Floating Blue Ammonia Production: Creating a Zero-Carbon Emission Fuel

Golar LNG

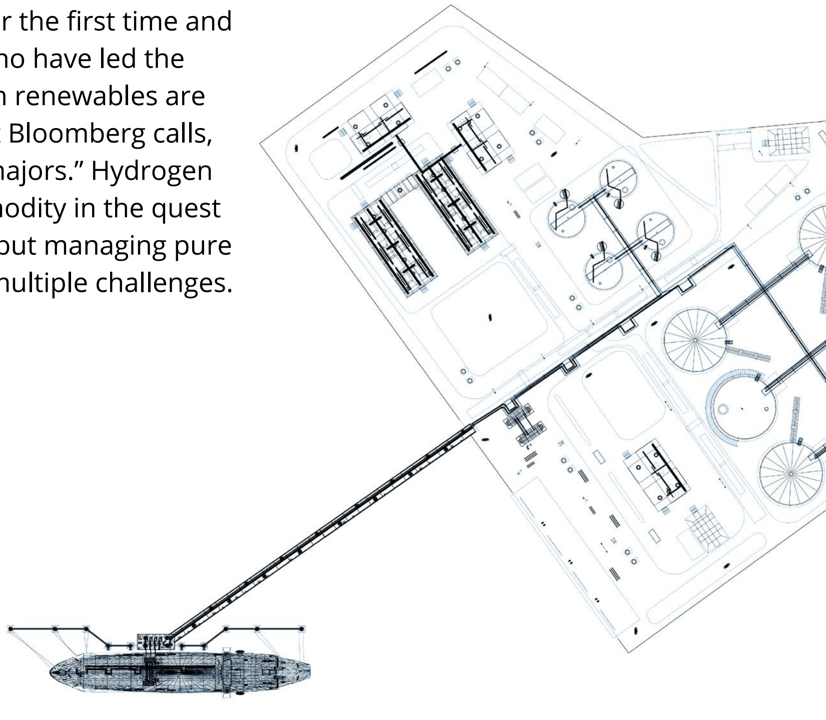
BLACK & VEATCH

Economic Investment Opportunities Exist While Transforming the Global Gas Industry

Decarbonization efforts are gathering momentum across governments, big business and financial institutions. China, Japan and Korea – the three biggest importers of liquified natural gas (LNG) – have all announced national pledges to go carbon neutral no later than 2050 to 2060. The impetus has spread to the business world as well, with many of the world's largest and most influential corporations leading the charge to set ambitious net-zero targets, setting in motion decarbonization drives throughout their supply chains.

More than any other time, there is now a strong economic incentive for decarbonization solutions. As of mid-2020, the value of assets under management applying environmental, social and corporate governance (ESG) principles is estimated at more than US$40 trillion as these companies continue to seek out new, low- or zero-carbon investment opportunities. In addition, investors are looking for opportunities to invest in bankable decarbonization projects. This reflects a growing realization that to achieve these goals, the pace and scale of solutions needs to rapidly increase. Golar, an industry leader in floating LNG and Black & Veatch, a leader in oil, gas and chemical infrastructure, are building on their established relationship to accelerate the hydrogen economy and the low carbon energy future.

With such decarbonization pledges and activities progressing, disruption of the world's energy markets is inevitable and already in motion. Affordable, scalable energy alternatives to fossil fuels are emerging and financing is lining up to propel critical low carbon infrastructure development. Goldman Sachs Group Inc. projects that in 2021 spending on renewable power alone will overtake that of oil and gas drilling for the first time and several utilities who have led the way in investing in renewables are emerging as what Bloomberg calls, "the clean supermajors." Hydrogen is a leading commodity in the quest for clean energy, but managing pure hydrogen poses multiple challenges.



Ammonia: The Catalyst for the Hydrogen Economy

With initial projections indicating that electrification will only be able to make up about 40 to 50 percent of the decarbonized energy market according to the IEA World Energy Outlook, the drivers for other carbon-free energy sources and energy carriers are as relevant as ever.

Investment in a global hydrogen economy will total trillions of dollars in the coming decade as sectors ranging from transportation, power generation, commercial, industrial and manufacturing, and real estate seek to decarbonize operations and align various ESG commitments.

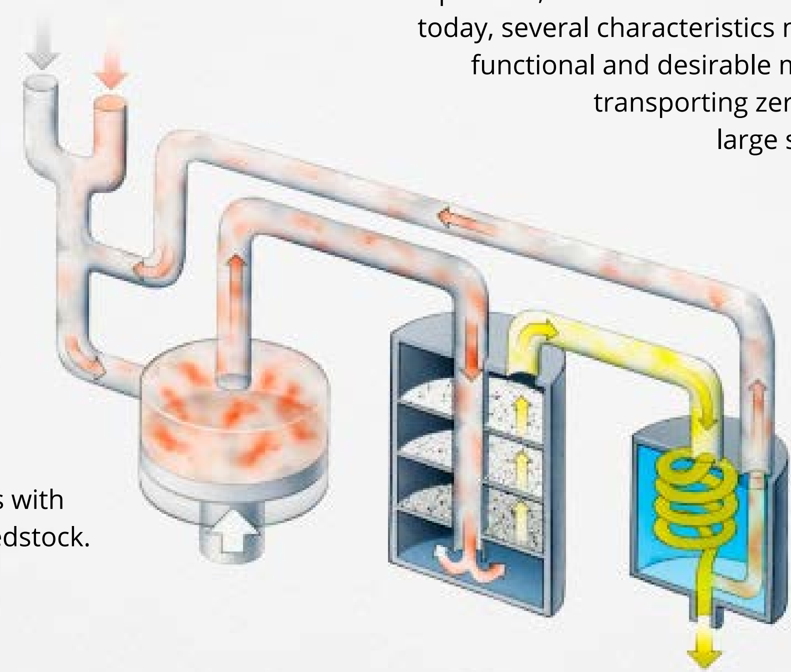
Heavy industrial production of basic materials like petrochemicals, steel, aluminum and cement, as well as other energy-intensive activities like shipping, aviation and road freight are often termed hard-to-abate sectors given the higher abatement cost to switch to lower carbon technologies. These sectors require sustainable economic pathways to reduce carbon and transition to greener fuel use and demand high-density fuels that are easy to transport, requiring a complete overhaul of the global bulk energy mix.

Ammonia is a stable compound and cost-effective transporter of hydrogen. Ammonia is currently produced in large quantities using commercially proven processes that often starts with natural gas (NG) as the feedstock.

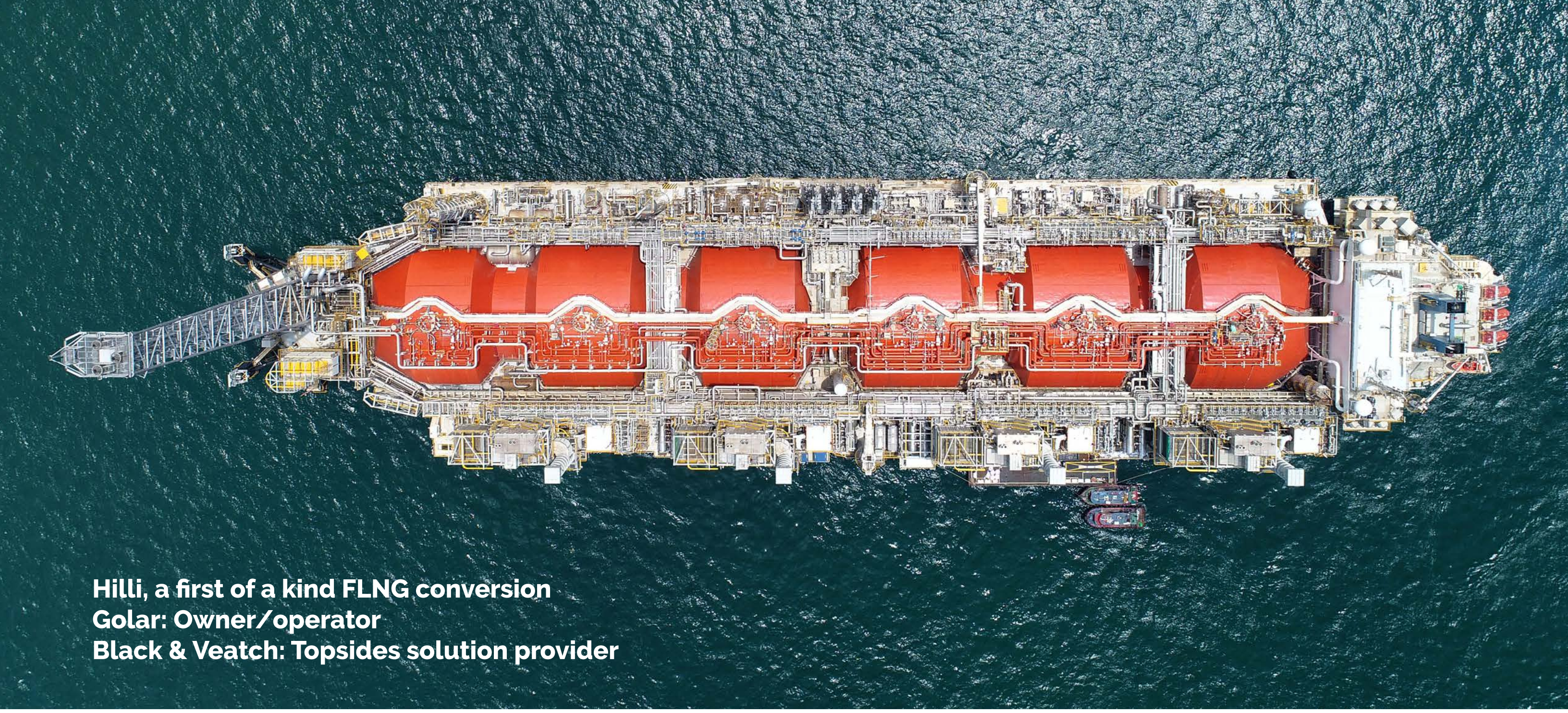
The NG, along with water, is first fed to a catalytic steam methane reformer (SMR) where hydrogen is produced from the methane ($CH_4 + H_2O \rightarrow CO + 3H_2$). This gas is then fed to a catalytic shift conversion where further hydrogen is produced from water ($CO + H_2O \rightarrow CO_2 + H_2$). In the next step, the CO_2 is removed using a chemical solvent leaving a pure stream of hydrogen. This hydrogen is then combined with nitrogen, using the Haber-Bosch process, to produce ammonia ($3H_2 + N_2 \rightarrow 2NH_3$).

Ammonia produced in the above method, when the CO_2 is appropriately sequestered, is often referred to as blue ammonia (see future papers on CO_2 uses and solutions). Ammonia can also be produced from hydrogen made through the electrolysis of water with renewable energy and is then referred to as green ammonia.

Until very recently, ammonia was primarily used in fertilizer and the chemical manufacturing of plastics, explosives, textiles and other industrial products. But today, several characteristics make ammonia a highly functional and desirable means of storing and transporting zero-carbon energy at a very large scale.



Haber-Bosch process: *Pure hydrogen catalytically reacted with pure nitrogen in a reactor to form anhydrous liquid ammonia*



Why Ammonia Instead of Hydrogen

In the effort to accelerate the zero-carbon energy future, decarbonization efforts must balance a complex web of political and regulatory considerations, long-term capital asset decisions and the presence of incumbent technologies and market participants. As governments, consumers and industry leaders seek to lower carbon emissions, ammonia offers a level of scale, portability and flexibility the developing green hydrogen market will not achieve for decades.

Liquid ammonia is more energy dense than liquid hydrogen, allowing it to store more energy at the same volume. Liquefied ammonia also provides a safer, cheaper and less energy-intensive means of transport across long distances than the transport of liquified hydrogen.

	Energy/Weight (kJ/kg)	Energy/Volume (kJ/m3)	Liquid Temperature (C)	Energy Efficiency (Energy out/Energy In)
Hydrogen (Compressed Gas)	120,000	2,110,132	-253	83%
Hydrogen (Liquid)	120,000	9,323,189	-253	56%
Ammonia	18,600	11,457,600	-33	62%
LNG	49,000	21,217,000	-162	93%

(1) Table is based on lower heating values (LHV)
(2) Energy/Volume based on storage conditions
(3) Compressed hydrogen is at 245 barg and 20 C

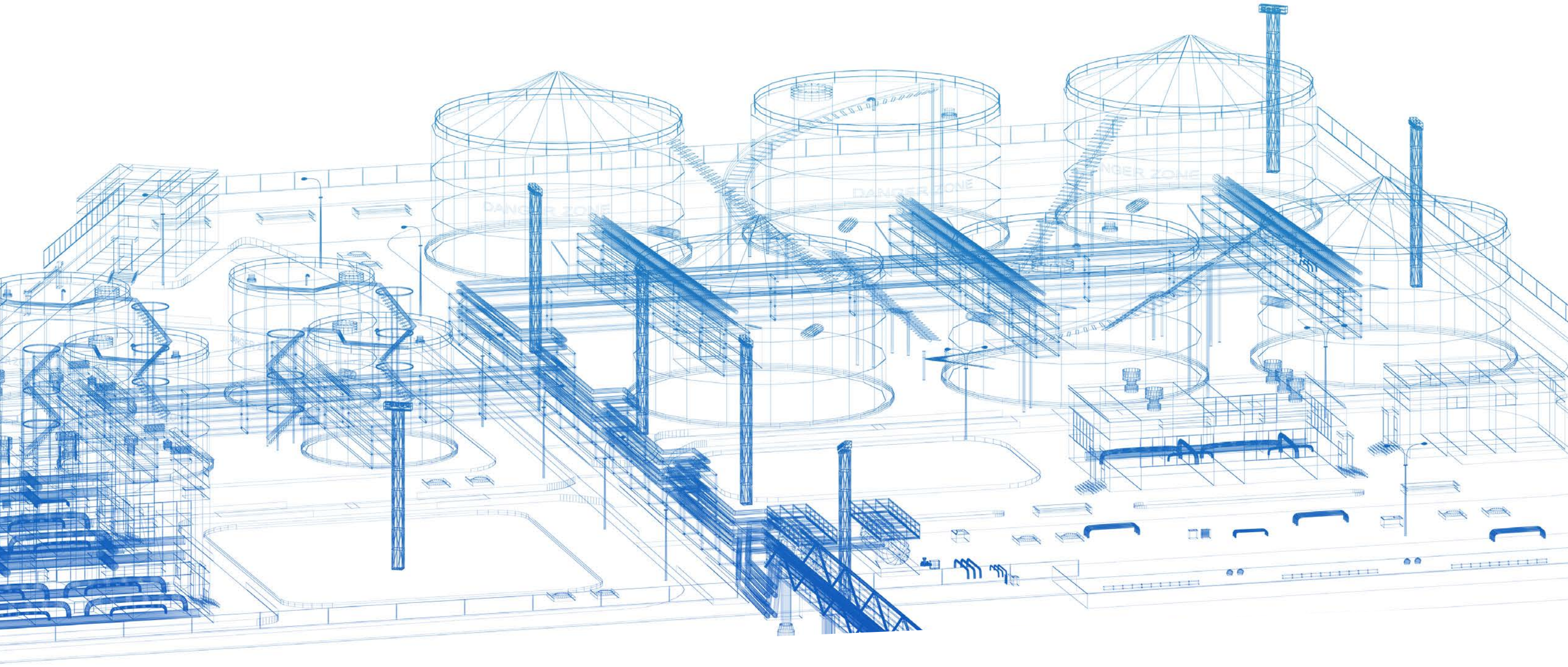
Upon delivery, ammonia can be used directly as a fuel or converted back to hydrogen by cracking technology. In either scenario a clean-burning fuel, that releases no CO_2 at the point of combustion, is available. This combination highlights ammonia's potential to accelerate the transition to carbon free energy across energy-intensive industries such as power generation, transportation and green chemicals.

Existing Infrastructure Enables the Blue Ammonia Transition

While moving to fully green hydrogen may be the eventual end-game of 2050 commitments, the more immediate, compelling and realistic economic proposition lies first with the adoption of blue ammonia, which can help reduce many industries' carbon footprint while laying the groundwork for further decarbonization gains.

Blue ammonia holds extra promise as it can be produced, stored and transported using the large-scale ammonia infrastructure currently in existence. A gas at room temperature, ammonia's stability facilitates deployment via multiple modes of transport thereby expanding its reach. In addition to existing import and export terminals, a considerable portion of the existing LPG fleet is capable of transporting ammonia.

Utilization of this infrastructure will be critical as new hydrogen powered technologies including combustion turbines and fuel cells (in particular) are deployed in regions where production of, or easy access to green hydrogen, will lag. This ability to rapidly deploy ammonia to energy-intensive demand centers will help achieve increasingly aggressive climate targets.



Floating Versus Onshore Ammonia Production

Together, Golar and Black & Veatch's experience and success with FLNG solutions has shown that floating vessels – whether designed for nearshore or offshore use – offer a number of advantages to traditional onshore facilities.

Compared to land-based facilities, the development of floating LNG liquefaction vessels offers a faster return on investment due to the shorter period from final investment decision (FID) to commercial operation. This is in large part due to shipyard construction often being more efficient than building onshore. Floating units are also not fixed to one location and mobility can extend the life of the facility by redeploying to new resource locations.

It is likely that these same benefits can be obtained with floating blue ammonia production units (FNH3). We envision the possibility of the use of these units, similar to natural gas liquefaction and storage on ships by building upon the established track record of Golar and Black & Veatch's FLNG partnership. These mobile assets do everything from processing the gas onboard the vessel, to offloading the LNG to tankers for transport. They are versatile, allowing access to offshore gas fields that are otherwise uneconomic.

An additional strength of floating blue ammonia production is associated with CO2. After capturing the CO2, there will be a need for necessary infrastructure to transport and deposit the gas to the nearest feasible carbon storage unit. It is the very real possibility that there might be existing infrastructure in place to allow for direct disposal of the captured CO2 to depleted wells through existing pipelines which potentially could significantly reduce the cost associated with the liquefaction, transportation and storage of CO2 at another location.

Conclusion

To meet government commitments, companies must look at their current and future long-term assets through the lens of becoming net-zero by 2050, operational decisions and fuel choices made today will have ramifications for decades. Skeptics are quick to note that hydrogen has been teased as the fuel of the future before; however, many energy companies and asset owners are looking for opportunities to divest fossil assets and balance portfolios with decarbonization top of mind. This range of commercial and regulatory forces aligning behind its use, and its ability to scale rapidly across the value chain indicates ammonia, both blue and green, will be a key element in the decarbonization effort.

By embracing decarbonization, reevaluating current revenue streams, and being open to new revenue opportunities, companies can achieve their 2050 decarbonization targets in a sustainable way.

Future papers in the series: **Floating Ammonia Facilities - CO2 Capture and Uses**

For more information please visit **bv.com, golarlng.com**
Please contact us **MartinG2@bv.com, golarlng@golar.com**

Additional resources:

Golar LNG's Commitments to ESG and Sustainability
https://www.golarlng.com/sustainability

Black & Veatch Joins Hydrogen Council, Reflecting Commitment to Hydrogen as a Zero-Carbon Solution
https://www.bv.com/news/black-veatch-joins-hydrogen-council-reflecting-commitment-hydrogen-zero-carbon-solution

Black & Veatch 2020-2023 Sustainability Strategy
https://www.bv.com/resources/black-veatch-2020-2023-sustainability-strategy

Hybrid LNG & Ammonia Infrastructure: Key to a Green Economy eBook
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Ammonia: Fuel vs. Hydrogen Carrier
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Hydrogen Takes Center Stage
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