International Journal of Engineering Research And Management (IJERM)
ISSN: 2349- 2058, Volume-04, Issue-01, January 2017

Assessment of Hydrogen Infrastructure and Cryo-Compressed Hydrogen Storage Tank Systems

Ritesh Kumar

***Abstract*— This paper consists of a detailed study of the existing technologies for the production of hydrogen as a fuel, its storage and transportation. It also comprises of the various transportation and storage techniques which were deployed in some countries in the past and being deployed in the present. Finally, it concludes with the challenges faced by these technologies and the directions for further research.**

I. INTRODUCTION

A hydrogen infrastructure refers to the infrastructure of pipes and stations for distribution and sale of hydrogen fuel. It would consist mainly of industrial hydrogen pipeline transport and hydrogen-equipped filling stations like those found on a hydrogen highway. Hydrogen stations which were not situated near a hydrogen pipeline would get supply via hydrogen tanks, compressed hydrogen tube trailers, liquid hydrogen trailers, liquid hydrogen tank trucks or dedicated onsite production.

Most hydrogen used presently is produced at or close to where it is usedtypically at large industrial sites. As a result, there is not yet an effective infrastructure for distributing hydrogen to the nationwide network of fueling stations required for the widespread use of fuel cell vehicles.

Currently, there are three methods for the distribution of hydrogen:

- Pipeline: This least-expensive way to deliver large volumes of hydrogen is limited with only few thousand miles of pipelines located near large petroleum refineries and chemical plants.
- High-Pressure Tube Trailers: Transporting compressed hydrogen gas by truck, railcar, ship, or barge in high-pressure tube trailers is expensive and used primarily for distances of 200 miles or less.

Liquefied Hydrogen Tankers: Cryogenic liquefaction enables hydrogen to be transported more efficiently over longer distances by truck, railcar, ship, or barge compared with using high-pressure tube trailers, even though the liquefaction process is expensive.

II. TERMINOLOGIES RELATED TO HYDROGEN

A. Hydrogen Pipeline Transport

Hydrogen pipeline transport is a transportation of hydro-gen through a pipe as part of the hydrogen infrastructure. Hydrogen pipeline transport is used to connect the point of hydrogen production or delivery of hydrogen with the point of demand. Pipeline transport costs are similar to CNG, the technology is proven. However most hydrogen is produced on the place of demand with every 50 to 100 miles (80 to 161 km) having an industrial production facility.

Development of pipelines:

- 1938 : Rhine-Ruhr The first 240 kms hydrogen pipes that are constructed of regular pipe steel, compressed hydrogen pressure 210-20 bars (21,000-2,000 kPa), diameter 250-300 millimetres. Still in operation.
- 1973 : 30 km pipeline in Isbergues, France.
- 1985 : Extension of the pipeline from Isbergues to Zeebrugge.
- 1997 : Connection of the pipeline to Rotterdam.
- 1997-2000 : Development of two hydrogen networks, one near Corpus Christi, Texas, and one between Freeport and Texas City.
- 2009 : 150-mile (240 km) extension of the pipeline from Plaquemine to Chalmette.

B. Hydrogen Station

A hydrogen station is a storage or filling station for hydrogen, usually located along a road or hydrogen highway, or at home as part of the distributed generation resources concept. The stations are usually intended to power vehicles, but can also be used to power small devices. Vehicles use hydrogen as fuel in one of several ways, including fuel cells and mixed fuels like HCNG. The hydrogen fuel dispensers dispense the fuel by the kilogram. Hydrogen stations which are not situated near a hydrogen pipeline get supply via hydrogen tanks, compressed hydrogen tube trailers, liquid hydrogen trailers, liquid hydrogen tank trucks or dedicated onsite production. Some firms as ITM Power are also pro-viding solutions to make your own hydrogen (for use in the car) at home.

C. Hydrogen highway

A hydrogen highway is a chain of hydrogen-equipped fill-ing stations and other infrastructure along a road or highway which would allow hydrogen powered cars to travel. It is an element of the hydrogen infrastructure that is generally assumed to be a pre-requisite for mass utilization of hydrogen cars. Many companies are working to develop technologies that might efficiently exploit the potential of hydrogen energy for mobile uses. The attraction of using hydrogen as an energy currency is that, if hydrogen is prepared without using fossil fuel inputs, vehicle propulsion would not contribute to carbon dioxide emissions. The drawbacks of hydrogen use are low energy content per unit volume, high tank weights, very high storage vessel pressures, the storage, transportation and filling of gaseous or liquid hydrogen in vehicles, the large

Manuscript received Jan 25, 2017
Ritesh Kumar, Department of Civil Engineering (B.Tech), IIT Delhi

investment in infrastructure that would be required to fuel vehicles, and the inefficiency of production processes.

Development in U.S.: 70% of the U.S. population lives near a hydrogen-generating facility but has little access to hydrogen, despite its wide availability for commercial use. The distribution of hydrogen fuel for vehicles throughout the U.S. would require new hydrogen stations that would cost, by some estimates approximately 20 billion dollars and 4.6 billion in the EU. Other estimates place the cost as high as half trillion dollars in the United States alone. The California Hydrogen Highway is an initiative to build a series of hydrogen refueling stations along California state highways. As of June 2012, 23 stations were in operation, mostly in and around Los Angeles, with a few in the Bay area. South Carolina also has a hydrogen freeway project, and the first two hydrogen fueling stations opened in 2009 in Aiken and Columbia, South Carolina.

III. DISTRIBUTION OF HYDROGEN

Because of hydrogen embrittlement of steel, and corrosion, natural gas pipes require internal coatings or replacement in order to convey hydrogen. Techniques are well-known; over 2000 miles of hydrogen pipeline currently exist in the world. Although expensive, pipelines are the cheapest way to move hydrogen. Hydrogen gas piping is routine in large oil-refineries, because hydrogen is used to hydrocrack fuels from crude oil. Hydrogen piping can in theory be avoided in distributed systems of hydrogen production, where hydrogen is routinely made on site using medium or small-sized gen-erators which would produce enough hydrogen for personal use or perhaps a neighborhood. In the end, a combination of options for hydrogen gas distribution may succeed. While millions of tons of elemental hydrogen are distributed around the world each year in various ways, bringing hydrogen to individual consumers would require an evolution of the fuel infrastructure. For example, as mentioned 70% of the U.S. population lives near a hydrogen-generating facility but has little public access to that hydrogen. The same study however, shows that building the infrastructure in a systematic way is much more doable and affordable than most people think.

IV. PRODUCTION OF HYDROGEN

A. Centralized vs distributed production

In a future full hydrogen economy, primary energy sources and feedstock would be used to produce hydrogen gas as stored energy for use in various sectors of the economy. Producing hydrogen from primary energy sources other than coal, oil, and natural gas, would result in lower production of the greenhouse gases characteristic of the combustion of these fossil energy resources. One key feature of a hydrogen economy would be that in mobile applications (primarily vehicular transport) energy generation and use could be decoupled. The primary energy source would need no longer travel with the vehicle, as it currently does with hydrocarbon fuels. Instead of tailpipes creating dispersed emissions, the energy (and pollution) could be generated from point sources such as large-scale, centralized facilities with improved effi-ciency. This would allow the possibility of technologies such as carbon sequestration, which are otherwise impossible for mobile applications. Alternatively, distributed energy genera-tion schemes (such as small scale renewable energy sources) could be used, possibly associated with hydrogen stations. Aside from the energy generation, hydrogen production could be centralized, distributed or a mixture of both. While generating hydrogen at centralized primary energy plants promises higher hydrogen production efficiency, difficulties in high-volume, long range hydrogen transportation (due to factors such as hydrogen damage and the ease of hydrogen diffusion through solid materials) makes electrical energy distribution attractive within a hydrogen economy. In such a scenario, small regional plants or even local filling stations could generate hydrogen using energy provided through the electrical distribution grid. While hydrogen generation efficiency is likely to be lower than for centralized hydrogen generation, losses in hydrogen transport could make such a scheme more efficient in terms of the primary energy used per kilogram of hydrogen delivered to the end user. The proper balance between hydrogen distribution and long-distance electrical distribution is one of the primary questions that arises about the hydrogen economy. Again the dilemmas of production sources and transportation of hydrogen can now be overcome using on site (home, business, or fuel station) generation of hydrogen from off grid renewable sources.

B. Distributed electrolysis

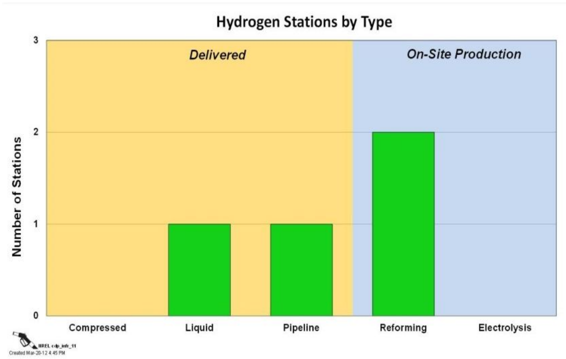
Distributed electrolysis would bypass the problems of distributing hydrogen by distributing electricity instead. It would use existing electrical networks to transport electricity to small, on-site electrolyzers located at filling stations. How-ever, accounting for the energy used to produce the electricity and transmission losses would reduce the overall efficiency. Natural gas combined cycle power plants, which account for almost all construction of new electricity generation plants in the United States, generate electricity at efficiencies of 60 percent or greater. Increased demand for electricity, whether due to hydrogen cars or other demand, would have the marginal impact of adding new combined cycle power plants. On this basis, distributed production of hydrogen would be roughly 40% efficient. However, if the marginal impact is referred to today's power grid, with an efficiency of roughly 40% owing to its mix of fuels and conversion methods, the efficiency of distributed hydrogen production would be roughly 25%. The distributed production of hydrogen in this fashion would be expected to generate air emissions of pollutants and carbon dioxide at various points in the supply chain, e.g., electrolysis, transportation and storage. Such externalities as pollution must be weighed against the potential advantages of a hydrogen economy.

C. Homefueller

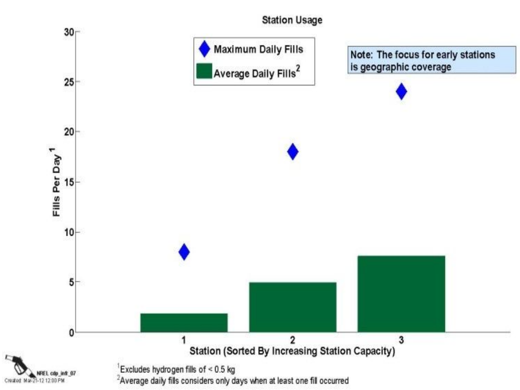
Homefueler is a home hydrogen station. It uses single phase AC power and water for the pressurized alkaline electrolyzer to generate hydrogen, a diaphragm compressor handles a filling pressure of 5,000 psig (350 bar). Storage is 13 kg, daily production is 2 kg H_2. The hydrogen dispensing system is aimed at providing enough energy for 1 - 2 cars.

D. Hydrogen Fueling Infrastructure Analysis

As the market grows for hydrogen fuel cell electric vehicles, so does the need for a comprehensive hydrogen fueling infrastructure. NREL's technology validation team is analyzing the availability and performance of existing hydrogen fueling stations, benchmarking the current status, and providing feedback related to capacity, utilization, station build time, maintenance, fueling, and geographic coverage. Participating partners (from the U.S.) hydrogen fueling sta-tion industry share raw data with NREL. NREL engineers perform uniform analyses on the detailed data and then report on their findings. Following data is from NREL:



Hydrogen stations in US



Number of fills

Meeting Vehicle Needs:

- Location/Capacity/Utilization: Stations need to provide coverage to meet needs of vehicle drivers in pre-commercial stage as well as have hydrogen availability with minimal wait time.
- Fueling: Vehicles need to be fueled in an acceptable amount of time.
- Maintenance/Availability: Maintenance and other factors may cause station downtime and increase cost.
- Cost: Hydrogen cost is dependent on several factors including where produced, how delivered, efficiencies and maintenance requirements.
- Station Timing: Need enough lead time to build infras-tructure to meet vehicle demand.

V. PRESENT DISTRIBUTION SCENARIO

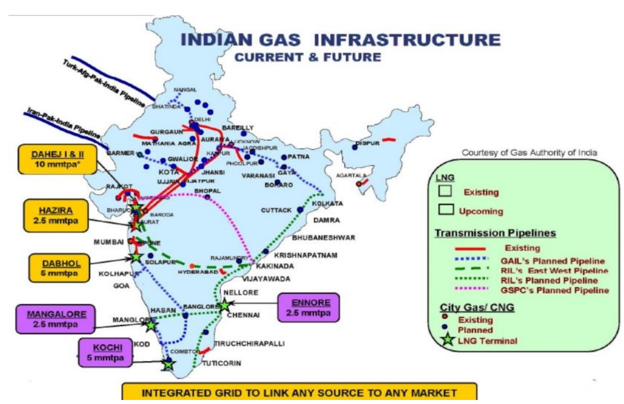
Suppliers currently transport hydrogen by pipeline or over roadways using tube trailers or cryogenic liquid hydrogen tankers. In special cases, liquefied hydrogen is transported by barge. Hydrogen is also moved using chemical carriers substances composed of substantial amounts of hydrogen as well as other elements; for example, ethanol(C_2H_5OH) and ammonia (NH_3). Several pipelines have been built in the U.S., specifically near large petroleum refineries and chemical plants in Illinois, California, and along the Gulf Coast. However in comparison with the more-than-one mil-lion miles of natural gas pipelines, the current hydrogen pipeline infrastructure in the U.S. is very small, less than 1,200 miles in length.

Hydrogen gas is also compressed and transported over the road in high-pressure tube trailers. This option is used primarily to move modest amounts of hydrogen over rela-tively short distances. It tends to become cost prohibitive when these distances are greater than approximately 200 miles from the point of production. By comparison, for a given volume, liquefied hydrogen (hydrogen that has been cooled to $-253\ ^{\circ}C$) is more dense and contains greater energy content than gaseous hydrogen. In the absence of an existing pipeline, this option is the preferred method of delivering hydrogen over long distances. However, liquefaction is costly because the process requires a substantial amount of energy.

A cryogenic tank truck

Nonetheless, due to the limited amount of pipeline avail-able, hydrogen is often transported as a liquid in super-insulated, cryogenic tank trucks and later vaporized for use at the customer site.

VI. PRESENT INFRASTRUCTURE IN OUR COUNTRY



Hydrogen infra-structure in India

Hydrogen fuelling station by IOCL in India:

- A total of 170 Hydrogen fuelling stations have been setup globally.
- An electrolyzer based Hydrogen production of 5mm^3/h and dispensing station has been set up by IOCL in its R&D centre at Faridabad, near New Delhi.
- IOCL is setting up one more such dispensing station in New Delhi.
- IOCL intends to setup two SMR based Hydrogen production (100nm^3/h capacity each) and dispensing stations in New Delhi within next two years.

Hydrogen Fueling Stations

Location	Fuel	Project	Partners	Dates	H2 Production Technique	Specifics/ Comments	Picture
Faridabad, India	HCNG blend & pure H2	Hydrogen Fueling Station at Indian Oil Corporation Ltd's R&D Center	Indian Oil Corporation, Ltd., Air Products and Chemicals, Inc., INOX Air Products	Opened October 2005	Uses APCI's HCNG mixing unit and dual dispensing unit that can fuel vehicles with either a HCNG blend or pureH2.	Station owned by Indian Oil Corporation. First phase of India's development of its hydrogen economy.	
Delhi, India	H2/CNG	Indian Oil Corporation hydrogen station	Indian Oil Corp	To be opened by 2010	Will deliver a 20:80 percent hydrogen: CNG mix	Will be located near the Commonwealth Games Village and be capable of fueling 100 vehicles.	
New Delhi, India	N/a	Hydrogen station	ICHET, UNIDO, IIT-Delhi	Two-year demonstration to start in July 2010	Will use Air Products refueling equipment	Will fuel a fleet of 15 Mahindra & Mahindra 3-wheeled H2 vehicles that will transport visitors at the Pragati Maidan public exhibition hall.	

Hydrogen fuelling stations in India

VII. CHALLENGES AND RESEARCH DIRECTIONS

For a given volume, hydrogen contains a smaller amount of usable energy than other fuels such as natural gas and gasoline. Because of its low volumetric energy density, hydrogen is comparatively more costly to transport and store. As mentioned, the primary means of reducing the as-delivered cost of hydrogen, via pipeline transmission, is currently lacking. Principally, this is because of the large initial capital investment required to construct a new pipeline infrastructure. However, there are also a number of technical concerns with pipeline transmission of hydrogen over long distances, including: the potential for hydrogen embrittlement in the base steel and in the welds used for pipeline construction, the need for lower cost/higher reliability hydrogen compression technology, and the desire to prevent hydrogen permeation and leakage from pipeline and other containment materials. The method by which hydrogen is produced also affects the cost and method of delivery. Distributed production at the point of use, such as directly at refuelling stations or at stationary power sites, eliminates the transportation costs for hydrogen delivery. Conversely, production in large central plants requires long-distance transport that increases delivery costs. However the latter approach also results in lower production costs due to greater economies of scale; i.e., the cost of production and delivery must be analyzed together.

Researchers are working to better understand the options and trade-offs for hydrogen delivery from central, semi-central, and distributed production sites under various trans-mission and transportation scenarios.

Research is also focused on developing:

- Lower-cost, more reliable hydrogen compression technology
- More cost-effective bulk hydrogen storage technology New materials for lower-cost hydrogen pipelines
- More energy-efficient and lower-cost hydrogen liquefaction processes
- Integrated production, delivery, and end-use technologies

Building a global hydrogen delivery infrastructure is a significant challenge. It will take time to develop and will likely include various combinations of technologies. Infras-tructure needs and resources will vary by region and by type of market; e.g., urban, interstate, or rural, and infrastructure options (or the delivery mix) will continue to evolve as the demand for hydrogen grows and as delivery technologies develop and mature.

REFERENCES

[1] Life-Cycle Analysis of Energy Systems: From Methodology to Appli-cations, 2011, Bent Srensen

[2] Hydrogen and Fuel Cells, 1st ed., 2005, Bent Srensen

[3] Life-cycle analysis of energy systems (with Kuemmel and Nielsen), 1997 Blegdamsvej 17, 1989, Bent Srensen

[4] Hydrogen and Fuel Cells, Emerging technologies and applications, Second Edition, Bent Srensen

[5] Abe, A., Nakamura, M., Sato, I., Uetani, H., Fujitani, T. (1998). Studies of the largescale sea transportation of liquid hydrogen. Int. J. Hydrogen Energy 23, 115-121.

[6] Adamson, K-A., Pearson, P. (2000). Hydrogen and methanol: a comparison of safety, economics, efficiencies and emissions. J. Power Sources 86, 548-555

[7] Ahluwalia, R., Hua, T., Peng, J-K., Lasher, S., McKenney, K., Sinha, J., Gardiner, M. (2010). Technical assessment of cryo-compressed hydrogen storage tank systems for automotive applications. Int. J. Hydrogen Energy 35, 4171-4184.

[8] Ahluwalia, R., Wang, X., Rousseau, A., Kumar, R. (2004). Fuel economy of hydrogen fuel cell vehicles. J. Power Sources 130, 192-201.

[9] Akansu, S., Dulger, Z., Kahraman, N., Veziroglu, T. (2004). Internal combustion engines fueled by natural gas-hydrogen mixtures. Int. J. Hydrogen Energy 29, 1527-1539

[10] https://energy.gov/eere/fuelcells/hydrogen-storage

[11] https://www.ncbi.nlm.nih.gov/pubmed/15085273