Moreira, Murray Douglas, and Alexander Elliott, "*Avoiding pand-ammonia: How to kick-start a global low-carbon ammonia industry*," Wood Mackenzie, November 2022. https://bit.ly/3NnJ6de

limitations and disadvantages as a potential means for transporting hydrogen and/or replacement for pure hydrogen. These factors play a pivotal role in assessing the feasibility and suitability of ammonia as an organic hydrogen carrier and clean energy alternative to pure, unadulterated hydrogen.

1. Toxicity and Safety Risks

Ammonia is a highly toxic and corrosive substance. While proponents argue that protocols for safe handling are in place, recent incidents underscore the potential dangers. In October 2023, a truck carrying ammonia overturned in Illinois, resulting in five fatalities, including two children, and forcing hundreds of residents to evacuate their homes. A similar incident occurred in January 2020, when nearly 800 gallons of liquid ammonia fertilizer spilled in Illinois, resulting in over 80 people being hospitalized with various health issues.[19] These events emphasize the safety risks associated with ammonia transport and its potential impact on communities. Considering ammonia as an energy carrier raises questions about whether expanding its production and exposing more areas to such toxicity risks are justified, especially to the extent safer alternatives are available.

2. Environmental Concerns

Ammonia usage in industrial processes contributes to environmental risks, particularly concerning NO_X emissions. Nitrogen oxides (NO_X) are hazardous, carcinogenic air pollutants that contribute to air pollution and smog formation. The widespread concern about NO_X emissions led to the introduction of catalytic converters in vehicles to mitigate these pollutants. If introduced as a replacement for natural gas or coal, ammonia would introduce similar environmental challenges from NO_X emissions produced when burned. In contrast, hydrogen provides a cleaner alternative for any applications in which combustion is required, *emitting virtually no* NO_X, and aligning better with efforts to reduce air pollution and enhance air quality.

3. Complex Hydrogen Conversion

Advocates of ammonia sometimes suggest its use in fuel cells. However, use of ammonia in fuel cells is very limited due to the tendency of ammonia to severely deteriorate PEM stack cell structures, and thus the only fuel cells in which ammonia is an acceptable fuel are solid-oxide fuel cells (SOFC) and "alkaline process" fuel cells, both of which are predominantly large and have serious drawbacks (*e.g.*, SOFCs can't ramp up and down efficiently, alkaline requires a very large building, etcetra). As indicated above, ammonia presents challenges concerning NO_X emissions when replacing natural gas or coal in various applications. These emissions are harmful, as evidenced by requiring catalytic converters in vehicles to combat smog. In contrast, hydrogen,

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[19] Associated Press, "*A truck crash in Illinois kills 5 and forces temporary evacuation over ammonia leak*," National Public Radio, October 1, 2023. [*https://n.pr/3v1L3px*](https://n.pr/3v1L3px)

particularly when utilized with Proton Exchange Membrane (PEM) stack fuel cells, produces zero emissions except for pure water vapor.

While most policymakers and corporate leaders acknowledge hydrogen's status as the ultimate renewable, clean energy fuel, many argue that ammonia can play a pivotal role in accelerating the critical decarbonization of the economy to combat global warming. However, it's worth noting that ammonia's use as a hydrogen carrier is frequently overstated because a fundamental technological limitation exists in converting ammonia back into a sufficiently pure level of hydrogen for use in PEM stack fuel cells. Such conversion to the requisite 99.7% or greater purity is currently not economically nor technically feasible for commercial use, despite extensive efforts and investment. Moreover, *even if* such a process were to be developed in the future, the associated costs are likely to be prohibitively high.[20] This complexity underscores the challenges of using ammonia for hydrogen transport compared to the direct use of hydrogen in efficient fuel cells.

4. Multiple Cost Cycles

Utilizing ammonia as an intermediary for hydrogen introduces three cost cycles. First, there's the cost of producing hydrogen, followed by the cost of converting it into ammonia. And then, additional costs must be incurred in attempting to "crack" the ammonia back into hydrogen, a process that remains scientifically challenging and, as yet, is not possible to produce the purity required for PEM stack use. This redundancy in cost cycles raises questions about the economic viability of ammonia as an energy carrier versus incurring the single cost of liquefaction and keeping hydrogen unadulterated from source to end-user.

5. Emissions Mitigation and Environmental Impact

The combustion of ammonia as a fuel source generates emissions, including nitrous oxides (NO_X) and nitrogen dioxide. These emissions contribute to air pollution, smog, and acid rain. While catalytic converters can mitigate these emissions, implementing them on an industrial scale adds further costs. The introduction of such emissions in the context of a transitioning energy landscape inherently conflicts with the broader goals of reducing greenhouse gas emissions and environmental harm.

As Hydrogen Europe rightly emphasizes, the costs associated with ammonia cracking, if achievable, would become a significant portion of the hydrogen delivery costs.[21] This would affect the cost

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[20] Compared with liquefaction, which takes place at the point of origin where energy costs are low, reconversion necessarily must take place at the destination, where energy costs are higher.

[21] Hydrogen Europe, "*Clean Ammonia in the Future Energy System*," March 2023, pages 30-31. *https://bit.ly/41lt9Kw* "[T]he costs of ammonia cracking can form, by far, the largest portion of hydrogen delivery costs (excluding costs of hydrogen itself) - drastically impacting the cost competitiveness of imported hydrogen…. Therefore, avoiding the dehydrogenation costs altogether, by direct use of ammonia as a fuel or as a feedstock – could, in many cases be the key condition for ensuring the financial viability of importing renewable energy in the form of ammonia."

competitiveness of imported hydrogen. While concerns about the costs of long-distance hydrogen transportation within the existing maritime system are valid, it is essential to consider these major drawbacks when evaluating the potential of ammonia as a liquid organic energy carrier.[22]

Long-Distance Transport of Liquid Hydrogen

In the pursuit of harnessing hydrogen's potential as a clean energy carrier and combating climate change, the efficient and cost-effective transport of hydrogen over long distances emerges as a critical challenge. As we have shown, being an exceedingly light gas with low energy density compared with other fuels, hydrogen presents unique transportation demands.

According to traditional thinking, long-distance hydrogen transport must rely on conventional technologies such as pipelines, trucks, and ships. Each of these has major limitations for long distance transport. Pipelines, while efficient, require extensive infrastructure development, complex right-of-way acquisition, and a fixed investment that makes them unsuitable for developing new and emerging markets or for trans-oceanic transport. Trucks are only suited to land based short distances, and generally entail high operating costs; and ships, while capable of long-distance transport, face the challenges noted above associated with boil-off from cryogenic hydrogen during extended voyages – particularly warm ocean waters on either side of the equator – and the need for very large storage facilities.

A promising alternative to these conventional modes for long-distance transport is the use of specially designed airships for transport of liquid hydrogen. Airships offer unique advantages that make them a compelling choice for this purpose. These advantages include:

1. Economic Efficiency

Airships have for decades demonstrated the potential for carrying significant payloads over long distances with remarkable efficiency. Their ability to harness buoyancy, combined with modern advances in aerodynamics and propulsion, allows them to cover long distances while consuming less energy compared with traditional vessels.

Modern airships are capable of crossing ocean expanses in 1-2 days whereas a ship would require several weeks. Airships can use hydrogen for lift, enabling them to rise to altitude without expending energy for take-off like conventional airplanes. Moreover, shipping liquid hydrogen by sea entails addressing already congested and strategically risky shipping corridors such as the Suez Canal and the Straits of Hormuz. Airships avoid these and other seaborne bottlenecks.

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[22] Rachel Parks, "*Don't crack imported blue ammonia back into hydrogen – it raises costs by 50%*," Accelerate Hydrogen, October 6, 2023. *https://bit.ly/47Sze3c* [citing Clean Air Task Force (CATF), "*Techno-economic realities of long-distance hydrogen transport*," September 2023. *https://bit.ly/3uVTZN2*]

The table below summarizes a volume and economic analysis of a hypothetical hydrogen production facility transporting its daily production of 250 Tonnes Per Day (TPD) 1,500 miles to market.[23] As shown in this illustration, for such service, airships can transport liquid hydrogen at a lower cost per kilogram than ships transporting either liquid hydrogen or ammonia:

	Airship (Liquid H_2)	**Small Ship (Liquid H_2)**	**Small Ship (Ammonia)**	**Large Ship (Liquid H_2)**	**Large Ship (Ammonia)**
Example	H_2 Clipper	Suiso Frontier	Equivalent Size	Kawasaki	Equivalent Size
Characteristics:					
Maximum volume (m^3)	2,143	26,000	26,000	120,000	120,000
Ship speed (mph)	150	21.9	21.9	21.9	21.9
Total round-trip time (days)	1.0	7.7	7.7	7.7	7.7
Hydrogen Delivered:					
Total capacity (tonnes H_2)	150	1,820	3,192	8,400	14,731
Boil-off losses in route (%)	n/a	3.85%	0%	3.85%	0%
Quantity delivered per trip	123.4	1,659	3,192	7,656	14,731
Resulting delivery per day	123.4	215	414	993	1,911
Other Factors:					
Storage needed (m^3)	12,477	34,412	26,747	46,429	26,747
Backhaul capacity (tonnes)	139	0	0	0	0
Economics ($ per kg):					
Hydrogen production	$ 1.50	$ 1.50	$ 1.50	$ 1.50	$ 1.50
Liquefaction cost	.65	.65	--	.65	--
Conversion to NH_3	--	--	.70	--	.70
Storage	.15	.55	.21	.72	.21
Transport (with 45% markup)	1.82	.79	.20	.33	.08
Backhaul revenue	- 1.12	--	--	--	--
Conversion to H_2	--	--	.80	--	.80
Total Delivered Cost	**$ 3.00**	**$ 3.49**	**$ 3.41**	**$ 3.20**	**$ 3.29**

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[23] Reference sources used include Yuki Ishimoto, *et al.*, "*Value-chain analysis of liquefied hydrogen, ammonia and pipeline for long distance hydrogen transport*," Institute of Applied Energy, October 12, 2019 (https://bit.ly/3v4E1QM); R.K. Ahluwalia, *et al.*, "*Systems level analysis of hydrogen storage options*," Argonne National Laboratory, April 29, 2019 (https://bit.ly/3NxG8mm); Qianqian Song, *et al.* "*A comparative study on energy efficiency of the maritime supply chains for liquefied hydrogen, ammonia, methanol and natural gas*," Carbon Capture Science & Technology, Volume 4, 2022 (https://bit.ly/47TjbCt); Trevor Brown, "*Round-trip efficiency of ammonia as a renewable energy transportation medium*," Ammonia Energy Association, October 2017 (https://bit.ly/47RofXP); Collin Smith, *et al.*, "*Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape*," Royal Society of Chemistry, Volume 13, 2020 (https://rsc.li/48gHryi); Dionissios Papadias, *et al.* (Argonne National Labs), "*Hydrogen carriers: Production, transmission, decomposition, and storage*," International Journal of Hydrogen Energy, Volume 46, July 2021 (https://bit.ly/46V4Jsj); and H2 Clipper in-house estimates.

2. Hydrogen Compatibility

Specially designed airships can safely accommodate cryogenic hydrogen storage and transport, mitigating the challenges associated with transporting hydrogen in its gaseous or liquid form via ships. When operated at speeds of between 125 and 150 miles per hour, any boiloff from the liquid hydrogen tanks becomes a significant asset. This gaseous hydrogen can be matched to the fuel required to produce electricity for propulsion from hydrogen fuel cells. Consequently, the operational costs of airships can be significantly lower for transporting hydrogen than conventional ships carrying liquid hydrogen or ammonia products between 500 and 3,500 miles or further.

3. Minimal Environmental Impact

When powered by hydrogen fuel cells, airships produce no carbon emissions. Their efficient operation, with clean water vapor as their only by-product, aligns with global efforts to reduce greenhouse gas emissions and minimize environmental impacts.

4. Flexibility in Route Planning

Unlike conventional transportation modes, airships are not bound by fixed routes and can access remote or hard-to-reach areas that may lack conventional infrastructure. This flexibility makes them well suited for transporting hydrogen from regions with limited accessibility and minimal infrastructure. A hydrogen delivery airship can transport clean fuel directly from production sources to industrial facilities, power plants, or a central storage depot supplying nearby fueling stations and other users. Ports and waterways, runways and airports, or lengthy road or rail networks are unnecessary. This flexibility ensures that airships can deliver fuel even during natural crises, such as in disaster-stricken areas where ports and airports may be inoperative. The dramatic congestion already being experienced by the Suez Canal and the Strait of Hormuz, as well as the supply chain congestion in ports globally, suggests that getting emergency relief supplies anywhere by ship is going to be far riskier than using an airship designed for that purpose.

5. Safety

Modern airships offer secure and controlled hydrogen transport without the safety concerns associated with transporting highly toxic ammonia. While the Hindenburg tragedy in 1937 raised suspicions about hydrogen's safety, it's crucial to note that the disaster occurred after 27 years of accident-free passenger operations, including over 1,000,000 miles on 590 flights by the Graf Zeppelin between 1928 and 1937. Moreover, the Hindenburg fire wasn't caused by hydrogen but rather by the highly flammable aluminum hydroxide paint used on the ship's surface – a feature that is no longer used in modern airships. In fact, most scientists today understand hydrogen to be a safer fuel than oil, diesel, or natural gas. Hydrogen disperses quickly in the air below the concentration level of 4% (40,000 ppm) required for combustion to occur. In comparison, gasoline lingers and is flammable at concentrations as low as 1.4%.

6. Rapidly Scalable

Airships can be designed and scaled according to specific hydrogen transport requirements, making them adaptable to various cargo sizes and distances. With pre-programmed robotics, airships can be rapidly produced from production facilities in multiple countries.

H2 Clipper, Inc. has focused on this novel approach to long-distance transport of hydrogen and air cargo since its inception.[24] Dating back to the company's earliest patent filing in 2008, its proprietary airship designs are the subject of 12 issued and another 30 pending patent applications that focus on enabling the use of hydrogen as a lifting gas, a fuel source for propulsion, and as a means for transporting hundreds of tons of liquid hydrogen per day from remote locations to consumer markets, with the ability to transport freight on the return flight to eliminate "dead heading" costs on the return voyage, which no seaborne ship can avoid.

A fleet of specially designed airships can provide a *Pipeline in the Sky*™ to supply green hydrogen from production sites, where hydrogen can be made and liquefied using abundant low-cost renewable electricity, directly to major users or depots located near or within major urban centers and other areas facing urgent clean energy needs. Such airships, by H2 Clipper and others,[25] have the potential to revolutionize hydrogen transport, providing a cost-effective and sustainable means of transporting hydrogen as well as freight across oceans and over long distances. As these technologies continue to evolve and mature, they are expected to play a crucial role in realizing the full potential of hydrogen as a clean and sustainable energy carrier.

Conclusion: A Vision of the Future of Hydrogen Transport

In the race to combat climate change and transition to a clean energy future, the efficient, speedy, cost effective, and safe transport of hydrogen emerges as a critical challenge. Hydrogen, often hailed as the ultimate clean and sustainable fuel, possesses unique properties that can revolutionize the planetary energy landscape. It can store intermittent energy, boosting the efficiency and affordability of renewable sources, generate electricity, and transform hard-to-abate heavy industries, aviation, and long distance commercial trucking. Green hydrogen, produced

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[24] For further information, see the H2 Clipper website at *https://www.h2clipper.com/solutions/clipper*.

[25] Graham Warwick, "*LTA's Large Rigid Airship Gets Airborne, Aviation Week Network*," June 14, 2023. *https://bit.ly/3TlUA4Q*. Lighter Than Air (LTA) Research, an airship company founded in 2015 by Google co-founder, Sergey Brin, specializes in large airships designed for humanitarian missions, disaster relief, and air cargo operations. In September 2023, LTA obtained a special airworthiness certificate from the FAA to conduct flights with its 123 meter (400 foot) long Pathfinder 1 airship. Initially, the helium-filled airship was equipped with two battery packs powering 14 electric propulsion motors, which LTA intends to replace with a hybrid-electric power system using Jet A fuel and 24 batteries to enhance power redundancy. In addition, LTA's CEO, Alan Weston, has revealed the company's ongoing development of a hydrogen fuel cell propulsion system for Pathfinder 1. According to Weston, LTA plans to commence operations initially with gaseous hydrogen storage, and later transition to a liquid hydrogen tank. In addition, the company is exploring the potential use of a hydrogen-fueled turbogenerator and has investigated the use of hydrogen as a lifting gas.

using renewable energy sources, stands as the cornerstone in the mission to combat global warming and create a sustainable future.

However, this vision faces a fundamental hurdle: the cost-effective and rapid delivery of hydrogen from its most efficiently produced sources to the markets where it is in greatest consumer demand. Ammonia, with its established infrastructure and widespread use in various markets, has garnered considerable attention as a potential hydrogen carrier, as well as an alternative energy source. However, the present analysis suggests that while green ammonia may serve as a valuable resource for specific applications, it presents significant limitations and challenges. The complexities of converting ammonia back into pure hydrogen and its toxicity, coupled with environmental concerns and economic considerations, raise questions about its viability as a primary hydrogen carrier, let alone as a substitute for pure unadulterated hydrogen.

In contrast, specially designed airships like the H2 Clipper are a promising alternative for long-distance hydrogen transport. Airships offer unparalleled advantages, including superior economics, hydrogen compatibility, minimal environmental impact, route flexibility, safety, and rapid scalability. These qualities position airships as a game-changing solution for efficiently transporting hydrogen across oceans and over long distances.

The future of hydrogen transport, *requires* innovative technologies and strategies such as the transport of liquid hydrogen by airships. While ammonia may have niche applications, airships offer the potential to create a more efficient, safe, and sustainable hydrogen transport network. Embracing these innovations holds the key to moving beyond ammonia and unlocking hydrogen's full potential as a clean energy carrier and advancing toward a greener, more sustainable biosphere.

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[26] The World Business Academy is a 501(c)(3) non-profit think tank and action incubator focusing on the role and responsibility of business in relation to solving critical environmental and social chalelntes. The Acaemy's focus on climate change and energy security results from an analysis of the most important threats to human survival and thus the survival of business. Formed in 1987, the organization's 36-year track record of leadership includes the publication of cutting-edge books, articles, podcasts, and videos discussing these topics and other issues of primary importance to society and the business community.

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