Hydrogen: The Ultimate Energy Solution

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Prologue

Hydrogen is a new, highly versatile energy carrier which is a clean, safe and cheap fuel choice and when combined with super-efficient fuel cell vehicles, enables a profitable transition from the present hydrocarbon based fuel economy. While there is a growing interest due to climate and security issues, the key concerns regarding the so called hydrogen economy are: how can hydrogen be produced economically keeping in view absolute environmental concerns? What are the technologies for storage of hydrogen with ultimate energy concerns in mind? What kind of distribution system needs to be put in place and how is it to be sustained?

There is a need to create a policy framework encompassing all sectors and bring on board the key stakeholders – the decision makers who formulate the policy and the roadmap, the production units, the storage, delivery and distribution networks. Thereafter one can hope for a clean energy economy, worldwide.

– Editor

Introduction

The growing concern about depleting oil reserves, harmful effects of greenhouse gas emissions and the necessity to reduce emissions from power plants and vehicles are some of the key factors that increase the urgency for development of alternative energy options. Energy security is a major challenge, which needs imaginative and innovative solutions. Existing energy and power infrastructure exhibit several vulnerabilities. These include the risk of disruption of oil supply from politically volatile regions, the danger of electricity outages if power plants are targeted, and the risk of exposure to nuclear plant accidents.

Hydrogen, the lightest and most abundant element in the universe, is increasingly viewed by industry as the ultimate energy carrier. The major advantages with using hydrogen are that it forms ~75% of the known universe. Terrestrially, it is
not an energy source like oil or coal, only an energy carrier like electricity or gasoline. A most versatile energy carrier, it can be made from any source, can be produced and used at any scale for any service, readily stored in large amounts, fungible with the other highest-quality carrier, electricity. Hydrogen is almost never found by itself; and must be liberated by reforming HCs or CHs with heat and catalysts, electrolysis of water or by other experimental methods such as photolysis, plasma, microorganisms, etc. The majority of hydrogen produced on earth comes from fossil fuels.

Hydrogen Economy

The hydrogen economy is a proposal for the distribution of energy by using hydrogen. We already have, invisibly, a partly hydrogen economy. Two-thirds of the fossil-fuel atoms being burned today are hydrogen as a part of hydrocarbons. A large hydrogen industry exists today: it produces a fourth of the annual volume of the natural-gas industry worldwide. Between production and use, any commercial product is subject to the following processes: packaging, transportation, storage and transfer. The same is true for hydrogen in a “Hydrogen Economy”. Hydrogen has to be packaged by compression or liquefaction, has to be transported by surface vehicles or pipelines, it has to be stored and transferred. Generated by electrolysis or chemistry, the fuel gas has to go through these market procedures before it can be used by the customer, even if it is produced locally at filling stations. As there are no environmental or energetic advantages in producing hydrogen from natural gas or other hydrocarbons, we do not consider this option, although hydrogen can be chemically synthesized at relatively low cost. A reduction in carbon dioxide emission connected with hydrogen fuel is directly achieved only if the energy used to make hydrogen is obtained from non carbon-based sources.

Proponents for a world-scale hydrogen economy promote hydrogen as potential fuel for motive power (including cars and boats), the energy needs of buildings and portable electronics, as it is an environmentally cleaner source of energy to end-users, particularly in transportation applications, without release of pollutants (such as particulate matter) or greenhouse gases at the point of end use. A 2004 analysis asserted that “most of the hydrogen supply chain pathways would release significantly less carbon dioxide into the atmosphere than would gasoline used in hybrid electric vehicles” and that significant reductions in carbon dioxide emissions would be possible if carbon capture or carbon sequestration methods were utilized at the site of energy or hydrogen production.

Criticism of a hydrogen economy is centred on the following facts: hydrogen is not freely available, it is a gas at most temperatures, and particularly difficult to handle, it is more dangerous than most substances and equipment owned by consumers would have to be checked periodically; its production requires resources, and ultimately leads to energy loss. Hydrogen has been called the least efficient and most expensive possible replacement for gasoline (petrol) in terms of reducing greenhouse gases. A comprehensive study of hydrogen in transportation applications
has found that “there are major hurdles on the path to achieving the vision of the hydrogen economy; the path will not be simple or straightforward”.

The use of low cost materials and manufacturing processes challenges the popular critique. Hydrogen (renewable hydrogen) can be produced from renewable sources, thus enabling the intermittent and excess power generated to be stored for applications in transport, homes and businesses, thereby making off-grid wind and solar resources economic.

**Energy Balance**

Hydrogen is a fuel with the highest energy content per unit mass of all known fuels, which can be used for power generation and transportation at near zero pollution. Hydrogen (H₂) releases energy when it is combined with oxygen; however in practice, production of hydrogen from water requires more energy than is released when the hydrogen is used as fuel. The laws of physics require that any conversion from one form of energy to another yield less useful energy than you start with — otherwise it’d be a perpetual-motion machine. Making gasoline from crude oil is ~73–91% efficient, while making coal into delivered electricity is ~29–35% efficient. We make these energy carriers because they are worthwhile. Hydrogen production is quite efficient, ~70–82% efficient from natural gas, 75–80+% from electricity. The rest is heat that may also be recaptured and reused. As conversion efficiencies continue to rise; losses may be halved. In a study of the energy required to operate a pure hydrogen economy, the energy consumed by each stage was related to the energy content (higher heating value HHV) of the delivered hydrogen itself. (refer Table below)

**Table : Energy consumed at various stages of hydrogen economy (HHV higher heating value of hydrogen)**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Details</th>
<th>% of HHV</th>
<th>Energy consumed in the form of</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-DC conversion</td>
<td>-</td>
<td>5</td>
<td>Electricity</td>
</tr>
<tr>
<td>Electrolysis</td>
<td>-</td>
<td>35</td>
<td>Electricity</td>
</tr>
<tr>
<td>Compression</td>
<td>200 bar</td>
<td>8</td>
<td>Electricity</td>
</tr>
<tr>
<td></td>
<td>800 bar</td>
<td>13</td>
<td>Electricity</td>
</tr>
<tr>
<td>Liquefaction</td>
<td>Small plants</td>
<td>50</td>
<td>Electricity</td>
</tr>
<tr>
<td></td>
<td>Large plants</td>
<td>30</td>
<td>Electricity</td>
</tr>
<tr>
<td>Chemical hydrides</td>
<td>CaH₂, LiH</td>
<td>60</td>
<td>Electricity</td>
</tr>
<tr>
<td>Road transport</td>
<td>200 km 200 bar</td>
<td>13</td>
<td>Diesel fuel</td>
</tr>
<tr>
<td></td>
<td>200 km liquid</td>
<td>3</td>
<td>Diesel fuel</td>
</tr>
<tr>
<td>Pipeline</td>
<td>2000 km</td>
<td>20</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>On-site generation</td>
<td>100 bar</td>
<td>50</td>
<td>Electricity</td>
</tr>
<tr>
<td>Transfer</td>
<td>100to 850 bar</td>
<td>5</td>
<td>Electricity</td>
</tr>
<tr>
<td>Re-conversion</td>
<td>Fuel cell, 50%</td>
<td>5</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>DC-AC conversion</td>
<td>-</td>
<td>5</td>
<td>Electricity</td>
</tr>
</tbody>
</table>
Hydrogen Production

In the case of hydrogen production, the technologies available are (i) Thermochemical routes (ii) Electrolytic generation (iii) Photolytic means (iv) Bio-chemical pathways and (v) Chemical routes. Each of these technologies can be coupled with one another and one can generate further production methods. Photo-electrochemical and photo-microbial methods are some of these methods which have been receiving attention in the last two decades. However none of these technologies is at present commercially viable due to various materials and methodology related issues. This is one of the barriers for the availability of hydrogen in the large scale. The second barrier is the storage of hydrogen and release of the same at will.

Production Challenges and Implications

- Transportation energy demand varies substantially seasonally / daily. Processes whose dynamics / scale result in best fit to demand, need to be identified. Energy efficient storage could have a major impact.
- Capacity utilization is critical to cost efficiency. Scaleable / modular production systems required. Combined electricity / hydrogen generation should be planned.
- Carbon capture and sequestration needed for fossil fuel based options. Scaleable / modular capture systems are required. CO$_2$ distribution would be a factor in planning infrastructure.
- Scaleability, combined electricity / hydrogen generation would expand the options
- Efficient, scaleable storage a critical enabler for all production options.

Distribution Challenges

- High pressure tube trailers are suitable for small volumes only. Current technology requires ~130 kg steel per kg of H$_2$ transported. Approximately, 19 tube trailers would needed to supply energy equivalent of 1 gasoline tank truck.
- Cryogenic tankers are an economical way to transport large quantities of hydrogen over long distances but liquefaction is energy intensive. Energy per load is comparable to gasoline tank truck. Electricity needed to liquefy sufficient hydrogen to satisfy a developed country’s demand is typically equivalent to all the residential electricity use.
- Hydrogen pipelines are expensive and energy inefficient beyond short distances. Arterial design of pipelines is expensive.
- Natural gas systems are incompatible with hydrogen and result in embrittlement of steel, migration into plastics. Thus pressure monitoring, metering and safety systems, all require unique designs.
Micropower-Hydrogen Energy System

Two long-term trends underway in the world’s electricity and energy systems, toward micropower and hydrogen, can help in lessening existing security related vulnerabilities. Micropower, or distributed generation, limits the risk of disrupted power supplies. Terrorists would have great difficulty targeting hundreds of dispersed fuel cells or solar panels in office basements and backyards and on rooftops. Derived first from natural gas and later from renewable energy, hydrogen promises a clean, domestic source of energy that can lessen oil dependence. In addition to improving energy security, a micropower-hydrogen energy system could bring energy services to the 1.8 billion poor people around the world who lack access to modern energy—a common source of social unrest in many parts. It could also alleviate urban air pollution problems and lay the groundwork for a low-carbon, climate-benign energy economy. A micropower-hydrogen energy system presents enormous economic opportunities for forward-looking companies and countries that see the strategic advantage of switching to new energy sources—as did Winston Churchill, when he switched the British navy from coal to oil during the First World War.

Alternatives to the Hydrogen Economy

The closed carbon (CO₂) cycle has been proposed in addition to the closed hydrogen (water) cycle.

**Hydrogen production of greenhouse-neutral alcohol:** Hydrogen would be used captively to make fuel, and would not require expensive hydrogen transportation or storage. To be greenhouse-neutral, the source for CO₂ in such a plan would need to be from air, biomass, or from CO₂ which would otherwise be scheduled to be released into the air from non-carbon-capture fuel-burning power plants (of which there are likely to be many in the future, since economic carbon capture and storage is site-dependent and difficult to retrofit). Rather than be transported from its production site, hydrogen in such plants would instead be used centrally and immediately, to produce renewable liquid fuels which may be cycled into the present transportation infrastructure directly, requiring almost no infrastructure change. Fuel cells are beginning to be demonstrated, so alcohols may eventually compete directly with hydrogen in the fuel cell and hybrid market.

**Synthetic Hydrocarbon Economy:** A post-fossil fuel energy economy based on synthetic hydrocarbons envisages carbon atoms from biomass, organic waste materials or recycled carbon dioxide as carriers for hydrogen atoms thus saving precious energy. Hydrogen can be packaged chemically in a synthetic liquid hydrocarbon like methanol or dimethylether DME. Furthermore, the energy consuming electrolysis may be partially replaced by the less energy intensive chemical transformation of water and carbon to synthetic hydrocarbons. Captive hydrogen-mediated onsite production of greenhouse-neutral synthetic methane production has been proposed using the Sabatier reaction. Liquid methane has 3.2 times the energy
density of liquid hydrogen and is easier to store. Additionally, the pipe infrastructure (natural gas pipelines) are already in place. Natural-gas-powered vehicles already exist, and are known to be easier to adapt from existing internal engine technology, than internal combustion autos running directly on hydrogen. However, the cost of alcohol storage is even lower, so this technology would need to produce methane at a considerable savings with regard to alcohol production. Ultimate mature prices of fuels in the competing technologies are not presently known, but both are expected to offer substantial infrastructural savings over attempts to transport and use hydrogen directly.

Hybrid strategies described above, using captive hydrogen to generate other more easily usable fuels, might be more effective than hydrogen-production alone. Short term energy storage (meaning the energy is used not long after it has been captured) may be best accomplished with battery or even ultracapacitor storage. Longer term energy storage (meaning the energy is used weeks or months after capture) may be better done with synthetic methane or alcohols, which can be stored indefinitely at relatively low cost, and even used directly in some type of fuel cells, for electric vehicles. These strategies dovetail well with the recent interest in Plug-in Hybrid Electric Vehicles, or PHEVs, which use Hybrid strategy of electricity and the synthetic methanol has been proposed since electricity can be more efficiently used in a storage battery than electrolysing water to hydrogen. A storage battery may retain about 90% of the electricity used to charge it, and be able to provide about 90% of the electricity that it can store, resulting in a “round trip” efficiency of about 81%. This is compared with a 70% efficiency of electrolysis and perhaps 60% efficiency of a fuel cell. The electrical grid plus methanol fuel cells to be optimal in a narrow range of energy storage time, probably somewhere between a few days and a few weeks. This range is subject to further narrowing with any improvements in battery technology. It is always possible that some kind of breakthrough in hydrogen storage or generation could occur, but this is unlikely since the physical and chemical limitations of the technical choices are fairly well understood.

As long as the carbon comes from the biosphere ("biocarbon") the synthetic hydrocarbon economy would be as benign with respect to environment as a pure hydrogen economy. But the use of "geocarbons" from fossil sources should be avoided in order to uncouple energy use from global warming.

Fuel Cell

The enabling technology for hydrogen is the fuel cell, an electrochemical device, which combines hydrogen with oxygen in the presence of electrolyte to produce electricity and water. Fuel cells are now being vigorously developed as successors to batteries, power plants, and the internal combustion engine because of their advantages:

- The most efficient way to make electricity; ~ 50–70% efficient (the rest is recoverable heat) since they are not subject to the Carnot Limit (a
theoretical limit on the efficiency of an engine based on the flow of heat between two reservoirs), and that they can effectively extract more energy from fuel than combustion-based methods. Traditional internal combustion engines typically have efficiencies of around 30%.

- Extremely reliable, virtually silent, few or no moving parts, no combustion.
- Fully scaleable.
- Since the only product is water, it has huge environmental advantages over polluting combustion engines by making a significant contribution to reducing atmospheric emissions. For example, a fuel cell operating at 60% efficiency would emit 35-60% less CO₂ with fossil fuel and 80% less from hydrogen.

**Challenges in Fuel Cell Technology**

Typically, cars need 15,000 watts to run - achieving this wattage at an acceptable temperature has proved a significant challenge for those working in this area. Stanford University’s solid oxide membrane-based hydrogen fuel cell effectively cut the operating temperature of the fuel cell in half without compromising on any power (delivers a power density of 400mW/cm² at around 400°C, i.e. a fuel cell stack with a total membrane surface area of 4m² could produce sufficient power to run a car), making the likelihood of a commercially-viable fuel cell-driven car much more of a possibility.

Another exciting development in the application of fuel cell technology is the use of fuel cell power plants for electric power generation. Siemens, Ballard, and FuelCell Energy Inc, among others, are all developing these, albeit in some cases on a small scale (e.g. for home power generation). Most fuel systems convert natural gas or biofuels into hydrogen for processing with oxygen to generate multiple megawatts of useable electricity.

While existing fuel cell technology is already being applied in the auto industry and by power plant operators, electronics manufacturers are nearing commercialisation of their products. For example, Panasonic and Toshiba both demonstrated a direct methanol fuel cell for laptop computers at the International Consumer Electronics Show recently. Further, MTI Micro too has signed an agreement with Samsung to develop a series of prototypes for Samsung’s cell phones operating with a methanol fuel cell.

**Hydrogen Programmes in Other Countries**

Countries all over the world face the challenge of fluctuating oil prices, concerns about global warming and growth in energy demand. Hydrogen could help reduce greenhouse gas emissions, improve local air quality and enhance the security of energy supply. Hydrogen is most often seen as a future energy source for transport,
but it could also conceivably be used extensively to power factories and plants in the future.

Europe  The European Hydrogen and Fuel Cell Technology Platform has put forward proposals for the development of hydrogen and fuel cells for carrying and converting clean energy. According to Janez Potocnik, European Commissioner for Science and Research, the platform, with the support of the European Commission, can bring together all those with a stake in the future of hydrogen and fuel cell technology and can assure the best use of resources for research, in ways that meet the needs of this growing industry.

Japan  Japan has set up hydrogen fueling stations and plans to spend $20 billion by 2020.

Germany  It has the largest number of demonstration of hydrogen based applications and hydrogen fueling stations.

USA  The annual spending on hydrogen based initiatives is around $30M. The Hydrogen Freedom Fuel Initiative was announced in January, 2003 with a budget of US $2.2 billion.

Iceland  It plans to be world’s first hydrogen economy.

Indian Scenario  

With high growth rate of Indian economy, energy needs are also growing rapidly. India ranks fifth in the world in terms of energy consumption. Commercial energy consumption in India was 3.5% of the world consumption in 2002. Average annual growth rate of energy consumption was about 6% during 1981-2002. The energy demand of our country is expected to grow at the rate of 4.5% per annum at least until 2020 with economy growth pegged at 7-8%. This will lead to a growing gap between demand and supply of commercial energy with increasing dependence on imported oil which will rise from the present 70% to 80% in the next decade. In addition, the energy consumption share of India is only 3.5 % of the world consumption in spite of the fact that our population is nearly 1/6 of the world. This uneven distribution of energy consumption cannot be sustained for long.

There can be no unique solution for ensuring energy security for a country like India. All options for diversification of fuels and energy sources need to be pursued vigorously if the Indian economy is to achieve its economic and social goals.

Among the various alternatives, hydrogen is a promising candidate, which would provide clean and efficient production of electricity and heat as well as transportation requirements. Hydrogen is poised to become a major component in the energy mix in the coming decades for meeting the growing energy needs for
India’s economy, while protecting the environment and ensuring energy security. It is envisaged that hydrogen will be available for a wide range of applications including power generation, portable transport and heating applications. Hydrogen is especially suitable for meeting decentralised energy needs of the country’s population.

**National Hydrogen Energy Board**

In order to accelerate the development and utilisation of hydrogen energy in the country, a National Hydrogen Energy Board has been set up under Ministry of New and Renewable Energy, which consists of high-level representation from Government, Industry, Research institutions & Academia among others. The Steering Group has set up five Expert Groups on hydrogen production, storage, power, transport and systems integration.

**Charter of the National Hydrogen Energy Board**

- Guiding research & development programme in Hydrogen and Fuel cells. Demonstration and pilot programmes.
- Business development initiatives. Nationwide education and training programme.
- International cooperation.

**National Hydrogen Energy Road Map**

A Road Map has been formulated by the Board, which provides an integrated blueprint for the long-term public and private efforts required for hydrogen energy development in the country. The salient features are as below:

- Provide long term solution to meet growing energy needs of India while ensuring energy security.
- Identify paths for gradual introduction of hydrogen energy in the country.
- Accelerate commercialization efforts.
- Facilitate creation of hydrogen energy infrastructure.
- Adopt total systems approach for developing hydrogen energy technologies.
- Based on Public-Private Partnership.
- Roadmap is an industry driven planning process.
- Guided by Government, with support from Research Organizations, Academia, NGOs and other stakeholders.
- Development of sustainable and cost effective hydrogen energy technologies & infrastructure.
Issues relating to production, storage, delivery / transport, applications, safety and awareness, capacity building addressed.

Two major initiatives have been undertaken with goals and targets up to 2020:

- Green Initiative for Future Transport (GIFT)
- Green Initiative for Power Generation (GIP)

However, the transition to the hydrogen economy from the present fossil fuel based economy will require solutions to many challenges, specifically in the areas of production, storage, delivery and applications, and spanning infrastructure, technology, economics and large scale public awareness and acceptance.

The Road Map has highlighted hydrogen production as a key area of concern. In addition to the existing methods of hydrogen production, production of hydrogen from nuclear energy, coal gasification, biomass, biological and renewable methods need to be urgently developed to provide low cost and preferably carbon free hydrogen. Similarly, in the area of hydrogen storage, which includes gaseous, liquid & solid state storage, various goals concerning energy efficiency of storage, useful life on recycling, compactness and cost etc. have to be achieved. Necessary infrastructure for transport and delivery of hydrogen has to be developed and put in place. At the same time, all round and large scale awareness about hydrogen energy applications needs to be created. It has set a target of one million vehicles based on hydrogen energy and 1000 MW of power generating capacity based on hydrogen energy by 2020. The adoption of this Road Map would enable India to achieve the goal of sustainable energy security for all, through the transition to the new hydrogen energy economy in the coming decades.

**International Partnership on Hydrogen Economy (IPHE)**

International Partnership on Hydrogen Economy has been set up in Washington D.C. in November, 2003 and India is one of the 16 founder member countries of IPHE. China, India and Brazil are the three developing countries along with 13 advanced countries which include USA, Japan, European Union, U.K., Iceland etc. The Fourth Steering Committee Meeting of IPHE was held in Kyoto in September, 2005 in which India presented its achievements in Hydrogen Energy and the Road Map.

**Hydrogen Energy – Indian Achievements**

- Efficient production methods developed in laboratory conditions;
- Successful demonstration utilization in motorcycles and three wheelers; power generating units; catalytic combustor; air conditioning;
- Biological production of hydrogen from organic wastes;
- Demonstrated at pilot plant scale from bagasse.
Achievements in Fuel Cell Technology: Developed and demonstrated 50 KW PAFC power plant, 5 KW PEMFC power plants, 3 KW UPS systems, Reformers; Prototype Fuel Cell Vehicle; Fuel cell power packs for distributed power production.

Future Challenges

- Lower cost of hydrogen by a factor of 3-4 & improve production rates from different methods.

- Development of compact, inexpensive storage capacity up to 9 wt%, cycle life > 1,500 hrs, conveniently transportable and easy to refuel storage devices.

- Capacity of hydrogen storage system to be high enough to give a range of 150-500 km per charge, depending upon type of vehicle.

- Development of high pressure cylinders (~700 bars).

- Establishment of hydrogen gas pipeline network in high demand areas.

- Development of hydrogen fuelled IC engine having operating life > 30,000 hours and costs comparable to existing petroleum based IC engines.

- Efficiency improvement for different types of Fuel Cell Systems in 40 – 80 % range.

- Development of fuel cell stacks having operating life > 5,000 hours and cost comparable to existing vehicles for transport applications.

Conclusion

Hydrogen is widely perceived as the clean fuel of the future. However, many fundamental technological issues need to be addressed before hydrogen can become a significant part of the hydrogen economy. Problems related to hydrogen production, transportation, storage and distribution need to be resolved by the main stakeholders - the Government, research institutions and businesses. The market economy will always seek practical solutions and as energy becomes more expensive, the most energy efficient of all the options will be selected.

Energy sources of the future will have to be cleaner and more efficient than current sources - fuel cells fulfill these requirements. Several challenges remain before
we will see wide-spread commercialization, mainly because of restrictions on size, cost, reliability and safety, but an environmentally-friendly source of power is definitely on its way. While there are costs in building a hydrogen economy, they must be weighed against the risk of continuing to rely on oil imports.

References


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