The Challenges of Hydrogen Transport – and of Using Hydrogen for Transport

By Martin Flusberg
November 2023

Liquid Hydrogen Tanker Truck - Courtesy of MIT News

The Potential for Green Hydrogen as an Energy Source

A few months back I posted an article on LinkedIn about the potential for Green Hydrogen, currently produced by the electrolysis of water leveraging renewable energy sources. The article pointed out that hydrogen is already used widely as a fuel and that the growth of green hydrogen should lead the way to a greater expansion of hydrogen use and play a role in the transition to net zero emissions. For example, hydrogen can potentially replace fossil fuels in industrial processes as well as in transportation. It can also provide long term energy storage and help address the intermittency of wind and solar by being used to store excess power generated on windy or sunny days to be dispatched at times of peak demand.

In the article I mentioned in passing that the transport of hydrogen poses certain challenges that may impact the growth of hydrogen as an energy source. The focus of this article is to explore what those challenges are and what is being done to address them. And, while on the topic of transportation, this article also explores the challenges of, potential for, and status of using hydrogen as a clean transportation fuel once it is delivered.

How is Hydrogen Transported Today – and What are the Challenges?

The transport of hydrogen to the location at which it is going to be used is a challenge since hydrogen has the lowest density of all gases and is also flammable when mixed with the smallest amount of air. Because of hydrogen's low volumetric energy density, its transportation, storage, and final delivery to the point of use may represent a significant cost. And there can be safety issues as well.

Today, hydrogen is almost exclusively transported from the point of production to the point of use via pipeline and over the road - in liquid tanker trucks or gaseous tube trailers.

Approximately 1,600 miles of hydrogen pipelines are currently operating in the United States. These pipelines are located where large hydrogen users, such as petroleum refineries and chemical plants, are concentrated, in particular in the Gulf Coast region

In the absence of pipelines, for longer distances hydrogen is most commonly transported and delivered as a *liquid* in super-insulated tanker trucks referred to as *liquid tankers*. (See photo on page 1). To liquefy hydrogen, it must be cooled to cryogenic temperatures (−253°C /−423°F) through a liquefaction process. Once hydrogen is liquefied it can be stored at the liquefaction plant in large, insulated tanks at very low temperatures. When the liquid hydrogen is delivered it can be stored as a liquid, but ultimately must be vaporized to a high-pressure gas for dispensing.

It takes energy to liquefy hydrogen—liquefaction currently consumes more than 30% of the energy content of the hydrogen and is expensive. In addition, some amount of stored liquid hydrogen will be lost through evaporation, or "boil off", especially when small tanks with large surface-to-volume ratios are used. Basically, hydrogen liquefaction is an energy-intensive process, and maintaining the low temperature required for long-distance transportation and storage purposes results in additional energy losses and accompanying costs. This further contributes to the overall cost of using hydrogen as an energy source.

To transport *gaseous* hydrogen, it must be compressed to pressures of 180 bar or higher and pumped into long cylinders that are stacked on a trailer. This gives the appearance of long tubes; hence the name *tube trailer*.

Tube trailers are currently limited to pressures of 250 bar by the U.S. Department of Transportation (DOT) regulations, but exemptions have been granted to enable operation at higher pressures (e.g., 500 bar or higher). Steel tube trailers are most commonly employed and carry approximately 380 kg; their

Tube Trailer. Image courtesy of US Department of Energy

carrying capacity is limited by the weight of the steel tubes. Recently, composite storage vessels have been developed that have capacities of 560–900 kg of hydrogen per trailer. (Such tube trailers are currently being used to deliver compressed natural gas in other countries).

Liquid vs. Gaseous Hydrogen Transport

It is generally accepted that over long distances trucking liquid hydrogen is more economical than trucking gaseous hydrogen because a liquid tanker truck can hold a much larger mass of hydrogen than a gaseous tube trailer can - even with the risk of boil-off during delivery. That being said, it is perhaps not surprising that there are different opinions on the best way to transport hydrogen.

For example, NPROXX, a Dutch company that offers high pressure gas storage and transport, agrees that there are pros and cons of both liquid and gas as a means of hydrogen storage and transport. They admit that, due to its significantly reduced volume, liquid storage can work better when vast quantities are being transported. However, and here is a specific quote: “we believe that the battle over hydrogen storage already is, and will continue to be, won by high-pressure gas, stored in strong, light carbon fiber type IV pressure vessels”.

They go on to cite the following advantages of gas:

- **Issues with cryogenic storage.** They argue that one of the major drawbacks of liquid transport is the cost; liquid hydrogen requires well-insulated cryogenic storage vessels that maintain the required temperature. In addition, as noted earlier, the gas-to-liquid transformation process consumes up to 30% of the energy content of the stored hydrogen. They also note that there may be hazards associated with converting liquid hydrogen back into a gas.
- **Speed and simplicity of delivery.** The main advantage of employing a compressed hydrogen gas storage system they note is that it allows for the rapid refueling of vehicles. With a high-pressure gas storage system, refueling can be achieved in minutes, while – according to NPROXX - liquid storage refueling protocols and processes are not yet available.

- **Storage footprint.** Liquid storage requires large footprints – about three times the size of industry-standard gasoline tanks – to address both housing the hydrogen and performing onsite conversion. (This does not really relate in the same way to the transport of hydrogen).

NPROXX Tube Trailer

Needless to say, there are other perspectives as well – often tied to what the company with those perspectives actually does.

The storage of hydrogen shares many of the same issues as its transport, but is not the focus here.

Cooling Hydrogen for Transport as a Liquid

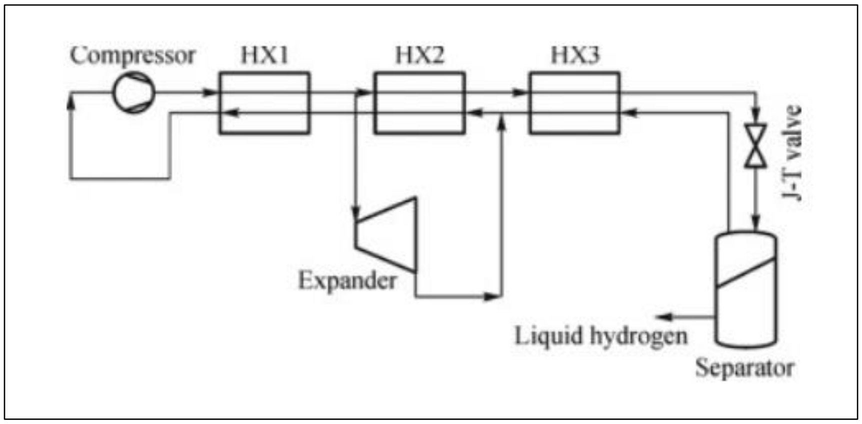
The most common method of hydrogen cooling is *Direct* cooling, which uses a diffusion-bonded heat exchanger to cool down hydrogen. *Indirect* cooling uses a cooling medium such as a water/glycol mixture as an intermediate medium, but this is generally significantly less efficient.

Key components of liquefaction plants typically include aluminum-plate heat exchangers and expansion turbines with dynamic gas bearings.

For small capacity liquefaction plants, a closed helium circuit can be used to supply the refrigeration necessary to cool the hydrogen. Pure hydrogen gas at approximately 20 bar is fed into a vacuum-insulated cold box and, after a certain degree of subcooling at the end of the refrigeration process, it

Cooling Hydrogen. Image Source: Absolut Hydrogen expands through a (Joule-Thomson) valve into the storage tank. The helium refrigeration cycle and hydrogen liquefaction are completely separated. The main components of the system are the helium compressor with oil purification, the cold box with heat exchangers and helium expansion turbines, the liquid hydrogen tank, and filling stations for transportable containers.

For larger liquefaction capacities, refrigeration for cooling and conversion of the hydrogen may be achieved by means of what is known as the *Claude* process. This process consists of precooling the hydrogen in a nitrogen loop, then subjecting it to quasi-isentropic expansion in an expansion turbine.



Claude Process. Source: ScienceDirect

For larger-scale systems, separate cold boxes can be considered – a first box for cooling the hydrogen from ambient temperature to -315°F and a second box to go down to -420°F. Other components might include hydrogen purification, raw gas compressors, storage tanks, and filling devices.

Liquification plant operated by Linde, major player in the space based in Germany. Image from Linde website.

As noted earlier, hydrogen liquefaction is an extremely energy-intensive process, and maintaining the low temperature required for long-distance transportation and storage purposes results in additional energy losses and accompanying costs. There are, however, some novel liquefaction methods, such as an active magnetic regenerative liquefier, which could result in lower energy use.

Hydrogen Compression for Transport as a Gas

Hydrogen is typically produced at relatively low pressures (20–30 bar) and, as noted above, must be compressed prior to transport if it is not liquified. Most compressors used today are *positive displacement* compressors – either reciprocating or rotary - or *centrifugal compressors*.

- **Reciprocating compressors**, sometimes called *recips*, are the most commonly used hydrogen compressors for truck transport. They use a motor with a linear drive to move a piston or diaphragm back and forth. This motion compresses the hydrogen by reducing its volume.

- **Rotary compressors** leverage the rotation of gears, lobes, screws, vanes, or rollers. Hydrogen compression is a challenging application for positive displacement compressors due to the tight tolerances needed to prevent leakage.

- **Centrifugal compressors** are the most common for pipeline applications due to their high throughput and moderate compression ratio. Centrifugal compressors rotate a turbine at very high speeds to compress the gas. Hydrogen centrifugal compressors must operate at top speeds 3 times faster than natural gas compressors to achieve the same compression ratio because of the low molecular weight of hydrogen.

Alternatives to mechanical compression like those described above are currently in the R&D stage:

- **Electrochemical compressors** use proton exchange membranes flanked by electrodes and an external power source to drive the dissociation of hydrogen at the anode and its recombination at the cathode at higher pressures.

- **Metal hydride compressors** use metals that form hydrides via exothermic reactions and then release hydrogen at high pressures when heat is applied.

- **Ionic compressors** are similar to reciprocating compressors but use ionic liquids in place of a piston. These compressors do not require bearings or seals, two of the most common causes of failure in reciprocating compressors.

The compression of hydrogen is an energy-intensive process that increases the overall cost. Estimates are that compressing hydrogen (isothermally) from 20 bar to 350 bar uses more than 1 kWh per kilogram of hydrogen.

Alternative Approaches to Hydrogen Transport

There are several other approaches to hydrogen transport that are in various stages of development. One of them is referred to as a *Liquid Organic Hydrogen Carrier (LOHC).*

LOHC is a liquid capable of absorbing and releasing hydrogen through a chemical reaction. The LOHC is brought into contact with hydrogen through a hydrogenation reaction that absorbs the hydrogen. This chemical reaction occurs under increased pressure and temperature with a catalyst present.

Several agents can be used as a LOHC. A good example is dibenzyl toluene. This 'carrier' can absorb large amounts of hydrogen using the technique described above.

LOHC shipping without heat recycling reportedly has an energy efficiency of 60-70%, depending on the dehydrogenation rate, which is equivalent to liquid hydrogen shipping. With heat recycling, energy efficiency may increase to 80-90%. Overall, the process is considered relatively inexpensive and safe. Another advantage; the LOHC is a diesel-like substance which can be stored and transported under atmospheric pressure and temperature with regular vehicles used for gasoline or diesel.

On the con side; hydrogenation requires a lot of heat. In large-scale use, the costs can mount as a result. Additionally, the production of LOHC causes extra CO_2 emissions. Exactly how much depends on how long the LOHC lasts and how often it can be reused.

Earlier this year *Honeywell* announced the release of an LOHC option. In their system, hydrogen gas is combined chemically through Honeywell's *UOP Toluene Saturation Process* into a liquid carrier compatible with existing infrastructures. The carrier can then be essentially transported in the same way as gasoline. Once at its destination, the hydrogen is recovered from the carrier using Honeywell's *UOP Methylcyclohexane Dehydrogenation Process*. Existing idle oil refining assets can be revamped to release the hydrogen from the liquid carrier for use in multiple commercial and industrial applications. According to Honeywell, the carrier used in its LOHC solution is readily available and requires minimal makeup.

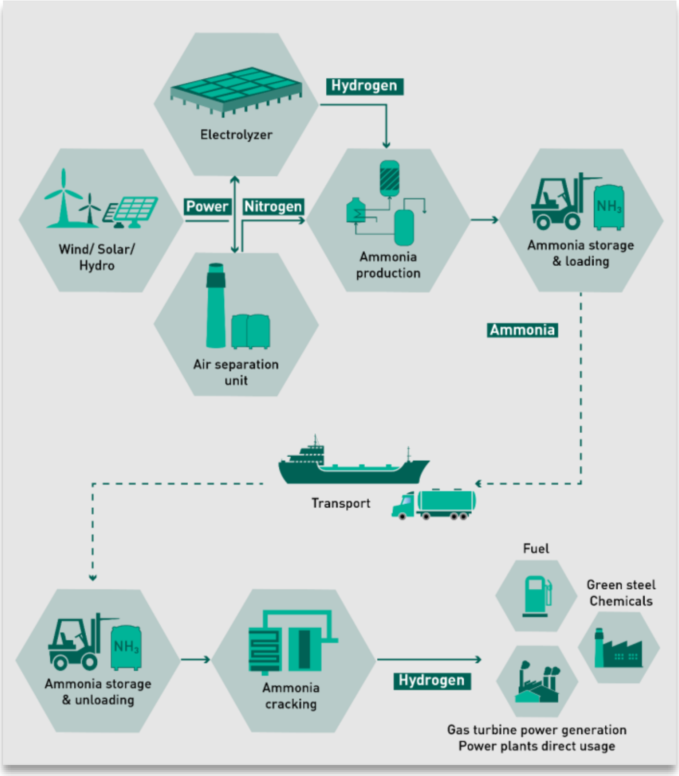
Another company pushing LOHC for hydrogen storage and transport is Ayrton Energy.

There is also another transport alternative being tested. Hydrogen can be converted into multiple carriers that have a higher energy density and higher transport capacity and can potentially be cheaper to transport over long distances. This is referred to as *materials-based storage*, where solids and liquids that are chemically able to absorb or react with hydrogen are used to bind it**.** Among the substances currently identified as potential hydrogen carriers are liquid ammonia and methanol.

Using ammonia as a carrier for hydrogen is probably the option with the most potential. Its energy density by volume is nearly double that of liquefied hydrogen, making it far easier to store and transport.

Under this approach. ammonia as an energy carrier for hydrogen is produced through ammonia synthesis. This chemical process allows hydrogen and nitrogen to react and convert to liquid ammonia.

The ammonia is then transported to its destination and "cracked" to release the hydrogen at its point of use. Currently, cracking is estimated to result in a 13-34% energy loss, but there is ongoing development to try to lower that.



Using Ammonia as a Hydrogen Energy Carrier. Source: Flexim

Hydrogen transport using ammonia has several advantages. For example, ammonia has been used in various industries for a long time and there is a widespread infrastructure for ammonia synthesis. Also, ammonia can be stored in slightly refrigerated tanks at -33 °C or at ambient temperatures under a pressure of 8-10 bar. This makes storing and transporting ammonia relatively straightforward and affordable.

Using ammonia also has disadvantages. Although as noted above the infrastructure for producing ammonia is in place, the process of cracking it is still relatively new and not energy efficient. Moreover, after cracking, additional steps are required to purify the hydrogen for use. In addition, some concerns have been expressed about the fact that ammonia is a toxic substance which, in the case of leaks, could have a negative impact on the air, soil, and water quality as well as the health of people living nearby.

There are a number of companies across multiple countries enabling ammonia as a hydrogen carrier. As one example, *Ammogen* in the UK is working on completing an ammonia to hydrogen project at a hydrogen refueling station at Tyseley Energy Park in Birmingham England. Based on technology developed by *H2SITE*, Ammogen will deliver 200kg/day of transport-grade hydrogen to the site. The technology uses endothermic ammonia cracking in a membrane reactor, providing high conversion efficiency. The ammonia feedstock is a hydrogen carrier for the transport and storage of hydrogen. The reduced cost and efficiency of the process is made possible by integrating the ammonia conversion, recovery, and purification process into a single unit.

Several other companies are testing ammonia carriers as well, and there is a lot of optimism about where this may lead.

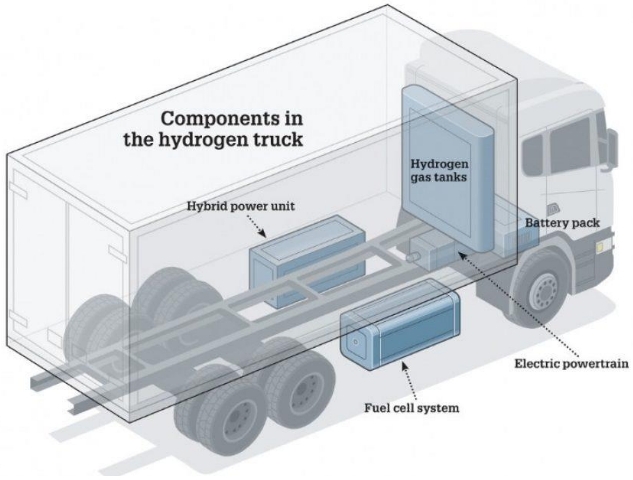
Hydrogen as a Transport Fuel

In my previous article on green hydrogen, I noted that the excitement about hydrogen as a fuel for automobiles has waned, but there is still considerable interest in hydrogen as a fuel for heavy duty trucking, as well as potentially for both aviation and maritime transportation. Let's expand on that to address the approaches being developed for hydrogen as a truck transport fuel – and its associated challenges.

There are currently 2 approaches being pursued for hydrogen fuel for trucking:

- A *hydrogen internal combustion engine vehicle (HICEV)* uses an engine very similar to a gasoline or diesel engine – but fueled by hydrogen.

- *A fuel cell hydrogen vehicle (HFCEV or FCEV)* generates electricity from hydrogen via a fuel cell and uses that electricity to power an electric motor, much like in an electric vehicle. Hydrogen fuel cells generate electricity through an electrochemical reaction between hydrogen and oxygen, which combine to generate electricity, heat, and water. One fuel cell can generate about 300 watts of power; to generate enough power to run a truck's electric motor, the fuel cells need to be combined into a fuel cell stack. Like electric vehicles, FCEVs can also capture energy through regenerative braking.



Source: Scania Group

Both approaches compete with a pure battery electric vehicle (BEV) truck for clean energy transportation.

There are multiple companies working on delivering hydrogen-powered trucks

For example, in 2022 **Cummins**, a well-known manufacturer of engines and other power generating products, debuted a 15-Liter hydrogen internal combustion engine (shown below) at the ACT (Advanced Clean Transportation) Expo. The engine, which is designed for heavy-duty trucks and shares the same platform as Cummins natural gas engine, is rated at 590 hp. Cummins gave 2027 as the date for widespread availability.

Image Courtesy of Cummins

In 2022 Cummins also introduced the B6.7H hydrogen engine – in a Mercedes truck - at the IAA Transportation Exhibition. This engine is rated at 290 hp and features a 700-bar pressure high-capacity hydrogen storage system. It is designed for medium trucks in the 10-to-26-ton gross vehicle weight range. Cummins projects a potential operating range of up to 500-kilometres.

Transportation and logistics provider Werner Enterprises signed a letter of intent in 2022 to purchase 500 Cummins' 15-liter hydrogen internal combustion engines upon availability. The project will start with Werner validating and integrating Cummins' X15H hydrogen engine (as well as their natural gas engine), into their fleet beginning in late 2023.

Indian company **Reliance Industries** along with partner **Ashok Leyland** introduced a hydrogen combustion engine for heavy-duty trucks in 2023. Several other companies have announced HICEV engines as well.

FCEVs appear to be a bit further along in the development process. Perhaps the major current player in the FCEV space is **Nikola**. In August 2023, Nikola reported that it had more than 200 orders for FCEVs from about 20 operators, some of which are trying out the trucks in demonstration programs. This included 10 vehicles ordered by J.B. Hunt, one of the US's largest trucking companies[1]. Deliveries are expected to begin before the end of the year. The official commercial launch of the Nikola hydrogen fuel

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[1] Nikola once claimed it had 14,000 reservations for hydrogen fuel cell trucks, but there is no clear evidence of that. In addition to the vehicle orders, the company announced $16.3 million in grants for hydrogen stations. It has gotten the help of more than $58 million in grants from the state of California for hydrogen fueling stations, while infrastructure startup Voltera has committed up to $1 billion for 50 hydrogen stations open to all hydrogen trucks under Nikola's Hyla brand.

cell electric vehicle happened at Nikola's manufacturing facility in Coolidge, Arizona in September 2023. Nikola claims a range of 500 miles and a refueling time of 20 minutes.

Official Nikola Launch Event

Nikola FCEV

Another company that has entered the FCEV market is **Toyota**. Toyota, in partnership with Kenworth Truck Company, successfully demonstrated their jointly designed heavy-duty, Class 8 fuel cell electric vehicle in the Zero-and Near-Zero Emissions Freight Facilities (ZANZEFF) "Shore to Store" project at the Port of Los Angeles and some neighboring areas. Kenworth designed and built the Class 8 T680 FCEVs, while Toyota designed and built the powertrain's fuel cell electric power system. The T680 FCEV has a range of about 300 miles when fully loaded to 82,000 lbs. The 10-truck pilot program was concluded in 2022, but some of the trucks have remained in use as demonstration models, including one being used to support Toyota operations in the lower LA Basin.

Toyota – Kenworth Trucks

Fairly recently Toyota's UK arm showed off a *Hilux pickup truck* built with hardware taken from their Mirai hydrogen fuel-cell automobile which has been around for almost a decade. The Hilux has three high-pressure hydrogen fuel tanks coupled with a battery and electric motors, giving the truck a range of 365 miles

The Hilux prototype – image below - was built by the consortium of Toyota Motor Europe along with **Ricardo, ETL**, **Thatcham Research**, and **D2H Advanced Technologies**. The project kicked off in 2022, but construction began in June of this year, with the team completing the prototype over the course of just three weeks.

Toyota has not provided any plans regarding introducing the vehicle into the US.

Hyzon Motors, a spin-off from Singapore-based Horizon Fuel Cell Technologies based in Rochester NY, has also announced several FCEVs. In late October 2023 Hyzon reported that it had signed a revised agreement with TR Group, New Zealand's largest heavy-duty truck fleet owner, for up to 20 FCEVs with Hyzon's single stack 200kW fuel cell system. The first 2 trucks are scheduled to be ready for trial in March 2024, and will be deployed for up to 3 months. Following the initial trial, TR Group has an option to purchase the 2 trial trucks as well as to get another 18 trucks with Hyzon's to be assembled at Hyzon's Melbourne, Australia facility. This new agreement cancels and supersedes a previously announced agreement from January 2021.

Comparison of HICEVs and FCEVs

It is generally agreed that HICEVs tend to be most efficient under heavy loads. So, for heavy-duty trucks that spend most of their time hauling large loads, HICEVs are expected to be the more efficient choice.

FCEVs, in contrast, are most efficient at lighter loads. Therefore, vehicles that frequently operate with small loads—such as tow trucks or concrete mixer trucks - may be more efficient with an FCEV.

Hydrogen fuel cells contain a higher amount of energy-per-unit mass than a lithium battery or diesel fuel. A truck can have a higher amount of energy available without significantly increasing the weight — an important consideration for long-haul trucks that have weight penalty policies.

Hyzon Truck, Courtesy of Hyzon Motors

FCEVs produce no emissions at all besides water vapor. This is a very attractive feature for vehicles operating in closed spaces or spaces with limited ventilation. While HICEVs release near zero amounts of CO_2, they can produce nitrogen oxides, or NOx. As a result, they are not ideal for indoor use. HICEVs are often able to operate with lower grade hydrogen, which could make them easier to fuel in some cases.

In October 2020, the DOE Hydrogen and Fuel Cell Technologies Office, (HFTO) launched the Million Mile Fuel Cell Truck Consortium, (M2FCT) to support opportunities for fuel cell adoption in the Heavy-Duty Truck market. M2FCT, composed of five national laboratories, is working to meet the efficiency, durability, and cost requirements of the trucking industry with $50 million in funding.

Internal combustion engines have been around for more than 100 years, so switching to hydrogen drivetrains with respect to HICEVs should be relatively straightforward for truck manufacturers and operators. That will probably prove less so for FCEVs.

That being said, stated opinions on the best way to move forward with clean energy for heavy duty trucking vary even more widely than those for the best way to transport hydrogen.

For example, the former CEO and co-founder of Hyzon Motors, Craig Knight, strongly argued that hydrogen fuel cells are the only viable carbon-free solution to long-distance trucking[2].

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[2] Hyzon Motors has been accused of fraud for overstating its orders and customer list and is in danger of being delisted by NASDAQ. These issues led to the ouster of Craig Knight last year.

"Doing a few battery electric trucks is easy; doing hundreds is near impossible," Knight was quoted as saying by *Recharge*. "Doing a few fuel-cell trucks is a pain in the butt; doing hundreds is a walk in the park."

He says that those advocating against long-distance fuel-cell trucks and in favor of battery-electric versions, such as Germany's **Fraunhofer Institute for Systems and Innovation Research,** are missing several key points:

- Electric grids will not be able to cope with the sheer amount of electricity required to fast-charge multiple battery trucks at the same time;
- Longer charging times for battery trucks means that an all-electric system would require eight times as many charge points as a fuel-cell truck network;
- Long-range truck batteries are very heavy, reducing the efficiency and adding to the cost of transporting goods over long distances;
- It should be easier and cheaper to increase the range of a fuel-cell truck than a battery one;
- Batteries require more hard-to-obtain raw materials – such as lithium - than fuel cells;
- Low-cost green hydrogen can be produced locally from waste, or made from excess electricity, taking pressure off the grid, and removing the need to transport hydrogen across long distances.

Taking a very different position, the head of Cummins' HICEV program was reported by *Hydrogen Insight* as having said that a risk-averse industry like heavy trucking is reluctant to decarbonize at all, but since it needs to move in that direction, hydrogen internal combustion engines are both more familiar than a BEV electric drivetrain and less capital intensive. He stated that freight companies would rather pay less upfront — even if it costs them more money in the long run.

He also noted that a HICEV truck is projected to cost about 50% more than a diesel equivalent even a few years but claims that a FCEV truck would cost double that and a BEV truck with a 500-mile range would cost roughly 120% more than a diesel.

Projections of the upfront costs of zero emission heavy-duty trucks vary widely, and Cummin's numbers are very different from those of DOE, for example. DOE recently estimated the cost of a heavy-duty BEV at $457,000, vs. $265,000 for an FCEV and $160,000 for a diesel. Automotive News suggested that a heavy-duty BEV costs $400,000, vs. $420,000 for an FCEV and $250,000 for a HICEV – the latter number more closely matching Cummin's estimate. To make the numbers even murkier, in a separate report DOE projects that medium and heavy-duty BEVs will be cheaper than diesel-powered trucks by 2035.

In an interview with Hydrogen Insight, the Cummin's representative went on to contrast HICEV and FCEV by stating that "fuel cells have more heat generation, so they run hotter; you have to put more energy towards the cooling fans and they degrade over time. An engine doesn't really age, but a fuel cell will age, and it won't be as efficient at the end of its life compared to its beginning." He also said that combustion engines are less likely to be affected by dusty environments, or hydrogen impurities that could "poison" a fuel cell.

He claimed that trucking firms - such as Werner Enterprises which has pre-ordered Cummins' hydrogen internal combustion engines as noted above - are attracted by the familiarity of a combustion engine, which requires very little operator retraining.

And then, as the former CEO of Hyzon was quoted above as saying, the Fraunhofer Institute for Systems and Innovation Research has a totally different perspective. According to renewable energy site Recharge, Fraunhofer has noted that 30,000 battery-electric trucks are already deployed globally (albeit mostly in China). By contrast, FCEVs from a handful of manufacturers have only been operated in test trials to date and are not yet really commercially available. Several truck manufacturers and fuel-cell developers have jointly announced a target of 100,000 fuel-cell trucks on European roads by 2030, but Fraunhofer argues that this seems unlikely given announcements that indicate the earliest start date for the commercial production of most fuel-cell electric trucks is 2027 - by which time second-generation BEVs will already be in operation. They noted several studies indicating that the total ownership costs for fuel-cell trucks will be higher than for battery-powered models – even with more powerful and expensive charging systems expected to hit the market.

Fraunhofer acknowledges that there is a challenge for BEVs in terms of long-haul operations and transport of very heavy goods, and that this is the use case often discussed for hydrogen trucks. While noting that FCEVs could still have a practical advantage for "really heavy transport in remote areas", Fraunhofer questions whether such areas are large enough to sustain the commercialization and the economies of scale required to produce fuel cell electric trucks and their infrastructure.

A Fraunhofer researcher is quoted as saying: "If truck manufacturers do not start the mass production of fuel cell trucks soon to reduce costs, such vehicles will never succeed in low-carbon road transport. Policymakers and industry need to decide quickly whether the fuel-cell electric truck niche is large enough to sustain further hydrogen technology development, or whether it is time to cut their losses and focus efforts elsewhere":

Fraunhofer's position is seconded by Professor David Cebon, director of the Center for Sustainable Road Freight at the University of Cambridge in England. He has noted that hydrogen fuel cell trucks are double the price of battery electric trucks. Both technologies require an electric drive train, lithium-ion battery, and inverter, but an FCEV also requires a fuel cell, hydrogen storage tanks, and hydrogen delivery equipment, which are much more complex and costly than the larger battery capacity needed by a BEV.

Source: YouTube Video with Prof. Cebon

He goes on to say that converting renewable electricity into hydrogen via electrolysis, compressing and storing the hydrogen, and then running it through a fuel cell to generate electricity to drive an electric motor has an overall efficiency of around 23%. By contrast, for every 100kWh of energy generated, around 69 kWh reaches the wheels of a BEV. Consequently, the FCEV requires three times more renewable electricity to drive it the same distance as a BEV. This means that it will cost at least three times more to provide the energy for an FCEV than for a BEV. And the additional complex components on FCEVs will undoubtedly mean that they are more expensive to maintain than BEVs. He concludes that FCEVs will likely require about double the CAPEX and at least triple the OPEX of BEVs into the foreseeable future.

And just to confuse things further, there is a company called **Verne** working on enhanced cryo-compression techniques. Verne is building a high-density, low-cost hydrogen storage system for heavy-duty trucks. Verne reports that their cryo-compression technology (combining compression and cryo-temperatures) maximizes hydrogen density for heavy duty vehicles which more than doubles the hydrogen in each tank compared to standard H2 compression solutions. They claim that vehicles with Verne hydrogen storage will achieve ranges at least comparable to diesel (while maintaining similar weight), reaching from 450-900 miles - and therefore longer distanced than BEVs.

So, the future of hydrogen as a fuel for trucking is clear.

Not.

In Summary

Both the transport of hydrogen and the use of hydrogen as a transport fuel clearly have many challenges. There also seem to be extremely diverse opinions on the best way to tackle the issues.

That being said, there is clearly progress being made on both fronts. New approaches to transporting hydrogen, such as using ammonia or methanol as a carrier, may drive down costs significantly. Improvements to the more standard approaches of transporting liquid hydrogen or compressed gas are being made as well.

In terms of hydrogen as a fuel for trucking, both Hydrogen Internal Combustion Engine Vehicles and Hydrogen Fuel Cells Electric Vehicles are essentially in their infancy. Therefore, we can expect significant enhancements to be made over the coming several years.

So, while challenges on both fronts remain formidable, with the number of companies tackling the challenges there is room for some optimism. By the time Green Hydrogen becomes cost competitive with the less green approaches to creating hydrogen it should be easier to transport the hydrogen to its final destinations, and to use they hydrogen in the trucking industry – and elsewhere.