National Hydrogen Energy Road Map

Path Way for Transition to Hydrogen Energy for India

National Hydrogen Energy Board
Ministry of New and Renewable Energy
Government of India
2006

(ABRIDGED VERSION , 2007)

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FOREWORD

Through the ages, man has depleted non-renewable resources in his quest for sources of energy-first for heat, and then for electric and motive power. As the global demand for energy increases exponentially, the energy resources, mainly fossil fuels, are being seriously depleted.

There is therefore a critical need to find means of conserving non-renewable energy sources as well as to identify new forms of non-polluting renewable energy resources which will fuel our energy needs in our long-term future. Hydrogen is emerging as a leading contender for the "ideal" energy option of the future.

The concept of a hydrogen economy is very promising in terms of the abundant availability of hydrogen in our environment and especially in water, but the concept presently has formidable problems relating to the economic generation of hydrogen, its storage and its delivery. Several different approaches are being pursued for end use, from the direct use of hydrogen in internal combustion engines, to the generation of hydrogen through on-board reforming from natural gas as fuel for fuel cells, which in turn would generate electric power.

For India, it is important that we chart a time-bound course for ourselves that will provide us with energy security, and abundant energy resources to meet the nation's growing needs. It is necessary that we take a holistic approach to conserve our current fossil fuel reserves while at the same time take bold steps to be in the forefront of technology development of new energy options like hydrogen.

The Government's far-sighted initiative to address the issues related to the adoption of hydrogen energy are commendable. The challenge for us will be to define an implementable strategic direction that best meets our national interest.

Ratan N. Tata

Preface

Hydrogen holds promise to provide clean, reliable and sustainable energy supply for meeting the growing demand of energy in the country. 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. However, developing hydrogen as an energy carrier requires solutions to many challenges in the areas of production, storage, technology development, infrastructure, energy economy and public acceptance. 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 National Hydrogen Energy Board in its first meeting on 23rd February, 2004 decided to set up a Steering Group under Mr. Ratan Tata, Member of the Board and Chairman of Tata Sons to prepare a National Hydrogen Energy Road Map. Mr. Anand Mahindra was the Co-chairman of this Steering Group, with members from Government, Industry, Academia and Experts. The Steering Group set up five Expert Groups on hydrogen production, storage, power, transport and systems integration. This Road Map is based on the Reports of the Expert Groups and deliberations of the National Hydrogen Energy Board. It provides an integrated blueprint for the long-term public and private efforts required for hydrogen energy development in the country.

This Road Map discusses the wide range of solutions for utilising hydrogen energy to solve the country's energy security problems and meet environmental quality standards. The Road Map is intended to provide information and guidelines to the large number of organisations in the public and private sectors and business and agencies in the Centre and the States and the non-government sector to become involved in a comprehensive National Programme for bringing about the transition from the present hydrocarbon based energy economy to a secure, clean and reliable hydrogen energy economy.

The National Hydrogen Energy Road Map will be used for preparation of Action Plans and Programmes on different components of the hydrogen energy system, to realise the Vision of Hydrogen energy for India in the coming decades.

Executive Summary

1. The growing concern about depleting oil reserves, harmful effects of green house 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. With high growth rate of Indian economy, energy needs are also growing rapidly. Energy security is a major challenge, which needs imaginative and innovative solutions. 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.

2. 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. 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.

3. The National Hydrogen Energy Road Map is an industry driven planning process that offers long-term energy solutions to the growing energy needs of India, while ensuring energy security for the country. The main objective of the National Hydrogen Energy Road Map is to identify the paths which will lead to a gradual introduction of Hydrogen Energy in the country, accelerate commercialization efforts and facilitate the creation of the Hydrogen Energy Infrastructure in the country.

4. The Road Map has identified technology gaps and challenges to be overcome for a large-scale introduction of hydrogen as an energy carrier in a phased manner. The Road Map has suggested suitable pathways that will help the Industry, Government, Research Organizations, Academia, NGO's and other stakeholders to achieve the national goals for sustainable energy development.

5. The Road Map identifies the need for public-private initiatives to achieve the objectives which would bring about the development of hydrogen energy technologies suitable for transition to the Hydrogen Economy.

6. The National Hydrogen Energy Road Map, which will lead to the implementation of the National Hydrogen Energy Programme, has identified policies, legislation, financing and support infrastructure alongwith research, development and demonstration programmes to develop and commercialize various hydrogen energy technologies.

7. The policy and legal framework would in turn require large-scale awareness and understanding of the potential of hydrogen as the next transition fuel and identification of various issues relating to production, storage, delivery and use of hydrogen energy. Several properties of hydrogen require safe handling, which are different from other fuels. Therefore, it will be necessary to have new safety standards & codes, and regulations.

8. The Road Map has called for the adoption of a total systems approach for developing hydrogen energy technologies though public private partnership. Various components of the hydrogen economy would require specific strategies and action plan which have been identified in the Road Map. Systematic efforts are required to develop and demonstrate technically and commercially viable hydrogen energy applications. In order to achieve the goal of energy security for the country, large-scale use of hydrogen for production of electricity and heat, transport and mobile applications, among other strategies, alongwith a planned and well-coordinated technology development and demonstration programme would be required. The Road Map has recognized that it would be possible to achieve this goal in a time bound manner through a public private partnership programme of action.

9. Public private partnership would especially be necessary to develop a vibrant industrial base in the country covering various aspects of hydrogen and fuel cell technologies including hydrogen production, its storage, transport and delivery, materials, components, equipment and applications. This would be achieved though a collaborative effort by supporting research and development, product development, pilot production and demonstration projects.

10. 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.

11. Similarly, in the area of hydrogen storage, which include 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..

12. In this context, the Road Map has proposed setting up of demonstration projects which would not only provide operating experience in key hydrogen applications such as decentralized power generation and use in automobiles, but also facilitate public-private partnership involving the major stakeholders of government, industry, research and user groups. These actions will require solution to many challenges in developing technologies, creating infrastructure and achieving economic levels to make hydrogen applications feasible and affordable.

13. The Road Map has brought out that demonstration of technologies for power generation and automobile applications would facilitate creation of infrastructure required for large-scale introduction of hydrogen in selected locations. This

would also facilitate development of low cost, safe and reliable technologies for production of hydrogen, its storage and safe transport and delivery. While, large-scale use of hydrogen would also help in mitigating green house gas emissions, the ultimate goal of developing hydrogen energy technologies is to achieve energy security for India and offer consumers cost effective, safe and reliable hydrogen energy applications.

14. The demonstration of use of hydrogen in IC engines can be done in the short run and would require significantly lower investments and infrastructure. Therefore, the Road Map has proposed support for developmental activities for immediate use of hydrogen in IC engines as well as in fuel cells. Demonstration of hydrogen use in IC engines would also help in the creation of public awareness, development of codes, standards, regulations and policies. This would also facilitate development of support infrastructure in the country.

15. Keeping in view the present status of development of hydrogen energy technologies in the country and the need to systematically upgrade these technologies to make them technically and commercially viable, the Road Map has identified two major initiatives; namely Green Initiatives for Future Transport (GIFT) and Green Initiative for Power Generation (GIP).

16. The Green Initiative for Future Transport (GIFT) aims to develop and demonstrate hydrogen powered IC engine and fuel cell based vehicles ranging from small two/three wheelers to heavy vehicles through different phases of development. It is recognized that the performance of hydrogen fuelled vehicles have to be at par with the commercially available options to the consumers in terms of performance, safety, convenience and costs. This would require a well-planned and coordinated industry driven action plan. The Indian automobile industry is fully committed and geared to take up the challenges in this task. It is envisaged that if the National Hydrogen Energy Road Map is implemented as proposed, one million hydrogen fuelled vehicles would be on Indian roads by 2020.

17. The Green Initiative for Power Generation (GIP) envisages developing and demonstrating hydrogen powered IC engine/turbine and fuel cell based decentralized power generating systems ranging from small watt capacity to MW size systems through different phases of technology development and demonstration. This initiative would help the country in providing clean energy in a decentralized manner to rural and remote areas, besides power generation for the urban centres. It is envisaged in the Roadmap that decentralized hydrogen based power generation of about 1,000 MW aggregate capacity would be set up in the country by 2020.

18. In conclusion, the key issues and the likely options as identified in the Road Map need to be vigorously pursued and for this purpose large scale introduction of hydrogen based power generating systems and vehicles needs to be taken up as part of well-coordinated programme based on the public private partnership. This program will cover all elements of the hydrogen energy system. Hydrogen production, transportation, storage and application systems are to be developed and demonstrated in a coordinated manner. Apart from R & D efforts on all aspects, ranging from production to applications, the other key issues that have to be tackled relate to the development of codes and standards and the

generation of public awareness about hydrogen energy and its safe use by the common man.

19. The pathway for bringing about the transition from the present hydrocarbon energy economy to the new hydrogen economy in the coming decades is full of challenges. But the country is well equipped to meet these challenges in a planned and systematic manner through the adoption of this Road Map, which 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 achievement of these targets will require actions at different levels for the various components of the hydrogen energy system, which have been identified in the Road Map. The Road Map will be modified and upgraded based on field experience in our country and new developments world wide. The Road Map provides the path for expanding hydrogen energy use in the country and for the eventual switch over from the present hydro-carbon based economy to the new hydrogen energy economy. 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.

1. Hydrogen Energy for India

1.1 Introduction

1.1.1 The Indian economy is dependent on a complex energy mix. About 133,000 MW grid power generating capacity has been set up in the country and it is expected that by 2012 this capacity may exceed 200,000 MW. The Indian economy is poised to achieve higher growth rates, which will result in corresponding higher demand for energy.

1.1.2 The share of the transport sector in the total energy consumption in the country is significant. Liquid fossil fuels are the main source of energy supply for the transport sector. India has a very large variety of vehicles, ranging from manually driven bullock carts and cycles to fossil fuel driven light weight vehicles such as two / three wheelers, cars and heavy vehicles like buses and trucks etc. The largest number of vehicles are two and three wheelers with an estimated population of more than 40 million, out of the estimated 60 million vehicles in the country. The two / three wheelers are a major source of urban air pollution. Transport sector consumes most of the liquid fossil fuels.

1.1.3 At present coal and petroleum products occupy the central place in the country's overall energy mix. The known resources of liquid fossil fuels are likely to last another 50 years if the consumption pattern continues to grow at existing rate. Its consumption has been increasing at a very steep rate and with the present indigenous production of about 34 MMT, being less than 30% of annual requirement, India is heavily dependent on imported crude oil. With the uncertain and volatile nature of international crude oil prices, which have reached alarming levels in recent months, it has become vitally important to urgently tap the alternative energy sources for ensuring energy security for the country.

1.1.4 Energy security is a major challenge that needs imaginative and innovative solutions. There can be no unique solutions 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.

1.1.5 While a number of options are available for decentralized power generation, few alternatives are available for the transport sector, as it requires on-board storage of the fuel. These options include alcohols, bio-diesel and hydrogen. Recently, the use of bio-fuels has also been taken up in internal combustion engines. Production of bio-diesel would require considerable amount of land area, as compared to an equivalent centralized hydrogen production plant.

1.2 Hydrogen as a Fuel

1.2.1 Hydrogen is a clean fuel and an efficient energy carrier. Hydrogen is found in water, organic compounds and hydrocarbons such as petrol, natural gas, methanol and propane. The properties of hydrogen as compared to other conventional fuels are given in Table-1.1. Hydrogen is high in energy content as it contains 120.7 MJ/kg, which is the highest for any known fuel. However, its energy content compared to volume is rather low. This poses challenges with regard to its storage for civilian applications, when compared to storage of liquid fossil fuels. When burnt, hydrogen produces water as a by-product and is, therefore, environmentally benign. Although no CO_2, etc. are produced if hydrogen is burnt in air, yet NO_x will be formed at high temperatures. One of the advantages of hydrogen as a fuel is that it can be used directly in the existing internal combustion engines and turbines. It can also be used as a fuel in fuel cells for electricity generation. Hydrogen applications, besides industrial application, cover power generation, transport applications and heat. However, when compared to other alternatives, use of hydrogen in transport sector appears to be more beneficial as it is possible to store hydrogen on-board.

Table 1.1: Properties of Hydrogen vs. other conventional fuels

Fuel/property	Hydrogen	Natural Gas	Petrol	LPG
Lower heating value (MJ/kg)	120.7	49.54	41.87 - 44.19	46.05
Higher heating value (MJ/kg)	141.89	54.89	43.73 - 47.45	50.24
Density at standard conditions (kg/m^3)	0.08	0.6	720 – 780	510
Phase at standard conditions	Gas	Gas	Liquid	Liquid
Auto-ignition temperature[1] in air (°C)	566 – 582	540	257	454 – 510
Ignition limit[2] in air (Vol%)	4.1 – 74	5.3 – 15	1.4 – 7.6	2.2 – 9.5
Diffusion coefficient[3] in air (cm^2/s)	0.61	0.16	0.05	0.11

1. *Auto-ignition temperature is the lowest temperature at which a fuel will ignite when an external source of ignition is present*
2. *Ignition limit is the range of concentration within which the fuel will ignite, if an ignition source is present*
3. *Diffusion coefficient is used to determine the rate at which the fuel disperses (the higher the co-efficient, the faster the rate)*

1.2.2 In view of its unique properties, large-scale use of hydrogen in transport sector can help India in achieving energy security through reduction in import of fossil fuels and also reduction in the urban air pollution. Therefore, it is necessary to develop hydrogen energy technologies for large-scale use especially for the transport sector. In the Indian context, apart from substitution of liquid fossil fuels by hydrogen produced from locally available resources, development of hydrogen based decentralized energy systems is relevant for meeting energy needs, in the remote, far-flung and un-electrified regions.

1.2.3 Hydrogen is seen as a potential alternative to fossil fuels, which can produce clean electricity and heat, efficiently. However, the transition to the hydrogen economy from the present fossil fuel based economy will require solutions to many challenges in the areas of production, storage, delivery and applications and spanning infrastructure, technology, economics and large scale public awareness.

1.3 Development of Hydrogen Energy Technologies

1.3.1 Several major countries, including Canada, Germany, Japan, UK, USA. etc. are supporting comprehensive research, technology development and demonstration programme for developing and deploying fuel cell systems for stationary, portable and transport applications. The focus of research in these countries is on producing fuel cells for automobiles and also for electricity generation by 2020.

1.3.2 India is one of the few developing countries alongwith China and Brazil, which have strong hydrogen energy research and development programme. In view of the large number of two and three wheelers in the country, apart from development of hydrogen fuel cell vehicles and generators, India is also focusing on the direct use of hydrogen in IC engines. The Ministry of New and Renewable Energy has been supporting research and demonstration activities to develop Hydrogen and Fuel Cell Technologies and their applications for more than a decade. As a result of these efforts, hydrogen operated motorcycles; three-wheelers and small generators have been developed in the country. In addition, Fuel Cells to directly produce electricity from hydrogen and Fuel Cells – Battery Hybrid Van have been developed. Hydrogen production from distillery waste, bagasse and other renewable methods is under development. Hydrogen storage in metal hydrides has also been developed and demonstrated. At present, research is in progress to further improve the technologies for prototype vehicles and generators developed so far. There is need to accelerate the development of hydrogen energy technologies in India as a substitute to petroleum products in partnership with industry and research organizations.

1.4 National Hydrogen Energy Board

1.4.1 Realizing the importance of hydrogen as a fuel in the coming years, the Ministry of New and Renewable Energy decided to prepare a National Hydrogen Energy Road Map for the country. In order to prepare, implement and monitor the National Hydrogen Energy Road Map and the National Hydrogen Energy and Fuel Cell Programme a National Hydrogen Energy Board was set up under the Chairmanship of Minister for New and Renewable Energy in October, 2003. The Board has high level representation from Government, industry, industry associations, academic institutions and experts. The Board will also suggest policy initiatives, fiscal/regulatory measures and other measures for promotion of hydrogen as a clean fuel. The Board will assist in developing specific projects with Public-Private partnership, which would also facilitate generation of resources from the private sector.

1.4.2 The main objective of the National Hydrogen Energy Road Map is to identify the paths, which will lead to a gradual introduction of Hydrogen Energy in the country, accelerate commercialization efforts and facilitate creation of Hydrogen Energy Infrastructure in the country. The National Hydrogen Energy Road Map provides a comprehensive approach to the development of the components of the hydrogen energy system, ranging from production, storage, transport, delivery, applications, safety and standards, education and awareness among others.

2. Hydrogen Energy System

2.1 Introduction

2.1.1 The long-term energy security, environmental concerns, socio-economic benefits etc. are the main drivers for embarking on the hydrogen energy path. Keeping these drivers in view, India would prefer to adopt hydrogen production methods based on cost effective solutions, mainly from non-fossil fuels. It is recognized that the end users of hydrogen applications would be more concerned about the safe and reliable functioning of the products in use. Therefore, it would be essential to develop all components of hydrogen infrastructure including its production, storage, transport, delivery, safety and devices/systems required for the applications in a coordinated manner. The development of hydrogen as an energy carrier and also the technologies for application of hydrogen energy would require significant improvements and compatibility to work as a total system.

2.2 Issues and Barriers

Identify performance requirements and existing gaps

2.2.1 India has identified decentralized power generation and transportation as the key areas for hydrogen applications The development of hydrogen energy applications for power generation and transport would require identification of technical, economic, social and policy requirements necessary to put an optimum system in place. It would be necessary to define the product performance requirements and identify gaps at various levels for evolving an integrated hydrogen energy system

2.3 Path Ahead

Develop Standards, Codes, Regulations and Policy for acceptance of Hydrogen Energy

2.3.1 The social issues include acceptance of hydrogen energy and its applications by common man. This would require significant efforts to create public awareness about the benefits of hydrogen as a safe and efficient fuel. A stream of hydrogen from a leak is invisible. Hydrogen is about 14 times lighter than air and easily mixes in air. Hydrogen flame is also invisible during the daylight. Hydrogen is flammable over a very wide range of mixtures in air (4% – 75% hydrogen in air) and is also explosive over a wide range (15% – 59%) at normal temperatures. At higher temperatures even small leaks of hydrogen have the potential to cause burning or explosion. Development of suitable technique, standards, codes and regulation will be put in place to ensure safe usage of hydrogen and create public awareness about it. It would also be necessary to enact favourable Government policies to accelerate development of hydrogen energy applications and make them cost competitive. This would require a package of financial and fiscal policy measures, which would support technological innovation for bringing about the accelerated development and commercialization of hydrogen energy technologies in India.

Develop a Technology Plan for Hydrogen Energy

2.3.2 It would be necessary to prepare a technical plan to develop various technologies required to produce, store, transport and deliver hydrogen for power generation and transport applications in a manner that the output of the first process is fully compatible with the input requirements of the next process.

2.3.3 The overall performance of hydrogen energy devices/systems needs to be comparable to the products already available. It would be possible to achieve this if the performance of various inputs required viz. standards for safe and reliable operation of the products and hydrogen supply, storage, transport and production are well understood and satisfy the requirement of each individual segment.

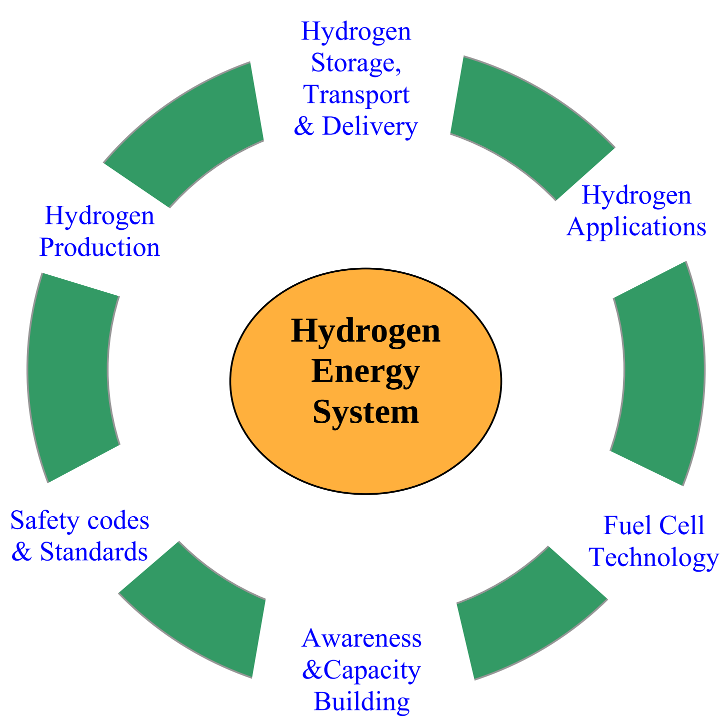
Develop Public-Private Partnership Projects

2.3.4 It will be necessary for the country to quickly take up development and demonstration of hydrogen energy through Public-Private Partnership Projects. In this context, it will be desirable to run a large number of vehicles, specially the two/ three wheelers and the public transport system with hydrogen as early as possible. About one million vehicles are proposed to be run with hydrogen as a fuel by 2020. Similarly it is proposed that about 1,000 MW aggregate hydrogen based power generating capacity will be set up in the country by 2020. The success of these actions will offer solutions to many other challenges in developing technologies, creating infrastructure and achieving economic operating levels to make hydrogen applications affordable and reduce dependence on fossil fuels.

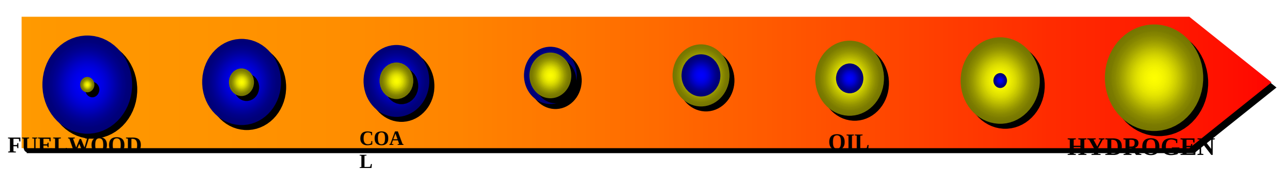
Develop Hydrogen Energy System for Transition to Hydrogen Economy

2.3.5 The development of total hydrogen energy system would be achieved through integration of the technology plan with the development of standards, codes, regulations and policies for acceptance of hydrogen energy.

Hydrogen Energy System



Transition to Hydrogen Economy



3. Hydrogen Production / Supply Plans

3.1 Introduction

3.1.1 Hydrogen (H_2) is one the most abundant elements available on earth. However, it is not found in elemental form. The richest source of hydrogen is water. The other major sources include fossil fuels like petroleum, natural gas, coal and biomass. Hydrogen energy like electricity is a secondary energy source. A primary energy source is required to produce hydrogen. Hydrogen production technologies in commercial use today are catalytic steam reforming of natural gas, naphtha and other hydrocarbons, partial oxidation of hydrocarbons, gasification of coal and electrolysis of water. Hydrogen is currently being produced in India on large scale in fertilizer and petroleum refining industries, mainly based on steam reforming of naphtha and natural gas. Hydrogen is also produced as a by-product in the chemical industry. The present cost of commercially available hydrogen is high for applications in automobiles and for power generation etc. Several other methods of hydrogen production such as biomass gasification or pyrolysis, dissociation of methanol or ammonia, thermo-chemical and electrochemical splitting of water, biological photosynthesis or fermentation etc. are still at different stages of development. These emerging hydrogen production technologies may provide low cost clean hydrogen in the future. Emphasis of research is on the development of H_2 production techniques which do not emit CO_2.

3.1.2 It is envisaged that in the coming decades hydrogen will be produced from large centralized plants as well as decentralized plants, close to the point of use. Renewable energy technologies are expected to play a significant role in the production of low cost and carbon free hydrogen on a decentralized basis.

3.2 Hydrogen Supply Plans and Production Technologies

Hydrogen supplies for short term and immediate needs

3.2.1 Substantial quantities of hydrogen is available as by-product or excess hydrogen, which is currently being flared in many chemical industries, can be tapped to meet immediate hydrogen requirement of the transport sector. There is a need for estimating the availability of by-product hydrogen from different sources by carrying out a nation-wide survey for meeting immediate requirements of hydrogen for transport and power generation applications.

Steam reforming

3.2.2 Steam methane reforming is at present the most common and least expensive method of producing hydrogen. Steam reforming process refers to the endothermic catalytic conversion of light hydrocarbons with water vapour. The reforming reaction is endothermic and requires external heat input. Most of the modern plants use multi-bed pressure swing adsorption (PSA) to remove water, methane, CO_2, N_2, and CO from the shift reactor to produce a high purity product (>99.99%). This is a commercially proven, cost effective technology, contributing to about 40-50% of total hydrogen production capacity worldwide. This process is extensively used in India in the fertilizer and petroleum refineries. Large numbers of reformers utilizing various feedstock need to be deployed to produce hydrogen in larger quantities. A phased growth of reformers based on different feedstock needs to be planned. Small and medium scale SMR units (capacity ranging from 50 to 24,000 kg/day) are commercially available for distributed production of hydrogen. Efforts for development of skid-mounted reformer for producing hydrogen from methanol have also been initiated.

Electrolysis

3.2.3 Electrolysis is the decomposition of water into hydrogen and oxygen. The major factor in the electrolysis route of hydrogen production is the cost of electricity, which is about three to five times more as compared to the cost of fossil fuel feed stock. In view of the high cost of electrolysis, new techniques such as high temperature steam electrolysis are being developed, where about 40% of the energy required could be supplied as heat. Many agencies in the country are involved in the development of electrolysis -based hydrogen production processes.

Partial oxidation of heavy hydrocarbons

3.2.4 Partial oxidation of hydrocarbons is another method of hydrogen production. In this process a hydrocarbon fuel reacts with limited supply of oxygen to produce a hydrogen mixture, which is then purified. Partial oxidation can be applied to a wide range of hydrocarbons including natural gas, heavy oils, solid biomass, and coal. Its primary by-product is carbon dioxide.

Gasification or partial oxidation of coal

3.2.5 Hydrogen production from gasification of coal is a well-established technology. Gasification can be used to produce syngas from residual oil and coal. More recently, it has been used to process petroleum coke. Coal is ground to a fine powder and then mixed with water to create a 50 - 70% solid content suspension, suitable for pumping. When gasifying liquids, it is necessary to remove and recover soot, ash, and any metals that are present in the feed. Feed preparation and handling steps beyond the basic gasification process are needed for coal, petroleum coke, and other solids such as biomass. CO_2 sequestration is necessary to produce large quantities of hydrogen from this method. There are significant coal reserves in India, but Indian coal has around 40% ash content. With appropriate technologies like IGCC, coal can replace natural gas and oil as the primary feedstock for production of hydrogen or synthetic liquid fuel apart from producing electricity.

For mid-term supplies, coal gasification is the preferred route for hydrogen production to ensure supplies of large quantities of hydrogen. IGCC for Indian coals is under development. In addition, work related to under ground gasification of coal (UGGC) for producing hydrogen/synthetic fluid fuel has been initiated by ONGC and NTPC.

Production from biomass

3.2.6 The different methods for hydrogen production from biomass are: gasification / pyrolysis of solid biomass, fermentation of liquid manure and biological hydrogen production. Biomass gasification is similar to coal gasification in many ways. The feedstock is relatively inexpensive. In the pyrolysis method biomass is thermally decomposed at a high temperatures (450-550^o 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.

3.2.7 The biological processes by which hydrogen is released or appears as an intermediate product can be mainly identified as of two types: Photosynthesis (using algae and photosynthetic bacteria) and fermentation (anaerobic decomposition of organic matter). These processes are at different stages of research and demonstration. Fermentative process is presently considered better due to higher hydrogen yield. In India, production of hydrogen from biomass holds considerable promise. Being agricultural country and having variety of climatic conditions, India has wide range of biomass available.

3.2.8 Hydrogen production from industrial effluents can be a possible production route for mid-term supplies. Distributed hydrogen production can be achieved by using organic industrial waste from distilleries etc. by employing photochemical, electrochemical or biological processes.

Hydrogen Production from Bio-organic Wastes

3.2.9 Many laboratories in the country are involved in the development of technologies for hydrogen production from biomass.

High temperature thermo chemical splitting of water

3.2.10 Thermo-chemical splitting of water by getting heat from an external source such as high temperature nuclear reactor or solar concentrators, seems to be the most promising route for providing long-term hydrogen supplies and for large centralized hydrogen production. Large-scale hydrogen production by this process offers quite attractive concept for future CO_2 free and efficient energy systems. This process for splitting of water is carried out through multi step chemical reaction at high temperatures in the range of 550-1000^{o}C depending on the chemical processes adopted. Processes like Iodine-Sulfur (I-S), Calcium - Bromine (Ca-Br) and Copper-Chlorine (Cu-Cl) have been considered promising for further development. High temperature nuclear reactors are suitable for supplying heat to endothermic process steps involved in these processes. Department of Atomic Energy through its Bhabha Atomic Research Centre (BARC) is involved in developing technologies related to high temperature reactors.

Low temperature water splitting

3.2.11 Photo-catalytic processes involve semiconducting powders spread on water containing solutions, which produce hydrogen on exposure to sunlight. These techniques are still in the early stages of development.

3.2.12 Photo-electrochemical processes involving wet photovoltaic systems to produce hydrogen through splitting of water in one step.

3.2.13 Hydrogen can also be produced from water using alkali metal sodium. During the reaction, sodium is transformed to sodium hydroxide. However, the reaction is not reversible and sodium can be recovered from sodium hydroxide using solar furnace. Such processes hold promise for future as viable processes for hydrogen production.

Postproduction cleaning processes

3.2.14 In the post production cleaning stage, all remaining unwanted elements are separated from the hydrogen gas. This especially applies to the products of incomplete reforming like CO, H_2O, O_2, NH_3 and CO_2. The catalytic processes serve exclusively for the removal of CO, while the other processes like adsorption process / membrane process / metal hydrides can also be applied for removal of other elements, depending on the materials used.

Carbon dioxide sequestration

3.2.15 CO_2 is a by-product in many methods to produce hydrogen from fossil fuels,. This CO_2 has to be sequestered / stored so that the total process is nearly clean from the environmental emissions. The main options include (i) use of deep saline reservoirs, (ii) injection of CO_2 into hydrocarbon deposits to enhance oil recovery (EOR) or production of coal-bed methane (CBM), and (iii) injection into the deep ocean. Without capture and storage of CO_2, the reforming or gasification processes would normally release this gas into atmosphere. Capture of CO_2 would add about 25 – 30% to the cost of producing hydrogen.

Synthetic fluid fuel

3.2.16 Production of synthetic fluid fuel along with hydrogen production from coal, biomass, etc., which can be used as fuel in IC engines, also needs to be looked into. A synthetic fluid fuel i.e. methanol would be easy to produce, transport and utilize efficiently in IC engines.

3.3 Issues / Barriers

Hydrocarbon based hydrogen production

3.3.1 At present hydrogen is being produced from hydrocarbons, mostly in centralized production plants for in house consumption. A limited network exists to supply this hydrogen in pressurized vessels for a variety of applications. On site hydrogen production based on hydrocarbons are still in early stages of development. Lack of infrastructure to supply hydrogen for decentralized power generation and transport applications is another limiting factor.

Emerging production methods

3.3.2 Most of the hydrogen production techniques from non-fossil fuels such as biomass gasification or pyrolysis, biological, photo catalytic, thermo-chemical methods using nuclear and solar energy etc. are in the early stages of development. These technologies need to be developed further and demonstrated so that they become technically viable, reliable, safe and cost competitive with conventional fuels.

3.4 Path Ahead

Estimation and utilization of by-product hydrogen

3.4.1 Hydrogen is available as a by-product in the chemical industry. The quantity of hydrogen available as a by-product needs to be estimated for meeting immediate requirements of hydrogen for initiating demonstration projects in the identified areas for power generation and for transport applications.

Develop infrastructure for hydrocarbon based hydrogen production

3.4.2 It is proposed that initially centralized hydrogen production plants would be used to provide hydrogen for the demonstration programme. On-site reforming of natural gas in the vicinity of existing natural gas pipeline network in the country can also be used to produce hydrogen. Existing natural gas dispensing stations will require on site reformers for production of hydrogen from natural gas. After successful demonstration, SMR based hydrogen production plants can be deployed wherever CNG infrastructure is available and fuel requirement for transport sector is high. This will help in switching over from CNG based vehicles to hydrogen-based vehicles gradually.

Demonstrate on site hydrogen production and fuelling stations

3.4.3 In the initial R&D and demonstration phase natural gas reforming based on-site hydrogen production and fuelling stations would be required to be set up. These stations will utilize natural gas available through the existing pipeline network. These stations will be used for refueling of hydrogen vehicles, IC engines/ generator sets as well as feeding hydrogen to fuel cells to produce electricity.

Develop Coal Gasification Methods

3.4.4 Coal based hydrogen production is potentially attractive for India. No gasifier operates on coal having ash content more than 40%. Integrated Gasification Combined Cycle (IGCC) for Indian coals is under development. Gas clean up technology to achieve desired hydrogen purity, CO_2 separation and capture, maximizing conversion efficiency, quality of coal and development of suitable sensors are some of the key issues for this technology. This option ensures long term energy security.

Develop Nuclear Energy method for Water Splitting

3.4.5 High temperature nuclear reactors have the potential to produce clean hydrogen on a large scale. However, apart from the feasibility of thermo chemical water splitting process, efficiency, stability of close loop operation, safety, cost, materials etc. are key issues, which need to be tackled. Harnessing the intrinsic potential of these processes for large-scale production of hydrogen is a scientific and technological challenge.

3.4.6 Development of high temperature nuclear reactor and other hydrogen related technologies are key issues.

Develop renewable methods in a cost effective manner

3.4.7 In order to facilitate large-scale use of hydrogen as an energy carrier for power generation and transport applications, it is necessary to ensure that hydrogen is produced in a cost effective manner without emitting greenhouse gases. Low cost electrolysers need to be developed to make the electrolysis process more efficient and cost effective. Electrolysis using electricity from renewable sources is considered as the long-term solution and is a technology favored by environmentalists provided it is cost competitive.

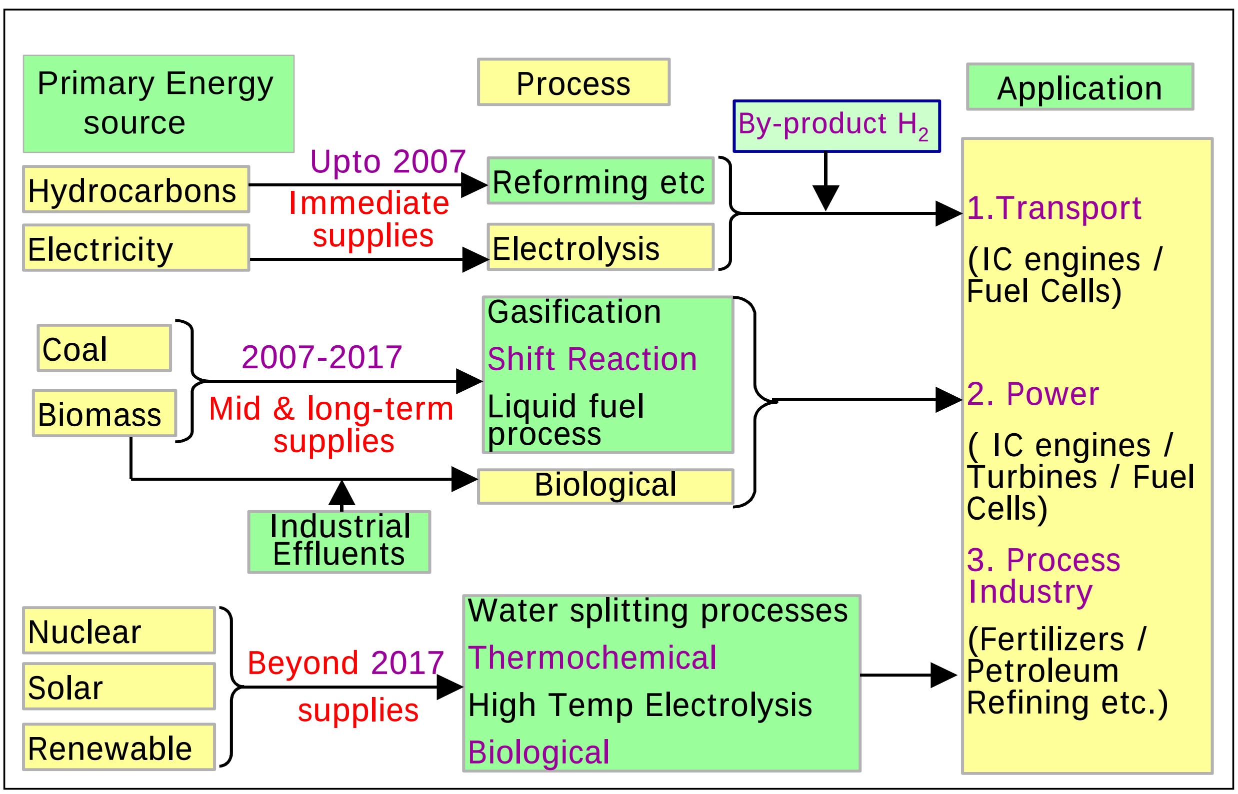
3.4.8 A well-coordinated programme for research and development needs to be undertaken to develop and demonstrate renewable energy based hydrogen production.

Develop and demonstrate small reformers

3.4.9 Development of efficient small reformers will be taken up for use in mobile/ transport/ on-site applications. Small efficient reformers will facilitate demonstration of on board and on- site use of hydrogen for various applications.

3.5 Primary Energy Sources & Hydrogen Production Processes

3.5.1 A schematic showing processes for production of hydrogen for meeting its requirement for immediate supplies, medium and long-term supplies and for the period beyond 2017 using different primary energy sources for transport sector, power generation and also for process industries like fertilizers and petroleum refining is shown below:



3.6 Conclusions

3.6.1 Further research is required to be undertaken to lower the cost of hydrogen and improve production rates from different methods. The present cost of hydrogen at delivery point needs to be reduced by a factor of 3 to 4. Apart from setting up of central hydrogen production facilities for emerging hydrogen applications, the technology for on-site generation of hydrogen by reformation of hydrocarbons needs to be further improved and demonstrated in a phased manner. It will be necessary to provide hydrogen in selected locations for proposed demonstrations of hydrogen energy applications. Similarly, renewable energy based hydrogen production methods have to be improved to enhance the existing hydrogen production rates and thereby reduce the cost of hydrogen production. Research, development and demonstration efforts are needed to lower the cost of production, improve the efficiency and develop better techniques both for central station and distributed hydrogen production.

3.6.2 No single production technology is likely to meet the requirement of hydrogen for the new emerging applications in power generation and transport sector. Therefore, suitable policies are required to support further research, technology development and demonstration of various hydrogen production technologies in a cost effective manner, which should eventually lead to development of hydrogen production network and infrastructure in the country. Research efforts also need to be undertaken for the production of hydrogen based on coal and nuclear energy. The final mix of renewable energy, coal and nuclear energy should provide the basis for ensuring sustainable supply of hydrogen for the new hydrogen economy.

4. Hydrogen Storage

4.1 Introduction

4.1.1 The most common method of storage of hydrogen is in gaseous form in pressurized cylinders/tanks. However, since hydrogen is the lightest element in the universe, gaseous storage requires large volumes and preferably high pressure. Hydrogen is also being stored in liquid form, which requires low temperatures with cryogenic storage systems. It is also possible to store hydrogen in certain solid-state materials and chemicals. Solid state storage requires moderate temperatures and pressures to store and release hydrogen.

Hydrogen Storage Options

1. High pressure gaseous storage
2. Storage as liquid hydrogen
3. Solid State Storage
   - Intermetallic hydrides
   - Complex hydrides
   - Carbon Nanotubes and Nanofibres
   - Metal Organic Complexes,
   - Clatherate Hydrates H_2-(H_2O) etc.
   - Glass microspheres
   - Liquid hydride (e.g. cyclohexane).
   - Zeolities and Aerogels.
4. Storage in Chemicals
   - Ammonia
   - Methanol
5. Bulk Storage
   - Underground storage
   - Gas pipelines

4.2 Hydrogen Storage Methods

Compressed Hydrogen

4.2.1 Hydrogen storage in pressurized tanks/cylinders has been done successfully for a very long time. These cylinders/ tanks are being made from (i) steel (ii) aluminium core encased with fiberglass and (iii) plastic core encased with fiberglass. Commercially used tanks/ cylinders generally store hydrogen at pressures upto 175 bars. The main problem associated with commercially available compressed gas storage is low storage density, which depends on storage pressure. High storage pressure results in higher capital and operating costs. However, in recent years new types of composite tanks/cylinders, which can store hydrogen at about 350-700 bar pressure, have been developed in USA, Japan and some other countries. Such tanks can store up to 10 –12 weight percent hydrogen. 350 bar pressure cylinders are in use in automobile applications. Worldwide research efforts are in progress to develop tanks and materials that can store hydrogen at a pressure higher than 700 bar.

Liquid Hydrogen Storage

4.2.2 Liquid hydrogen can be stored just below its normal boiling point of 20 K at or close to ambient pressure in cryogenic dewars. Liquid hydrogen tanks do not need to be as strong as high-pressure gas cylinders although they do need to be adequately robust for transportation. However, hydrogen cannot be stored in the liquid form indefinitely. All tanks, no matter how good the insulation, allow some heat to transfer from the ambient surroundings due to thermal losses. At present liquid hydrogen is being used mainly in spacecrafts and on a limited basis for other type of vehicles under development. Liquid hydrogen storage is not economical at low production rates (high capital cost of liquefier)

Solid State Storage

4.2.3 Some metals readily absorb gaseous hydrogen under conditions of pressure and moderate temperature to form metal hydrides. The reversible metallic hydrides are Intermetallic (alloy) types instead of singular metal. Since hydrogen is released from the hydride for use at low pressure, hydrides are the most intrinsically safe of all methods of storing hydrogen. Hydrogen is released from the alloy hydride when heat is applied. An alloy hydride tank is considered to be a very safe fuel system in the event of a collision because the loss of pressure in a punctured tank will cool down the metal hydride, which will then cease to release hydrogen. Though hydrides have good volumetric efficiency of hydrogen storage, they have poor gravimetric storage capacity. This results in weight penalty for hydrides. At 6-wt% storage capacity (about 4 kg) of hydride can store same amount of energy generally stored in 1 litre of petrol.

Other storage methods

4.2.4 Nanoforms of carbon have a very large surface area and research has been going on for several years to try to store hydrogen in these materials. Carbon nanostructures such as nanofibers, nanotubes and fullerenes have shown promising abilities to absorb hydrogen. Global research efforts are in progress to establish nano-carbons as viable hydrogen storage systems. Glass microsphere storage systems is another method for hydrogen.

Storage in Chemicals

Cyclohexane (C_6H_{12})

4.2.5 Some liquids e.g. cyclohexane contain large hydrogen content and hence can be considered as hydrogen storage system. Cyclohexane can desorbs ~ 7.1 wt% hydrogen. However, completely reversible hydrogenation to form the starting component is not easy to obtain.

Methanol

4.2.6 Methanol is considered to be a transitional fuel solution especially for smaller vehicles. The advantage of methanol is that it is liquid under normal air pressure and room temperature, and has a high content of hydrogen compared to other fossil fuels. In a vehicle having methanol storage, methanol is reformed into hydrogen, which is then used in the fuel cell. The energy loss in these two processes is high and the over all system efficiency becomes low.

Ammonia

4.2.7 Ammonia-based hydrogen generation produces a mixture of 75% hydrogen and 25% nitrogen, the predominant component of the earth's atmosphere. Nitrogen is separated and harmlessly exhausted to the atmosphere, whereas the hydrogen is compressed for storage.

Bulk Storage Methods

Gas Pipelines

4.2.8 In many countries limited hydrogen pipeline network has been set up. Pipeline transport of hydrogen could be an effective way of transporting energy over long distances. Hydrogen pipes that are in use today are made of regular pipe steel. Embrittlement of such pipelines limits the life of pipelines. Gas pipelines, in addition to being used for transportation, have an advantage, as large quantities of hydrogen can remain stored in the pipeline itself. By regulating the pressure in the pipes, it is possible to use large volume of pipeline as storage during peak situations.

Underground Storage

4.2.9 Depending on the geology of an area, underground storage of hydrogen gas may be possible. For underground storage of hydrogen, a large cavern or area of porous rock with an impermeable cap rock above it is needed to contain the gas. A porous layer of rock saturated with water is an example of a good cap rock layer. Other options include abandoned natural gas wells; solution mined salt caverns, and manmade caverns and depleted or abandoned coal or mineral mines. As in the case of compressed gas containers, one consideration is the cushion gas that occupies the underground storage volume at the end of the discharge cycle. This can be as much as 50% of the working volume of gas. Underground storage is the cheapest method at all production rates and storage times (due to low capital cost of the cavern);

4.3 Issues and Barriers

Issues in Hydrogen Storage

- Cost
- Weight &Volume
- Efficiency
- Life
- Refuelling Time
- Compatability
- Safety

4.3.1 The existing storage methods with some improvements may be adequate for stationary power generation plants. However, on-board storage requirements for vehicular applications are far more stringent. The present cost of on-board hydrogen storage systems is very high, as compared to petroleum fuels.

4.3.2 Low-cost materials and components for hydrogen storage systems are needed, along with low-cost, high-volume manufacturing methods. The weight and volume of hydrogen storage systems are also high, resulting in inadequate vehicle range compared to conventional petroleum fueled vehicles.

4.3.3 Energy efficiency is a major challenge for all hydrogen storage approaches including reversible solid-state materials, compression and liquefaction techniques. The life of hydrogen storage systems needs to be improved, especially for the solid-state storage methods. Materials and components are needed that allow hydrogen storage systems with a lifetime of ≥ 1500 cycles. Refueling time for on-board storage is another important issue. This is also linked with the performance characteristics of the fuelling station and its compatibility with the on-board storage system.

4.3.4 Further research is necessary for developing techniques for higher compression pressure beyond 300 bar, preferably up to 700 bar. This will also require research on special materials to store hydrogen. This will in turn reduce the tank size, which is necessary for transport applications. The goal for research on hydrides and other solid-state storage materials is to achieve 9-wt % storage by 2020 with a recycle life ≥ 1500. This goal can be achieved in phases.

Safety devices for hydrogen storage

4.3.5 As hydrogen is a colourless and odourless gas, suitable methods will have to be developed to detect possible leakages in pipelines and in stacks of tanks/cylinders at refueling stations. The technical solutions to some of the safety challenges in using hydrogen are strong odorant additives, additions for visibility and to reduce explosion risk, alarm detection systems, improved ventilation and containment systems, embrittlement inhibitions, new pipeline materials, hydrogen-capturing canisters / hydrides This will in turn reduce the tank size, which is necessary for transport applications.

Liquid hydrogen Storage

4.3.6 A major concern in liquid hydrogen storage is minimizing hydrogen losses from liquid boil-off. Any evaporation will result in a net loss in system efficiency. But there will be an even greater loss if the hydrogen is released to the atmosphere instead of being recovered. In the Indian context where the ambient temperatures are higher, storage of liquid hydrogen may lead to still higher boil-off losses.

Solid state storage materials

4.3.7 Currently used hydrides have low weight percentage of hydrogen storage capacity, which makes them bulky. The recycle life of hydrides is also low and needs to be significantly improved. The metal hydride alloy must also be structurally and thermally stable to withstand numerous charge/discharge cycles. It is necessary to develop efficient carbon nano-structures for hydrogen storage.

4.3.8 Metal hydride storage is perceived to have no economies of scale. 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 also considered the safest storage option, this makes it a leading candidate for on-vehicle storage, subject to achieving satisfactory energy densities.

4.4 Path Ahead

Develop and demonstrate improved pressurized tanks/cylinders

4.4.1 In case of pressurized tanks / cylinders, further research is required to develop new materials/composites to achieve low cost and low weight storage.

Develop safe and cost effective solid state storage methods

4.4.2 The main objective of research on solid state storage materials will be to reduce size of storage material, their weight and cost. This would require significant improvements in the weight percent storage capacity of hydrogen in the existing materials. Advanced research is required for the development of carbon nanostructures to achieve the desired storage goals.

4.4.3 It should be possible to recharge the hydride pack in a reasonable time period, especially for use in automobile applications and to release hydrogen at moderate temperatures i.e. up to 80^0 C. Solid state storage systems would be viable for transport applications if they have around 6 – 9 weight percent of hydrogen and a cycle life of > 1500.

4.4.4 India has a very large number of two-wheelers. Therefore, compact and efficient storage system that can be put on-board of a two wheeler is a major challenge in the development of storage systems for automobile applications.

4.5 Conclusions

4.5.1 Low cost, efficient storage devices and their convenient transport and refueling characteristics are key to the successful introduction of hydrogen as an energy carrier.

4.5.2 In view of the limited space available on vehicles, energy density of storage materials should be high enough to give a range of about 150 - 500 km per charge. In the case of two / three wheelers, which have a very high population in India, 150 – 300 km range will be acceptable. Advanced storage methods such as high compression storage in cylinders/tanks, hydrides, carbon nanostructures will have to be developed to achieve system storage efficiency of > 9 weight percent, reduce over all size, improve recycle life and ensure safe transportation and refueling.

5. Hydrogen Transportation and Delivery

5.1 Introduction

5.1.1 Transportation of hydrogen and its delivery to the actual point of use in a cost effective and efficient manner is a key component of hydrogen energy system development. There are several known methods of transportation of various fuels of which road, rail, sea and pipelines are commonly in use.

5.1.2 One of the most common methods is transportation of hydrogen in pressurized tanks/cylinders (pressures ranging from 150 to 400 bars) through road or rail. Hydrogen transportation is directly related to hydrogen storage methods. In general, compact forms of hydrogen storage are more economical to transport as diffused forms are bulky and more expensive. Transporting liquid hydrogen is far more efficient than a high-pressure gas, particularly where large quantities are required.

Road

5.1.3 Transport of hydrogen by road is the most commonly practiced method for short distance delivery of hydrogen. Hydrogen can be stored in tanks / cylinders appropriate to hydrogen storage method and transport medium. It is possible to use road transport for hydrogen stored in solid-state materials. .

Rail

5.1.4 Transporting hydrogen by rail is similar to the road transport method. However, rail transport is viable for relatively longer distances and significantly larger quantities.

Air

5.1.5 There are several advantages in transporting liquid hydrogen by air, as it is lightweight and the delivery time is much shorter, and evaporation is therefore not a serious problem. However, transport of pressurized gas through air is not desirable due to safety and weight considerations.

Sea

5.1.6 Hydrogen can be transported as a liquid in tank ships. These are not too different from LNG tankers, aside from the fact that better insulation is required to keep the hydrogen cooled down over long distances. The evaporated hydrogen may be used as a fuel on-board.

Gas pipelines

5.1.7 Pipeline transport of hydrogen could be an effective way of transporting energy over long distance. Hydrogen pipes that are in use today are made of regular pipe steel. Embrittlement of such pipelines limits the life of pipelines. The majority of existing natural gas pipelines can also be used to transport mixtures of natural gas and hydrogen.

On site manufacture

5.1.8 By manufacturing hydrogen at or near the location where it is required, the high cost and energy inefficiency of transport network can be avoided. On-site manufacture may require a limited pipeline network for distribution of hydrogen.

5.2 Issues/ Barriers

High cost of transporting hydrogen

5.2.1 The limited infrastructure to transport and supply large quantities of hydrogen in a cost effective, safe and reliable manner for decentralized, mobile and transport applications is a major barrier in the introduction of hydrogen as an energy carrier.

Pipeline infrastructure

5.2.2 In view of the likely problem of pipeline imbrittlement (leading to shortage of life) for transport of hydrogen, it is necessary to develop suitable materials, before this option could be considered on a large scale.

Safety devices for hydrogen transport and delivery

5.2.3 Hydrogen being a colourless and odourless gas, suitable cost-effective methods for safe transport and detection of possible leakage in pipelines, stacks of tanks/cylinders and delivery equipment etc. is essential.

5.3 Path Ahead

Develop and demonstrate safe transport of hydrogen through pipelines

5.3.1 Further research is required to develop new materials and composites, which can reduce the imbrittlement of gas pipelines and also allow transportation of hydrogen at high pressures followed by demonstration for transport of hydrogen in safe manner.

Develop and demonstrate improved pressurized tanks/cylinders for road/rail transport

5.3.2 In case of pressurized tanks / cylinders, further research is required to develop new materials/composites to achieve low cost and low weight storage.

Develop safe and cost effective solid state storage methods

5.3.3 At present none of the existing methods of transport and storage is perfect for regular use of hydrogen as a cost effective and safe energy carrier. Significant research efforts are required to develop new / alternate, preferably solid state storage techniques where safe transportation will be non-issue.

5.4 Conclusions

5.4.1 Low cost, efficient storage devices and their convenient transport and refueling are key to successful introduction of hydrogen as an energy carrier. In the initial phase, it will be possible to use road and rail for hydrogen transportation. However, in the long run other methods of transport, especially pipeline infrastructure would play a important role in transport of hydrogen to the point of use. Pipelines will distribute hydrogen to high-demand areas, and road and rail will be adopted to distribute hydrogen to rural and other lower-demand areas. On-site hydrogen production and delivery facilities may be set up, where localized demand is sufficient to sustain the facility.

6. Fuel Cells

6.1 Introduction

6.1.1 Fuel Cells have emerged as one of the most promising technologies for the power source of the future. Fuel cell is an electrochemical device that converts energy into electricity and heat without combustion.

6.1.2 Fuel cells are modular in construction, their efficiency is independent of size and have flexibility of using a wide range of fuels to produce hydrogen/reformate suitable for fuel cell applications. Fuel cells require relatively pure hydrogen free of contaminants such as sulphur and carbon compounds etc. When hydrogen rich reformate gas mixture is used, it results in some emissions similar to lean hydrogen – air mixture burning in IC engines. The fuel cell systems are more efficient than IC engines and turbines. Fuel cells are considered suitable for a broad spectrum of applications ranging from a few milli watts to several kilowatts.

6.1.3 Fuel cells are the long term option for hydrogen applications both for transportation and power generation. Fuel cells especially for vehicular applications are in the development stage and the country needs to identify the path for fuel cell development taking into account technology development efforts going on worldwide and the country's specific priorities and the achievements in this area so far.

6.2 Fuel Cell Technologies

6.2.1 There are six major fuel cell technologies of interest viz., Proton Exchange Membrane Fuel Cells (PEMFC), Phosphoric Acid Fuel Cells (PAFC), Alkaline Fuel Cells (AFC), Direct Methanol Fuel Cells (DMFC), Molten Carbonate Fuel Cells (MCFC); and Solid Oxide Fuel Cells (SOFC). These fuel cells operate with different fuels in a wide range of temperatures (60^0C–1000^0C) depending on the technology. These technologies are at different stages of development and demonstration.

Phosphoric Acid Fuel Cell (PAFC)

6.2.2 The Phosphoric Acid Fuel cell (PAFC) technology is the most commercially developed fuel cell technology. PAFC stacks use phosphoric acid as an electrolyte. PAFC is being used in applications such as hospitals, hotels, offices, schools, etc. It can also be used in larger vehicles such as buses, etc. The efficiency of PAFC is about 40%. Phosphoric acid fuel cells (PAFC) were the first to be developed in the country more than a decade ago. PAFC power packs of various capacities have been developed, demonstrated and evaluated in actual field conditions.

Proton Exchange Membrane Fuel Cell (PEMFC)

6.2.3. Polymer electrolyte membrane fuel cells (PEMFC) have been developed for use in stationary and transport applications. The mechanism of PEMFC is same as PAFC. They differ in that PEMFCs operate at relatively low temperatures (about 90 ^{0}C). In view of low operating temperatures PEM fuel cells are considered appropriate for use in automobiles. They have high power density and can vary their output quickly to meet quick shifts in power demand.

Molten Carbonate Fuel Cell (MCFC)

6.2.4 The Molten Carbonate Fuel Cells (MCFC) uses an alkali metal carbonate (Li, Na, K) as the electrolyte. However an alkali metal carbonate must be in the liquid phase to function as an electrolyte. This cell operates at higher temperature of about 600 ^{0}C. The high operating temperature is required to achieve sufficient conductivity of the electrolyte. The higher operating temperature of MCFCs provides the opportunity for achieving higher overall system efficiencies and greater flexibility in the use of available fuels. The high operating temperature, however, impose limitations and constraints on choosing materials suitable for long life time operations. This technology also require significant improvements

Solid Oxide Fuel Cell (SOFC)

6.2.5 Solid Oxide Fuel cells (SOFC) use solid, nonporous metal oxide electrolytes. The metal electrolyte normally used in manufacturing SOFCs is stabilized Zirconia. This cell operates at a higher temperature of about 1000 ^{0}C. This high operating temperature allows internal reforming, promotes rapid kinetics with non-precious materials and produces high quality heat. The solid state character of SOFC components implies that there is no restriction on the cell configuration. It is possible to shape the cell according to the criteria such as overcoming design or application issues. The combined heat and power efficiencies of SOFC could be as high as 80%.

Direct Methanol Fuel Cell (DMFC)

6.2.6 Direct Methanol Fuel Cells use methanol as the fuel. These fuel cells work at lower temperatures and have found application in mobile power generation applications such as laptops etc.

Alkaline Fuel Cell (AFC)

6.2.7 AFC uses alkaline potassium hydroxide as the electrolyte. These cells can achieve power generating efficiencies of upto 70%. The low operating temperatures of Alkaline fuel cells is one of the main advantages for pursuing further improvements in the technology for terrestrial applications.

6.3 Issues and Barriers

Develop fuel cell systems

6.3.1 Fuel cell technologies are still in the early stages of development. Several technological issues concerning choice of materials, improvements in design and performance of fuel cell stacks and systems are yet to be fully resolved. A better understanding of the issues concerning purity of materials, gas diffusion/distribution system, contamination, temperature tolerance and durability is also required. There are several engineering issues that need to be resolved to make fuel cell systems compact and cost effective. In addition, issues concerning reliability, reproducibility and life expectancy of fuel cell system need to be resolved. Their performance under different climatic conditions remains to be evaluated. Air, thermal and water management are other important issues from the system integration point of view. The performance requirements for stationary use of fuel cells are different from the transport application.

6.3.2 Significant research efforts are required to make fuel cell systems more tolerant to impurities. Catalysts, which are more tolerant to CO, needs to be developed and tested. Use of non-precious metals as catalyst, improved membranes for higher cycle life and better tolerance to temperatures are other key areas of research. It will be necessary to identify, characterize and develop new materials for use in electrodes, stacks and membranes etc. It is equally important to apply uniform approach to testing of fuel cell stacks and assembly.

Key Issues

i Durability
ii Cost reduction
iii New catalysts substituting platinum
iv New membranes performing at higher temperatures
v Stack design
vi Power density
vii Cooling arrangement
viii Reduction in auxiliary power consumption
ix Compact size
x Load tracking system
xi Fuel cell system development

Standards for safe handling of hydrogen and fuel cells

6.3.3 The present standards are for hydrogen use in industrial applications. Standards are available for internal combustion engines for stationary and transport use. However, there are no firm standards available for use of hydrogen as an energy carrier. Standards are yet to be finalized for fuel cell systems.

Manufacturing set up

6.3.4 Mature industrial base exists for manufacture of internal combustion engines and turbines. Engineering issues concerning modifications in engines to suit hydrogen fuel can be resolved in a reasonably short time. However, at present there is no manufacturing base for fuel cells in India. Suitable devices/systems or vehicles that can operate with fuel cells are still under development. Relevant codes and safety devices/systems required for the manufacturing unit and the power plants/ vehicles are some other barriers.

6.4 Path Ahead

Develop fuel cell technologies

6.4.1 Advanced research and technology developments are necessary to improve the performance and efficiency of fuel cells. The efficiency of fuel cells needs to be improved in the range 40% to 80% depending on the fuel cell design. The performance requirement of fuel cells for stationary use will be different from those to be used for transport application. The transient response of fuel cells needs to be improved.

Develop materials and components for fuel cells

6.4.2 Research will be needed to make fuel cell system more tolerant to impurities, use of non-precious metals as catalyst, improved membranes for higher cycle life and better tolerance to temperatures. Research efforts will be required to develop new materials for cathodes, stacks and membrane.

Develop fuel cell systems

6.4.3 A total system approach is required for fuel cells to address various issues concerning the performance of fuel cell and integration of other sub-systems such as fuel processing system, power conditioning system, auxiliary power management and thermal energy system. The response time of fuel cells to attain full power will have to be reduced significantly. The cost and life expectancy of fuel cells will have to be improved further to facilitate demonstration. In the near term fuel cell – battery hybrid vehicles will be developed to generate performance data under different operating conditions.

Demonstrate fuel cell applications

6.4.4 An expanded programme to demonstrate use of hydrogen in fuel cells will have to be taken up. The main objective of such demonstrations will be to collect and analyze the performance data to facilitate further improvements in the fuel cell stacks, systems and development of safety requirements, codes and standards. The demonstration programme will also help in understanding public opinion about acceptance of hydrogen fuel cell devices/systems.

Develop standards, codes and training programme

6.4.5 Introduction of fuel cell power packs and vehicles etc. in various sectors require involvement of a number of agencies. Safety regulations, codes and standards will be required for this purpose. Extensive educational and awareness programmes will be required for various agencies including local authorities dealing with building codes, fire, electricity distribution, transport authorities etc.

6.5 Conclusions

6.5.1 Fuel cells are still in early stages of development and are not yet cost competitive. Considerable research efforts are necessary to develop various materials used for electrodes, catalysts, membranes and separators. Low cost replacement for expensive noble metals, used as catalysts, have to be found. The life expectancy and reliability of fuel cells also needs to be significantly improved.

6.5.2 Fuel cells are better suited, as compared to IC engines, for transport applications. The fuel cell powered vehicles will have to be designed in a manner to offer a vehicle, which will be comparable in performance to the existing petrol/diesel driven vehicles. A complete vehicle design approach will be required to achieve this task. The range of fuel cell vehicles will have to be 150 – 400 km to make them convenient for refueling similar to the petrol driven vehicles.

6.5.3 The two key applications of fuel cells i.e. for stationary application of power production and mobile application for automobiles would require undertaking demonstration projects for getting operational experience and bringing about wider awareness about the new hydrogen energy economy.

7. Hydrogen Applications

7.1 Introduction

7.1.1 Hydrogen has been used as a raw material and utility over a long period in the fertilizer, chemical and petroleum refining industries. The current applications of hydrogen are in industrial processes, semi conductor industry, rocket fuel, spacecrafts and other applications.

7.1.2 Hydrogen can be used as an energy carrier directly in internal combustion engines and turbines in place of fossil fuels or as blended mixture with fossil fuels. It can also be used in the fuel cells to generate electricity. Hydrogen to electricity conversion efficiency in fuel cell systems, which are based on electrochemical conversion, is higher than thermal energy based conversion in internal combustion engines and turbines. There are two possible routes for hydrogen application in vehicles. These are (a) direct use of hydrogen in IC engine leading to Internal Combustion Engine Vehicle (ICEV), and (b) indirect use of hydrogen through fuel cells where electricity is produced first, which then drives the vehicle through electric motors (FCV). The present day technologies for hydrogen energy are not yet optimized for use as energy carrier for power generation or use in automobiles. These technologies do not match the performance of existing devices and systems and are not cost effective.

7.1.3 Development of cost competitive fuel cells has great relevance for India both in urban and rural areas. Fuel cells are expected to serve the needs of distributed power generation when cost effective products are available, mainly due to the fact that fuel cells inherently have higher energy conversion efficiency as compared to IC engines. One of the most important applications of low temperature fuel cells is in automobile sector. PEM fuel cells are considered to be best suited for automobile applications. Fuel cell vehicles can offer substantial reductions in greenhouse gas emissions. Since fuel cell vehicles use electric drive which has very few moving parts, vehicle vibrations and noise are expected to be significantly reduced and routine maintenance as compared to IC engine vehicles is expected to be lower. Also unlike IC engines, fuel cells continue to remain efficient even at low loads.

7.1.4 The main goal of research groups and industry would be to develop and field test fuel cell technology, which would be ready for large scale introduction for transport and power generation applications, by 2020. This could be achieved through the major projects for fuel cell based transport and power generation applications. The emerging applications of hydrogen as an energy carrier include:

(a) Combustion Applications

- Direct fuel in IC engine vehicles
- Blending with Compressed Natural Gas (CNG) or Diesel
- Stationary power generation applications based on Internal Combustion engines
- Direct use in spark ignition engines
- Blended mixture in compression ignition engines

- Other emerging applications of hydrogen for cooking, heating, etc.
- Turbines

(b) Hydrogen use as a fuel in Fuel Cells

- Stationary power generation (centralized or distributed/on-site)
- Vehicular applications (Fuel cell cars, buses, etc.)
- Portable devices (Laptops, camcorders, phones, digital diaries, palmtops, etc.)

7.2 Combustion Applications of Hydrogen

A brief account of these applications is given in the following paragraphs.

Hydrogen applications in internal combustion engine based vehicles

7.2.1 The wide range of vehicles on Indian roads includes light vehicles like two wheelers, three wheelers, passenger cars, taxis and heavy duty vehicles such as buses and trucks, etc. The number of two and three wheelers is more than 40 million. Therefore, two and three wheelers become the first choice for conversion to hydrogen fuel.

7.2.2 Use of hydrogen in existing internal combustion engines is under development. Small vehicles and generators, using internal combustion engines, have been modified to work with hydrogen. Hydrogen operated motorcycles and three wheelers have been developed and demonstrated.

Blending of hydrogen for vehicular applications

7.2.3 CNG is already in use in buses, taxis and three wheelers as a regular fuel. Hydrogen and CNG are miscible in all proportions. Therefore, mixing small percentage of hydrogen to existing CNG-operated vehicles is a very pragmatic approach to introduce hydrogen into the transportation system. Hydrogen can initially be added in small volumes to CNG to improve the overall exhaust emission characteristics of the engine/ vehicle. Subsequently, the level of hydrogen can be gradually increased up to ~ 30%. Blending of hydrogen with diesel/CNG has also been demonstrated.

Stationary power generation based on internal combustion engines

7.2.4 At present a large number of diesel and petrol operated generator sets are in use for distributed power generation. Use of hydrogen as an alternative fuel in these generator sets (both petrol and diesel) can be an immediate viable option.

7.2.5 Spark Ignition engine generator sets can be suitably modified / developed to operate on hydrogen whereas diesel generator sets can be developed to work on dual fuel mode. However, the system development in terms of the fuel induction techniques and associated safety features are to be very clearly specified to ensure smooth and reliable operation. Hydrogen powered IC engines for power generation have been developed and demonstrated.

7.3 Fuel Cell Applications

Fuel Cells for Power Generation

7.3.1 Fuel cell systems have been used for generating electricity and several projects have been set up to demonstrate use of different fuel cell technologies for stationary and mobile power generation. It is possible to use low temperature and high temperature fuel cell power plants for grid interactive as well as for stand alone power generation.

Fuel Cells for Vehicles

7.3.2 As compared to IC engine vehicles fuel cell vehicles are more efficient even at low speeds and emit no pollution. Use of fuel cell vehicles would help in containing green house emissions. A fuel cell – battery van and car has been developed and demonstrated in the country. Efficient and compact fuel cells having excellent transient response are required for automobile applications.

7.4 Issues and Barriers

Internal combustion engines are not optimized for use with hydrogen

7.4.1 Use of hydrogen in existing internal combustion engines has been demonstrated. However, based on the specific characteristics of hydrogen combustion, advance research is required to choose suitable materials and designs to optimize hydrogen combustion system. Low cost, long life hydrogen sensors, flow controllers, fuel injection systems and safety related devices and instrumentation have to be developed.

Efficient storage systems for vehicular and stationary use

7.4.2 While it is possible to use hydrogen in vehicles; hydrogen storage is one of the major constraints to expand the demonstration and in this context several engineering issues for vehicular use need to be resolved. The hydride storage methods need significant improvements in the hydrogen storage capacity. Internal combustion engines can work with pressurized hydrogen. However, use of existing hydrocarbon based hydrogen in such engines would require low cost and efficient reformers to be set up at on-site fuelling stations.

7.4.3 This approach will help in addressing various issues concerning performance of individual fuel cell stacks, their assembly and integration of other sub-systems such as fuel processing system, fuel flow management system, load tracking, power conditioning system, air, water, auxiliary power and thermal management system. This would in turn require development of suitable electronics, instrumentation, compressors, pumps, heat exchangers etc. to be designed and developed to optimize overall system performance.

Develop fuel cells suitable for transport applications

7.4.4 Use of fuel cells in automobile application requires certain additional parameters to be optimized to suit vehicle operations. Transient response is one of the main issues in vehicular applications. Fuel flow rates and supply should follow the requirement of fuel cell to meet increasing power during acceleration. Similarly sudden reduction in fuel cell power during braking would require quick stop of hydrogen supply to fuel cell to avoid pressure buildup. This process can significantly affect fuel cell performance, its durability, and vehicle control. Similarly for a vehicle to start and pick up speed without a second storage medium (batteries/capacitors) adequate fuel flow would be necessary in a reasonably short time to attain full power of fuel cell system.

7.5 Path Ahead

Optimize / design internal combustion engines for use with hydrogen

7.5.1 In internal combustion engines further efforts are required to improve designs to include efficient flow handling and energy management. New designs, which are based on hydrogen flame characteristics, are also required to be developed.

Optimize and demonstrate hydrogen blending

7.5.2 Though hydrogen can be easily mixed with natural gas in various percentages, extensive studies and field trials through demonstration are required to optimize blending of hydrogen in natural gas for vehicular use and for ensuring lower emissions studies are needed for different blends.

7.5.3 It is also possible to blend hydrogen in diesel engines. Studies are needed to optimize hydrogen blending in various types of diesel engines used in power generation and agricultural pumps.

Develop fuel cell systems

7.5.4 A total systems approach will be required for decentralized power generation system using fuel cells. This approach will address various issues concerning performance of fuel cell and integration of other sub-systems such as fuel processing system, power conditioning system, auxiliary power management and thermal energy system.

7.5.5 Research efforts will be focused on further improvements in the efficiency of fuel cell systems including the reformers, stacks and electronics. The life expectancy and reliability of fuel cells also needs to be significantly improved. The requirement of safety features, standards and codes for stationary and transport applications will be separately identified and developed. The response time of fuel cells to attain full power will have to be reduced significantly. The cost and life expectancy of fuel cells will have to be improved further to facilitate demonstration. In the near term fuel cell – battery hybrid vehicles will be developed to generate performance data under different operating conditions.

Demonstrate hydrogen applications

7.5.6 An expanded programme to demonstrate use of hydrogen energy in internal combustion engines and fuel cells will be taken up. The main objective of such demonstrations will be to collect and analyze the performance data to facilitate further improvements in the hydrogen energy devices / systems and development of safety requirements, codes and standards. The demonstration programme will also help in sensitizing public about the advantages of hydrogen devices and their reliability as well as in resolving several engineering and management issues, relevant to establishment of infrastructure and manufacturing.

Develop standards, codes and training programme

7.5.7 Introduction of hydrogen energy in various sectors requires the involvement of a number of agencies. Safety regulations, codes and standards will have to be put in place for this purpose. Extensive educational and awareness programmes will be required for various agencies including local authorities dealing with building codes, fire, electricity distribution, transport authorities etc.

Develop linkages with industry

7.5.8 Hydrogen and fuel cells have no other known use for a common man as compared to the petroleum products. Therefore, large-scale introduction of hydrogen and fuel cells will require creation of different market conditions. The infrastructure for fuel cell production, fuel storage, transport and delivery for vehicular and power generation applications require large investments. Unless products are ready, industry will not invest in the creation of infrastructure, and without such infrastructure large-scale production will not take place.

7.5.9 In order to break this impasse **Public Private Partnership** for industry driven research and demonstration from the early stages of development would be required. Without involvement of industry it would not be possible to complete product engineering, which is critical to develop commercial markets. Industry will be required to play a lead role in further research on hydrogen energy applications.

7.6 Demonstration Projects under Public-Private Partnership

Hydrogen Demonstration Projects

7.6.1 It will be necessary for the country to quickly take up demonstration projects which would not only provide operating experience in key hydrogen applications such as decentralized power generation and use in automobiles, but also facilitate creation of support infrastructure through public-private partnership involving major stakeholders, including government, industry, research and user groups. These actions will offer solutions to many challenges in developing technologies, creating infrastructure and achieving the economic levels to make hydrogen applications affordable.

7.6.2 It is recognized that demonstrating use of hydrogen in IC engines can be done reasonably fast and would require significantly lower investments and infrastructure. Therefore, it is necessary to support developmental activities for immediate use of hydrogen especially in IC engines. It is also recognized that early demonstration of hydrogen use in IC engine based public transport system would help in creation of public awareness, development of codes, standards, regulations and policies. This would facilitate development of support infrastructure in the country.

7.6.3 Keeping in view the present status of development of hydrogen energy technologies in the country and the need to systematically improve these technologies to make them technically and commercially viable, it is necessary to take major initiatives in the development and demonstration of **transport** and **power generation applications**.

Green Initiative for Future Transport (GIFT)

7.6.4 The Green Initiative for Future Transport (GIFT) is aimed at developing and demonstrating hydrogen powered IC engine and fuel cell based vehicles ranging from small two/three wheelers to heavy vehicles through different phases of development. Hydrogen based IC engines have the potential to provide a useful bridge to future pure hydrogen and fuel cell vehicles, particularly through the cost effective introduction of a hydrogen infrastructure. Market drivers will determine, if and when fuel cell technology is commercially viable for transport applications. Moreover, pure electric vehicle technology is also improving rapidly and would help with introduction of fuel cell based power trains. It is recognized that the performance of the hydrogen fuelled vehicles have to be at par with the commercially available options to the consumer in performance, safety, convenience and also in the cost. This would require a well-planned and coordinated industry driven action plan. The Indian automobile industry is committed and geared to take up the challenges in this task. It is envisaged that by 2020 about one million vehicles would be on Indian roads that would use hydrogen as a fuel. The ultimate aim by 2020 should be to introduce such vehicles which are capable of providing technical performance matching with conventional petroleum driven vehicle.

Hydrogen Vehicles

Two options
- Direct use in internal combustion engines including blending with natural gas
- Fuel cell powered electric drive

Hydrogen Storage System

- Pressurized gas (up to 700 bar)
- Solid state materials (up to 9 wt %, to be achieved in phases by 2020)

Safety Features
- Sensors and monitoring system for hydrogen

Main Features of Vehicles

* Vehicle Range per charge of hydrogen stored on board to be up to 500 km; depending upon the type of vehicle, Fuel Cell stack life > 5,000 operating hours
* Convenient refueling; Time to refuel the storage system to be ≤ 5 minutes
* Reduction in emissions
* Safety features for hydrogen
* Other features of vehicles including engine power to remain similar to existing systems

Green Initiative for Power Generation (GIP)

7.6.5 The Green Initiative for Power Generation (GIP) envisages developing and demonstrating hydrogen powered IC engine/turbine and fuel cell based decentralized power generating systems ranging from small milli watt capacity to MW size systems through different phases of technology development and demonstration. High temperature fuel cells offer a promising option for decentralized generation of efficient and clean power. This initiative would help in providing clean energy in a decentralized manner to rural and remote areas, apart from power generation in urban centres. The ultimate goal by 2020 would be to introduce such power generating systems in large numbers, which are capable of providing technical performance matching with a conventional fossil fuel driven generator.

Hydrogen Power Generating Systems

Two options

- Direct use in internal combustion engines/turbines including blending with natural gas
- Through fuel cells

Hydrogen Supply System

- Pipelines
- Pressurized gas (up to 700 bar)
- On-site reformation
- Liquefied gas
- Solid state materials (up to 9 wt %, to be achieved in phases by 2020)

Features of Generators

* Capacity of single unit upto 500 kW
* Continuous operation
* Heat Management System
* Fuel cell stack efficiency $\geq$70%, life > 50,000 operating hours
  - Other features to be similar to existing systems

Safety Features

- Sensors and monitoring system for hydrogen and their integration with the electrical system

7.6.6 It is envisaged that by 2020 a large number of decentralized power generating systems with a cumulative capacity of 1000 MW would be set up in the country that would use hydrogen as a fuel.

7.7 Conclusion

7.7.1 In the near term existing internal combustion engines and turbines can be suitably modified to run on hydrogen including hydrogen blending for diesel operated engines. In view of the unique characteristics of hydrogen, modifications are necessary in IC engines to introduce various safety devices. The present day IC engines are designed to optimize combustion of petrol and diesel in an efficient manner. They are not optimized for hydrogen combustion. Therefore, new engine designs will be required to be developed for hydrogen fuelled IC engines, incorporating all the required features for safe and efficient use of hydrogen. In the present Indian context, the direct use of hydrogen in internal combustion engine vehicles (ICEV) can be considered as a preferred transport application in the immediate future.

7.7.2 Fuel cells are better suited, as compared to IC engines, for transport applications. Fuel cell powered vehicles will have to be designed in a manner to offer a vehicle, which will be comparable in performance to the existing petrol/diesel driven vehicles. A complete vehicle design approach will have to be adopted to achieve this task. Apart from a compact and efficient reformer, fuel storage arrangement, fuel cells and associated electronics will have to be designed. The AC/DC drive will be required for optimum energy transfer from fuel cell system to the vehicle engine. The range of fuel cell vehicles will have to be 150 – 400 km to make them convenient for refueling similar to the petrol driven vehicles.

8. Hydrogen Safety, Codes and Standards

8.1 Introduction

8.1.1 Hydrogen is already being produced, stored, transported and consumed in various chemical and industrial processes. The use of hydrogen as an energy carrier is yet to be exploited. During its usage in industrial processes, several relevant safety codes and standards have been developed. In addition, most of the large gas manufacturers have developed their own supplementary standards. These standards are predominantly concerned with the industrial applications of hydrogen. The present regulations involve transportation of hydrogen to and from sites. However, for hydrogen applications in power generation, mobile and transport sector, existing codes and standards would need major additions and up-gradations.

8.1.2 Development of suitable standards for hydrogen and fuel cells will not only help ensure safety but also facilitates business in hydrogen as an energy carrier / commodity and in the products, services and systems that are being developed to make hydrogen easily available and acceptable especially for consumer applications.

8.2 Status of Standards

International standards for hydrogen technologies

8.2.1 Several international organizations like International Standards Organization (ISO) and International Electrotechnical Commission (IEC) have been working on the development of standards and codes relevant to use of hydrogen energy and fuel cells. The main objective of developing these standards is to facilitate use of hydrogen energy technologies in a user-friendly manner.

Indian Codes and Standards for Hydrogen

8.2.2 Hydrogen has been in use in Indian industry for a long period. During this period several regulations and codes for safe handling of hydrogen have been developed. The Bureau of Indian Standards (BIS) has also issued specification for compressed gaseous hydrogen storage (IS – 1090).

The Department of Explosives is entrusted with the administration of Explosives Act, 1884, Petroleum Act, 1934, Inflammable Act, 1952 and other rules framed under these acts which also includes static and mobile pressure vessel (unfired) rules, 1981 and the gas cylinder rules, 1981. These rules are published & administered by the Chief Controller of Explosives, Department of Explosives, Nagpur. Recently this organization has been renamed as Petroleum and Explosives Safety Organization (PESO). The Oil Industry Safety Directorate (OISD) has formulated and coordinated implementation of a series of self-regulatory measures aimed at enhancing the safety in oil and gas industry in India.

Hydrogen Codes & Standards in India

Codes

- Rules published & administered by Chief Controller of Explosives, Department of Explosives, Govt. Of India
  - The static & mobile pressure vessels (unfired) rules, 1981
  - Gas cylinder rules, 1981

Standards

- BIS certified IS-1090, Specification for compressed gaseous hydrogen storage

8.3 Issues and Barriers

Absence of relevant codes and standards

8.3.1 Codes and standards have been identified as one of the major institutional barriers in development of hydrogen technologies for energy applications and thus moving ahead on road to a hydrogen economy.

8.4 Path Ahead

Develop codes and standards for entire range of hydrogen energy

8.4.1 The existing standards and codes will be reviewed to incorporate necessary modifications to suit the energy applications of hydrogen. New standards and codes will be developed, or the standards being developed world-wide would be adopted, keeping in view the use of hydrogen by the common man and its storage in non-industrial areas.

Develop separate codes and standards for application in transport sector

8.4.2 For automotive applications of hydrogen technologies, hydrogen operated vehicle will have to meet several national regulations, including safety norms for refueling and on-board storage of hydrogen. The up-stream delivery of hydrogen to refueling station will also have to be taken into consideration, whether from a centralized production facility or a decentralized generation based on appropriate feedstock. This will require an additional set of standards, codes and other regulations for the transport sector.

Develop Educational and training materials

8.4.3 It will be necessary to develop extensive educational and training material to generate awareness about the safety aspects for various stakeholders concerned with non-industrial use including the local authorities dealing with building codes, fire, electricity distribution, transport authorities etc.

8.5 Conclusions

8.5.1 The existing standards and codes need to be further expanded to include the role of hydrogen as an energy carrier. Safe practices in the production, storage, distribution, and use of hydrogen are essential to ensure the widespread acceptance of hydrogen technologies. The safety aspects of hydrogen usage for energy applications have to be addressed for the large and small scale. The advanced research on various aspects of hydrogen technologies will also address related safety requirements and suggest/develop appropriate measures. Educational and training programmes will be developed to create awareness about safety aspects of hydrogen energy in different applications. Relevant Acts concerning transport sector, environment and air quality may require amendments to encourage safe use of hydrogen.

9. Hydrogen Industry in India

9.1 Introduction

9.1.1 Hydrogen has been used as a raw material and utility over a long period in the fertilizer, chemical and petroleum refining industries. Worldwide more than 95% hydrogen is being produced from hydrocarbons. About 4% hydrogen is produced through electrolysis of water. Steam reforming of natural gas/naphtha, partial oxidation of heavy hydrocarbons contributes to about 78% hydrogen production in the world. In India the oil & gas companies and fertilizer companies are already producing hydrogen and it is also available as a by-product from chlor alkali industry. Currently hydrogen is stored in pressurized cylinders or as liquefied gas. An industrial base already exists in the country for the production of hydrogen, its safe storage and handling. The current applications of hydrogen are in industrial processes, semiconductor industry, rocket fuel, spacecrafts and other applications.

9.2 Present Status

9.2.1 The Indian industry is producing hydrogen commercially for use in oil refineries, fertilizer plants and chemical industry. The chlor-alkali industry also produces hydrogen as a by-product. On a limited basis, electrolysis route is also used for manufacture of hydrogen. Hydrogen storage in pressurized cylinders is the most common method of commercial supply of hydrogen and a number of companies are involved in this activity. Necessary support industries for manufacture of components, sub-systems, safety equipment, sensors etc. have also been set up in the country. However, industrial base for hydrogen energy applications including fuel cells is still in the early stages of development. Table 9.1 gives information on experience of Indian industry in handling of hydrogen for different applications.

Table 9.1: Experience of Indian industries in handling hydrogen

Industry/ Experience	Production process/ feedstock	Use	Transport over long distance
Refineries	Natural gas reforming, Naphtha cracking	Hydro- de-sulphurisation	None
Petro-chemical	Dehydrogenation of ethane	Gaseous fuel, Chemical processes	None
Fertilizer	Natural gas reforming	Ammonia production	None
Chlor-alkali	Electrolysis of Brine	Gaseous fuel, Merchant hydrogen	Limited (as compressed H2)
Power plants	Electrolysis	Coolant for generators	None
Space Research Organization	Naphtha cracking	Rocket propellant	Exists

(Source: Report of the Group of Hydrogen Energy, Planning Commission, July, 2004)

9.3 Issues and Barriers

Lack of industrial infrastructure for energy applications

9.3.1 There are several challenges in creation of industrial infrastructure in the country for introducing a new fuel like hydrogen. These include (i) large investments with long-term payback and uncertainty about demand/requirement, (ii) development of new safety standards and codes, (iii) training of personnel in safe handling of hydrogen, and (iv) the most important - changing the customers attitude.

Lack of awareness about benefits of hydrogen as energy carrier

9.3.2 The present day technologies for hydrogen energy are not yet optimized for use as energy carrier for power generation or use in automobiles. Currently these technologies do not match the performance of existing devices and systems and are not cost effective. The industry is not yet fully involved in research and demonstration and is not clear about the way in which hydrogen applications will play a dominant role in India in the coming years.

9.4 Path Ahead

Develop Public Private Partnership

9.4.1 Strong public-private initiatives are necessary for the accelerated development of hydrogen energy technologies and infrastructure suitable for the country, leading to smooth transition to the hydrogen economy. Public-private partnership would accelerate development of a vibrant industrial base in the country covering various aspects of hydrogen and fuel cell technologies including hydrogen production, its storage, transport and delivery, materials, components, equipment and applications of hydrogen energy. This could be achieved through industry driven collaborative effort to support research and development, product development, pilot production and demonstration projects.

Expand Industrial Base

9.4.2 The existing industrial base needs to be expanded further to take up new methods of hydrogen production from gasification of coal, biomass / biological methods, water splitting using photo-electrochemical, nuclear and solar routes as well as electrolysis of water using renewable energy technologies. These technologies are expected to mature and become viable over a varying period of time. Industry linked research and technology assessment would be beneficial to introduce these technologies through pilot plants and commercial plants.

9.4.3 The existing energy infrastructure is largely owned and managed by oil and gas companies, power generating companies and the automobile industry. With the emergence of hydrogen as an alternative fuel, the existing industries are expected to expand their industrial base further to include requirement for hydrogen production, storage and supply to the point of use. In addition, a new industrial base would have to be developed to accommodate new methods of hydrogen production, storage, supply and manufacture of fuel cell stacks and systems. This could be done by the existing companies as well as the new companies through their own R&D, technology acquisition, technology transfer, joint ventures etc. The industry is already involved to a limited extent in development and demonstration of fuel cell stacks and related components and materials in the country. However, this needs to be expanded to accelerate quickly to develop fuel cell based vehicles and power packs suitable for India as well as to keep pace with international developments in fuel cell technologies for different applications.

Cost competitive hydrogen to accelerate expansion of industrial infrastructure

9.4.4 At present price of hydrogen is higher than conventional fuels. It is envisaged that in the long run costs will become more competitive as (i) technologies advance further, (ii) economies of scale reached, (iii) externalities are included in conventional fuel pricing and (iv) availability of existing resources change in favour of alternatives. Early demonstration of use of hydrogen in IC engines is expected to pave way for smooth adoption of hydrogen energy by the automobile industry and facilitate establishment of initial industrial infrastructure for hydrogen in the country.

Mobilize investments for hydrogen industry

9.4.5 It is also recognized that setting up of suitable infrastructure in the country for hydrogen production, storage, supply and applications would require large investments. The success of the coordinated effort to undertake a goal oriented programme would be possible only if adequate resources are mobilized in the initial stages to develop the technologies and the industrial infrastructure. It will be necessary to provide fiscal and financial incentives for setting up production facilities for hydrogen production, its safe storage, hydrogen fueling stations, especially designed vehicles and other systems to work exclusively with hydrogen and/or fuel cells, fuel cell systems and kits for conversion of existing IC engines to operate with hydrogen fuel. Private sector's financial participation from the early stages would ensure that the coordinated efforts result in commercially viable applications and technologies with the industry playing key role not only in development but also in the demonstration and utilization of hydrogen energy applications in the country in the coming decades.

9.5 Conclusion

9.5.1 India has a modest industrial base relevant to the use of hydrogen energy technologies as an energy carrier. The Indian industry has realized the importance of alternative fuels. The Government is committed to support industry led development and demonstration of hydrogen energy technologies in the country for which the key players would be brought together to develop a joint plan for exploitation of hydrogen resources and creation of necessary infrastructure.

10. Public Awareness and Capacity Building

10.1 Introduction

10.1.1 Public awareness and capacity building are the key components for successful introduction of any new technology in the market place. Hydrogen energy technologies are to be widely used by the common man in vehicles, homes and other places. Therefore, it is essential that from the early stages of development, the public is kept aware about the benefits of the technology. Further, it will be essential to develop institutional arrangements to impart education, training, maintaining database, coordination, and information dissemination and also to conduct research on different aspects of the technology.

10.2 Present Status

10.2.1 The efforts by the Government and other agencies through organization of exhibitions and display of products have also helped in creating some awareness about benefits of hydrogen energy among prominent public figures, researchers, policy makers and others.

10.3 Issues / Barriers

Lack of awareness

10.3.1 Decision makers at various levels in the Government, industry, academic institutions and other public opinion makers are not aware of the potential and the benefits of hydrogen as a potential alternative to fossil fuels.

Limited demonstration

10.3.2 In the initial stages of development of hydrogen energy technologies, demonstration of processes and products will take time. This will also be restricted due to lack of infrastructure, which in turn, will also hinder investments.

Educational Programme

10.3.3 There is lack of education among various stakeholders about applications of hydrogen energy and other benefits. Governmental agencies, industry and academics need to be educated about the benefits of hydrogen energy. Lack of specialized centres to impart education, training and conduct research is another limitation.

Safety concerns

10.3.4 Though hydrogen has been handled safely in the industrial processes and research institutions, often hydrogen is considered to be risky for use in vehicles and other non-industrial applications

10.4 Path Ahead

Develop awareness programme

10.4.1 There is an urgent need to develop multi pronged publicity and awareness programme for various stakeholders. This will include organization of seminars and workshops on hydrogen energy, sustained publicity campaign in the media including newspapers and TV, organize programmes to sensitize policy makers, industry and media.

Demonstrate technologies

10.4.2 Demonstration of hydrogen energy applications such as direct use of hydrogen in two / three wheelers, IC engines for power generation and irrigation pump sets etc will help in building opinion among various stakeholders. This will also help in creation of much needed awareness. Such success stories will help further improvements in technologies and make them cost effective.

Education and Training Programme

10.4.3 Extensive educational and awareness programmes will be required to cover different target groups.

Develop database and network

10.4.5 It will be necessary to develop a database covering different aspects of hydrogen energy technologies, specific projects, research and engineering needs. The results of research and demonstration will be catalogued and widely disseminated. Various research and industrial groups working on different aspects of hydrogen energy can share their experience through networking. A website on hydrogen energy programme will be set up to disseminate information and seek feed back for regular updates.

Set up specialized centres

10.4.6 With a view to consolidate research efforts and take up advanced research and demonstration specialized nodal centres on hydrogen energy will be set up. These centres will also help in developing of educational and training materials, organizing workshops and seminars and also coordinating research and technology development efforts.

Develop institutional arrangements

10.4.7 In view of the involvement of a number of agencies in development and demonstration of whole range of activities in hydrogen energy development, it will be necessary to develop appropriate institutional arrangements to define roles and responsibilities of the stakeholders. Various activities of hydrogen energy starting from production, storage, transport and applications are interlinked. Each activity will need support from other stakeholders. A common approach will be required to develop products, which are affordable and safe. As a first step in this direction the Ministry of New and Renewable Energy has set up a National Hydrogen Energy Board. The Board is chaired by the Minister for New and Renewable Energy. The members of the Board include Member (Energy) Planning Commission, Secretaries to the concerned Ministries/Departments of the Government, leading industrialists, president of industry associations, academics, experts and other public figures. The Board is guiding the preparation and implementation of the National Hydrogen Energy Road Map.

National Hydrogen Energy Board - Terms of Reference

10.4.8 The terms of reference the National Hydrogen energy Board would be as follows:

i) To direct and guide the preparation of a National Hydrogen Energy Roadmap.

ii) To define measures for strengthening science and technology capabilities in the country in existing organisations and by creating new organisations, wherever required, on different aspects of hydrogen energy e.g. production, storage, transportation and applications.

iii) To design and evolve a comprehensive R&D and Demonstration Programme for hydrogen energy in the country.

iv) To guide in the setting up of technology development and demonstration projects by providing interface between R&D organisations and industry.

v) To guide and direct the preparation of feasibility studies for setting up of demonstration projects on different aspects of hydrogen production, storage and applications.

vi) To guide and direct the patenting and intellectual property rights of technology developed under the R&D and demonstration projects.

vii) To guide in the development of safety measures, codes and standards of production, storage and distribution, handling the use of hydrogen as a fuel for various applications.

viii) To suggest policy initiatives, fiscal/regulatory measures and other measures for promotion of hydrogen as clean fuel and implementation of the Hydrogen Energy Roadmap.

ix) To guide in the activities related to human resource development, awareness building, education and information and publicity in all aspects of hydrogen.

x) To take such other measures which are considered necessary for spreading the use of Hydrogen energy and bring about the transition to Hydrogen Economy in the country.

Composition of National Hydrogen Energy Board

10.4.9 The composition of the National Hydrogen Energy Board (NHEB) is given below:

Chairman: Minister for New and Renewable Energy

Members:

Member (Energy), Planning Commission

Secretary, MNRE
Economic Adviser to Prime Minister
Secretary, Planning Commission
Secretary, Ministry of Finance
Secretary, Department of Space
Secretary, Department of Atomic Energy
Secretary, Ministry of Power
Secretary (ER), Ministry of External Affairs
Secretary, MOEF
Secretary, DSIR
Secretary, DST
Secretary, MOP&NG
Scientific Adviser to the Minister of Defence
Shri Ratan Tata, Chairman, Tata Sons
Shri Mukesh Ambani, Chairman, Reliance Group
Dr. M.S. Swaminathan
Chairman, IIT, Kanpur
Chairman, IIT, Chennai
President, Confederation of Indian Industry
President, Associated Chamber of Commerce & Industry
President, FICCI
CMD, BHEL
CMD, Indian Oil Corporation
Dr. R. Natarajan, Chairman, AICTE
Prof. O.N. Srivastava, BHU, Varanasi
Principal Adviser & Special Secretary, MNRE…………………… Member Secretary

Steering Group of the National Hydrogen Energy Board

10.4.10 The National Hydrogen Energy Board has constituted a Steering Group under the Chairmanship of Shri Ratan Tata with Shri Anand Mahindra as Co-Chairman. Members of the Steering Group included Dr. K. Kasturirangan, MP, Chairman, IIT Madras, Chennai and former Chairman, ISRO; Dr. Anil Kakodkar, Chairman, Atomic Energy Commission; Dr. S. Banerjee, Director, BARC; Prof. O.N. Srivastava, BHU; Chairman, BHEL; Chairman, IOC; and President, SIAM. Dr. S.K. Chopra, Principal Adviser & Special Secretary, MNRE was Member-Secretary of the Steering Group.

The Steering Group has constituted the following Expert Groups for preparation of National Hydrogen Energy Road Map:

S.No.	Subject Area	Chairman of Expert Group
1.	Hydrogen Production	Dr. S. Banerjee, Director, BARC
2.	Hydrogen Storage	Prof. O.N. Srivastava, BHU
3.	Hydrogen Application in Power Generation	Shri Ramjee Rai, Director (ER&D), BHEL
4.	Hydrogen Application in Automobiles	Dr. V. Sumantran, SIAM
5.	Hydrogen System Integration	Dr. K.Kasturirangan, MP, Chairman, IIT, Chennai and former Chairman ISRO

11. National Hydrogen Energy Road Map : Vision 2020, Prioritized Action Plan

11.1 Vision 2020

11.1.1 Indian scientists, engineers working on hydrogen energy, together with industry, are in a position to develop and absorb appropriate hydrogen energy technologies suitable for India. Their efforts are expected to result in creation of hydrogen energy infrastructure, industrial base, specialized research centres, institutional set up, trained and qualified manpower, codes, standards, specifications, regulations, legislations and policy measures, which would facilitate acceptance of hydrogen as a fuel by consumers. These efforts will lead to the beginning of the first phase of Hydrogen Economy in India by 2020. This would require an integrated hydrogen energy system to be developed and put in place. This would in turn, require continuous development, demonstration and validation of various technologies related policy issues and other measures. Strong ***Public-Private Partnership Projects*** would be implemented to achieve this national task.

11.1.2 For this purpose two major initiatives on transport and power generation have been identified - **Green Initiative for Future Transport (GIFT)**, which aims to develop and demonstrate hydrogen powered IC engine and fuel cell based vehicles ranging from small two/three wheelers to heavy vehicles through different phases of development and demonstration; and **Green Initiative for Power Generation (GIP)**, which envisages developing and demonstrating hydrogen powered IC engine/turbine and fuel cell based decentralized power generating systems ranging from small milli watt capacity to MW size systems through different phases of technology development and demonstration.

11.1.3 The commencement of hydrogen era, which is inevitable but complex and requires large resources will face the paradoxical problems relating to the questions from auto and power companies “Where is the Hydrogen?” and a reverse question from hydrogen producers and suppliers “Where is the Market for Hydrogen?” In order to circumvent this and indeed to break this deadlock, it is proposed that instead of waiting for the development of cost effective and clean hydrogen production routes, demonstration projects for transport and power, which will use the available hydrogen including by-product hydrogen and SMR produced hydrogen may be urgently setup. This approach would prove the feasibility for transport and power applications and would also seed the market and motivate the involvement of hydrogen producers and suppliers in the proposed demonstration programme.

11.2 Green Initiative for Future Transport (GIFT)

Demonstrate 1 Million Vehicles on Road by 2020

11.2.1 The hydrogen powered IC engine and fuel cell vehicles will be optimized through extensive research and engineering development. The initial demonstration will be confined to limited locations which will also help in testing the basic support infrastructure for operating these vehicles on the road. This demonstration project would help in understanding the requirements of codes, standards and related regulatory, legislative and policy measures including the fiscal and financial policies. It is envisaged that by 2020, the measures taken by the Government and industry would facilitate expansion of the demonstration projects to more locations and larger numbers

11.2.2 The initial phase of development would primarily concentrate on public transport vehicles like buses, three wheelers, vans and taxis. The next phase of development would cover passenger vehicles including cars, etc. In the third phase when cost competitive availability of hydrogen and its storage is achieved, the number of vehicles on road would be substantially expanded. Considering that by 2020 the price of hydrogen at the delivery point is likely to be Rs. 60 – 70 per kg and the storage capacity would be around 9 weight%, it would be possible to effectively use hydrogen as a fuel in a large number of vehicles. Two wheelers, which constitute the largest share of vehicles on the Indian roads, would be a natural leader in the over all mix of hydrogen powered vehicles, apart from cars, taxis, vans, buses and other types of vehicles. Broadly about 750,000 two and three wheelers, 150,000 cars and taxis and 100,000 buses and vans etc would aggregate to about 1,000,000 vehicles on Indian roads.

11.2.3Apart from technical issues concerning design and performance of vehicles, safety, convenience and reliability, the cost competitive availability of hydrogen as an automotive fuel would be another challenge for large-scale acceptance of hydrogen in the transport sector. **The present price of hydrogen at the delivery point is estimated to be about Rs.240/kG. This needs to be brought down by a factor of 3 - 4.** Sharp rise in the petrol prices would make hydrogen attractive to automobile use.

Hydrogen Vision 2020 - GIFT

- Hydrogen cost at delivery point @ Rs. 60-70 /Kg
- Hydrogen storage capacity to be 9 weight %
- Adequate support infrastructure including a large number of dispensing stations to be in place
- Safety regulations, legislations, codes and standards to be fully in place
- 1,000,000 vehicles on road
  - 750,000 two/three wheelers
  - 150,000 cars/taxis etc.
  - 100,000 buses, vans etc.

11.3 Green Initiative for Power Generation (GIP)

Set up 1,000 MW Power Generation capacity by 2020

11.3.1 The initial demonstration has shown that hydrogen fuelled power generation through IC engine and fuel cells can meet dispersed and decentralized power requirements in India. Hydrogen powered turbines and fuel cell plants can also contribute to grid interactive power generation. It is envisaged that in the initial phase of development small generators from 50 to 100 kW capacity and fuel cell power packs would be field-tested at several locations, where sufficient hydrogen is conveniently available. As fuel cell technologies mature, a phased and progressive demonstration of fuel cell power plants, both stand-alone and grid interactive mode would be taken up. IC engine based generators would continue to be used for rural, remote and congested locations. With the development of coal gasification technologies, Integrated Gasification Combined Cycle (IGCC) would be used for power generation using turbines with hydrogen as a fuel. It is expected that by 2020 an aggregate capacity of 1,000 MW would be set up in the country, which will use hydrogen as a fuel.

Hydrogen Vision 2020 - GIP

- Hydrogen cost at delivery point @ Rs. 60-70 /Kg
- Hydrogen bulk storage methods and pipeline network to be in place
- Adequate support infrastructure including a large number of dispensing stations to be in place
- Safety regulations, legislations, codes and standards to be fully in place
- 1000 MW power generating Capacity to be set up
  - 50 MW capacity small IC engine stand alone generators
  - 50 MW capacity stand alone Fuel cell Power packs.
  - 900 MW aggregate capacity centralized plants

11.4 Hydrogen for Demonstration Projects

11.4.1 As outlined above, the progressive development and demonstration of hydrogen applications in transport and power generation would require hydrogen. In the initial phase of development, when the requirement of hydrogen would be limited, commercially available hydrogen from existing sources would be used. As requirement grows and technologies require demonstration, hydrogen from other sources would also be utilized. It is envisaged that by 2020 production capacity of about 1.1 MMT hydrogen/year would be required to supply sufficient quantities of hydrogen to run 1 million vehicles and operate 1,000 MW power generation capacity set up in the country This would in turn require setting up of new production facilities, based on centralized and decentralized production plants using both hydrocarbon, coal and other emerging production facilities. Various types of transport and delivery methods and storage methods would have also developed including on-board storage capacity of 9-weight %

11.5 Objectives of the National Hydrogen Energy Programme

11.5.1 With a view to develop appropriate hydrogen energy technologies and applications for India, the Road Map has identified certain objectives for the National Hydrogen Energy Programme, to be achieved by 2020. The objectives of the Indian National Hydrogen Energy Programme are as follows:

- Reduce India’s dependence on import of petroleum products
- Promote the use of diverse, domestic, and sustainable new and renewable energy resources

- Provide electricity to remote, far-flung, rural and other electricity deficient areas
- Promote use of hydrogen as a fuel for transport and power generation
- Reduce carbon emissions from energy production and consumption
- Increase reliability and efficiency of electricity generation

11.6 Plan of Action - Broad based Research and Development Programme

A broad based research and development programme covering different aspects of hydrogen energy, including its production, storage, transportation, delivery, applications and safety aspects will be undertaken through national laboratories, universities, IITs, NITs and other research organizations. The focus of these R & D efforts will be directed towards development of new materials, processes and components. For these projects funding will primarily be provided by the Government. R & D projects may be supported under this category in the following areas:

11.6.1 Hydrogen Production

Estimation of by-product hydrogen; pilot scale reactors for production of hydrogen through biological, biomass routes; electrolysers including high pressure electrolysers, small reformers suitable for on-site and on-board reformation, gasification of coal for hydrogen production, carbon dioxide sequestration, thermo-chemical methods of hydrogen production using nuclear and solar energy, emerging methods of hydrogen production such as photo-electrochemical and photolytic routes.

11.6.2 Hydrogen Storage

Intermetallic hydrides; improvement in hydride storage efficiency and cycle life; other novel solid state storage materials like carbon nano-structures; complex hydrides like alanates, amides, catherates etc., liquid hydrides, glass microspheres, zeolites, high pressure hydrogen storage tanks and their testing ($\geq$ 300 Bar), etc.

11.6.3 Hydrogen Applications

Testing of hydrogen based IC Engines for evaluating their performance for automotive applications and decentralized power generation; development of PEMFC & AFC for automotive and decentralized power generation, development of PAFC for decentralized power generation, other types of fuel cells (both low and high temperature type), development of micro- fuel cells for power supplies of air-borne systems, components of fuel cells, sensors and reformers, testing procedures for fuel cells, techno-economic viability of fuel cell systems

11.6.4 Safety , Codes and Standards

Study of specific safety requirements for hydrogen production, transport, storage and applications; develop safety devices, sensors and systems for various hydrogen applications; study present Indian codes and standards; international codes and standards and identify the areas where additional / new codes and standards are required.

11.6.5 Capacity Building

Setting up of National Centers of Excellence for hydrogen and fuel cells, including a National Test Facility for fuel cells, develop international cooperation on hydrogen and fuel cell technologies, develop linkages among research groups and industry, initiation of hydrogen education in universities and institutes. Technological status, gaps and time frame for bridging the gaps for each of the above components the National Hydrogen Energy Programme are given in **ANNEXURE.**

11.6.6 - Prioritized Action Plan

The international and national technology status for different aspects of hydrogen production, its storage and application has been summarized in Annexure along with technology gaps and time frame for bridging these gaps. Keeping this in view, a prioritized action plan for immediate (upto 2007), short term (2008-2012), medium term (2013-2017) and long term (2018-2020 and beyond) is outlined below:

11.6.6.1 Plans for hydrogen production, supply and R & D activities

(A) Plans for Hydrogen Production and Supply

Period	Prioritized Plan
Immediate & Short Term (2005-2012)	(i) Tapping of 10% by-product/spare hydrogen available in industries like chlor-alkali industries, fertilizer plants & petroleum refineries to supply hydrogen for GIFT and GIP. (ii) Deployment of 5 numbers of skid-mounted small scale steam methane reformers (SMR) for distributed generation of hydrogen for blending with CNG for use in IC-engines. (iii) Use of 10 numbers of compact water electrolysers, including solid polymer electrolyte water electrolyser (SPEWE), for distributed hydrogen production. (iv) Tap remaining 90% by-product/spare hydrogen from wider network of industries for GIFT and GIP. (v) Induct 200 numbers of small scale SMRs (vi) Set up more number of compact water electrolysers, including SPEWE, for distributed hydrogen production. (vii) Set up 2 demonstration plants for centralized hydrogen and synthetic fluid fuel production by coal gasification. (viii) Set up 10 pilot plants for on-site hydrogen production from industrial organic waste at multiple locations.
Medium Term (2013-2017)	(i) Setting up of 5 commercial plants for centralized hydrogen and synthetic fluid fuel production by coal gasification. (ii) Setting up of 50 reformers based on different feedstock

	(iii) Setting up of 20 commercial plants based on renewable biological sources and industrial effluents. (iv) Setting up of 5000 scaled up SPEWE electrolysers. (v) Setting up of 5 numbers of solar based water-splitting plants.
Long Term **(2018-2020 & beyond)**	(i) Set up 10 commercial coal gasification plants for production of hydrogen/ synthetic fluid fuel. (ii) Increase production volumes in distributed plants based on renewable energy sources, especially solar energy, based on low temperature water splitting. (iii) Deployment of large 500 reformers for producing hydrogen from different feedstocks. (iv) Setting up of thermo-chemical water splitting plants utilizing nuclear reactors for commercial production of hydrogen. (v) Setting up of 5 numbers high temperature steam electrolysis (HTSE) plants based on nuclear / solar heat.

(B) Research and Development Plans for Hydrogen Production and Supply

S.No.	Prioritized Plan	Period
1.	***By-product Hydrogen*** • Research and Development for purification, pressurization, storage and transportation	2005-2010
2.	***Steam Methane Reforming*** • Research and Development for purification, pressurization, storage and transportation • R&D for small reformers for on-site and on-board reformation	2005-2012 2005-2012
3.	***Biological Hydrogen Production*** • Pilot scale generation of hydrogen by biological processes utilizing industrial organic waste • R&D on other processes like hydrogen from carbohydrates bio- organic wastes • Pilot scale demonstration of hydrogen production from carbohydrate bio-organic waste by different processes. • R&D for low temperature water splitting using biological route	2005-2010 2005-2012 2005-2012 2008-2012

	• Pilot plant for low temperature water splitting by biological route.	2008-2012
4.	***Integrated Gasification Combined Cycle*** • Pilot plant scale demonstration for production of hydrogen and synthetic fluid fuel by adopting IGCC technology for Indian coal as well as biomass	 2005-2012
5.	***Electrolysis*** • R&D on high temperature steam electrolysis (HTSE) • Development & demonstration of 1 Nm^3/hr HTSE and 5 Nm^3/hr indigenously developed SPEWE	 2005-2012 2007-2012
6.	***Solar Energy Based Methods*** • R&D on small scale solar based water splitting processes • Demonstration of small scale solar based water splitting process	 2005-2010 2010-2017
7.	***Nuclear Energy Based Methods*** • R&D on nuclear heat based thermo-chemical processes for water splitting. • Development of materials, fuel and engineering systems for high temperature nuclear reactor • Qualification of structural materials of nuclear reactor with liquid metal coolant at very high temperatures (1000 °C). • Lab scale demonstration of nuclear based thermo-chemical water splitting processes and design and demonstration of pilot scale operation. • Critical facility for high temperature nuclear reactor. • Detailed design and setting up of facilities for 600 MW_{th} nuclear reactor • Demonstration of 100 kW_{th} high temperature nuclear reactor • Demonstration of pilot scale thermo-chemical process with nuclear heat & design of commercial scale plants. • Detailed design, additional material related trials, additional engineering systems development for 600 MW_{th} high temperature nuclear reactor.	 2005-2007 2005-2007 2008-2012 2008-2012 2008-2012 2008-2012 2013-2017 2013-2017 2013-2017

	• Integration and demonstration of high temperature steam electrolysis using nuclear heat	2013-2017
8.	Improvement in efficiency, purity, production volumes for the above mentioned methods	2005-2020 and beyond

11.6.6.2 Hydrogen Storage, Transportation and Delivery

(A) Plans for Hydrogen Storage

Period	Prioritized Plan
Immediate & Short Term (2005-2012)	(i) Use of inter-metallic hydrides with storage efficiency : 2 to ~3 wt% & cycle life of 1,000 cycles (ii) Use of high pressure (~300 bar) gaseous cylinder (iii) Use of inter-metallic hydrides with storage efficiency : 5 wt% & cycle life of >1,000 cycles (iv) Use of high pressure (~500 bar) gaseous cylinders (v) Development of Nano-materials including carbon nano-tubes / nano- fibres (vi) Development of alanates, including Na and Mg alanates (vii) Exploration of unusual storage modes like depleted mines
Medium Term (2013-2017)	(i) Use of inter-metallic hydrides with storage efficiency : 7.5 wt% & cycle life of 1,500 cycles (ii) Use of high pressure (500 – 700 bar) gaseous cylinders (iii) Long term R&D for high storage capacity (>3wt% and upto 6wt%) hydrogen storage on clatherates, zeolites, glass microsphers, liquid hydride (iv) Storage in unusual solids like cluster compounds
Long Term (2018-2020 & beyond)	(i) Use of inter-metallic hydrides with storage efficiency : 9.0 wt% & cycle life of > 1,500 cycles (ii) Use of high pressure (700 bar) gaseous cylinder (iii) Use of novel /other hydrogen storage materials like clatherates, zeolites, glass microsphers, liquid hydride.

(B) Hydrogen Delivery

Period	Prioritized Plan
Immediate & Short Term (2005-2012)	(i) Decentralized distribution through high pressure (>200 bar) gaseous cylinders employing trucks. (ii) Decentralized distribution through hydrides canisters (iii) Decentralized distribution through high pressure (500 bar) gaseous cylinders employing trucks. (iv) Limited use of pipeline network (v) Decentralized distribution through hydrides canisters
Medium Term (2013-2017)	(i) Decentralized distribution through high pressure (>500 bar) gaseous cylinders employing trucks. (ii) Hydrogen distribution through pipeline network in areas having concentration of users (iii) Large scale hydrogen distribution through hydride canisters (low gas pressure ~30 bar)
Long Term (2018-2020 & beyond)	(i) Decentralized distribution through high pressure (700 bar) gaseous cylinders employing trucks. (ii) Extensive hydrogen distribution through pipeline network (iii) Large scale hydrogen distribution through hydride canisters (low gas pressure ~30 bar)

11.6.6.3 Application of hydrogen for Power Generation application

(A) – ***IC Engine Route***

Period	Prioritized Plan
Immediate & Short Term (2005-2012)	(i) Set up necessary infrastructure for modification of Petrol and Diesel IC Engines for use with Hydrogen. (ii) Identification of SI/CI Engine – Genset capacities for modification for taking up demonstration projects. (iii) Design, fabrication / procurement of components of a Hydrogen induction system, safety system and loading arrangement. (iv) Development of NO_x emission reduction methods (v) Optimization of engine parameters and H_2 percentage for best performance and least emissions for each type of engine (vi) To set up demonstration plants of 1 MW aggregate power generation capacity (vii) Development and large scale manufacture of retrofit H_2 injecting systems into manifolds of existing engines of portable gen-sets, including modification of engines. (viii) Measurement of emission reductions with increase of H_2 percentage (in CI engines) and with neat H_2 (in SI engines) (ix) Data analysis, documentation and preparation of report with a view to provide recommendations for large scale introduction of H_2 fueled IC engine based gensets. (x) Development of dedicated IC engine for Hydrogen Fuel. (xi) To set up demonstration plants of 9 MW aggregate power generation capacity.
Medium Term (2013-2017)	To set up 20 MW aggregate power generation capacity
Long Term (2018-2020 & beyond)	To set up 20 MW aggregate power generation capacity

(B) - ***Fuel Cells Route***

I. ***Low Temperature Fuel Cells***

Period	Prioritized Plan
Immediate & Short Term (2005-2012)	(i) Decide the rating of individual PEMFC and AFC power packs (ii) Decide which fuel to use (Bottled or piped H_2 / On-site reformed fuel with CNG, LPG, Methanol). (iii) PEMFC : Undertake R&D in the following areas: ➢ Development of indigenous, low cost 'proton exchange' membranes as a substitute to costly imported membrane. ➢ Development of low-cost bipolar plates (graphite based, high conductivity, impervious), preferably with flow grooves incorporated during moulding itself. ➢ Development of higher CO tolerant anode catalyst ➢ Development of cheaper cathode catalyst ➢ Development of electrode support substrate (graphite paper) (iv) AFC : undertake R&D in the following areas : ➢ Development of compact, low-power electrolyte re-circulating system ➢ Development of low cost CO_2 scrubber & alkali-water heat exchanger ➢ Development of low-cost catalysts (Ni-Co spinel, MnO_2/C) ➢ Ensure availability of low-cost, resin based mono-polar plates / cell enclosures ➢ Generation of long term performance data & operational experience ➢ Development of regenerative CO_2 scrubbing system. (v) Finalize suitable design for stand-alone operation of the power packs including C&I and inverter systems (vi) Optimize design of various components (bipolar plates, MEAs etc for PEMFC and electrode frames, seals, CO_2 scrubbing / electrolyte re-circulating systems for AFC) (vii) Assemble and test the stacks (viii) Integrate the AFC and PEMFC stacks with other subsystems (ix) Demonstration of 2 MW aggregate capacity PEMFC and AFC power packs for decentralized applications, including PAFC power packs. (x) Carry out performance evaluation
Medium Term (2013-2017)	To set up decentralized demonstration of PEMFC, AFC & PAFC power packs of 8 MW aggregate capacity
Long Term (2018-2020 & beyond)	To set up decentralized demonstration of PEMFC, AFC & PAFC power packs of 42 MW aggregate capacity

II. *High Temperature Fuel Cells*

Period	Prioritized Plan
Immediate & Short Term (2008-2012)	(i) Development of SOFC stacks (5 kW) and of MCFC stacks (10 kW) : ➢ Decide, which SOFC technology is to be pursued (Planar or Tubular); ➢ Develop, optimize and freeze component and stack design for SOFC and MCFC. Identify fuel to be used. (ii) Development & demonstration (5 MW aggregate capacity) of SOFC stacks and of MCFC stacks: ➢ Develop various components (electrodes, electrolyte, seals) including identifying the materials to be used & processing techniques to be adopted. Design inter-connects (between adjacent cells) and overall current collectors. ➢ Design mechanical systems (clamping / stacking arrangements, flow field design etc.) Finalize stack assembly & testing procedures. Integrate the complete system and test. ➢ Design C&I and inverter systems and incorporate safety systems. ➢ Design skid mounted sub-assemblies / systems for ease of transportation to site. Install, Commission & test the integrated system.
Medium Term (2013-2017)	Demonstration (45 MW aggregate capacity) of SOFC stacks and of MCFC stacks and conduct long-term testing, compile & analyze performance
Long Term (2018-2020 & beyond)	Expanded demonstration (450 MW aggregate capacity) of SOFC and MCFC.

11.6.6.7 Development and Demonstration of Products / Devices for Hydrogen Applications

Projects for development and demonstration of products / devices for the end use applications in transportation and for decentralized power generation will be taken up under this category. These projects will be implemented jointly by research organizations and industry on cost sharing basis between the Government and Industry. Some of the demonstration projects suggested by the Four Expert Groups constituted by the Steering Group of the National Hydrogen Energy Board (NHEB) on Hydrogen Production, Storage, Applications in Transport & Power Generation Sectors are indicated below:

I. Hydrogen Production

(i) To procure, install and operate one SMR and one electrolyser units of 50 Nm^3/hr capacity each to supply hydrogen for IC Engine trials at DTC & IGL with minimum efficiency of 70%, which is to be improved to 80% and hydrogen purity level of above 99.9%.

(ii) To procure, install and operate two numbers of SMR units of total 6500 kg /day of hydrogen production capacity for development of a suitable hydrogen fueled transport system using IC engine vehicles and run a demonstration fleet of the same.

II Hydrogen Storage

(i) Development and demonstration of 10 nos. of hydrogen fuelled three wheelers, based on metal hydride hydrogen storage with maximum speed of 50 kmph and range of 100 kms per charge.

III Hydrogen Applications in Transport Sector

(i) Use of hydrogen (up to 30%) in CNG as fuel for automotive vehicles to achieve hands on experience on different aspects like production, storage, transportation, and utilization of hydrogen as an automotive fuel.

(ii) Development of a suitable hydrogen fuelled transportation system using internal combustion engine vehicles and run a demonstration fleet of the same.

IV Hydrogen Applications for Power Generation

(i) Development and demonstration of 5 units of Solid Oxide Fuel Cell (SOFC) of 5 kW capacity for premium power applications with 40% efficiency in power only mode and 70% efficiency in combined heat and power mode.

(ii) Development and demonstration of 3 units of Molten Carbonate Fuel Cell (MCFC) of 10 kW capacity with 40% efficiency in power only mode and 70% efficiency in combined heat and power mode.

(iii) Development and demonstration of 1-5 kW modules of PEMFC and AFC units for distributed power generation applications

(iv) Selection of best commercially available NO_x trap technology on the basis of experimental trials with diesel and bio-diesel and tests of re-generation hydrogen

(v) Determination of optimum percentage of hydrogen in diesel/bio-diesel for reducing emissions without significant loss of engine power

(vi) Development of a retrofit for injecting hydrogen into the manifolds of engines of portable gensets running on kerosene/petrol/diesel and estimation of cost of retrofit

(vii) Measurement of emission reduction with increase in hydrogen percentage and with neat hydrogen for each type and capacity of engine proposed to be used in the demonstration programme

For achieving the overall growth in the entire hydrogen energy sector, the following projects may be considered for taking up in Mission Mode

Technology Development Projects
Suggested for taking up in Mission Mode

- Clean Coal Gasification Technologies for Hydrogen Production
- Hydrogen Production through Biological Routes
- Hydrogen Production through Renewable Energy Routes
- Hydrogen Production through Nuclear thermo-chemical water splitting route
- Hydrogen Storage in Hydrides
- Hydrogen Storage in Carbon Nano-structures
- Development of IC Engine for Hydrogen fuel
- Development of PEM and SOFC Fuel Cell Technologies

11.6.6.8 Demonstration of Integrated Hydrogen System

- It is proposed to initiate a project for demonstration of integrated hydrogen energy system for vehicular transportation in a geographical location where regular supply of hydrogen can be ensured. The proposed site for this type of demonstration could be an industrial township, close to which hydrogen supply is available on sustainable basis e.g. fertilizer factory, petroleum refinery or chlor-alkali industry. Necessary infrastructure for storage, delivery and refueling of hydrogen vehicles will have to be created through public-private partnership.

- Demonstration of public transport vehicles such as buses, taxis, vans and three wheelers would be covered in the proposed concept. In addition, private vehicles such as two wheelers would also be included as a part of the proposed demonstration. The number of vehicles to be included in the demonstration programme would be determined on the basis of availability of hydrogen at the location and other site specific parameters.

- Expert Group on Transport Applications in their Report has identified that a demonstration project for 200 buses, 300 large and 500 small three wheelers based on internal combustion engine route be undertaken. State Transport Corporations will be encouraged to participate in this demonstration activity. To begin with this demonstration could be taken up at one or two suitable locations and thereafter, it could be expanded to other locations. This would ensure that the entire chain of production, supply, delivery and utilization is demonstrated, end to end, at a single geographical location, which would have tremendous impact on the general public about this new and emerging technology. Initial projects for demonstration of hydrogen energy system concept would be taken up for implementation through government support. Subsequent projects would be implemented through public private partnership.

11.7 Conclusion

National Programme on Hydrogen Energy

11.7.1 A well structured and coordinated National Programme on Hydrogen Energy is necessary to translate the goals identified in the National Hydrogen Energy Road Map. This would require all stakeholders to closely work together to pool the limited technical, financial and human resources and undertake a focused national programme. Participation of Government, research and academic institutions, industries, regulatory authorities, organizations working on development of standards, NGOs and media needs to be ensured at the appropriate stage. However, in the initial development phase of the programme a strong research and technology development and demonstration plan is essential.

Research and Demonstration plan

11.7.2 The focus of R & D efforts will be to develop efficient and cost effective technologies. Goal oriented research will have to be identified and supported. A suitable mechanism will need to be put in place to ensure dissemination of the results of research and wherever feasible tie up between research groups and industry will be established. Advanced research and engineering development on hydrogen applications will have to be primarily industry driven. Government will act as the prime facilitator in this process. Apart from R & D efforts on all aspects, ranging from production to application, other important issues relating to development of codes and standards are to be adequately dealt with. This will also help in generating public awareness about hydrogen energy and its safe use by the common man.

Fiscal Incentives

11.7.3 It is recognized that large scale use of hydrogen in power generation and transportation will be possible only when hydrogen production and supply infrastructure is set up in the country. The two demonstration projects on transport and power generation applications i.e. GIFT and GIP would require large investments in setting up the support infrastructure as well as in development of products. This would also require accelerated research efforts to develop appropriate technologies. At present investment made in R&D activities is eligible for tax benefits. No other specific concession is available for use of hydrogen as an energy carrier. Therefore, for promoting hydrogen as an alternative fuel and attract private investment in setting up infrastructure and industrial base in the country, it will be necessary to provide long term fiscal and financial incentives for setting up production facilities for hydrogen production based on renewable energy and other non-hydrocarbon methods, solid state and other storage methods, reformers, hydrogen fueling stations, specially designed vehicles, fuel cells and other systems / sub systems to work exclusively with hydrogen and/or fuel cells, fuel cell systems and kits for conversion of existing IC engines to operate with hydrogen fuel. Some of the proposed incentives that would accelerate the growth and attract investment are given in **Table 11.1**

Table 11.1 : Fiscal Incentives for Hydrogen Energy Development in India

1. **Investments in hydrogen related activities as energy carrier to be notified as investment in infrastructure sector and be eligible for all tax benefits as applicable to infrastructure sector under the Income Tax Act.**

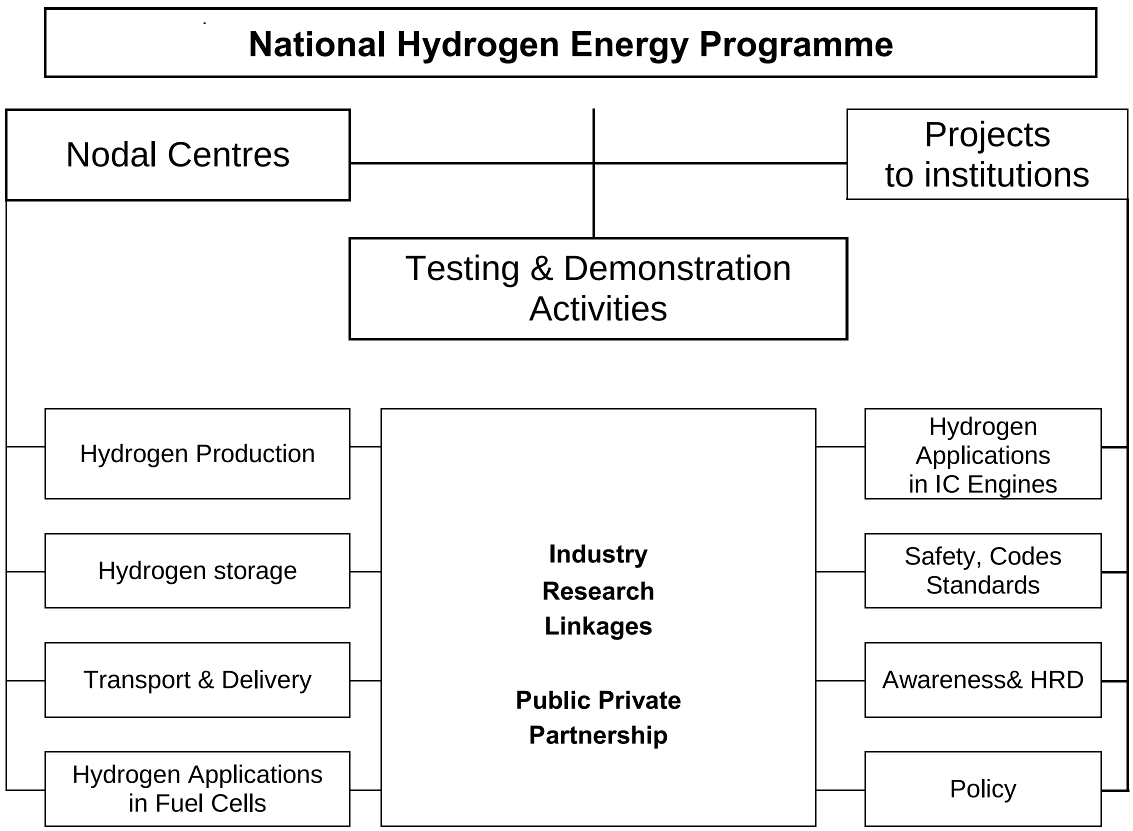
2. **Accelerated depreciation (100 %) in the first year on new investments, in development and production of hydrogen and fuel cell technologies.**

3. **Low interest bearing loan for setting up demonstration and production facilities.**

4. **Corpus fund for development of hydrogen and fuel cell technologies to be set up with contributions from the Government and also the industry. The fund to be managed through public-private partnership.**

(Source : Report of the Group of Hydrogen Energy, Planning Commission, July 2004)

The main purpose of this document is to identify the key issues and the likely options that need to be vigorously pursued to develop hydrogen energy for India. Large scale introduction of hydrogen based power generating systems and vehicles will be possible only if a well coordinated programme is launched, which will cover all elements of hydrogen energy system. Hydrogen production, transportation, storage and application systems are to be developed and demonstrated through a coordinated research, demonstration and commercialization plan. Development of hydrogen energy applications is a complex multi disciplinary programme which requires significant scientific, technical and engineering inputs on all aspects of hydrogen energy including production, transportation, storage and application devices/systems.



Transition to Hydrogen Energy in the Indian Energy mix

In order to bring about the gradual introduction of hydrogen energy in the Indian energy mix, in addition to various technical and engineering development and demonstration, development and validation of safety regulations, codes and standards need to be developed with the active involvement of concerned agencies. Suitable policies have to be put in place to encourage research, development, production, infrastructure creation including manufacturing and hydrogen applications. Further, Government in association with industry, environment groups, NGOs, educational institutions and public opinion makers will develop suitable policies and legislation to address various issues concerning public health, safety and also awareness about environmental benefits of hydrogen. It is only through such a comprehensive and an integrated approach that it would be possible to bring about the phased transition from the present hydro carbon to the new hydrogen economy in the coming decades of the twenty first century.

ANNEXURE

TECHNOLOGY STATUS, TECHNOLOGY GAPS AND TIME FRAME FOR BRIDGING GAPS

I. HYDROGEN PRODUCTION

Technology	International Status	National Status	Technology Gaps	Time Frame for bridging the gaps
By-product hydrogen	By-product hydrogen is available from chemical industry	By-product hydrogen is available from chemical industry	- Purification, pressurization and storage of by-product hydrogen	2005-10
Steam Reformation (natural gas, naptha etc.)/	Technology is proven and commercially available	Used in oil refineries and fertilizer industry	- Indigenisation of technology - Efficiency improvement - Hydrogen purity (>99.9%) - Carbon sequestration	2005-15
Electrolysis of water	Technology is proven and commercially available	Technology is proven and commercially available	Improvement in efficiency and reduction in energy consumption through development of new materials, components, sub-systems etc. for conventional alkaline and PEM electrolysers including high temperature electrolysis, using renewable energy sources like small hydro and wind energy etc.	2005-15
Gasification of coal and heavy residues	Technology is commercially available	Efforts underway for development of technology	- R&D for pilot scale FBG for producing hydrogen through coal gasification for Indian coal - Gas clean-up technology - CO_2 separation (PSA & membrane) - Conversion to methanol (Fischer Tropsh process) - Integrated Gasification Combined Cycle - Carbon sequestration	2005-15
Biomass Gasification / Pyrolysis,	In pre-commercial stage	In R&D stage	R&D for pilot scale gassifiers for producing hydrogen through biomass	2005-15
Biological Routes	In pre-commercial	In pre-commercial	- Scale up - Purification and recovery	2005-12

	stage	stage	- Compression - Screening of microbes - Bio-reactor design Specific energy consumption	
Photo-electrochemical, Photo catalytic,	In R&D stage	In R&D stage	-	2005-20
Thermo-chemical splitting of water using nuclear/ solar heat	In R&D stage	In R&D stage	*<u>Thermo-chemical process</u>*: - Technology development for reactions & separations etc. - Materials, Catalyst, Membranes development - Development of Special processing methods & equipment - Measurement and control – instruments & methods development - Close loop operation and stability - Solar thermal assisted thermo chemical splitting of water - Integration with Nuclear reactor *<u>High temperature nuclear reactors:</u>* - Special materials development - Corrosion and oxidation resistant coatings development - High temperature & High performance fuel related development - Technology development for passive reactor safety system - Technology development for passive high flux heat removal system - Liquid metal related technologies - High temperature instrumentation	2005-20

II. HYDROGEN STORAGE

Technology	International Status	National Status	Technology Gaps	Time Frame for bridging the gaps
High Pressure Gaseous Storage	Several companies involved in development of high pressure gaseous storage (350-700 bar)	No high pressure gaseous storage technology exists in the country.	Indigenous development of high pressure gaseous storage	2005-10
Liquid hydrogen	Technology is commercially available	Liquid hydrogen plant is installed near Trivandrum by ISRO, used in space programme.	No experience of using liquid hydrogen for vehicular transport or power generation	-
Hydrides	R&D efforts are in progress in Japan, USA and other countries. Hydrogen storage capacity 1.5–2.0wt% for ambient conditions and 5-6wt% for high temperature hydrides achieved.	Research groups at BHU, IIT, Madras and ARCI, Hyderabad engaged in development. Hydrides with 2.42wt% storage capacity developed.	Hydrides with (a) storage capacity up to 3 through 6 to 9wt%, and (b) cycle life of greater than 1500 are required to be developed for transport application.	2005-15
Other new Hydrogen Storage Materials and complex hydrides (carbon nanotubes, sodium alanates, etc.)	In R&D stage.	In R&D stage. BHU, IITM and other upcoming institutions	R&D efforts need to supported and strengthened.	2005-2020
Unusual Routes	Efforts being made on several unusual routes such as storage in zeolites, glass microspheres, chemical hydrides.	R&D efforts to be initiated. Geological Survey of India to map out depleted mines	R & D and exploration efforts to be initiated	2005-20

	Storage in depleted mines (underground storage) is being investigated.			

II. HYDROGEN APPLICATIONS

Technology	International Status	National Status	Technology Gaps	Time Frame for bridging the gaps
Hydrogen use in IC Engine	CNG-Hydrogen blends used in IC engines	In R&D and initial demonstration stage	- To gain experience in CNG-hydrogen blending for use in IC engines - To overcome problems of pre-ignition, backfire and reduced output - To develop an IC engine suitable for hydrogen	2005-10
Fuel Cells				
Phosphoric Acid Fuel Cell (PAFC)	Commercially available. More than 200 units of 200 kW capacity each deployed world over.	Technology for development of units up to 25 kW capacity developed and demonstrated by BHEL.	The Expert Group on Power Generation has indicated that there is declining interest in this technology world over. However, the relevance of PAFC has to be assessed in the context of requirements in the country and our experience and achievements in it so far.	
Polymer Electrolyte Membrane Fuel Cell (PEMFC)	Commercially available. Number of companies are engaged in manufacturing such fuel cells.	Fuel Cell stacks up to 5 kW developed and demonstrated by SPIC Science Foundation (SSF). SSF and BHEL are presently involved in development	- To develop indigenous low cost proton exchange membrane. - To develop low cost bipolar plates (graphite based, high conductivity, impervious) preferably with flow grooves incorporated during moulding itself. Assembled stacks with imported materials for performance data. - To develop higher CO-tolerant anode catalyst - To undertake extensive testing to ascertain reliability and life. - To develop cheaper	2005-2012

			cathode catalyst. - To develop electrode support substrate (graphite paper)	
Alkaline Fuel Cell (AFC)	Mature technology for space application	In R&D stage. CECRI worked in this area earlier. Currently BHEL is working on development and supply of a 500 W power pack.	- To develop compact, low power electrolyte re-circulation system. - To develop low cost CO_2 scrubber & alkali-water heat exchanger. - To develop low cost catalysts (Ni-Co spinel, MnO_2/C). - To develop suppliers for low-cost resin based mono-plates/cell enclosures. - To generate long term performance data & operational experience. - To develop regenerative CO_2 scrubbing system	2005-2012
Solid Oxide Fuel Cell (SOFC)	In R&D and demonstration stage	In initial stages of R&D. CGCRI, BHEL and NAL are engaged in development.	- To develop technology for low temperature Planar and Tubular type SOFC - To develop indigenous sources for raw materials required for SOFC	2005-17
Molten Carbonate Fuel Cell (MCFC)	Technology developed in USA. Presently in demonstration and early commercialization phase	In early R&D stage. CECRI was involved in development. NTPC is keen to pursue this technology	Technology yet to be developed in India even in R&D stage. Technological gaps can be identified after some progress is achieved in R&D efforts	2005-20