WP-2007-004

Hydrogen Energy For Indian Transport Sector:
A Well-To-Wheel Techno-Economic and Environmental Feasibility Analysis

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March 2007

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Abstract

With the alarming rate of growth in vehicle population and travel demand, the energy consumption has increased significantly contributing to the rise of GHG emissions. Therefore, the development of a viable environmentally benign technology/fuel, which minimises both global and local environmental impacts, is the need of the hour. There are four interconnected reasons for propagating a shift towards alternative fuels/technologies: (i) Energy Supply: world oil reserves are rapidly diminishing, (ii) Environment: local pollution from vehicles is creating an atmosphere that is increasingly damaging public health and environment, (iii) Economic competitiveness: the cost of producing oil and regulating the by-products of oil consumption continues to increase, and (iv) Energy security: the military and political costs of maintaining energy security in international markets are becoming untenable. Hydrogen energy has been demonstrated as a viable alternative automotive fuel in three technological modes: internal combustion engines connected mechanically to conventional vehicles; fuel cells that produce electricity to power electric vehicles; and hybrids that involve combinations of engines or fuel cells with electrical storage systems, such as batteries The present study provides a well-to-wheel analysis of the economic and environmental implications of technologies to deliver the hydrogen energy to the vehicles. The main objectives of the study are: (i) prioritization of technologies of hydrogen production, transportation, storage and refueling, (ii) economic analysis of prioritized technology alternatives to estimate the delivered cost of hydrogen at the end-use point, and (iii) estimating the environmental impacts. To achieve the desired objectives, various quantitative life-cycle-cost analyses have been carried out for numerous pathways (i.e. technologies and processes) for hydrogen production, storage, transportation/distribution and dispensing. The total cost implications are arrived at by combining the costs of hydrogen (at end-use point) and the estimated demand for hydrogen for transport. The environmental benefits (potential to abate GHG emissions) of alternative hydrogen energy technology pathways have been worked out by using the standard emission factors. Finally, the GHG emission levels of hydrogen supply pathways are compared with those of diesel and petrol pathways. The application of this systematic methodology will simulate a realistic decision-making process.

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[1] To be published in the volume edited by B.Sudhakara Reddy and Jyoti K.Parikh.

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1. INTRODUCTION

Transportation has revolutionised our lives in the 20th century and has become indispensable in the life of man kind. But, transport is almost synonymous with energy and requires oil which is a finite energy source. Automobile is also the single largest cause of air-pollution which has serious effect upon the health of human and all other animals, plants and structures. Therefore, another efficient and cheap energy source needs to be found which should be unlimited in its supply and friendly to the environment. Alternative fuels - those not derived from oil - have already made some inroads in the transportation energy market. By the middle of the 21st century, these fuels might be destined to become the norm for the world's passenger vehicles.

Hydrogen energy is one such fuel which may provide key solutions for the 21st century, enabling clean efficient production of power and heat from a range of primary energy sources. Hydrogen gas (H_2) is being explored for use in combustion engines and fuel cell electric vehicles. When combusted (oxidized) it releases only water vapor as a by-product. When burned in an internal combustion engine, however, it also produces small amounts of nitrogen dioxides and unburned hydrocarbons and carbon monoxide because of engine lubricants but the exhaust is free from carbon dioxide. It is a gas at normal temperature and pressure, which presents greater transportation and storage hurdles. Current technology allows for many different methods of producing hydrogen with varying environmental consequences. For example, hydrogen produced by coal gasification without carbon sequestration will release almost twice as much carbon to the atmosphere per unit of energy as is contained in gasoline. Production methods have other environmental impacts as well, such as the effects of mining for coal, drilling for gas, growing biomass on plantations, or siting large solar arrays and wind turbines.

The present paper provides a detailed economic and environmental analysis of utilization of hydrogen energy for transport. There are many ways of producing, transporting and storing hydrogen as well as using it. Optimal selection of these technology-pathways is an essential step in achieving the objective of sustainable transport system based on hydrogen energy. The present study attempts to develop such an approach.

2. METHODOLOGY

After an extensive literature review, some quantitative life-cycle data are found on numerous pathways (i.e. technologies and processes) for hydrogen production, storage, distribution and dispensing. Some authors attempt to evaluate one or more of these alternative pathways to yield insights into the possible future development of hydrogen use. However, few works attempt to perform an integrated assessment of all relevant pathways. Moreover, it is difficult to find data for hydrogen alternatives, particularly for India, that are comparable and detailed enough for strictly quantitative types of analyses. The significant contribution of this work is development of a systematic methodology to simulate a realistic decision-making process based on a hypothetical situation. The numerous simplifying assumptions and associated limitations are described in the following sections.

The analysis considers the situation of a hypothetical setup that examines the feasibility of several options to produce, distribute, store and refuel hydrogen to a set of vehicles. A brief description and analysis (economic and environmental) of the prioritized technological alternatives are carried out and final unit costs are estimated. Finally, the GHG emission levels of hydrogen supply pathways are compared with that of diesel and petrol pathways.

3. HYDROGEN TECHNOLOGIES – A BRIEF DESCRIPTION

Hydrogen is a secondary energy source that can be obtained after processing the hydrogen-contained matter. It is produced using primary energy, then stored and transmitted before converting to an energy service in an end use technology such as a vehicle. The brief descriptions on hydrogen technologies have been developed based on Amos (1998), Simbeck and Chang (2002), Padró and Putsche (1999), Solomon and Banerjee (2006), and HNEI-SI (2004), Kothari, *et al* (2004), Bossel (2003) and Rifkin (2003).

Hydrogen Production

Three distinct types of commercially proven technologies are the prominent ones to extract hydrogen from different feedstock: (i) Reforming: a technology of choice for converting gaseous and light liquid hydrocarbons, (ii) Gasification or partial oxidation (PO): a flexible one than reforming which could process a range of gaseous, liquid, and solid feedstock and (iii) Electrolysis: splits hydrogen from water.

3.1.1 Steam Methane Reforming of Natural Gas

Steam methane reforming (SMR) is the most common and least expensive method of producing hydrogen (almost 48% of the world's hydrogen is produced from SMR). There are two basic steps in steam methane reforming. The first one involves the mixing of methane with steam to produce a gaseous mixture that is mostly hydrogen with about 12% CO and 10% CO_2. This process occurs at about 800^oC. The next step is called water gas shift reaction which involves combining the carbon monoxide with water to produce hydrogen gas and carbon dioxide. The shift conversion may be conducted in either one or two stages operating at three temperature levels. High temperature (350°C) shift utilizes an iron-based catalyst, whereas medium and low (205°C) temperature shifts use a copper based catalyst. Assuming a 76% SMR efficiency coupled with CO shift, the hydrogen yield from methane on a volume is 2.4:1. This process results in mostly CO_2 and H_2 as gas outputs with smaller amounts of carbon monoxide, methane, water and other gases. CO is removed by absorption or membrane separation. Hydrogen is separated from carbon dioxide and other gases using Pressure Swing Absorption (PSA), which results in pure (>99.9%) hydrogen.

3.1.2 Coal Gasification

The first step in hydrogen production from coal is to gasify it by combining it with steam and oxygen to produce a raw gas mixture. After the ash is removed, the raw gas is de-sulfurized to produce synthetic gas (often called "syn gas") which contains mostly hydrogen, carbon monoxide and carbon dioxide. Carbon monoxide is converted to carbon dioxide and hydrogen using water gas shift reaction and hydrogen is separated from the carbon dioxide using PSA (Pressure Swing Absorption) or other separation techniques. The drawback in the cost of hydrogen produced by coal gasification is the cost of CO_2 abatement. Hydrogen production from gasification releases about 38 kg of carbon per GJ of hydrogen.

3.1.3 Biomass Gasification

The process of biomass gasification starts by heating the biomass to produce a syn gas consisting mostly of hydrogen, carbon monoxide, carbon dioxide, and water. The gas is cleaned and steam is introduced to cause the water gas shift reaction to convert energy in carbon monoxide into hydrogen. Pressure swing absorption separates the hydrogen from carbon dioxide. This process is similar to coal gasification in many ways. Biomass has several advantages over coal as a hydrogen feedstock. The feedstock is relatively inexpensive. However, it is uneconomical to build biomass plant as big as coal plants since biomass has less energy density by volume and therefore is more expensive to transport. The cost and availability of feedstock is probably the most important consideration for the future of biomass gasification.

3.1.4 Electrolysis of Water

A small amount (4%) of the world's hydrogen is produced by electrolysis of water. Electrolysis process uses electricity to split water into hydrogen and oxygen atoms. In these process two electrodes, one positive and another negative, are submerged in pure water that has been made more conductive by the addition of an electrolyte. When direct current (DC) is applied, hydrogen bubbles up at negatively charged electrodes and oxygen at positively charged electrode. Alkaline water electrolysis is the most common technology used in larger production capacity units (0.2 kg/day).

Electrolysis is an energy intensive process. The power consumption at 100% efficiency is about 40 kWh/kg hydrogen; however, in practice it is closer to 50 kWh/kg. Since electrolysis units operate at relatively low pressures (10 atmospheres), higher compression is needed to distribute the hydrogen by pipelines or tube trailers compared to other hydrogen production technologies. This process offers the potential to produce hydrogen with almost no pollution or greenhouse gas production. The environmental effects of renewable electrolysis depend on the technique that is used to produce electricity. Nuclear energy can also produce carbon free electricity that can be used to split water into hydrogen and oxygen.

3.1.5 Biomass Pyrolysis

The process of biomass pyrolysis (complete combustion of the feedstock) is still in the development stage and not a commercial process. In this process, biomass is thermally decomposed at a high temperature (450-550 degrees C) in an inert atmosphere to form a bio-oil composed of about 85% oxygenated organics and 15% water. The bio-oil is then steam-reformed using conventional technology to produce hydrogen. Alternatively, the phenolic components of the bio-oil can be extracted with ethyl acetate to produce an adhesive/phenolic resin co-product, and the remaining components can be reformed as in the first option. The product gas from both alternatives is purified using a standard pressure swing adsorption (PSA) system.

Hydrogen Storage

3.2.1 Compressed Gas Storage

Compressed gas storage of hydrogen is the simplest storage solution. The equipments required are a compressor and a pressure vessel. The main problem with compressed gas storage is the low storage density which depends on the storage pressure. High storage pressure results in higher capital and operating costs. At low production rates, the capital cost of the pressure vessel dominates while at higher volumes the critical factor is the electricity cost for compression. As storage time increases, the capital cost of the pressure vessel begins to dictate the cost. One option is to increase the operating pressure of the system (smaller, lower cost tank; higher compressor capital and compression running costs): for short times, there is a balance between these costs, at longer times the capital cost reduction is the dominant factor resulting in an optimum at maximum operating pressure.

3.2.2 Liquid Hydrogen Storage

Liquefaction is done by cooling a gas to form a liquid. A combination of compressors, heat exchangers, expansion engines, and throttle valves are used in liquefaction processes to achieve the desired cooling. The simplest liquefaction process is the linde cycle or Joule-Thompson expansion cycle. In this process, the gas is compressed at ambient pressure, and then cooled in a heat exchanger, before passing through a throttle valve where it undergoes an isenthalpic Joule-Thompson expansion, producing some liquid. This liquid is removed and the cool gas is returned to the compressor via the heat exchanger.

An alternative to this process is to pass the high-pressure gas through an expansion engine which consists of an isothermal compressor, followed by an isentropic expansion to cool the gas and produce a liquid. It is used as a theoretical basis for the amount of energy required for liquefaction and also to compare liquefaction processes. In practice, an expansion engine can be used only to cool the gas stream, not to condense it because excessive liquid formation in the expansion engine would damage the turbine blades.

Liquid hydrogen storage is not economical at low production rates (due to the high capital cost of liquefier) and is difficult to compete with compressed gas at higher production rates unless longer storage times are required, when the lower capital cost of liquid hydrogen dewars compared to compressed gas pressure vessels becomes the chief factor.

3.2.3 Metal Hydride Storage

Metal hydrides store hydrogen by chemically bonding it to metal or metalloid elements and alloys. Hydrides are unique because they can adsorb hydrogen at or below atmospheric pressure and then release at significantly higher pressures when heated—the higher the temperature, the higher the pressure. There is a wide operating range of temperatures and pressures for hydrides depending on the alloy chosen. Each alloy has different performance characteristics, such as cycle life and heat of reaction. When the partial pressure of hydrogen is increased, it dissolves in the metal or alloy and then begins to bond to the metal. During the bonding period the equilibrium or plateau pressure remains constant from the time that 10% of hydrogen has been stored until about 90% of the storage capacity is reached. After the 90% point, higher pressures are required to reach 100% of the hydride storage capacity. Heat released during hydride formation must be continuously removed to prevent the hydride from heating up. If the temperature is allowed to increase the equilibrium pressure will increase until no more bonding occurs. If hydrogen is being recovered from another gas, some hydrogen can be allowed to escape or blow off; taking away any contaminants that did not bond to the hydride.

To recover the hydrogen from the metal hydride, heat must be added to break the bonds between the hydrogen and the metal. Again, the higher the temperature, the higher the release pressure. Initially the pressure of the gas is high as any free hydrogen is released, and then the pressure plateaus as the hydride bonds are broken. When only about 10% of the hydrogen remains the equilibrium pressure drops off. This last bit of hydrogen dissolved in the metal matrix is difficult to remove, and represents strongly bonded hydrogen that cannot be recovered in the normal charge/discharge cycle.

Metal hydride storage is perceived to have no economy of scale (high capital cost of storage alloy). So it does not compete with other options at high production rates or long storage times, but may be ideal at low flow rates and short storage times. Since it is considered as the safest storage option, this makes it a leading candidate for on-vehicle storage, subject to achieving satisfactory energy densities.

3.2.3 Underground Storage

Depending on the geology of an area, underground storage of hydrogen gas may be possible. Underground storage of natural gas is common and underground storage of helium, which diffuses faster than hydrogen, has been practiced successfully in Texas. For underground storage of hydrogen, a large cavern or area of porous rock with an impermeable caprock above it is needed to contain the gas. A porous layer of rock saturated with water is an example of a good caprock layer. Other options include abandoned natural gas wells, solution mined salt caverns, and manmade caverns. Underground storage is the cheapest method at all production rates and storage times (due to low capital cost of the cavern): biggest cost item is electricity cost for compression; relatively insensitive to changes in production rate and storage time; additional transport cost to consumer may be high, but underground storage may have applications for seasonal storage or security of supply.

3.2.4 Storage in Pipelines

Piping systems are usually several miles long, and in some cases may be hundreds of miles long. Because of great length, and therefore great volume, of these piping systems, a slight change in the operating pressure of a pipeline system can result in a large change in the amount of gas contained within the piping network. By making small changes in operating pressure, the pipeline can be used to handle fluctuations in supply and demand, avoiding the cost of onsite storage.

Hydrogen Transportation

3.3.1 Compressed Gas Transportation

Compressed gas can be transported using high-pressure cylinders, tube trailers or pipelines. If hydrogen is to be transported as a gas, it should be compressed to a very high pressure to maximize tank capacities. High pressure gas cylinders, for example, are rated as 40 Mpa and hold about 1.8 kg of hydrogen, but are very expensive to handle and transport. Tube trailers, consists of several steel cylinders mounted to a protective framework, can be configured to hold 63-460 kg of hydrogen depending on the number of tubes. Operating pressures are 20-60 Mpa.

3.3.2 Liquid Hydrogen Transportation

Liquid hydrogen is transported using special double walled insulated tanks to prevent boil off of the liquid hydrogen. Some tankers also use liquid nitrogen heat shields to cool the outer wall of the liquid hydrogen vessel to further minimize heat transfer. Tank trucks can carry 360-4,300 kg of liquid hydrogen where as rail cars have capacities ranging from 2,300 to 9,100 kg of hydrogen. Boil off rates for trucks and rail cars are 0.3%-0.6%/day. Barges or sea-going vessels have been considered for long distance transport of hydrogen. Each barge would carry 21,000 kg of hydrogen with no venting during a 50-day trip. Insulated pipeline (which includes a super conducting wire) can also be considered. The liquid hydrogen acts as a refrigerant for superconductor and would allow long distance transport of electricity with out the high current losses of conventional power lines. The main problem with this would be the specialized insulating requirement and losses from pumping and re-cooling the liquid hydrogen along the way.

3.3.3 Metal Hydride Transportation

Metal hydrides can be used for transport by absorbing hydrogen with a metal hydride, then loading the entire container onto a truck or railcar for transport to the customer's site where it can be exchanged for an empty hydride container, or used as a conventional tanker.

Hydrogen Applications

3.4.1 Using hydrogen in Internal Combustion Engines

Conventional combustion engines require modification to burn hydrogen. The proven commercially available technology to use natural gas in combustion engines is similar to the one needed to use hydrogen. Hydrogen combustion releases no carbon monoxide, hydrocarbons, particulate pollution, or carbon dioxide but there is emission of nitrogen oxides which are very low. Use of hydrogen in an internal combustion engines has several potential advantages, like increased efficiency (25%-30%), a wide range of ignition limits, and high flame and diffusion speeds.

3.4.2 Using hydrogen in fuel cells

Hydrogen and oxygen merge in a fuel cell, forming water and releasing electricity. Because fuel cells require no lubricating oil, and no combustion to generate high temperatures that lead to the formation of nitrogen oxides, fuel cell-powered electric vehicles offer the cleanest way of using hydrogen (they are zero-emission vehicles). Fuel cells are two to three times as energy efficient as combustion engines. An internal combustion engine loses more than 80% of energy it generates, either as waste heat or friction. When a hydrogen fuel cell is used, the energy loss is 40 to 60%, so the percent of energy that is delivered as movement is much greater. However, various technological hurdles must be overcome before fuel cells can compete effectively, in terms of overall performance and cost, with internal combustion engines in automotive applications. Fuel cell demonstration projects now under way around the world will likely yield improved solutions to these technical challenges

3.4.3 Hydrogen Electric Hybrid vehicles

By combining onboard engines or fuel cells that generate power with electrical systems that store power, electric hybrids may offer greater market potential than vehicles powered solely by single systems. Demonstrations of hybrid technology, involving hydrogen, indicate that these vehicles may be lighter, smaller, more versatile, and offer better performance than vehicles running solely on hydrogen engines, fuel cells, or batteries. There are two primary types of hydrogen hybrid electric vehicles that are proposed ─ parallel and series. In parallel hybrid vehicle, both electric motor and the ICE are coupled through the transmission to the wheels. In series, the ICE is not connected to the wheels and the power to the wheels comes from the electric motor. The overall efficiencies for these vehicles are estimated at 39% for ICE series version and 35% for the fuel cell series version. Efficiency of series hybrid ICE vehicles ranges between 38 and 39%, for parallel hybrid ICE vehicles it is 25%.

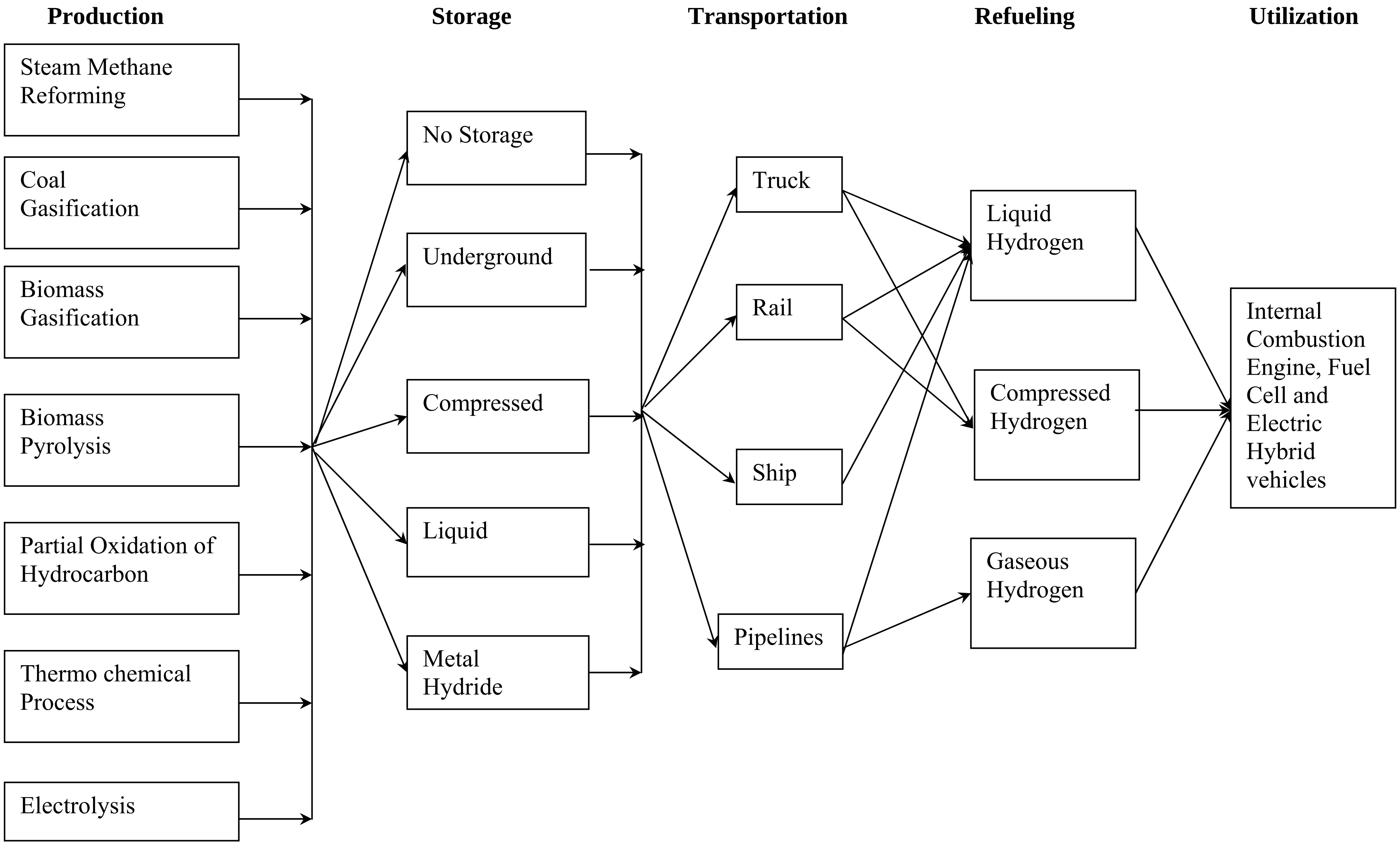
Hydrogen Pathways

Figure 1 presents different hydrogen pathways which represent the flow of hydrogen from production to utilization. The figure is self-explanatory.

4. ECONOMICS OF LARGE-SCALE CENTRALIZED HYDROGEN TECHNOLOGIES

For economic analysis, we consider only large-scale centralized hydrogen production facilities. We have used many assumptions and various kinds of data inputs. The final cost estimates are the direct result of these input parameters. Any variations in the input parameters used will have significant implications for the cost estimates. Most of the data are obtained from various secondary sources and are related mainly to international experiences. Majority of the technical and cost details have been obtained from the following sources – Amos (1998), Simbeck and Chang (2002), Padró and Putsche (1999), Koljonen, *et al* (2004), Wurster and Zittel (1994), EC-Report (2004), Brinkman (2003), Ramage (2003) and HNEI-SI (2004).

Figure 1: Hydrogen Pathways (Production to Utilization)



Hydrogen Production

The selected technologies of hydrogen production include: biomass gasification and electrolysis of water. The scale of production is assumed to be in large-scale which is same for all the technologies. The economic analysis has been performed for a plant with a capacity to produce 150 tonnes of hydrogen per day which is equivalent of producing 6.25 tonnes per hour. With an assumed load factor of 90%, the actual hydrogen production is estimated to be about 135 tonnes per day and the annual production is about 49,275 tonnes. The basic data inputs required and the assumptions made in estimating the hydrogen production costs and the prevailing prices of various fuel inputs are given in Table 1.

In the gasification series, coal gasification is the second technology considered for economic analysis. The capital cost requirements are similar to those of petroleum coke gasification technology. The total capital cost of Rs. 99,340 million includes the equipment cost of Rs. 6,855 million. The cost of coal and electricity are dominant components in the annual variable cost of Rs. 1,342 million. The capital charges at 12% rate works out to be Rs. 1,192 million. Based on this data, the estimated hydrogen production cost works out to Rs. 57.50 per kg of hydrogen, which is higher compared to earlier two alternatives.

The economic analysis of various hydrogen production processes are given in Table 2. The cost of production through steam methane reforming (SMR) shows that the major capital costs are for steam methane reformer and hydrogen compressor. The total capital cost for a hydrogen production capacity of 6,250 kg/hour using this technology works out to be about Rs. 2,870 million. In addition to cost information, the table also contains technical details related to natural gas requirements, calorific values, electricity requirement, etc. The total annual cost of hydrogen production is estimated to be about Rs. 1,264 million per year which includes the cost of natural gas (about Rs. 700 million). The unit cost of hydrogen production using SMR of natural gas is equal to Rs.25.67 per kg of hydrogen. It is clear that the cost of natural gas is the most important determinant of final unit hydrogen cost.

Table 1: Basic Data inputs/assumptions used for Hydrogen Cost Estimates

Items	Units	Value
Common Data and Assumptions		
Design Hydrogen Production Capacity	kg/day	150000
Annual average Load Factor	%/year	90
Hydrogen Production Rate per hour	kg/hr	6250
Actual Hydrogen Production	kg/day	135000
Annual Hydrogen Production	kg/year	49,275,000
Non-fuel Variable O&M Cost	% of Capital Cost per year	1
Fixed O&M Costs	% of Capital Cost per year	3
Dollar to Rupee Conversion	Rs per US $	45
Capital Charges	% per year	12
Contingencies	% of Capital Cost	6
Specific to Hydrogen Production		
General Facilities	% of Capital Cost	15
Engineering, Permitting & Startup	% of Capital Cost	10
Contingencies	% of Capital Cost	6
Working Capital, Land & Misc.	% of Capital Cost	4
Natural Gas price	Rs./1000 M^3	3200
Biomass production costs	Rs./ha/yr gross revenues	13500
Coal Price	Rs./tonne	1500
Petroleum Coke	Rs. /Tonne	800
Petroleum Coke	Rs./MM Btu HHV	26.38
Residue (Pitch)	Rs./MM Btu HHV	67.5
Specific to Hydrogen Storage		
Storage Capacity	kg	300000
Electricity Cost	Rs./kWh	3
Cooling Cost	Rs./KL	0.83
Days of Storage	days	2
Boil-off Rate for liquid storage	% per day	0.10
Specific to Hydrogen Transportation		
General Facilities	% of Capital Cost	15
Engineering, Permitting & Startup	% of Capital Cost	8
Working Capital, Land & Misc.	% of Capital Cost	4
Diesel price	Rs./litre	25
Delivery Distance	km (one-way)	200
Specific to Hydrogen Refueling		
Fueling Station Design capacity	kg/day/station	470
Annual average Load Factor	%/yr	70
Actual Average Hydrogen per day	kg/day/station	329
Total number of stations required	No.	411
General Facilities	% of Capital Cost	18
Engineering, Permitting & Startup	% of Capital Cost	8
Working Capital, Land & Misc.	% of Capital Cost	5
Non-fuel Variable O&M Cost	% of Capital Cost per year	0.5

The details of economic analysis of hydrogen production through petroleum coke gasification process shows that the total equipment cost is of the order of Rs. 6,635 Million and the total capital cost including other fixed cost is Rs. 9,621 million. At a production rate of 6,250 kg of hydrogen per hour, the quantity of petroleum coke required is 37,568 kg per hour. The total variable cost including electricity cost is Rs. 825 million per year. The estimated per unit hydrogen production cost through petroleum coke gasification is likely to be Rs. 46.04 per kg. It may be observed that this cost is significantly higher than the cost of hydrogen through SMR of natural gas. One of the important factors contributing to this is the cleaning of gas and emission control cost.

The capital cost (Rs. 10,800 million) as well as annual cost through biomass gasification (including equipment cost) seem to be high. Out of a total annual variable cost of Rs. 1,708 million, biomass cost alone is about Rs. 886 million. This cost can vary depending on the source of biomass. The resulting unit hydrogen cost is Rs. 67.50 per kg. If environmental benefits (in terms of CO_2 mitigation possibilities) are included, this technology can become an attractive proposition for hydrogen production.

Another technology of hydrogen production following the gasification mode is using petroleum residue. Like any gasification process using fossil fuel, the petroleum residue gasification also needs CO cleaning and emission control equipments (sulphur removal). Including these, the total equipment cost is about Rs. 5,112 million. The total cost (including equipment, other fixed costs - Rs. 7,412 million, annual variable cost - Rs. 1,015 million) works out Rs.13,539 million. The estimated unit cost of hydrogen production using this technology is Rs. 43.17 per kg of hydrogen.

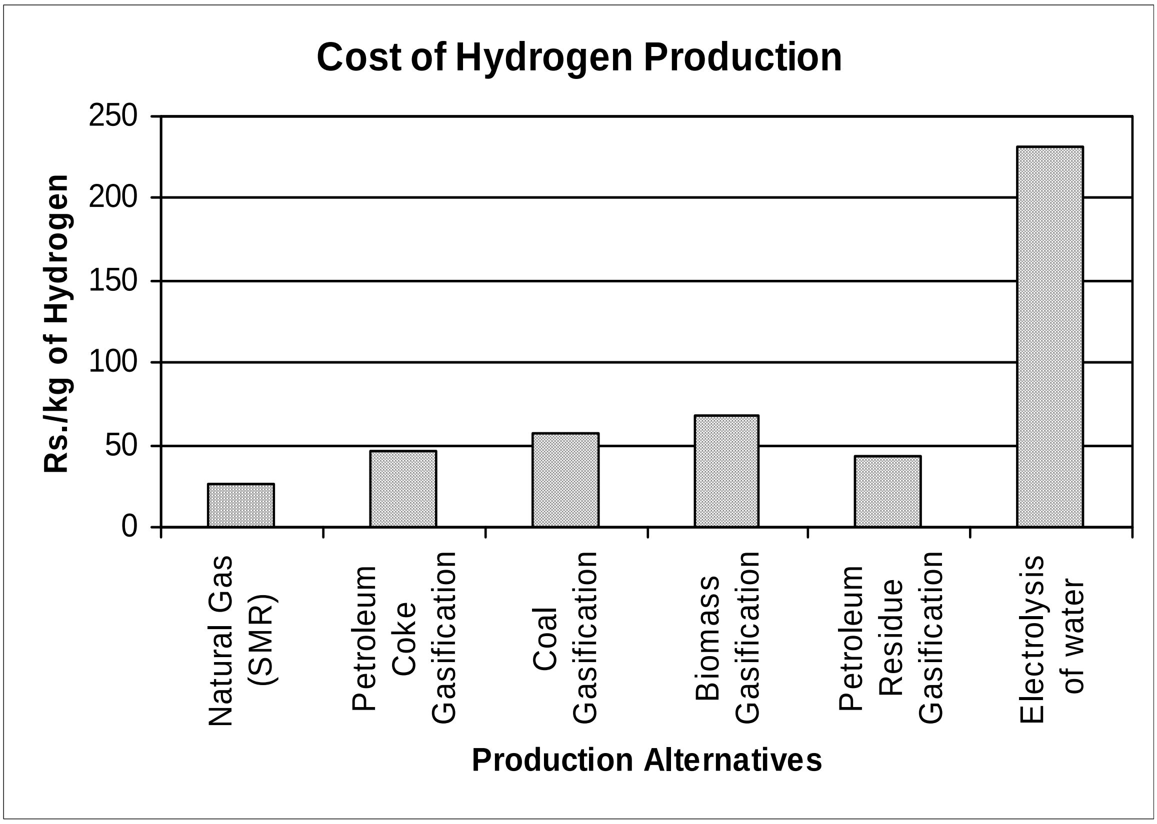
The last technology of hydrogen production is through electrolysis of water. This process requires large amount of electricity, which may be fossil fuel-originated, but can be claimed to be the cleanest one (ignoring the indirect emissions). In terms of equipment costs, it is the most expensive one. The total equipment cost of Rs. 15,240 million includes cost on electrolysis equipment and hydrogen compressor. The total capital cost is about Rs. 20,574 million, annual variable cost is Rs. 8,301 million, and the electricity cost is about Rs. 8,099 million. Including the interest charges, the total annual cost is Rs. 11,387 million. This results in a hydrogen production cost of Rs. 231.10 per kg of hydrogen.

Table 2: Cost of Hydrogen Production

Items	**Units**	SMR of Natural Gas	Petroleum Coke Gasification	Coal Gasification	Biomass Gasification	Petroleum Residue Gasification	Electrolysis of Water
Total Capital Cost	Million Rs.	2870	9620	99340	10800	7410	20575
Variable Non-fuel O&M Cost	Million Rs./year	287	96	99	108	74	205
Cost of Fuel	Million Rs./year	700	232	712	886	560	
Fuel Calorific Value	Btu/lb HHV	23000	13500	12000	8000	17500	
Unit Cost of the Fuel	Rs./MM Btu HHV based	85.80	26.38	79.13	90.72	67.50	
Fuel per year	tonne/yr	161109	296186	340092	553995	214949	443475
Days/year	Days	328	328	328	328	328	328
Fuel per hour	kg/hr	20435	37568	43137	70268	27264	56250
Fuel per hour at high heating value (HHV)	MM Btu/hr	1036.18	1118.11	1141.21	1239.32	1051.87	
Fuel per per hour at low heating value (LHV)	MM Btu/hr	934.17	1086.11	1108.20	1169.30	1001.88	
System Efficiency- LHV	%	76	75	73	80	80	75
Total Power Required	kW	4420	20989	22465	30177	16116	342301
Total Electricity Consumption	kWh/day	106080	503725	539155	724257	386774	8218500
Electricity Cost per year	Million Rs./year	104	496	531	713	381	8099
Total Variable Operating Cost	Million Rs./year	834	825	1342	1708	1015	8301
Fixed Operating cost per year	Million Rs./year	86	288	298	323	222	617
Capital Charges per year	Million Rs./year	344	1154	1192	1295	889	2468
Total Annual Cost	Million Rs./year	1264	2268	2833	3327	2126	11387
Cost per kg of Hydrogen	**Rs./kg of H_2**	**25.7**	**46.0**	**57.5**	**67.5**	**43.2**	**231.1**

Among the technologies considered for economic analysis, the natural gas option seems to be the cheapest one and the electrolysis is the costliest in terms of cost implications (Figure 2). Except for biomass gasification and electrolysis technologies, others depend on fossil fuels for hydrogen production. Either direct or indirect, all these technologies have implications for environmental degradation.

Figure 2: Cost of Hydrogen Production Alternatives



Hydrogen Storage

The hydrogen produced in a centralized production system needs secure storage facilities. The possible storage modes are: compressed Hydrogen Gas Storage, Liquid Hydrogen Storage, Metal Hydride Storage and Underground Hydrogen Gas Storage. The basic data inputs and assumptions needed for storage costs estimates are given in Table 1. The days of storage is assumed to be equal to two days. This is a critical assumption and the entire cost estimates depends on this assumption. The compressed hydrogen gas storage cost estimates are given in Table 3.

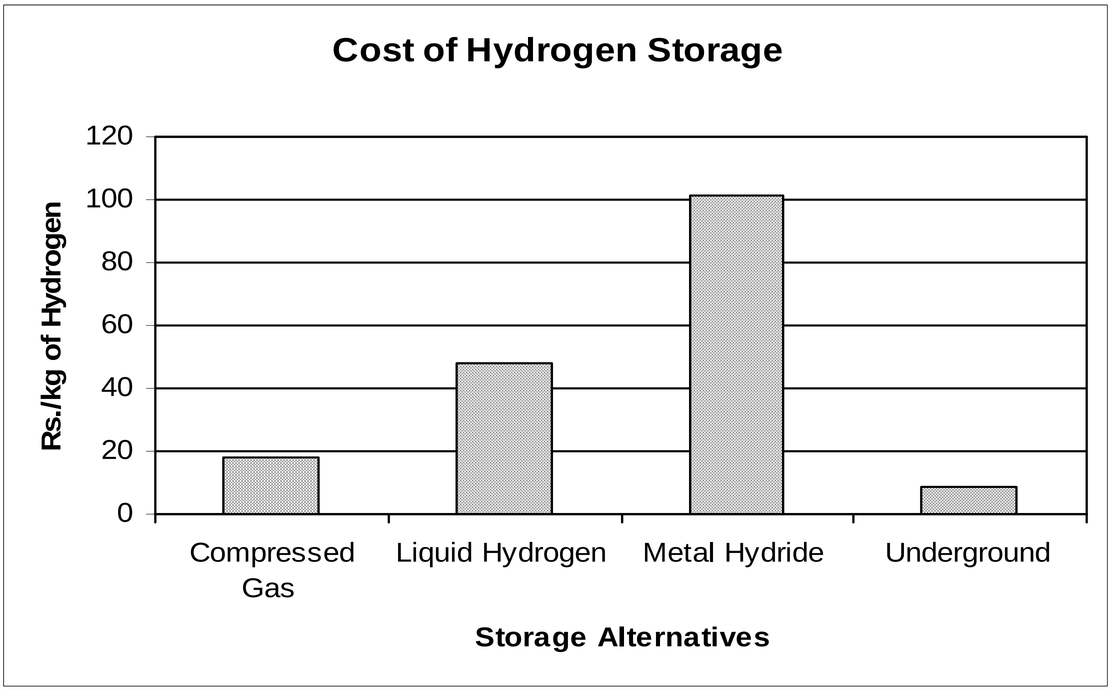
Table 3: Cost of Hydrogen Storage

Compressed Hydrogen			Liquid Hydrogen			Metal Hydride Hydrogen			Underground Hydrogen		
Items	**Units**	**Value**	**Items**	**Units**	**Value**	**Items**	**Units**	**Value**	**Items**	**Units**	**Value**
Compressor Capital Cost	Million Rs.	490	Liquefaction Capital Cost	Million Rs.	4960	Hydride Capital Cost	Million Rs.	29760	Compressor Capital Cost	Million Rs.	490
Gas Tank Capital Cost	Million Rs.	2960	Liquid Dewar Capital Cost	Million Rs.	425	Hydride Cooling	litres/kg	210	Underground Capital Cost	Million Rs.	120
Compressor Size	kW	4000	Liquefaction Size	kg/hr	454	Hydride Heating	kJ/kg	23,260	Compressor Size	kW	4000
Gas Tank Size	kg	227	Liquid Dewar Size	kg/hr	45	Steam Cost	Rs./GJ	170.61	Compressor Power	kWh/kg (@20 MPa)	2.2
Compressor Energy	kWh/kg (@20 MPa)	2.2	Liquefaction Power	kWh/kg	10				Compressor Cooling	litres/kg (@20 MPa)	50
Compressor Cooling	litres/kg (@20 MPa)	50	Liquefaction Cooling	litres/kg	626						
Compressor Size	kW	14000	Liquefaction Size	kg/hr	2499	Heat required	GJ/hr	145.38	Compressor Size	kW	14000
Operating Pressure	Mpa	20	Liquid Dewar Size	kg/hr	21428	Cooling required	KL/hr	1303.97	Operating Pressure	Mpa	20
Total Capital Cost	Million Rs.	3450			5380			29760			610
Variable non-fuel O&M cost	Million Rs./year	34.5			53.8			297.6			6.1
Fixed Operating Cost	Million Rs./year	103.5			161.5			892.9			18.3
Electricity Cost	Million Rs./year	325.9			1478.3			208.3			325.9
Cooling water cost	Million Rs./year	2.05			25.66			9.11			2.05
Capital Charges	% per year	12			12.00			12.00			12.00
Cost of Capital Charges	Million Rs./year	414.2			645.0			3571.5			73.1
Total Annual Cost	Million Rs./year	880.2			2365.2			4979.4			425.5
Cost per kg of Hydrogen	**Rs./kg of H_2**	**17.9**			**48.0**			**101.1**			**8.6**

According to the table, the total capital cost is Rs. 3,451 million and the variable annual cost is about Rs. 880 million. The unit cost of hydrogen storage using this mode is Rs. 17.86 per kg. For liquefied hydrogen storage, the capital cost required is about Rs. 5,383 million. The total annual cost is Rs. 2,365 million and the resulting unit liquid hydrogen storage cost is Rs. 48 per kg. For metal hydride storage the major cost is the hydride cost which is about Rs. 29, 762 million for the given storage requirement. The final estimated storage cost is Rs. 101.05 per kg of hydrogen, which is the highest among all the storage technologies.

The underground storage cost is the cheapest compared to all other technologies. The estimated unit cost is Rs. 8.63 per kg of hydrogen. Comparing the alternatives of hydrogen storage, metal hydride option appears to be the most expensive one (Figure 3).

Figure 3: Cost of Hydrogen Storage Alternatives



Hydrogen Transportation

The hydrogen produced from a centralized facility needs to be transported to different end-use locations (refueling stations). The possible alternative modes of transportation are truck, rail, ship and pipeline. The results of economic analysis of alternative modes of hydrogen transportation and the underlying assumptions and information on various basic data inputs are given in Table 4.

Table 4: Cost of Hydrogen Transportation

Truck					Rail				
Items	**Units**	**Compressed Hydrogen**	**Liquid Hydrogen**	**Metal Hydride**	**Items**	**Units**	**Compressed Hydrogen**	**Liquid Hydrogen**	**Metal Hydride**
Truck tube/hydride capacity	kg	181	4082	454	Rail Tube Unit	Rs./module	9,000,000	18,000,000	99,225∗
Truck tube unit cost	Rs./module	4,500,000	15,750,000	99,225∗	Rail Undercarriage	Rs./rail car	4,500,000	4,500,000	4,500,000
Truck Undercarriage cost	Rs./trailer	2,700,000	2,700,000	2,700,000	Rail Tube/hydride Capacity	kg	454	9072	907
Truck cab cost	Rs./cab	4,050,000	4,050,000	4,050,000	Rail load/unload time	hr/trip	24	24	24
Operating days /year	days /year	350	350	350	Rail car availability	hr/day	24	24	24
Truck load time/unload time	hours/trip	2	2	2	Rail freight charge	Rs./rail car/trip	18,000	18000	18000
Truck availability	hr/day	24	24	24	Rail speed	km/hr	40	40	40
Driver availability	hr/day	12	12	12	Working hours per day	hr/day	24	24	24
Driver wages	Rs./hr	50	50	50	Operating days in year	days/year	350	350	350
Number of trips	trips/year	272238	12,071	108,535	Number of trips	trips/year	108,535	5432	54,327
Total kms. driven	km/year	108,895,028	4,828,515	43,414,097	Total kms. driven	km/year	43,414,097	2,172,619	21,730,981
Time per trip	hr/trip	8	8	8	Time per trip	hr/trip	10	1.14	10
Total Drive time	hrs/year	2177901	96,570	868,282	Transit time	days/trip	2	2	2
Total Load/Unload time	hr/year	544475	24,143	217,070	Total Transit time	hrs/year	5,209,692	260,714	2,607,718
Trucks required	No.	325	15	130	Total Load/Unload time	hr/year	2,604,846	130,357	1,303,859
Driver required	No.	649	29	259	Rail car required	No.	931	47	466
Total Capital Cost	Million Rs.	3656.25	337.5	6733.76	Total Capital Cost	Million Rs.	12568.5	1057.5	44035.64
Variable non-fuel O&M cost	Million Rs./year	36.56	3.38	67.34	Variable non-fuel O&M cost	Million Rs./year	125.69	10.58	440.36
Fixed Operating Cost	Million Rs./year	109.69	10.13	202.01	Fixed Operating Cost	Million Rs./year	377.06	31.73	1321.07
Annual Fuel usage	KL	41882.70	1857.12	16697.73	Annual Freight Cost	Million Rs./year	3907.27	195.54	1955.79
Annual Fuel Cost	Million Rs./year	1047.07	46.43	417.44					
Annual Labour cost	Million Rs./year	136.12	6.04	54.27					
Cost of Capital Charges	Million Rs./year	438.75	40.50	808.05	Cost of Capital Charges	Million Rs./year	1508.22	126.90	5284.28
Total Annual Cost	Million Rs./year	1768.19	106.46	1549.11	Total Annual Cost	Million Rs./year	5918.23	364.74	9001.49
Cost per kg of Hydrogen	**Rs./kg of H_2**	**35.88**	**2.16**	**31.44**	**Cost per kg of Hydrogen**	**Rs./kg of H_2**	**120.11**	**7.40**	**182.68**

∗ Hydride Container cost is in Rs./kg of H_2

It has been assumed the transportation system (or fleet) should be capable of delivering all the hydrogen produced. A delivery distance of 200 km is assumed for the economic estimates. The cost estimates of hydrogen transportation (Rail and truck) show that the unit cost of compressed hydrogen transportation works out to be Rs. 35.88 per kg. Compared to this, the cost is Rs. 120.11 per kg in the case of rail transportation. One of the major reasons for increase in cost in the case of rail transport is due to inclusion of transit time (train cannot start again on the same day after delivery). With the increase in distance of transport, the cost of hydrogen transport through rail becomes cheaper. Table 5 shows the analysis for ship and pipe line transport.

From the tables it may be observed that the cheapest liquid hydrogen transportation is by truck at Rs. 2.16 per kg of hydrogen. By rail it costs Rs. 7.40 per kg and by ship it is Rs. 73.20 per kg. However, ship is not a feasible alternative in India because not many in-land water ways are available. However, this option can be explored for hydrogen imports. As mentioned earlier, these cost estimates are made for a distance of 200 km. It is observed that with the increase in distance, the cost of rail transport declines substantially and beyond some distance rail transport becomes cheaper than truck transport.

The third possible pathways of transportation are metal hydride hydrogen transportation either through trucks or railways. These are expensive propositions compared to earlier alternatives given the prevailing cost and technology considerations. By truck, the unit cost of metal hydride hydrogen transportation is Rs. 31.44 per kg and by rail it is Rs. 182.68 per kg (Table 4).

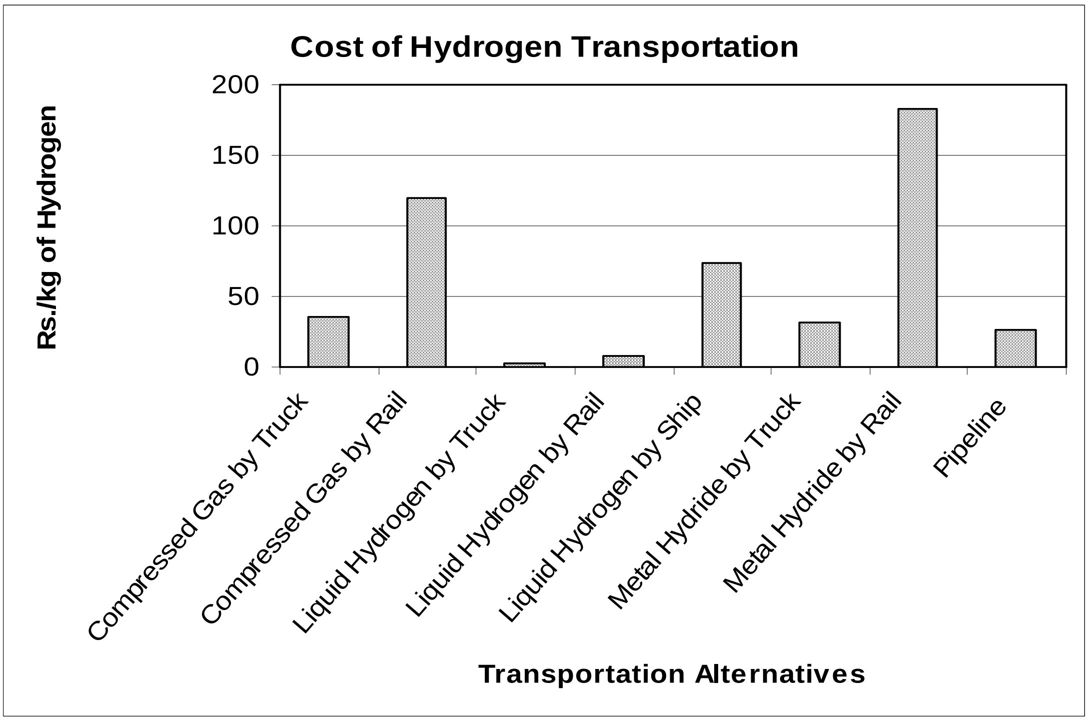
Finally, one of the most efficient and effective alternatives is delivery of hydrogen through gas pipelines. Even here we have assumed the distance of delivery to be equal to 200 km. The cost inputs, technical details and the estimates are provided in Table 5. It may be observed from the table that there are many technical parameters need to be used for estimating final costs. The unit cost of hydrogen delivery through pipeline is Rs. 25.85 per kg of hydrogen.

Table 5: Cost of Hydrogen Transportation by Ship and Pipeline

Ship			Pipeline		
Items	**Units**	**Value**	**Items**	**Units**	**Value**
Ship Liquid Tank Cost	Rs./container	15,750,000	Compressor Capital Cost	Rs./kW	45,000
Ship Liquid Capacity	kg/tank	4082	Compressor Size	kW	4000
Ship Average Speed	km/hr	16	Compressor Pressure	MPa	20
Ship Load/Unload Time	hr/trip	48	Pipeline Cost	Rs./km	27,960,000
Ship Tank Availability	hr/day	24	Pipe diameter	m	0.25
Shipping Charges	Rs./container	135,000	Delivery pressure	MPa	2
Operating days in year	days/year	350	Temperature	k	283
Working hours per day	hr/day	24	Compressor Power	kWh/kg	2.205
Delivery Distance	km (one-way)	200	Operating days	Days	350
Delivery Distance	km (two-way)	400	Operating hours	Hr	24
Tank Capacity	kg/tank	4082	Delivery Distance	km (one-way)	200
Number of trips	trips/year	12,071	Flow rate	kg/sec	1.74
Total kms. Driven	km/year	4,828,515	Area	m^2	0.0491
Time per trip	hr/trip	16.67	Inlet pressure	Mpa	5.2305
Transit time	days/trip	2	Compressor to overcome friction losses	kW	2500.56
Total Transit time	hrs/year	579,422	Annual Energy	GWh	21
Total Load/Unload time	hr/year	579,422	Compressor capital cost	Million Rs.	97.10
Total Delivery time	hr/year	1,158,844	General Facilities	Million Rs.	853.42
Tank availability	hr/year	8400	Engineering, Permitting & Startup	Million Rs.	455.16
Tanks required	No.	138	Contingencies	Million Rs.	341.37
Total Capital Cost	Million Rs.	2173.5	Working Capital, Land & Misc.	Million Rs.	227.58
Variable non-fuel O&M cost	Million Rs./year	21.74	Total Capital Cost	Million Rs.	7566.95
Fixed Operating Cost	Million Rs./year	65.21	Variable non-fuel O&M cost	Million Rs./year	75.67
Annual Freight Cost	Million Rs./year	3259.25	Fixed Operating Cost	Million Rs./year	227.01
Capital Charges	% per year	12	Annual energy Cost	Million Rs./year	63.01
Cost of Capital Charges	Million Rs./year	260.82	Cost of Capital Charges	Million Rs./year	908.03
Total Annual Cost	Million Rs./year	3607.01	Total Annual Cost	Million Rs./year	1273.73
Cost per kg of Hydrogen	**Rs./kg of H_2**	**73.20**	**Cost per kg of Hydrogen**	**Rs./kg of H_2**	**25.85**

For a distance of 200 km, the comparative cost of hydrogen transportation is depicted in Figure 4. From the figure, it may be observed that the cheapest option is liquid hydrogen transportation by truck and the most expensive option is hydrogen metal hydride delivery by rail.

Figure 4: Cost of Hydrogen Transportation Alternatives



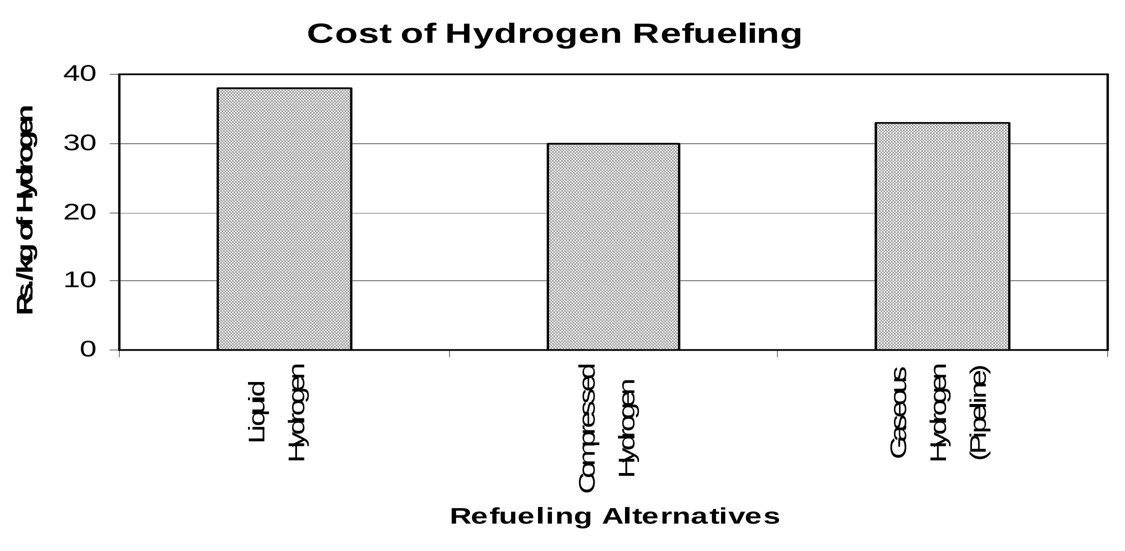
Hydrogen Refueling

Three types of refueling alternatives have been considered for economic analysis. Refueling of all the possible forms of hydrogen, i.e., liquid, compressed and gaseous hydrogen are included. The basic data inputs and assumptions used for economic analysis are given in Table 1. Based on the given assumptions there will be a requirement of 411 fueling stations to refuel 135,000 kg of hydrogen per day at a load factor of 70%. The design capacity of each station is 470 kg per day per station. The unit cost of liquid hydrogen refueling is Rs. 37.95 per kg, whereas it is Rs. 30.03 per kg for compressed hydrogen refueling and Rs. 33.03 per kg for gaseous hydrogen refueling (Table 6). Comparison of refueling costs is depicted in Figure 5.

Table 6: Cost of Hydrogen Fueling Stations

Items	Units	Liquid Hydrogen	Compressed Hydrogen	Gaseous Hydrogen
Total number of stations	No.	411	411	411
Hydrogen per day - Design capacity	kg/day/station	470	470	470
Actual Hydrogen per day	kg/day	329	329	329
Storage duration	days	7.00	7.00	-
Buffer storage of H_2	Kg	123	123	123
Liquid H_2 pump/vaporizer	Million Rs.	6.64	-	-
Compressor	Million Rs.		8.78	8.78
Liquid H_2 storage	Million Rs.	6.96	-	-
H_2 buffer storage	Million Rs.	5.15	5.15	5.15
H_2 dispenser	Million Rs.	1.35	1.35	1.35
Total Equipment Cost	Million Rs.	20.11	15.28	15.28
General Facilities	Million Rs.	3.62	2.75	2.75
Engineering, Permitting & Startup	Million Rs.	1.61	1.22	1.22
Contingencies	Million Rs.	1.21	0.92	0.92
Working Capital, Land & Misc.	Million Rs.	1.01	0.76	0.76
Total Capital Cost	Million Rs.	27.55	20.94	20.94
Capital Costs for all stations	Million Rs.	11321	8605.93	8605.93
Variable Non-fuel O&M Cost	Rs./year	137727	104,695	104,695
Electricity power	kW	22.00	56	56
Electricity norm	kWh/kg of H_2	0.80	2	2
Electricity Cost	Rs./year	288,204	360,255	720,510
Variable Operating cost	Rs./year	425,931	464,950	825,205
Fixed Operating cost	Rs./year	826,362	628,170	628,170
Capital Charges	Rs./year	3,305,449	2,512,679	2,512,679
Total Annual Cost	Rs./year	4,557,742	3,605,799	3,966,054
Cost per kg of Hydrogen	**Rs./kg of H_2**	**37.95**	**30.03**	**33.03**

Figure 5: Cost of Hydrogen Refueling Alternatives



5. ECONOMICS OF HYDROGEN SUPPLY PATHWAYS

The multiple combinations of technologies to supply hydrogen are called as "hydrogen supply pathways". Depending on the availability of resources, cost implications and technological complexities, it is possible to select best possible supply pathways. The next sections briefly discusses about the economics of these supply pathways.

Hydrogen Supply Pathways

In total we have developed 12 major hydrogen supply pathways. In each major pathway, there are six sub-pathways. In other words, with all possible combinations, one can have 72 hydrogen supply pathways which differ in terms of production technologies, transportation alternatives, storage methods and refueling methods. For example, one supply pathway could be: SMR of natural gas → Compressed storage → Truck transportation → Compressed gas refueling. Figure 6 contains the overall cost estimates of all the possible pathways. From the figure, we may observe that the unit cost of delivered hydrogen varies from a low of Rs. 84.54 per kg of hydrogen to a high of Rs. 547.86 per kg of hydrogen. The lowest cost pathway is SMR of natural gas → No storage → Pipeline transportation → Gas refueling and the highest cost pathway is Electrolysis of water → Metal hydride storage → Rail transportation → Gas refueling.

Summarized Hydrogen Supply Pathways

Figures 7 and 8 depict the summarized cost estimates of different streams of hydrogen supply pathways. The pathways related to hydrogen production through steam methane reforming of natural gas seem to be the cheapest among alternative pathways. A comparison of unit costs of petrol and diesel with equivalent unit cost of hydrogen presents interesting results (Figure 9). A total of 72 hydrogen supply pathways are used for comparison at both high and low heating values (HHV and LHV). At HHV, there are 49 hydrogen supply pathways which compare favourably with the prevailing petrol price of Rs. 53/litre (in 2006) whereas only 16 pathways have lower unit costs compared to a diesel price of Rs. 33/litre. However, at LHV, the favourable number of hydrogen supply pathways is only 37 and 5 in relation to petrol and diesel prices respectively. In other words, there are hydrogen pathways which are cheaper than the prevailing petrol and diesel prices. However, it is important to keep in mind that the prevailing petrol and diesel prices include high central and state government taxes and duties, whereas hydrogen costs does not include these.

Figure 6: Unit Cost of different Hydrogen Supply Pathways (Rs./kg of H_2)

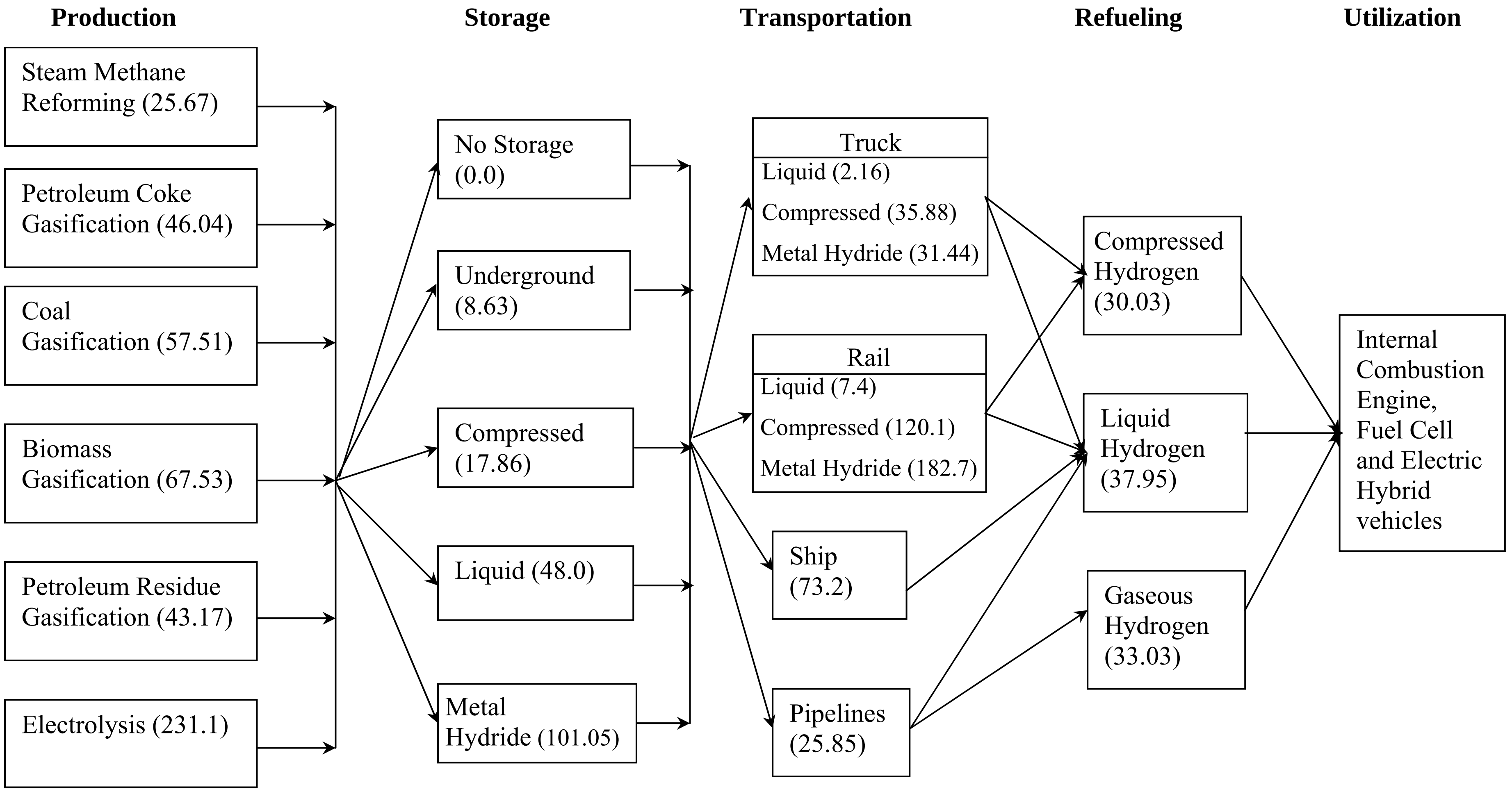


Figure 7: Cost of Hydrogen Supply Pathways - I

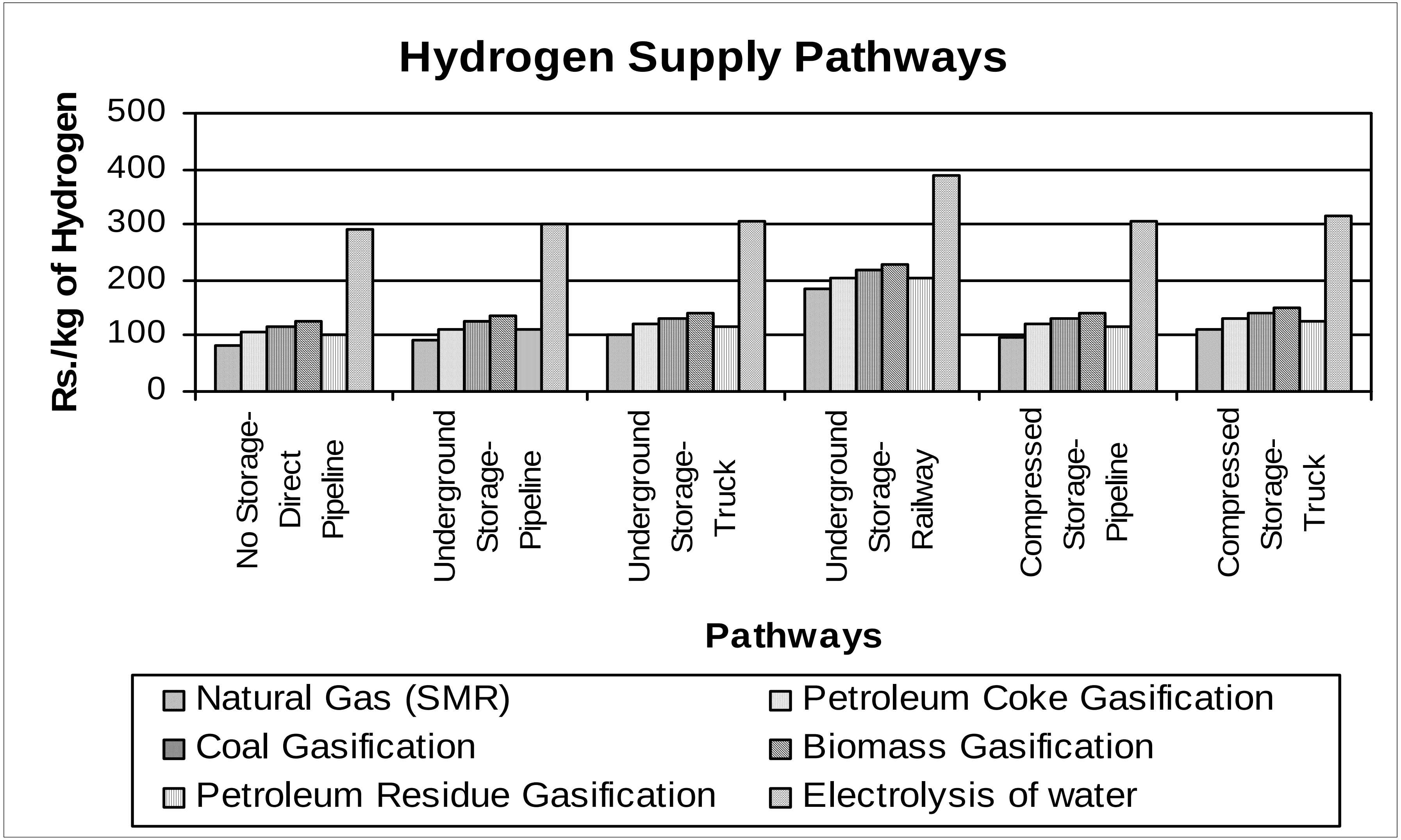


Figure 8: Cost of Hydrogen Supply Pathways - II

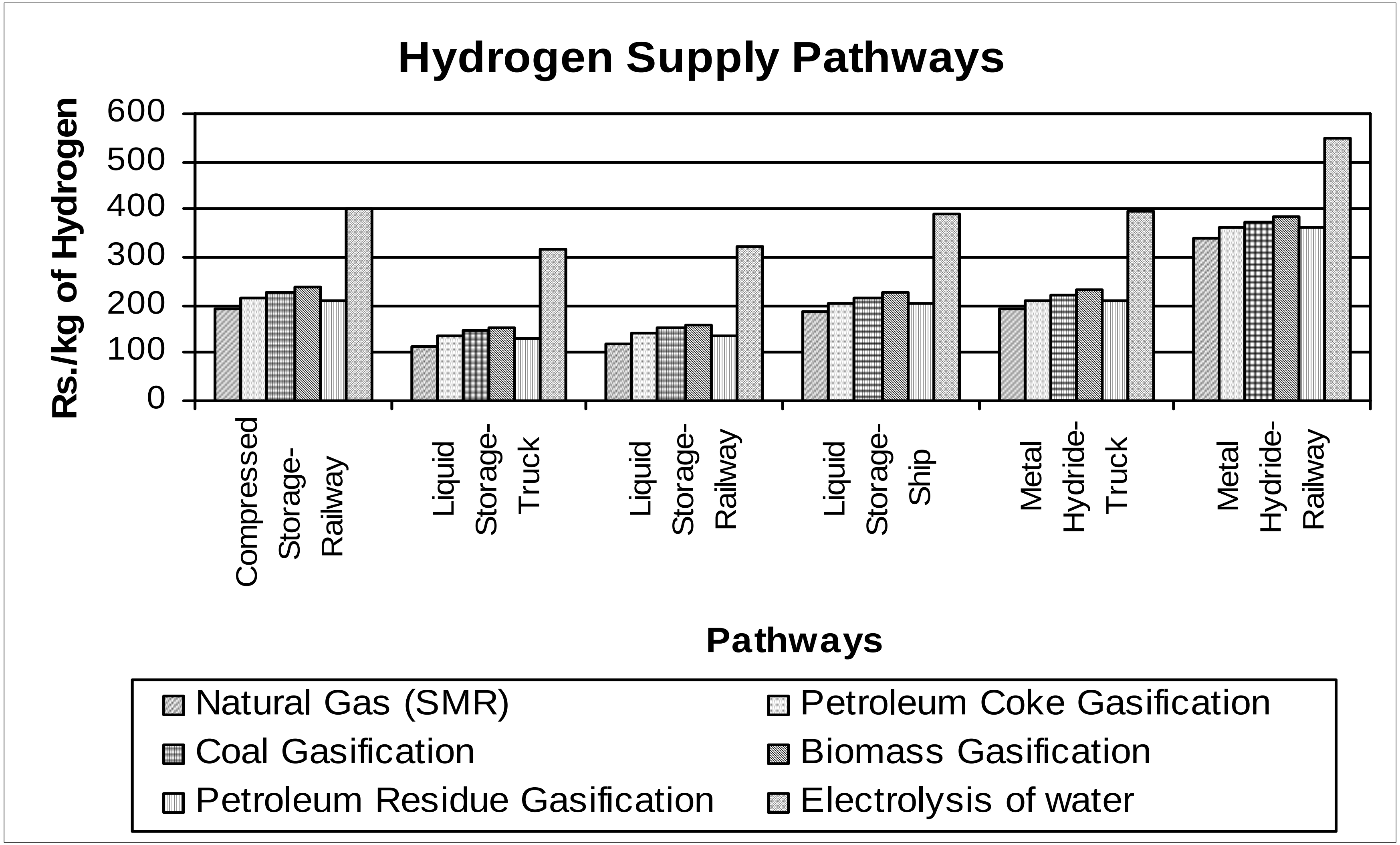
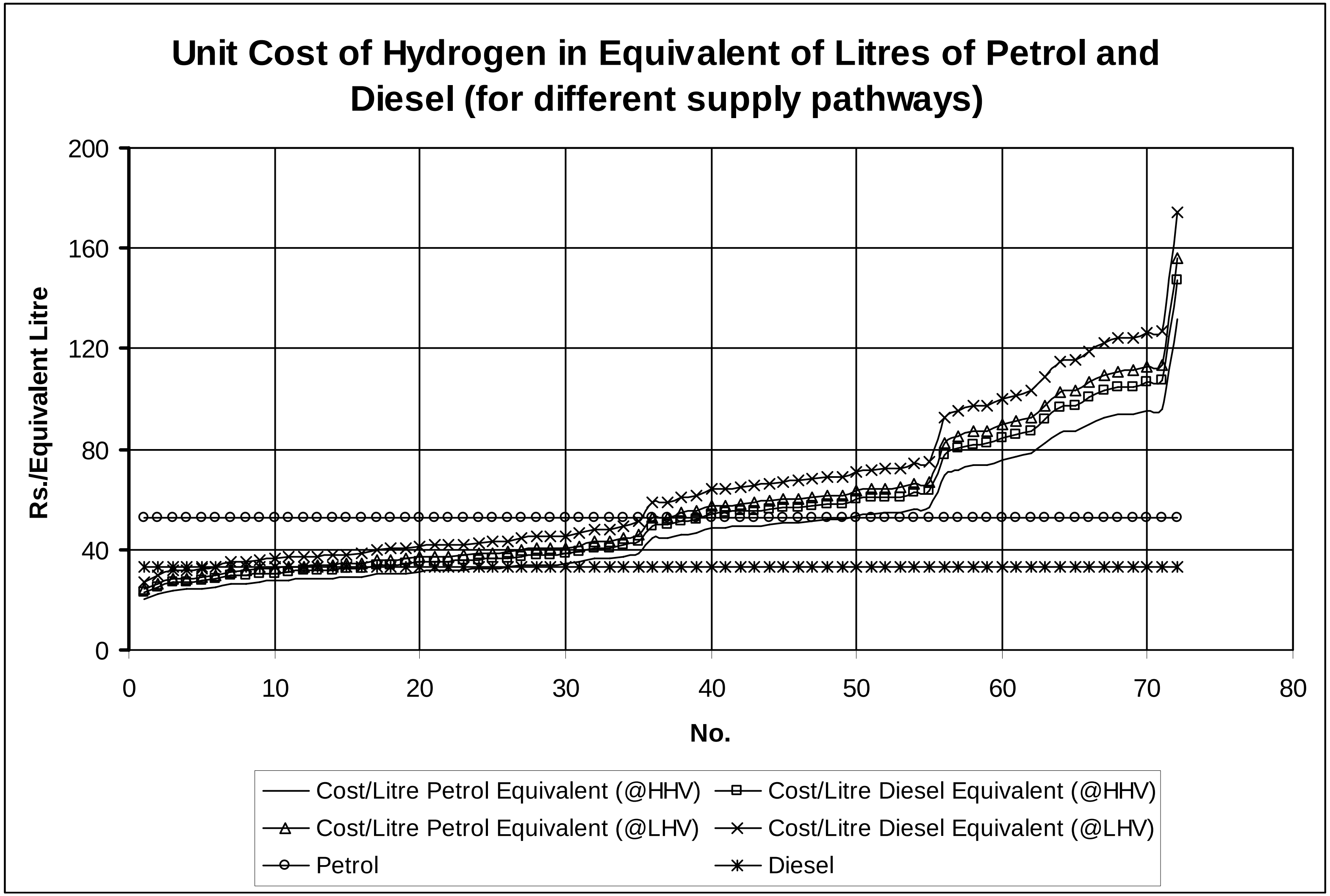


Figure 9: Unit cost of Hydrogen *vs* Petroleum Products



6. ENVIRONMENTAL ASSESSMENT OF HYDROGEN SUPPLY PATHWAYS

Need for Environmental Assessment

The local environmental benefits from Hydrogen Supply Pathways are obvious. Whether hydrogen is combusted or consumed in a fuel cell, it directly produces almost no local air pollutants or greenhouse gas emissions. If vehicles were all run on hydrogen, it would be a huge step towards solving air pollution problems in cities. Emissions of volatile organic compounds (VOCs, the precursors of ozone), SOx, NOx, carbon monoxide, and particulate matter could be dramatically reduced if all vehicles were fueled by hydrogen. When carbon-based fuels are reformed or gasified to produce hydrogen, a stream of nearly pure carbon dioxide is easily produced as a byproduct. These technologies effectively decarbonize the fossil fuels. Fossil fuel or un-sustainable biomass based hydrogen production and use of electricity from fossil fuel during hydrogen supply cycle contributes to both direct and indirect CO_2 emissions. In the present analysis, the CO_2 emissions for hydrogen supply pathways are estimated based on following assumptions:

- Both direct and indirect (from electricity) emissions are estimated
- Standard emission factors as provide by IPCC are used (IPCC, 1996)
- CO_2 emissions from electricity assumes 70% coal power generation
- 60% of the biomass used for hydrogen production assumed to be procured from un-sustainable sources.

GHG Emissions from Hydrogen Supply Pathways

The estimates of CO_2 emissions from hydrogen production and storage are presented in Table 8. The highest emissions are observed in the case of hydrogen production from electrolysis of water. However, the CO_2 emissions can be brought down to zero by depending on renewable electricity in the electrolysis process. Similarly in the case of biomass gasification (using biomass from sustainable supplies). In terms of storage alternatives, the CO_2 emission levels are significantly higher in the case of liquid storage.

Table 7: Well-to-Wheel CO_2 Emissions from Hydrogen (kg CO_2/kg of Hydrogen)

	SMR - natural gas	Petroleum Coke Gasification	Coal Gasification	Biomass Gasification	Petroleum Residue Gasification	Electrolysis of water
Production	9.41	27.35	16.75	13.91	15.15	48.76
Compressed/ UG Storage	1.96	1.96	1.96	1.96	1.96	1.96
Liquid Storage	8.90	8.90	8.90	8.90	8.90	8.90
Utilization	0.00	0.00	0.00	0.00	0.00	0.00

Note: Emissions from hydrogen transportation is not included

The CO_2 emissions levels for different hydrogen supply pathways as well as petroleum products pathways are estimated and presented in Table 8. From the table, we may observe that except for SMR of natural gas related pathways, in the case of all other pathways, the CO_2 emissions levels are significantly higher compared to petroleum products pathways.

The story can be entirely different if the sources of electricity and biomass are renewable and sustainable. In other words, use of grid electricity either in the electrolysis process or as provider of other end-use services should never be encouraged. To make the hydrogen supply pathways environment friendly, the only alternative left is to generate and use electricity from renewable sources like hydro, wind, solar, etc.

Table 8: Well-to-Wheel CO_2 Emissions for different Fuel Pathways

	Steam Methane Reforming -natural gas	Petroleum Coke Gasification	Coal Gasification	Biomass Gasification	Petroleum Residue Gasification	Electro-lysis of water
Hydrogen Pathways (kg CO_2/kg of Hydrogen)						
Production - No storage - Utilization	9.41	27.35	16.75	13.91	15.15	48.76
Production - Compressed/ Underground storage - Utilization	11.37	29.31	18.71	15.87	17.11	50.73
Production - Liquid storage – Utilization	18.31	36.25	25.65	22.81	24.05	57.66
Hydrogen Pathways (kg CO_2/GJ of Hydrogen)						
Production - No storage - Utilization	78.38	227.90	139.58	115.90	126.26	406.36
Production - Compressed/ Underground storage - Utilization	94.73	244.25	155.93	132.25	142.61	422.71
Production - Liquid storage – Utilization	152.54	302.07	213.75	190.07	200.43	480.53
Petroleum Products Pathways (kg CO_2/GJ of fuel)						
Diesel Production - Utilization	84.40	84.40	84.40	84.40	84.40	84.40
Petrol Production - Utilization	86.20	86.20	86.20	86.20	86.20	86.20

Note: Both the hydrogen and petroleum products pathways do not include emissions due to fuel transportation.

Table 9 contains the estimates of CO_2 emission levels for running any type of vehicle for a kilometer using hydrogen and petroleum products. All the hydrogen supply pathways are included in the analysis. As usual, except for hydrogen from SMR of natural gas pathways, other pathways of hydrogen are not comparable to diesel or petrol pathways in terms of kg of CO_2 per km. We reiterate that the only alternative left for hydrogen pathways is to depend on renewable sources in order to environmentally out beat the petroleum products pathways in replacing them as effective transportation fuel.

Table 9: Well-to-Wheel CO_2 Emissions for different Fuel Pathways

	Steam Methane Reforming -natural gas	Petroleum Coke Gasification	Coal Gasification	Biomass Gasification	Petroleum Residue Gasification	Electrolysis of water
Hydrogen Pathways (kg CO_2/km)						
For Bus						
Production - No storage - Utilization	0.76	2.20	1.35	1.12	1.22	3.92
Production - Compressed/ Underground storage - Utilization	0.91	2.36	1.50	1.28	1.38	4.08
Production - Liquid storage - Utilization	1.47	2.91	2.06	1.83	1.93	4.64
Diesel Production – Utilization	0.81	0.81	0.81	0.81	0.81	0.81
For Small 3-Wheeler						
Production - No storage - Utilization	0.11	0.31	0.19	0.16	0.17	0.56
Production - Compressed/ Underground storage - Utilization	0.13	0.33	0.21	0.18	0.20	0.58
Production - Liquid storage - Utilization	0.21	0.41	0.29	0.26	0.27	0.66
Petrol Production - Utilization	0.12	0.12	0.12	0.12	0.12	0.12
For Large 3-Wheeler						
Production - No storage - Utilization	0.13	0.39	0.24	0.20	0.22	0.69
Production - Compressed/ Underground storage - Utilization	0.16	0.42	0.27	0.23	0.24	0.72
Production - Liquid storage - Utilization	0.26	0.52	0.37	0.33	0.34	0.82
Petrol Production - Utilization	0.15	0.15	0.15	0.15	0.15	0.15

Note: CO_2 emissions due to hydrogen fuel pathways can be significantly reduced (even to zero level in few cases) by using electricity produced from renewable energy sources.

The present analysis has clearly indicated that unless we use renewable sources of energy for hydrogen pathways, we cannot expect them contribute positively to abate CO_2 emissions. However, the advantage of hydrogen pathways is the possibility of shifting the pollution to the locations where it is being produced from the locations where it is being used. In other words, utilization of hydrogen does not cause any pollution. This may be significant from the perspective of reducing the urban pollution related to transport.

7. SUMMARY AND CONCLUSIONS

The study investigates the main technical, economic and environmental aspects related to Hydrogen powering vehicles for transportation in the Indian context. The results confirm that SMR technology to produce Hydrogen for vehicles can be the best option, at least in the near future. Use of renewables is by far the most expensive option. Hence, it becomes crucial to consider the environmental externalities if these options have to become economically viable. The choice to select one technology against another should not only be related to technical costs but also to social acceptability. The environmental issue is to a greater extent part of new technology choice decisions.

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