A TEMPLATE FOR LIQUID HYDROGEN

Bob Oesterreich, Peter Gerstl, and Ty Webb, Chart Industries,
reveal how advances in LNG technology have paved the road for liquid hydrogen in the quest for zero carbon emissions.

As countries accelerate efforts to reduce greenhouse gas (GHG) emissions and increase energy independence, hydrogen is taking centre stage in many of the roadmaps. With advancements in fuel cell stack technologies and continued cost reductions, hydrogen can be used as an energy carrier to fulfil several roles in the energy sector. With its ability to store renewable power, produce electricity, and power light and heavy-duty vehicles with zero tailpipe emissions, hydrogen can be a global energy source at scale.

The liquefaction of hydrogen produced from low-cost sources will allow for the storage and transportation of hydrogen energy all over the world, using a supply chain very similar to how the LNG supply chain is structured today. The technologies for liquefaction and the storage and transportation of LNG can be used as a basis for developing global liquid hydrogen supply chains. In fact, Chart and others have been successfully producing many of these liquid hydrogen products for decades to support local markets for space and industrial applications. It is the globalisation of liquid hydrogen that will require large-scale transportation systems that are used with LNG, and that extensive LNG experience can be applied to, for example, liquid export and import terminals, bunkering systems, and railcars.

In many ways LNG, and the systems and supply chains currently in place to support a global LNG market, can be a template for building a global liquid hydrogen energy market. In this article, the similarities and differences of LNG and liquid hydrogen and their effect on how these liquefied gases are stored, transported, and used for their energy content, are discussed.

From humble beginnings: how natural gas became the first clean fuel

Since first commercialisation in the late 18th century, the benefits of natural gas have been used to improve lives. Initially used for

Figure 1. Small-scale LNG liquefaction in Texas, US.

Figure 2. Modularisation reduces overall project schedule.

Figure 3. Small-scale import terminal at Klaipeda, Lithuania.

lighting, its applications for fuel use grew in the 19th century after the invention of what is commonly known as the Bunsen burner. Over the past two centuries, natural gas has become a much larger fuel source for electricity generation, primarily due to lower associated particulate and other health impacting emissions, such as carbon monoxide, SO_X and NO_X, while also offering a higher efficiency and similar or lower cost than coal or petroleum-based fuels. During the 21st century, as the focus has shifted towards climate change, natural gas once again has been the leader in the transition due to it emitting 60% less CO_2 than coal. For nations that have limited access to natural gas from their own local resources, LNG has enabled access to the original clean fuel.

As demand for natural gas as a fuel expanded, so did the requirement for new equipment and technologies to support its production, liquefaction, transportation, storage, regasification, and end use. Perhaps chief amongst these is what has become known as small-scale LNG. Until relatively recently, natural gas was predominantly liquefied in huge base-load facilities and transported across oceans in large ships before being regasified in similarly large-scale import terminals. The development of small-scale LNG has revolutionised the landscape by providing a technically feasible and commercially viable solution for production and distribution of much smaller volumes of LNG, bringing power to off-grid locations and providing an alternative transport fuel for trucks, ships and even railway locomotives (Figure 1).

Companies rose to the challenge by developing components and solutions across the complete natural gas value chain. Previously, small-scale liquefaction plants – typically with capacities of between 150 000 to 450 000 gal./d – had been used for peak shaving but by developing and improving the small-scale concept, companies were able to create local LNG distribution centres through the liquefaction of pipeline natural gas. Keys to success were bringing LNG to market quickly and simple plant operation; hence the major feature of small-scale liquefaction plants is a range of standard plants rather than designing a custom plant each time. This significantly reduces the project timescale and delivers lower CAPEX.

The concept of modular mid-scale LNG was developed to meet larger liquefaction plant requirements, e.g. the export of North American shale gas. Instead of a single large custom-built facility, total plant capacity is achieved through a series of replicable modules. For example, a plant with a total liquefaction capacity of 12 million tpy could be achieved through four identical 3 million tpy modules. By using proven, standard equipment packages and maximising shop build and minimising on-site construction, the chief advantages of the modular approach are:

- Reduced overall project timescale.
- Lower risk profile.
- Modules can be brought on-line and operated independently for earlier revenue recognition, and plants can respond quickly to demand fluctuations.

In a relatively short timescale, developments in liquefaction technology and capital equipment resulted in the typical module size growing from 0.5 million tpy to › 3 million tpy. However, perhaps the best example of how creative thinking has shifted the energy balance to low carbon fuels is Cheniere Energy Inc.

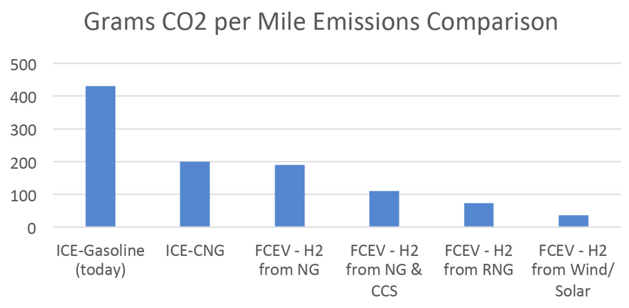

Figure 4. Comparison of vehicle emissions.[1]

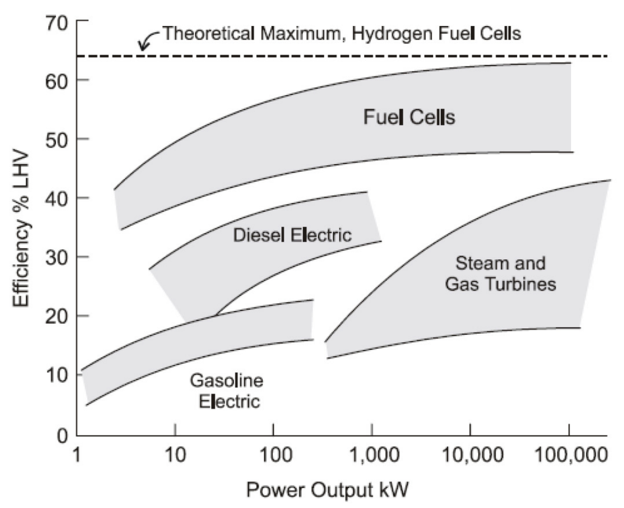

Figure 5. Fuel efficiency and power output comparisons.[2]

becoming the US' chief exporter of LNG when little more than a decade earlier it was building facilities to receive LNG from overseas (Figure 2).

Small-scale import terminals

The import terminal at Klaipeda has established the Lithuanian port as an LNG distribution hub for the Baltic region. Unable to compete with the economies of scale afforded by its much larger counterparts in Europe, Klaipeda instead offers a multi-function approach and offloaded LNG can be used for marine bunkering, loaded into road tankers for virtual pipeline distribution, or regasified for pipeline transmission. Just like with small-scale liquefaction, it is the facility's ability to quickly respond to local demand fluctuations that maintains its competitive edge (Figure 3).

Small-scale terminals also share many design and production features with their liquefaction plant counterparts. Shop-built equipment reduces cost and schedule, and modular construction reduces civil work and facilitates faster installation. Replicable modules also mean that potential future capacity expansions can be incorporated into the base design, as was the case at Klaipeda.

There are also some very good examples of successful single use small-scale import facilities. For example, Gibraltar switched from diesel-fuelled power generation via an 80 MW gas fired power station fed by a shore-built import terminal with 5000 m^3 of LNG storage. Multiple bunkering terminals use the same storage and vaporisation concept to fuel ships.

All the way along the value chain, there are examples of increased demand for natural gas leading to developments in the capacity and capability of LNG equipment. As both LNG and liquid hydrogen are stored and transported in insulated vessels, many of those developments are directly transferable, and mean the hydrogen infrastructure can similarly be expanded through shop-built, reliable and proven equipment.

LNG and LH_2 – similarities and differences along the supply chain

One of the main features of hydrogen is its ability to store and produce electrical energy, enabled through the use of fuel cell technology. Fuel cell engines convert pure hydrogen into electricity through an electrochemical process without generating CO_2 as a byproduct, resulting in zero carbon emissions in the power generation process. Applications using natural gas or LNG to produce electricity or motive power require the combustion of natural gas, resulting in CO_2 emissions at the point of use in the power generation process. As discussed earlier, natural gas and LNG offers the ability to reduce emissions compared to gasoline or coal in power generation or transportation. Producing hydrogen from natural gas, renewable natural gas (RNG) or renewable energy using fuel cell technology can reduce carbon emissions even further.

In addition to the carbon and emissions reduction benefits of natural gas in internal combustion engines (ICEs) and hydrogen and fuel cell technology in fuel cell electric vehicles (FCEVs) for the power generation and transportation markets, fuel cell technology is more efficient in the conversion to electrical energy as compared to the traditional combustion technologies primarily used today. Figures 4 and 5 compare the GHG emissions and energy efficiencies for natural gas and hydrogen to conventional gasoline.

While liquid hydrogen has an outstanding value regarding its gravimetric energy density, its volumetric energy density is very low compared to LNG, thus pushing the demand for larger volumes of storage tanks. Furthermore, hydrogen is a much smaller molecule than natural gas, and components which are tight under natural gas services might be leaking in hydrogen service. Liquid hydrogen boils at -252.8˚C (22.3 Kelvin) – only liquid helium has a lower boiling point. Due to this, the cold temperatures of liquid hydrogen carry the potential of liquefying air and generating oxygen-rich condensates where the cold energy meets normal air. Hence, the choice of potential refrigerants for a hydrogen liquefaction process and of purge gases for such cryogenic process units is extremely limited. The critical point of hydrogen is at 12.97 bar (a), above which hydrogen is a one-phase fluid and has only 50% of the density of cold liquid. Consequently, any warming up of liquid hydrogen leads to a significant volumetric expansion, with the risk of overflowing when stored in a tank compartment. Besides these fundamental characteristics, liquid hydrogen and gaseous hydrogen have more physical properties which need to be considered for all hydrogen equipment design and manufacturing in order to ensure safe and reliable operation.

Hydrogen can be liquefied by using open-loop pre-cooling with liquid nitrogen (LIN) and liquefaction by a closed refrigeration loop, or also having a closed-loop pre-cooling. The first approach is typically used for smaller liquefiers, and where CAPEX is key to economic success and LIN is available at

Figure 6. Liquid fuel supply chain.

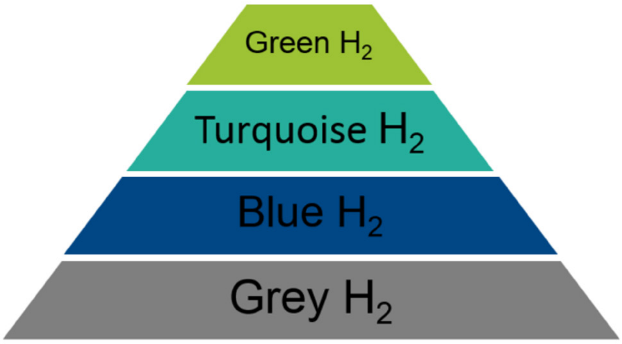

Figure 7. For liquefaction, storage and distribution all colours of hydrogen can be treated the same.

lower costs. The second is more attractive for larger-scale liquefiers as the additional CAPEX is comparably small, but the effort for providing large amounts of LIN would be tremendous. The typical range for the required electrical power consumption starts from 7.5 kWh/kg for the open-loop process and from 10 up to 15 kWh/kg for closed-loop processes.

Like natural gas, hydrogen can be liquefied at the production source and be transported locally and globally, allowing it to be exported from geographies with low-cost production to the markets it serves. Some examples are:

- Green hydrogen can be produced via electrolysis in geographies where there is an abundance of wind and solar energy.
- Blue hydrogen can be produced in geographies with low-cost natural gas via steam methane reformation and carbon capture.

The hydrogen gas produced from these sources can be liquefied and transported into the markets as a low or zero carbon electrical energy source for transportation or power generation. Like LNG, liquid hydrogen can be transported by truck, rail or water from regions with low-cost hydrogen production into regions needing low carbon energy feedstocks for transportation or power generation.

Figure 6 shows how the LNG supply chains used today can be applied to liquid hydrogen for the storage and transportation of green and blue hydrogen locally and globally.

Today, 10 million tpy of hydrogen capacity exists in the US, with most of that being 'grey' hydrogen produced from natural gas. Because of this large existing capacity and the low price of natural gas, this infrastructure can be used to advance hydrogen applications within the US and other areas of the world. Carbon capture utilisation and storage (CCUS) will play an important role in reducing the carbon emissions from these sources, which will help enable a transition to hydrogen playing a key role in energy. A large concentration of these hydrogen plants is in the US Gulf Coast, currently providing hydrogen for processing crude oil into transportation fuels. As the dependence on fossil fuels decreases, this hydrogen capacity can be used for other purposes such as mobility applications. Additionally, some of this hydrogen could be used for chemical applications as well as hydrotreating in renewable diesel production facilities.

Technologies are being developed and demonstrated for the production of different colours of hydrogen (Figure 7). There has also been a huge uptick in carbon capture, both on a large scale and, equally importantly, retrofits to existing facilities and decarbonising industries where it is previously proved, such as the cryogenic carbon capture (CCC) technology of Sustainable Energy Solutions (SES), which was recently acquired by Chart Industries. CCC is particularly well-suited for post-combustion carbon capture, and has some key advantages for retrofits to existing facilities.

Conclusion

Although there are undoubted challenges ahead, there is also significant evidence that the liquid hydrogen value chain is poised to play a significant part in the world's sustainable energy future. Liquefaction processes were developed in the middle of the previous century and there are multiple, proven processes that are being further optimised for larger capacity liquefaction facilities. A lot of the key capital equipment is the same for natural gas and hydrogen liquefaction and proven over many decades. Similarly, liquid hydrogen vessels and trailers, used for storage and transportation, are well-established across multiple cryogenic services, including hydrogen, and in applications such as high-tech manufacturing and aerospace where quality is paramount.

In summary, the cryogenic technology at the heart of LNG is uniquely positioned to play a key role in the build-out and scale-up of the global liquid hydrogen chain.

References

1. WANG, M., and ELGOWAINY, A., Systems Assessment Section Energy Systems Division, Argonne National Laboratory (October 2014).
2. KALKAN, N., 'Performance Evaluation of Fuel Cell', *International Journal of Engineering Research & Technology*, Vol. 3, Issue 3 (March 2014).