HYDROGEN AS AN ENERGY CARRIER - ITS PROMISES AND CHALLENGES*

Rakesh Agrawal
Air Products and Chemicals, Inc.
7201 Hamilton Blvd.
Allentown, PA 18195-1501

Abstract

The promise of hydrogen resides in its being a clean and efficient energy source. This paper examines this promise in the context of hydrogen production, transportation, delivery and end use. Several fossil fuel feedstocks as well as renewable sources are examined. The cost and efficiency analysis as well as a potential market scenario for the development of light duty vehicles using hydrogen fuel cells are presented from a recent NRC report (2004). Multiple challenges associated with the implementation of hydrogen for the light duty vehicles are discussed. This presents a number of exciting research opportunities for most chemical engineers including process systems subgroup.

Keywords

Hydrogen, Fuel cells, Hydrogen economy

Introduction

President Bush's proposal to spend $1.7 billion over the next five years to develop hydrogen vehicles and the associated infrastructure has drawn national attention to the use of hydrogen as an energy carrier (Abraham, 2003). The promise of hydrogen as an energy carrier resides in its clean conversion to power. There are no emission of pollutants or carbon dioxide and water is the only by product. This clean and efficient conversion to power has led a number of nations to increase their R&D effort towards the use of hydrogen as an energy feedstock.

While there are strong proponents for hydrogen economy, it also has strong detractors (Eliasson and Bossel, 2002; Shinnar, 2003). The criticism stems from the fact that hydrogen needs to be produced, packaged, transferred, delivered and stored. It has been said that most of these steps are energetically inefficient and expensive. Furthermore, if hydrogen were to be produced from certain fossil fuels then the inefficiencies can potentially lead to greater CO_2 emissions. Based on inefficiencies and cost, the argument has been made to not pursue goal of hydrogen economy.

*The opinion expressed in this paper does not necessarily reflect those of Air Products and Chemicals, Inc.

Due to differing views, the US National Academy of Engineering and the National Research Council (NRC), at the request of the US Department of Energy, set up a committee to study the pros and cons of the use of hydrogen as a primary energy carrier.[1] The committee recently issued its report that is available at the www.nap.edu website (NRC, 2004). The committee primarily studied the use of hydrogen for the light duty vehicles (LDVs) within the United States. Nearly one-third of the total energy used within the USA is consumed by the transportation sector. All the major aspects of hydrogen economy such as availability of the feedstocks, production, transportation, delivery and storage of hydrogen, as well as, transition scenarios for the evolution of hydrogen cars were considered in detail.

The objective of this paper is to present a glimpse of the major findings of the NRC report on hydrogen economy along with the challenges and opportunities for the process systems community. The first step in the hydrogen economy chain is production of hydrogen, followed by transportation, delivery to LDVs and on board storage of the vehicles. The next step is the use of

[1] The author was a member of this NRC committee.

hydrogen in the fuel cells to drive the vehicles. Issues such as availability of the feedstocks to produce hydrogen, energy efficiency of the total supply and use chain, i.e. from the feedstock recovery at its source to the end use in the automobiles (well-to-wheel), total carbon emissions and total cost of the various systems are discussed in detail. Each step in the chain has its challenges and provides opportunities for research and development.

Estimated Cost of Delivered Hydrogen

Hydrogen is generally produced from fossil fuels such as natural gas and coal (Dicks, 1996; Kwon et al, 1999). Attempts are underway to develop processes for hydrogen production from the biomass gasification/reforming (Bridgewater, 2003; Cortright et al, 2002). Hydrogen can also be produced from the electrolysis of water. The electricity needed for electrolysis can come directly from the existing grid or from wind, nuclear, and solar energy (photovoltaic cells). Nuclear reactors coupled with a thermochemical process for hydrogen production are also being developed.

The NRC report (2004) estimated the cost of hydrogen production on a consistent basis for each of the above feedstocks. Several scenarios were considered. First, three plant sizes were studied - (*i*) a 1.2 million kg/d central station plant to support about 2 million cars, (*ii*) a 24,000 kg/d midsize plant to support about 40,000 cars and (*iii*) a 480 kg/d distributed plant to support approximately 800 cars. Also costs associated with delivery and dispensing of H_2 to vehicles for each scenario was calculated. For large central station plants, delivery through pipelines were envisioned (Ogden, 1999). For midsize plants, liquid hydrogen tankers were used for delivery of hydrogen to the forecourts (equivalent to the current gasoline stations) (Campbell and Keenan, 2003). Distributed plants were assumed to be located at the forecourts and made hydrogen directly at the site. Figure 1 shows the unit cost of delivered hydrogen for various cases. The costs are shown for the current technology as well as for the future with anticipated technological advances. For future cost calculations, a collective judgment was made regarding the anticipated advances in each technology. An imputed cost of \$50 per ton of carbon emitted was also imposed. The details of the cost parameters and the description of each technology can be found in the NRC report.

In Figure 1, for comparison purposes, cost of gasoline after efficiency adjustments is also shown. The basis of efficiency adjustment is as follows: first, a gallon of gasoline has practically same energy content as a kg of H_2; second, fuel cell vehicles (FCVs) have been assumed to give a 66% efficiency gain when compared to gasoline hybrid electric vehicles (GHEVs). Thus cost of a 1.66 gallons of gasoline is compared to a kg of H_2. This allows the cost comparison based on same distance driven by each type of vehicle. It is readily seen from Figure 1 that both the current and future costs of delivered H_2 from natural gas and coal are expected to be quite comparable to that of gasoline. The future cost from a nuclear plant using thermochemical process is also expected to be similar. H_2 via electrolysis using grid electricity is expensive. In the future, wind has a potential to provide cost comparable to that of gasoline. On the other hand, biomass gasification as well as photovoltaic-electrolysis will require breakthrough technologies to be competitive.

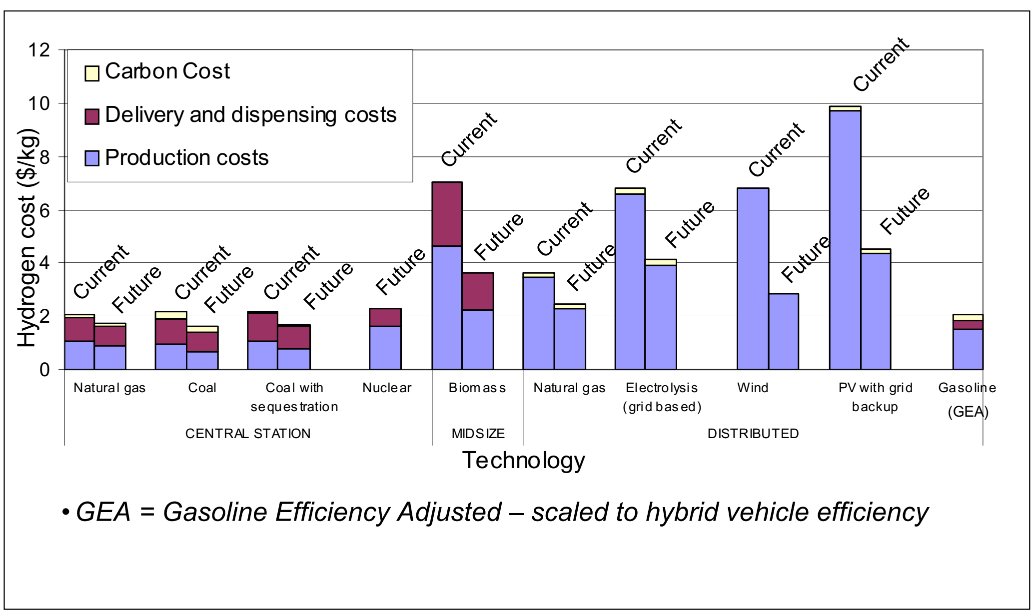

Figure 1: Delivered unit hydrogen costs from various feedstocks. (from the NRC report, 2004)

Estimated Overall System Efficiency

For hydrogen economy to take off, issues other than cost also need to be addressed. One such issue is the overall system efficiency. Energy is consumed in the recovery of a fossil fuel feedstock from underground and then its transportation to a H_2 plant. Energy is not only needed for the conversion to H_2 but also for the transportation and delivery of H_2 to a LDV. Ultimately some energy is wasted due to the inefficiencies in the fuel cell system. Therefore, it is of great interest to compare the overall energy consumed per unit distance driven by a H_2-LDV to that of a GHEV. Several studies are available in the literature (Wang, 2002).

In order to be consistent with the cost numbers presented in Figure 1, the corresponding overall energy consumed to drive a unit distance (BTU/mile) of a H_2 fuel cell LDV is reproduced from the NRC report in Figure 2. In this figure, the energy used for the recovery and delivery of natural gas to the reforming plant site is not included. Therefore, the actual numbers for the natural gas will be about 10% higher than the ones shown in the figure. The gasoline number is for a GHEV. The anticipated total energy use by a H_2 fuel cell LDV, when a fossil fuel is used as feedstock, is very similar to that of a GHEV. As expected, the electrolysis case using grid electricity is clearly inefficient (grid electricity has been assumed to be generated at 50% efficiency). Majority of the energy used for biomass comes from the biomass itself. Since biomass is a renewable energy, the major impact of the lower efficiency is in the increase of land use to grow the biomass. The energy usage for the current wind and both the PV cases are due to the use of grid electricity as backup power. The intermittent nature of wind and solar energy leads to partial utilization of the electrolyzer. To decrease the overall cost of hydrogen, electricity off the grid was used to operate electrolyzers around the clock. For the future wind case, enough advancement and reduction in the wind turbine electricity and electrolyzer costs are projected that it will be not necessary to operate the equipment around the clock. Therefore, future wind case does not show any energy use (from sources other than wind).

In a nutshell, Figure 2 shows that when compared to gasoline, the production of H_2 from fossil fuels can potentially lead to some gain in the overall energy efficiency. The renewables such as wind and solar need substantial cost improvements to avoid the use of backup grid electricity and fulfill their promise of being efficient while being cost effective. For solar PV modules, the electricity cost will have to drop below 4¢/kwh (as against current corresponding number in excess of 20¢/kwh).

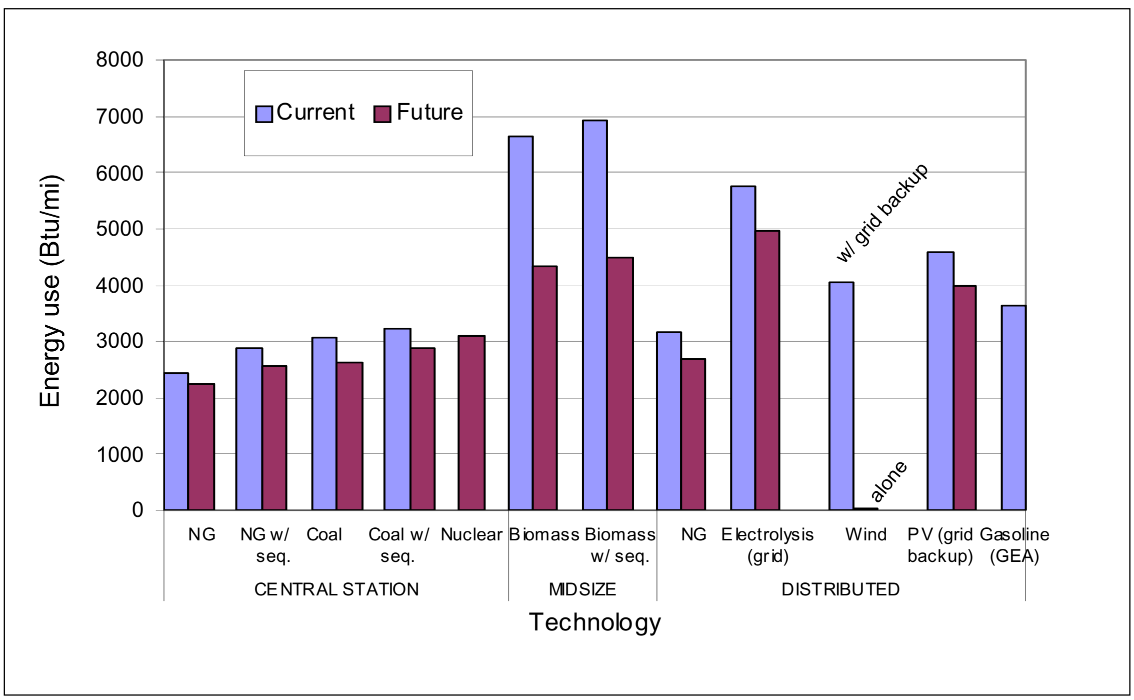

Figure 2: Overall energy used to drive a mile using H2-fuel cell LDVs. (from the NRC report, 2004)

Estimated Carbon Release

One of the factors driving the hydrogen economy is its promise to decrease carbon dioxide emission in the atmosphere. Figure 3 shows kg of carbon released per kg of H_2 used for several feedstocks using future technologies. Once again, the gasoline number in the figure is for 1.66 gallons of gasoline. It is observed that for the equidistance travel by a GHEV and a future H_2 LDV, the use of H_2 is not expected to lead to an increase in the carbon emission. The highest carbon release is when coal is used to produce hydrogen, and this number is comparable to that from gasoline. If hydrogen is produced from the fossil fuels, then for substantial reduction in carbon release, coproduct carbon dioxide from the gasification/reforming plants will have to be sequestered. On the other hand, sequestration of carbon dioxide from a biomass gasification plant has a potential to decrease carbon dioxide from the environment. Renewables such as wind and solar with no grid backup can provide hydrogen with no need to sequester carbon.

While separation and recovery of carbon dioxide from a reformer or a gasifier effluent stream can be achieved through the current technology, the sequestration of large quantities of carbon dioxide requires further work (Yamasaki, 2003). For CO_2 sequestration, use of empty gas reservoirs, unmineable coal beds and deep saline aquifers have been suggested. While there is enough capacity available, the gaps are with potential CO_2 leakage, contamination and mitigation. This requires study in geological timeframe on the integrity of sequestered well seals, monitoring etc.

Feedstock Availability

For the hydrogen economy to succeed, it is important to have a long-term availability of the feedstocks from which hydrogen is to be produced. For some nations, it can also be a national security issue to have their own indigenous supply of the feedstocks. The NRC committee specifically considered this supply issue in the context of the availability within the USA [2004]. In order to generate the demand curve for H_2 in the foreseeable future, an estimate of the penetration rate for the fuel cell vehicles is needed. While many scenarios can be generated, the committee took an optimistic posture. It assumed the same rate of penetration for the H_2 fuel cell vehicles (FCVs) as the current forecast for the GHEVs. Thus it was assumed that 1% of LDVs sold in 2015 will be FCVs, then sales will grow by 1% annually till 2024, after that market

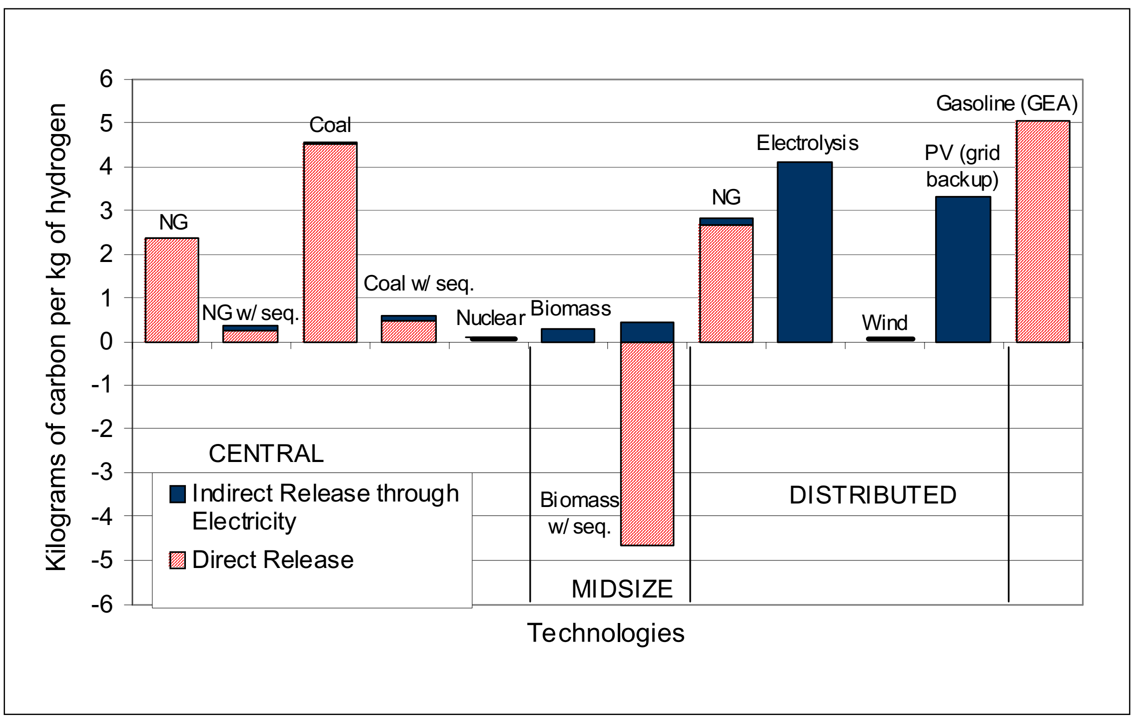

Figure 3: Total carbon released during hydrogen production, delivery, dispensing, and end use. These numbers are for future technologies. (from the NRC Report, 2004)

share will increase by 5% per year till 2034, finally this rate will increase to 10% and by 2038 all new LDVs will be FCVs. This optimistic scenario is shown in Figure 4. In this Figure, decline in the demand of conventional LDVs using internal combustion engine (ICE) is also shown. Not only the estimated sale of new vehicles is shown but also the estimated fraction of each type of vehicles on road in any given year is plotted. Since an automobile has a finite lifetime on road, it is expected that by 2050 all the vehicles on road will be FCVs. Note that this penetration rate is similar to the one currently forecasted for the GHEVs. Since no new supply infrastructure is to be built for the GHEVs, the FCVs scenario is an optimistic one and provides a fast penetration rate for the FCVs.

The USA market penetration curves for the FCVs in Figure 4 can then be used to generate corresponding hydrogen demand curve. For this purpose, some additional assumptions were made. The important one being that the existing conventional vehicles achieved an average of 21 miles per gallon of gasoline in 2002, and their fuel efficiency to increase by 1% per year during the entire time horizon. The GHEVs are estimated to have a 45% higher fuel economy than the conventional ICEs. As stated earlier, the FCVs are assumed to further have an increase of 66% over GHEVs. With further future assumptions of the average annual distances traveled by LDVs, the hydrogen demand curve in Figure 5 was generated (NRC, 2004). In this optimistic scenario, by the year 2050, LDVs in the USA would be consuming nearly 100 billion kilograms of H_2 per year. For comparison, the current annual U.S. industrial production of hydrogen is about 8 billion kilograms. Thus, if H_2 economy were to take off, the hydrogen production in the USA will have to increase by more than an order of magnitude.

It is informative to look at various feedstock availability within the USA to meet the hydrogen penetration scenario of Figure 5. According to the Energy Information Administration's (EIA's) forecast, the United States will be importing a significant fraction of the natural gas in the years 2010 onwards. Therefore, if all the hydrogen were to be produced from natural gas, then beyond the transition period of about 2030, additional natural gas will have to be imported. Therefore, in the long run, it is unlikely that a transition to hydrogen based on natural gas, would significantly improve energy independence of the USA. If all the hydrogen were to be produced from coal gasification, then by 2050, the additional quantity of coal mined would be very similar to the amount mined today. However, there are sufficient domestic coal reserves within the USA to meet the demand for quite some time. If Biomass gasification is used for the total supply of H_2, then depending on the crop yield and efficiency of the biomass gasification, the land area need is estimated to be somewhere between 300 thousand to 650 thousand square miles [NRC, 2004]. To put this in context, the current cropland used in the United States is roughly 700 thousand square miles and pastureland is about 900 thousand square miles. If pastureland is not amenable to biomass production for H_2, then this route of H_2 production will compete with the cropland. While there is ample supply of solar energy to meet the H_2 demand, the cost effectiveness is the key issue. Of course, all the H_2 need not be produced from one source, a mix of feedstocks may provide a better option.

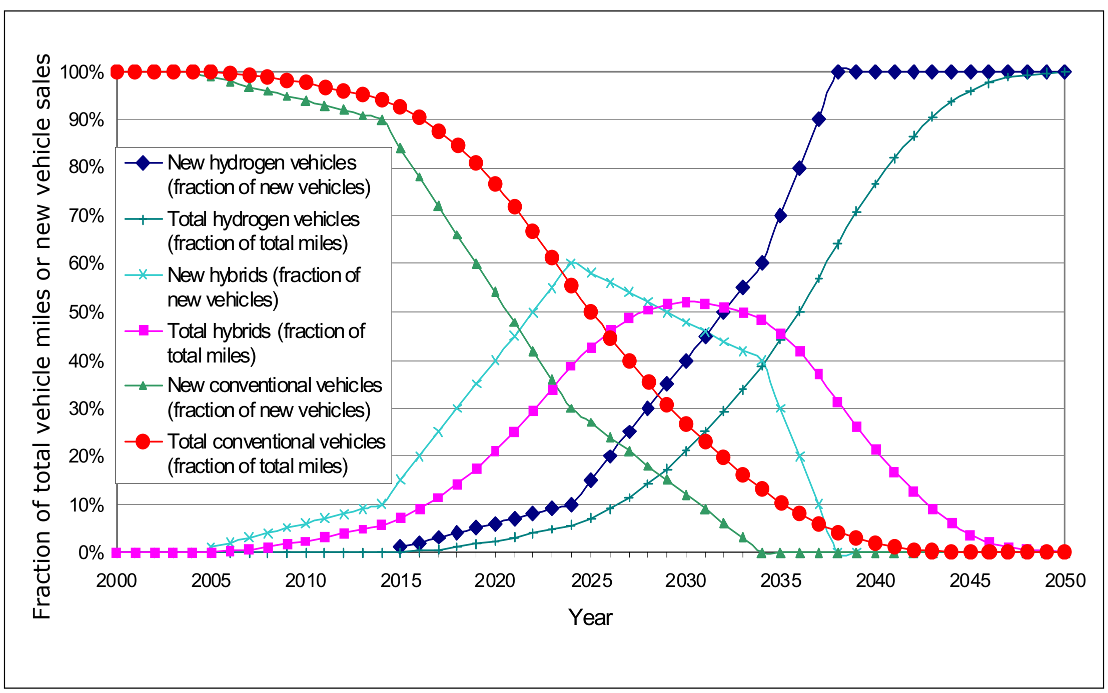

Figure 4: The optimistic fuel cell vehicle penetration curves for the USA market. (from the NRC Report, 2004)

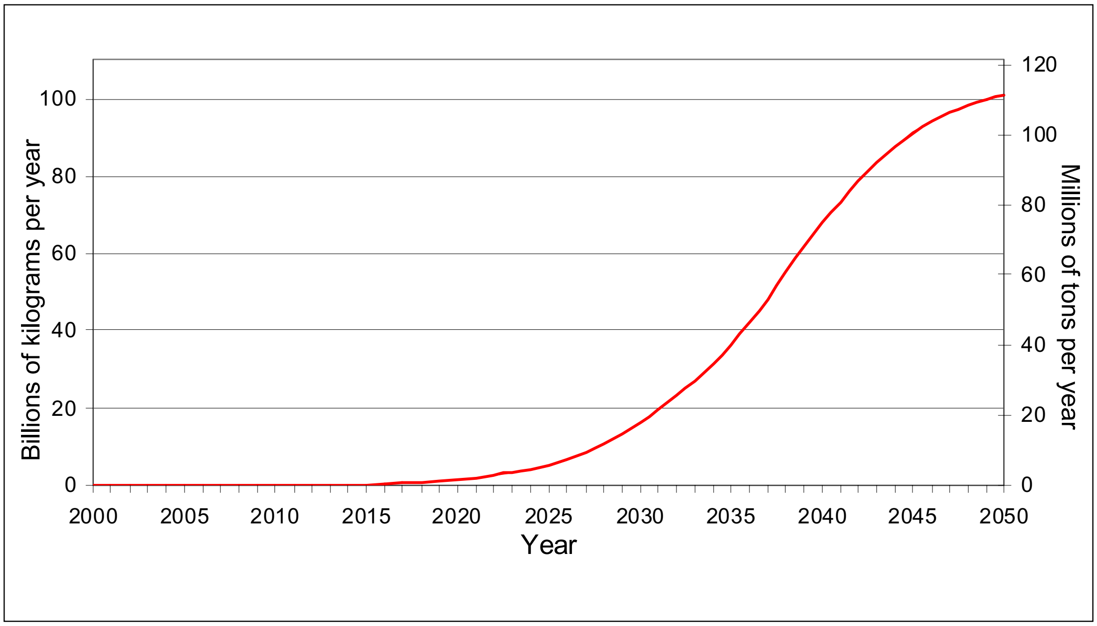

Figure 5: Demand curve for hydrogen for the optimistic scenario shown in Figure 4. (from NRC Report, 2004)

Delivery and Storage of H_2

While on a mass basis, H_2 has a high energy content (low heating value, LHV, of 33.3 kwh/kg); its volumetric energy density is considerably lower. At 680 atmospheric pressure, LHV of H_2 is about 5 kwh/gal. The same number for liquid H_2 is 8.9 kwh/gal. In contrast to this, the corresponding energy density for gasoline is 33.6 kwh/gal. This has several implications. To store the same amount of energy, hydrogen needs more space than gasoline. In a light duty vehicle with ten gallons of gasoline storage, the equivalent storage volume for 680 atm H_2 would be about 40 gallons and for liquid H_2 about 22 gallons. Compression and storage of H_2 can use energy that is equivalent to 5 to 10% of energy contained in H_2; the corresponding number for liquefaction can be around 30%. Furthermore, this also means that the transportation energy to move unit amount of energy as H_2 from a production plant to the dispensing station is considerably higher than that for gasoline. This is the primary reason for the delivery and dispensing costs for the central plant cases in Figure 1 to be comparable to the production costs. There is clearly a need to find a reversible high-density storage medium for H_2. This topic is currently a subject of intense research [DOE, 2003]. Several materials such as different forms of carbon, metal hydrides, sodium alanate etc. are being pursued. No satisfactory commercial alternative to gaseous or liquid H_2 storage is yet available.

Miscellaneous Issues

For the hydrogen economy to succeed in the LDV application, there are some additional challenges that must be met. One of them is the cost and performance improvements for the fuel cells. The current fuel cells for LDVs use polymeric proton exchange membranes. They operate around 80°C and cost in excess of \$3000/kw. In comparison, the cost of internal combustion engine used in an automobile is in the neighborhood of \$35/kw. Thus for a widespread use, the cost of fuel cells have to come below \$100/kw. This reduction in cost is to be accomplished while increasing the overall operating efficiency from about 50% to greater than 65%. Moreover, the lifetime of the fuel cells also need to be increased from today's value of less than 1000 hours to about 4000-5000 hours. Indeed these challenges provide an opportunity for research and development.

Another issue facing the H_2 economy is the development of an infrastructure to provide H_2 for the LDV use. This is 'chicken and egg' problem. For the H_2 LDVs to become popular, an established infrastructure for delivery of H_2 to the LDVs will be needed. Conversely, impetus to build an intensive H_2 infrastructure will require sufficient demand. Studies on various transition scenarios are available (Ogden, 1999; Campbell and Keenan, 2003). The early years' supply of H_2 could be made through liquid hydrogen trucks and onsite electrolysis. The transition could be met through small scale, less than 500 kg/day of H_2, onsite distributed reformers. In the long run, commercial scale central plants can produce H_2 that can be delivered through pipelines. However, the transition path is not totally clear and several options must be kept open as the use of H_2 in LDVs evolve.

Major Challenges and Research Opportunities

It is clear from the above discussion, that a number of challenges must be met for a successful evolution of the H_2 fueled LDV market. This provides several research opportunities for chemical engineers including process systems engineers. Such opportunities exist in every step of the H_2 production, supply and use chain.

In the transition period, H_2 will most likely be produced from the fossil fuels, such as natural gas and coal. Process design and product development activities can help to develop cost effective small (≈500 kg of H_2/day) onsite H_2 generators. Such onsite plants will most likely use natural gas reforming. For large size plants, process optimization activities are needed to further improve overall performance of the plants, especially if a decision is made to separate and sequester CO_2. Coproduction of electricity from such plants provide further process synthesis opportunities.

In the long run, H_2 will have to be produced from either nuclear energy or one or more renewable sources. For nuclear, the most efficient and cost effective means will be development of commercially feasible thermochemical cycles or high temperature electrolysis. Both options require not only process synthesis effort but also material development due to much higher temperatures (up to 900°C) involved. Production of H_2 or electricity from solar energy is a challenging exercise in process and product development. A big challenge is to reduce the cost. There are number of manufacturing challenges in the production of low-cost thin-film solar cells. New process opportunities are available with the advent of polymer based solar cells. Further challenge is to develop photoelectrochemical devices and/or photosynthetic microorganisms that would directly produce H_2 in a one-step process.

If by product CO_2 from the H_2 producing coal gasification plants were to be sequestered, then long term studies in the use of different reservoirs for CO_2 storage is needed. Issues such as leakage, contamination and mitigation must be addressed. Optimization studies for transportation and maximum use of reservoir capacities will have to be performed. Long-term risk analysis, monitoring and integrity of the well reservoirs in geological timeframe will be needed.

For the H_2 economy to succeed, it will require the evolution of a safe transmission and delivery infrastructure. Several options are available: trucking of liquid H_2 and/or compressed gaseous H_2, distributed onsite H_2 production, pipelines etc. The use of one or more systems over different time horizons can benefit from a systems analysis. Development of a small onsite H_2 production plant will be a good exercise in product development. Onboard storage of H_2 in a LDV and the associated heat management not only requires scientific breakthroughs but can also gain from a process systems/synthesis approach. Finally, the process community can also help in the cost reduction exercise for the fuel cells to be used in the LDVs.

Conclusions

The H_2 economy is one of the grand challenges of our time. It has a potential to fundamentally transform the U.S. energy system. One fundamental advantage of the H_2 based economy is that H_2 can be produced from several sources. The NRC (2004) analysis shows that H_2 can be produced and delivered in a cost effective manner from fossil fuels. However, that is only a transient solution. In the long run, H_2 will need to be produced from renewable sources and/or nuclear energy. Currently, none of these provide H_2 at a competitive cost. Considerable research and development activity is needed to achieve this goal.

Besides the production of H_2 from renewables, there are other potential hurdles to the adoption of H_2 for LDVs. A cost effective, durable and safe fuel cell system is needed. An effective onboard H_2 storage system is required for LDVs. An efficient and cost effective H_2 infrastructure to transport and deliver H_2 to the LDVs will be needed. These multiple challenges can potentially stop the development of H_2 economy for LDVs. To meet the technical and economic challenges, clearly a concerted effort is needed on the part of all the researchers, agencies and industries involved in this endeavor.

Even when all the challenges are met in a timely fashion, the time horizon for the adoption of hydrogen LDVs is projected to be over a period of the next 30 to 50 years. This requires patience and careful planning on the part of several stakeholders involved in this process.

Since H_2 economy requires multiple successes, it is desirable for the nations involved to maintain along with H_2, a balanced energy R&D program in areas other than H_2. In closing, energy is important to us and its future clearly depends on us.

Acknowledgements

Permission of Air Products and Chemicals to publish this paper is gratefully acknowledged. I would also like to thank members of the NRC committee on hydrogen for engaging and probing discussions.

References

Abraham, S. (March 2003). Emissions-Free Politics-Why a Republican President Wants to Invest Government Money in Hydrogen Fuel Cells, *Forbes*, 42.

Bridgewater, A. V. (2003). Renewable Fuels and Chemicals by Thermal Processing of Biomass, *Chemical Engineering Journal*, 91, 87.

Campbell, K., Keenan, G. (March 2003). Fueling Infrastructure Development: The Early Years, *14th Annual Meeting of the National Hydrogen Association*.

Cortright, R. D., Davda, R. R., Dumesic, J. A. (2002). Hydrogen from Catalytic Reforming of Biomass-Derived Hydrocarbons in Liquid Water, *Nature*, 418, 964.

Dicks, A. L. (1996). Hydrogen Generation from Natural Gas for the Fuel Cell Systems of Tomorrow, *J. of Power Sources*, 61, 113.

DOE (2003). Basic Research Needs for the Hydrogen Economy: Report of the Basic Energy Sciences Workshop on Hydrogen Production Storage and Use, Washington, D. C., U. S. Department of Energy.

Eliasson, B., Bossel, U. (July 5, 2002). The Future of the Hydrogen Economy: Bright or Bleak?, *Fuel Cell World*, Lucerne.

Kwon, S. -H., Shin, J. -W., Oh, J. -K., Heaven, D. L., Condorelli, P. (April 1999). Hydrogen Production Alternatives in an IGCC Plant, *Hydrocarbon Processing*, 73.

National Research Council (NRC) Report (2004). The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs, www.nap.edu.

Ogden, J. M. (1999). Prospects for Building a Hydrogen Energy Infrastructure, *Annu. Rev. Energy Environ.*, 24, 227.

Shinnar, R. (November 2003). The Hydrogen Economy, Fuel Cells, and Electric Cars, *Technology in Society*, 25 (4), 453.

Wang, M. (2002). Fuel Choices for Fuel Cell Vehicles: Well-to-Wheels Energy and Emissions Impacts, *J. of Power Sources*, 112, 307.

Yamasaki, A. (2003). An Overview of CO2 Mitigation Options for Global Warming - Emphasizing CO2 Sequestration Options, *J. Chem. Eng.*, Japan, 36 (4), 361.