Hydrogen Internal Combustion Engine Two Wheeler with on-board Metal Hydride Storage

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Abstract

The overall goal of this project is to demonstrate the potential for commercialization of a small, hydrogen fueled vehicle using ECD's proprietary metal hydride storage system as a fuel tank. Two of the major components of the project have been (a) the conversion of a gasoline-powered scooter to run on hydrogen and (b) integration of the metal hydride hydrogen storage system into the hydrogen-ICE scooter. Both these tasks have been successfully accomplished. The eventual goal is to fuel the vehicle with domestically produced renewable hydrogen. Renewable hydrogen can be obtained from sources such as electrolysis using low cost electricity, hydrogen as a by-product of the chlorine/caustic industry and hydrogen produced by the direct gasification of biomass. This approach allows for near-term entry of hydrogen into the transportation sector of the developing nations. The work done here is also applicable to the production of clean distributed power using metal hydride storage systems and hydrogen ICE's to replace highly polluting diesel and kerosene gen-sets. Our study has also shown that electrolytic hydrogen is viable for recharging the metal hydride tanks and the availability of cost-effective hydrogen in India (which we chose as a test case) is not a barrier. Thus, in the near to mid term, while the cost of fuel cell technology will act as a barrier to commercialization, as a transition, the hydrogen internal combustion engine can lead the way to a hydrogen economy, allowing developing countries to leap-frog.

Introduction and Significance of the Project

The average annual rate of energy consumption, and the gross domestic product have been growing at a significantly greater rate in India and China as compared to worldwide averages (Tables 1, 2). While the growth rate of renewable energy in these countries is also greater than in other countries (Table 3), the present utilization of renewable energy sources is very limited and needs to be aggressively increased. This will help combat the problems of air pollution, energy shortage, slow economic growth and energy security.

Table 1. World Total Energy Consumption in Quadrillion Btu (www.eia.doe.gov/oiaf/ieo)

Country	1990	1999	2005	2010	2020	AA% change
USA	84.9	96.7	107	114.1	120.7	1.3
Canada	10.9	12.8	14.3	15.4	16.6	1.2
W. Europe*	59.8	65.9	71.5	74.5	80.7	1.0
Japan	17.9	21.7	22.8	23.5	26.0	0.9
China	**27**	**32**	**43.2**	**55.3**	**84.1**	**4.7**
India	**7.8**	**12.2**	**15.5**	**18.4**	**26.1**	**3.7**
World	381.8 (1999) Quadrillion Btu					

Table 2. World Gross Domestic Product (GDP) (Billion 1997 US $)

Country	1990	1999	2005	2010	2020	AA%
USA	6,836	9,074	11,299	13,156	17,029	3.0
Canada	555	692	841	959	1,140	2.4
Japan	3.673	4,133	4,424	4,784	5,671	1.5
China	**427**	**1,036**	**1,590**	**2,276**	**4,245**	**6.9**
India	**268**	**440**	**621**	**818**	**1,396**	**5.7**
Total World	**24,392**	**30,299**	**37,041**	**43,479**	**59,082**	**3.2**

Table 3. World consumption of Hydroelectricity & other Renewables

Country	1990	1999	2005	2010	2020	AA% change
USA	5.8	7.0	7.7	8.1	8.5	1.0
Canada	3.1	3.6	4.3	4.9	5.2	1.8
Middle East	0.4	0.5	0.8	0.9	1.2	4.1
China	**1.3**	**2.3**	**3.5**	**4.4**	**6.6**	**5.1**
India	**0.7**	**0.9**	**1.1**	**1.2**	**1.7**	**3.3**
Total World	**17.2**	**20.1**	**22.8**	**24.7**	**27.8**	**1.6**

Economic growth in India and China is inevitable. But growth without due attention to the environment will have very detrimental long-term consequences. With abundance of sunshine, wind energy and biomass-based sources, maximizing the use of these can ease India's dependence on foreign oil, and also eliminate the drastic power shortage, which is responsible to a great degree in slowing progress on all fronts. These include education, health care, clean water and clean air. While the OECD countries are currently the largest contributors to greenhouse gas emissions, even though the absolute energy consumption in Asia and Pacific region is low, these regions are expected to replace OECD countries as the largest source of greenhouse gas emissions worldwide in about 2015. *Sustainable* growth is essential.

India's advantage

Transportation vehicles especially the 2 and 3 wheelers are primarily responsible for extremely poor air quality in India's major cities. Conversion of these 2/3-wheelers to run on hydrogen would result in dramatic improvement in air quality, in addition to economic benefits for the nation.While the industrialized world has begun to make the move towards a hydrogen economy that is free from fossil fuels the rate at which this will happen, and the pathways towards this goal must be different for different nations. The major automotive companies in the world are aiming towards hydrogen/fuel cell based light and heavy- duty vehicles, and the transition is expected to begin occurring sometime after 2012. This is expected to allow the technology developer's sufficient time for fuel cell costs to become affordable and also gives future energy companies time to develop a hydrogen infrastructure.

The fact that the daily needs of the average consumer in India and other developing nations are very modest as compared with the needs of the consumers in the highly industrialized countries can be put to advantage. For example, the US passenger vehicle will require 4-6 kg hydrogen fuel on board to deliver the desired performance, which includes the need for 480 Km range between charging or refueling, as compared to 100-500 grams of hydrogen required for a scooter for a range of 20-125 Km. The average daily driving distance in India is about 20 Km. India's lower per vehicle fuel requirements allow the country to leap frog by implementing hydrogen technologies in a much shorter time frame of 5-7 years.

Hydrogen vehicle and the hydrogen infrastructure

Developing clean hydrogen combustion technologies for transportation, will position developing countries for a smooth transition to fuel cell technologies, which are expected to be more energy efficient in the long run, but which are at least 15-20 years away from commercialization. Internal Combustion Engine (ICE) manufacturing and maintenance capabilities are already established and minimal re-tooling will be needed. The first fleet of BMW vehicles powered by hydrogen internal combustion engines has successfully completed 100,000 miles on public roads, clearly demonstrating the viability of hydrogen ICE technology and that of hydrogen as a transportation fuel.

Development of the hydrogen vehicles alone is not enough. Widespread availability of cost-effective hydrogen fuel is required. The following near-term possibilities exist:

- **(a)** Use of low cost electricity from the bagasse co-generation in sugar mills to produce hydrogen via electrolysis of water

- **(b)** Hydrogen by-product of other industrial or chemical processes, which is presently being 'wasted or flared' due to lack of demand – for example in the caustic-chlor-alkali industry

(c) Direct gasification of biomass to hydrogen

India is one of the world's largest producers of sugar, with more than 430 sugar factories operating in 18 states, producing approximately 12 million tons of sugar/year. The sugar mills have the potential to generate power significantly in excess of their captive needs. Market studies indicate that using advanced cogeneration technology in the sugar industry can generate up to 5,000 MW of electricity. It is estimated that just 1MW power can result in the production of about 162,000 Kg (162 tons) of hydrogen per year. This is sufficient for 32.4 million kilometers of driving with a scooter or about 16 million kilometers for a three-wheeler. Thus, even if a small fraction of the total power from bagasse cogeneration is used to produce clean fuel (hydrogen) for transportation and distributed power generation, it can have a very significant impact on air quality and reduction of imported fossil fuels, and help towards economic growth.

Huge amounts of hydrogen are also available from the chlorine-caustic industry as a by-product. After purification and drying this hydrogen can provide an immediate source of hydrogen fuel at a reasonable cost with practically zero capital investment required. Additionally, since the biomass-to-hydrogen conversion has the potential to produce the lowest cost hydrogen, this technology warrants serious consideration.

Hydrogen Storage

Several hydrogen storage technologies are available, including high- pressure gaseous storage, cryogenics storage of liquid hydrogen, and storage as a solid in metal hydrides. Each has advantages and disadvantages, depending on the application. For consumer application proposed here, namely small vehicles, safety being a top-most priority makes metal hydride storage a clear winner for on-board storage.

Metal hydrides that reversibly store hydrogen at ambient temperature offer a compact and safe means to store hydrogen on-board at low pressure. Enough hydrogen can be stored on –board in metal hydrides to have acceptable driving range between refueling. ECD is a leader in metal hydride technology and has developed a strong patent portfolio for various applications. Alloys have been developed where the kinetic and thermodynamic characteristics can be varied to suit different engineering applications. For the hydrogen ICE application, an alloy was developed that has the following characteristics:

- Fast hydrogen desorption kinetics- facilitates quick hydrogen release to meet the transient driving requirement

- Low enthalpy of desorption – Can release hydrogen at ambient temperature and at pressures suitable for hydrogen injection at low pressures. It also facilitates direct hydrogen absorption from commercially available medium pressure (150-300 psig) electrolyzer, without any further compression

- Long cycle life- over 1000 charge-discharge cycles with ultrahigh purity hydrogen

- High-density alloys- compact storage systems, high volumetric storage density of hydrogen

Transition metals based alloys with reversible hydrogen storage capacities between 1.8-3.0 wt% have been developed. These alloys release hydrogen at temperatures ranging from 25 deg C to 150 deg C. Additionally Mg and Mg-C based alloys have been developed that store between 5-7 wt% hydrogen, which can be released above 250-300 deg C.

Storage of hydrogen as a solid offers superior safety and volumetric attributes versus gaseous or liquid storage. In addition, the high production volumes of metal hydride alloys associated with the nickel metal-hydride battery industry already provide the economies of scale. ECD's storage alloys are mass- produced and packaged in specially engineered containers to provide maximum volumetric and gravimetric energy densities, while simultaneously optimizing heat transfer properties.

Preliminary results of the first prototype hydrogen ICE two-wheeler

The ICE two wheeler-manufacturing and maintenance infrastructure is well developed in India. If a gasoline ICE two and three-wheelers can be converted for hydrogen fuel and be optimized to meet the day-to-day commuting needs, it provides a solution to urban air pollution and domestic fuel shortage.

ECD has converted an 80 cc gasoline ICE scooter for hydrogen fuel. The conversion was achieved by making changes to the fuel delivery system and the ignition system. The details of the conversion process are discussed in the Proceedings of the DOE Review 2001 **(www.eren.doe.gov/hydrogen/pdfs/30535aa.pdf).** The hydrogen ICE scooter uses a fuel injector controlled by an Engine Control Unit (ECU). The carburetor was removed and the throttle body was redesigned.

The hydrogen ICE scooter with on-board metal hydride storage was field-tested to study the acceleration and the range. The tests were conducted under stop- and –go conditions and were spread over two days. The ambient temperature during test-driving varied between 38 – 55 deg F and the barometric pressure was approximately 30" Hg. The fuel consumption was determined to be approximately 8 gms/Km under the above driving conditions. Approximately 129 grams of hydrogen was drawn from the storage system during the test. Top speed during the road testing was 20 mph with one person on the vehicle. Figure 1 shows the hydrogen ICE scooter- Honda Elite converted at ECD for hydrogen fuel with the proprietary on-board metal hydride storage system.

This proof-of-concept prototype was demonstrated to the public during the DOE Annual Review Meeting, 2002 in Denver, Colorado and at the 14th World Hydrogen Energy Conference (June, 9th- 13th, 2002) in Montreal, Canada.

Refueling the metal hydride storage system

The metal hydride storage system is designed such that it can be charged on-board from either a compressed gas cylinder or with hydrogen produced by water electrolysis or other processes. Hydrogen is available as a by-product of industrial processes and can be generated renewably from biomass, solar, and wind etc at a low cost.

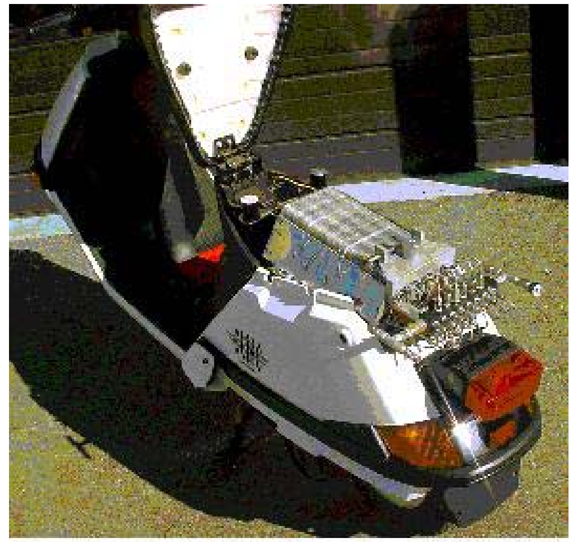

Figure 1: Honda Elite 80 cc scooter converted to run on hydrogen. ECD's proprietary metal hydride storage system on-board, under the seat

Water electrolysis is one way to produce hydrogen that is inherently pure but has to be dried further to be suitable for storage and distribution in a metal hydride. Through extensive research, ECD has determined the minimum dryness required for the hydrogen at which the metal hydride has long charge-discharge cycle life. ECD received the (IMET® 10) electrolyzer from Hydrogen Systems, Montreal, Canada in October 2001. This electrolyzer is capable of producing hydrogen up to a pressure of 150 psig, with a maximum capacity of 160 liters per minute. The electrolyzer and the dryer were installed at ECD and the unit has been operational since December 2001. The purity of hydrogen (for oxygen content) and dryness were monitored and meets the specification outlined by ECD based on laboratory tests of its metal hydride. Dew Point of –61 deg C and less than 0.2 ppm oxygen content were achieved for the product hydrogen.

Other applications

Distributed Power Generation for Portable and Stationary Use

It is estimated that 40% of the world's population is without electric power. These non-electrified regions of the world are potential markets for distributed small-scale power systems. Although about 80% of India's population now has access to electricity, power outages are common. As of May 2001, India's power generation capacity was about 102,000 MW. Peak load is expected to reach 131,000 MW by 2006-07. This means an additional capacity of 29,000 MW is needed within the next 5 years. Because of severe power shortages and the need to replace highly polluting diesel, gasoline and kerosene generators currently being used extensively in India, the demand for hydrogen for power generation can be enormous.

Today's hydrogen production, storage and conversion technologies can get India started the path towards hydrogen. While work is on-going worldwide to reduce the cost of PEM fuel cells, the 100 year old ICE (internal combustion engine) technology, modified to operate on hydrogen fuel can be used (Figure 2). The experience gained and infrastructure development that will take place will ease the transition later on, to fuel cell technology

Cooking

Hydrogen's versatility will allow it to be used as a cooking fuel with a very significant social impact. Hydrogen burners (Figure 3) have been under development in several countries, including Germany, the United States and India. Solid-state storage of hydrogen in the form of metal hydrides can provide a safe means of using hydrogen for this application.

Hence, the economic barriers often cited for the implementation of hydrogen energy do not necessarily apply to developing countries. Options are available to overcome these so called economic barriers. Of course implementation will require unique collaborative effort on an international level. The result will be the creation of new industries, high quality jobs and leading the way to sustainable, economic growth based on domestic renewable resources. The benefits reaped will be environmental and financial.

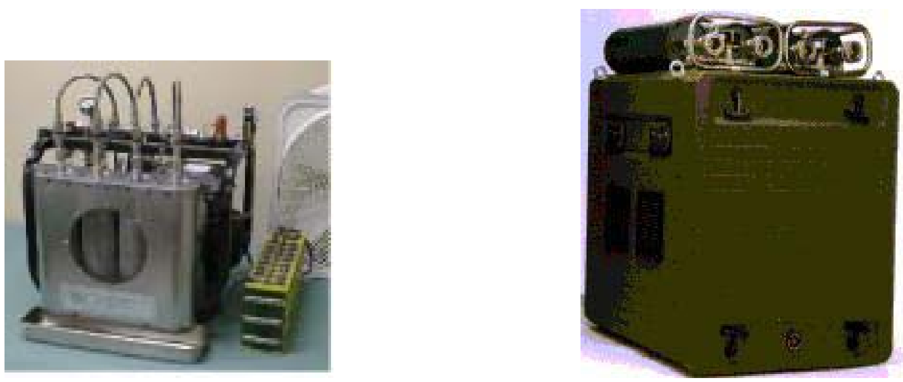

Figure 2: **Left**: Ovonic Hydrogen ICE Generator. **Right**: Ovonic Metal Hydride Storage system integrated with a 2.8 KWe PEM Fuel Cell. Hydrogen stored provides 3 hours of back-up power at 2KWe.

Photo of burner courtesy Dr. U.-P. Groβmann

Figure 3 Left: Metal Hydride Storage System used for cooking. **Right**: Small hand-held storage system (black cylinder) supplying fuel to a PEM fuel cell for portable power applications

Future Plan of Work

In order to go from 'proof-of-concept' to 'precommercialization' stage, further development will be required in the following areas:

- Improvement in engine power output and fuel economy (efficiency)
- Increase driving range through engine development and utilization of ECD's higher capacity alloys
- Cost reduction of component technologies
- Implementation of Safety Codes and Standards
- Appropriate manufacturing alliances

Conclusion

ECD has demonstrated the viability of hydrogen ICE scooter with Ovonic Metal Hydride for on-board hydrogen storage as a near-term application of hydrogen technology for transportation in developing countries. The proof-of-concept prototype was converted for hydrogen fuel at ECD. Further work is on-going to improve the performance of the hydrogen ICE scooter. The Ovonic Metal Hydrides storage systems also have widespread application for fuel cell and hydrogen ICE based distributed power generation.

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