

Sustainable Development Efforts in Hydrogen Energy Technologies

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Abstract: Although fossils are the main energy source for many countries, some alternative energy sources have been created to generate electricity. This new energy source would be sustainable and promising energy sources and change the current energy economy to a sustainable economy, which is hydrogen economy. Hydrogen is the most efficient fuel and it is about 26% more efficient than fossil fuels. On the other hand it is not a primary energy source, but a secondary energy source or an energy carrier. Actually, it is the cleanest energy carrier, since it does not produce greenhouse gases, or chemicals which deplete the ozone layer. In addition, it is the most cost-effective fuel, when its higher efficiency and the environmental damage caused by fossil fuels are considered. In this study, hydrogen delivery, storage, conversion and utilization methods are investigated for sustainable development strategy.

Keywords: Energy, hydrogen, sustainable development.

Introduction

The current means of generating and utilizing fuels and energy are not sustainable. Even though the fossil economy has provided significant advances for societies, it has also led to considerable environmental deterioration, health problems and security issues. These destructive consequences continue to impact societies, especially ones that are newly developing to adapt conventional fossil technologies to meet their increasing demands. Additionally, fossil resources are not infinite. All these factors necessitate a shift to a more sustainable energy system.

Hydrogen has many potential attractions as a new fuel. It may be derived from non-fossil sources, it burns cleanly to water with no pollutants being emitted, it is suitable for use in a fuel cell to generate electricity directly, and it has a high energy content expressed on a per mass basis. Unfortunately, these attractive features are counter balanced by many practical engineering and economic considerations that explain why hydrogen does not already find extensive use as a fuel (Dell & Rand 2004).

Most hydrogen today is made from fossil fuels by chemical reforming reactions and its major uses are in the refining of crude oil and the manufacture of ammonia. Lesser, non-energy, applications are found in the manufacture of other chemicals, as well as in the food, plastics, metals, electronics, glass, electric power and space industries.

Hydrogen Transmission, Distribution and Delivery Methods

Hydrogen delivery is defined as the transport of hydrogen from the production site to the consumption site, namely the end-user. The methods of delivery necessarily vary according to the method of production and

consumption. Hydrogen production will be classified in two categories; centralized hydrogen production sites such as natural gas-to-hydrogen conversion plants, clean coal conversion plants, megawatt wind farms etc. These will obviously require a sophisticated and high capacity hydrogen delivery infrastructure. Whereas, smaller hydrogen production sites, will depend on the storage methods rather than delivery methods, since the produced hydrogen will be consumed on-site. Excess hydrogen produced will be delivered to anywhere else with smaller capacities of delivery methods such as truck delivery.

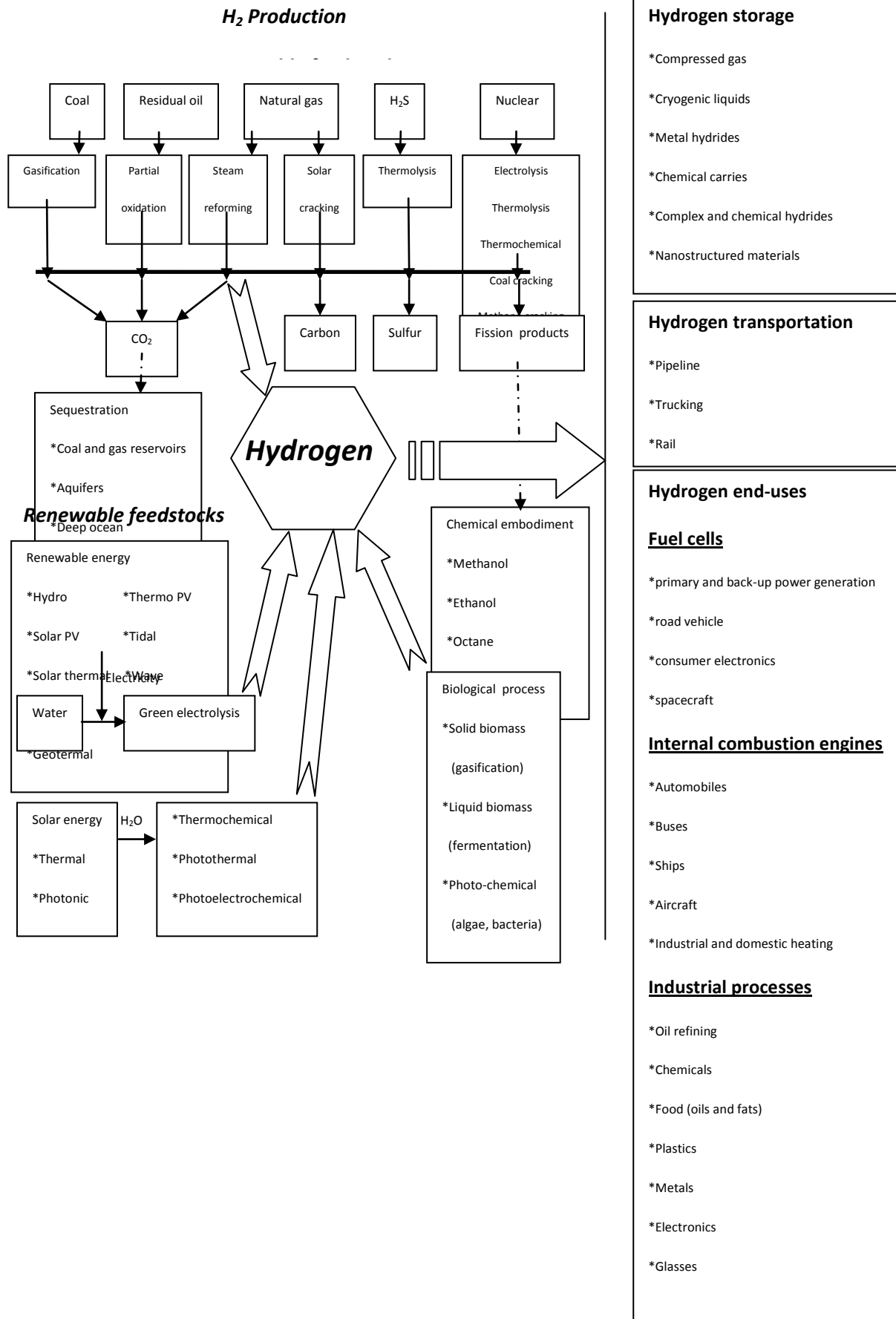


Figure 1: The hydrogen producing, storing, transportation and end-use (Adapted from Dell & Rand 2004)

Road Transport

Hydrogen delivery via road transport should be classified into sub-categories such as cylinders, tube-trailers and cryogenic cylinders. Each of the methods has advantages and disadvantages over the cost, distance and performance concerns. The most suitable method for every production site should be investigated according to these parameters, with the information of hydrogen production rate of the site. Production rate, with the distance-to-destination information will provide the decision data for which road transport option to use.

In general, when Turkish industrial conditions are taken into account, "high pressure stainless steel cylinders" will appear as the most suitable option for a wide variety of road transport applications of hydrogen. The reason is that Turkey has an experienced engineer and technician background in stainless steel industry with a sophisticated industrial organization. Turkish materials industry is still very dependent on conventional materials such as steel and commodity plastics, while developed countries are making the way in their materials research and industry in engineering plastics and ceramics fields, leaving the burden of commodity materials to the developing countries. This is also a chance to turn the situation reverse, by using the steel infrastructure and knowledge to produce high technology storage and delivery options for hydrogen. At this stage, efforts should be concentrated on cylinder design and manufacturing, specialized for hydrogen delivery by trucks and tube-trailers. Great potential for hydrogen delivery via road transport is seen, safety is a very important issue about the road transport of hydrogen. New safety standards should be developed for this topic.

Sea Transport

Hydrogen delivery via sea transport will be a very important option within the concept of off-shore and coastal wind-hydrogen projects. Turkey, with its three coasts, has great potential of wind-electricity and wind-hydrogen production. Although, a complex network of natural gas pipelines are being developed, most of the coastal and off-shore wind power farms will be costly to be interconnected to the hydrogen/natural gas pipeline. When the road transport is also costly to deliver the hydrogen produced from the production site to consumption site, or to a foreign country for export, sea transport will be the best option. The existing infrastructure of sea transport of compressed natural gas should be reviewed and necessary modifications for hydrogen transport using the same infrastructure should be investigated.

Through Pipelines

Hydrogen delivery via pipelines is the most promising technique for high capacity hydrogen transport. The key point of hydrogen delivery by this method is that, hydrogen and natural gas are very similar in their nature. Existing natural gas pipelines could be used for hydrogen delivery with small modifications, and newer ones without modification. Another advantage of pipeline delivery is that hydrogen could be injected to the natural gas flowing pipeline, enriching the natural gas in certain amounts. With a total of 5,000 km of natural gas pipeline (completed and under construction) Turkey has a big chance to distribute hydrogen via pipelines both internally and for export. Highly sophisticated network of natural gas pipelines would allow hydrogen production from a variety of suitable sites with cost effective distribution network.

As a rule, hydrogen transmission through pipelines requires larger diameter piping and more compression power than natural gas for the same energy throughput. However, due to lower pressure losses in the case of hydrogen, the recompression stations would need to be spaced twice as far apart. In economic terms, most of the studies found that the cost of large-scale transmission of hydrogen is about 1.5–1.8 times that of natural gas transmission (Veziroglu & Barbir 1998). Within this context, the availability of natural gas pipelines for hydrogen transport in terms of capacity should be investigated in great detail. Also modifications for pressure drop stations and gas quality stations should be researched to utilize this potential. Pipelines are one of the most important elements of hydrogen energy system and distribution network for Turkey, since they stand for the potential export route of hydrogen to nearby countries and especially European Union.

Hydrogen Storage Methods

Hydrogen is a non-polluting fuel, but since it is a light gas it occupies too much volume. Effective and safe storage of hydrogen has been a challenge for researchers world-wide for almost three decades. Hydrogen storage is a critical enabling element in the hydrogen cycle, from production and delivery to energy conversion and applications. Reaching the highest volumetric density by using as little additional material as possible and the reversibility of uptake and release of hydrogen are important criteria for hydrogen storage. Because of hydrogen's low density, its storage always requires relatively large volumes and is associated with either high pressure which requires heavy vessels, or extremely low temperatures, and/or combination with other materials. Basically, five main storage methods are considered:

Compressed Gas

The storage of compressed hydrogen gas in tanks is the most mature technology. Pressurized gas storage systems are used today in various sizes and pressure ranges from standard pressure cylinders (501,200 bar) to stationary high-pressure containers (over 200 bar) or low pressure spherical containers (<30,000 m³, 12 to 16 bar). Materials having high tensile strength, low density and which are non-reactive with hydrogen, i.e. austenitic stainless steel or Cu, are the best option for high pressure cylinders. The drawbacks of this method are safety issues and the relatively low hydrogen density together with the very high gas pressures in the system. Another hydrogen gas storage system -yet in research and development phase- is the underground storage of hydrogen in caverns, aquifers, depleted petroleum and natural gas fields and man-made caverns. This method is likely to be technologically and economically feasible (Taylor et al. 1986) in the future. Achievable storage density of this method is between 5 to 10 kgH₂/m³.

Liquid Hydrogen

Liquid hydrogen takes up less storage volume but the liquefaction process requires cryogenic tanks at -253K at ambient pressure. The drawback of this method is the large amount of energy necessary for liquefaction process (Sherif 1991). Approximately one-third of the energy content of hydrogen is lost during this process.

Storage via Chemical Reaction

Hydrogen can be generated via chemical oxidation of metals with water. The major challenge of this method is reversibility and control of the thermal reduction process.

Physisorption of hydrogen

Another storage method is physisorption, in the process of which a gas molecule interacts with several atoms at the surface of a solid. Activated or nanostructured carbon and carbon nanotubes, which have large surface areas, are possible substrates for physisorption. Hydrogen can be physically adsorbed on those materials. The adsorption rate increases at higher pressures and/or lower temperatures. For any practical use, temperatures below 100 K are needed. Carbon nanotubes are capable of storing between 4.2% to 65% of their own weight in hydrogen (FCS 2008).

Hydrogen can be stored in glass microspheres by heating them which increase the permeability of their walls. The spheres are then cooled, so that the hydrogen inside microspheres are locked. Hydrogen can be released again after reheating the spheres. At room temperature and 25 MPa pressure, a storage density of 14% mass fraction and 10 kgH₂/m³ is achieved (Rambach & Hendricks 1996). Besides those materials, zeolites have been investigated by scientists. At 77 K zeolites physisorb hydrogen in proportion to the specific surface area of the material. Metal hydrides are capable of absorbing and desorbing hydrogen with small pressure variations. Advantages of metal hydrides are low pressure storage of hydrogen in a safe and compact way and reasonable volumetric storage efficiency. Main challenge of this storage method is the weight reduction and thermal management issues.

Complex Hydrides

Complex hydride is another method used for hydrogen storage. The difference between complex and metal hydrides is the transition to an ionic or covalent compound upon hydrogen absorption. Complex hydrides consist of light metals, such as Li, Mg, B, Al. The borides offer the advantage of high gravimetric and volumetric hydrogen density. LiBH₄, which has the highest gravimetric hydrogen density (18% mass) among complex hydrides, could be ideal hydrogen storage material for mobile applications.

Conversion

Hydrogen can be converted into useful forms of energy via engines, turbines and fuel cells.

Combustion of Hydrogen in Engines and Turbines

Hydrogen use in internal combustion engines results in approximately 20% more efficient as compared to gasoline engines. However, use of hydrogen causes a power loss of approximately 15% (this can be reduced by using liquid hydrogen or advanced fuel injections techniques). Basically, the only products of hydrogen

combustion in air are water vapour and small amounts of nitrogen oxides. When hydrogen is used in turbines and jet engines the only emission is again NO_x . But this can be lowered by water injection, exhaust gas recirculation, or using liquid hydrogen. The usage of hydrogen in gas turbines increases the overall efficiency by pushing the gas inlet temperatures beyond 800°C . But there are some challenges for the use of hydrogen in internal combustion engines, turbines and jet engines. Flame characteristics of hydrogen combustion and the use of advanced materials in hydrogen combustion systems need to be understood well and searched more intensively. Use of hydrogen (liquid) for rocket engines in the space program has been extensive, and has brought about a great deal of experience in techniques for liquefaction, handling, storage and distribution.

Combustion of Hydrogen for Steam Generation

Hydrogen can be combusted with pure oxygen to produce steam for use in the electricity generation sector (e.g. for load electricity generation) and to meet steam needs of industry. High temperatures in flame zone can be reached via this reaction. Both saturated and superheated vapor can be produced, after arranging the steam temperature by means of water injection. Hydrogen steam generator can be used in power plants, industrial steam supply networks, medical technology and biotechnology.

Catalytic Combustion of Hydrogen

In the presence of a catalyst and at low temperatures (up to 500°C), hydrogen and oxygen can be combined to produce heat and emit only water vapor as a product of the reaction. Due to low temperature, NO_x emissions are not formed. The only product of catalytic combustion is water vapor. Catalytic burners can be designed using this principle and they can find application in household appliances. The usage of catalyst increases the cost. In order to lower the cost and implement the techniques in a wider field, there should be more investigations.

Electrochemical Conversion (Fuel Cells)

Electrochemical reaction of hydrogen and oxygen, which takes place in fuel cells, produce electricity and thermal energy. Various kinds of fuel cells, which distinguish by construction and mode of function, are under development worldwide for portable, transport and stationary applications.

Phosphoric acid fuel cells (PAFC) are already commercially available in container packages for stationary electricity generation. PAFCs are reliable and they tolerate approximately 1% of CO. Concentrated phosphoric acid is used as catalyst and the operating temperature of the fuel cell is between $150\text{-}220^\circ\text{C}$. One disadvantage of PAFC is that the fuel cell becomes unusable when phosphoric acid effloresces less than 42°C (HyNet 2008).

Proton exchange membrane or polymer electrolyte membrane fuel cells (PEMFC) can be used in automotive, mobile phones or combined heat and power applications. PEMFC has high power density. It's very efficient and it is easy to handle. Its operating temperature is typically between $60\text{-}80^\circ\text{C}$. The main disadvantage of PEMFCs is that very pure hydrogen is needed and PEMFCs are very sensitive to carbon monoxide.

Alkaline fuel cells have been used in space programs to provide electricity and drinking water since 1960's. Since the smallest amounts of dirt would destroy the fuel cell, hydrogen and oxygen should be in purest form.

Solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC), which are high temperature fuel cells, are appropriate for stationary electricity generation and cogeneration applications. They can also be used in transportation applications, especially in trucks. The operating temperature of MCFC is between $580\text{-}660^\circ\text{C}$. This type of fuel cell does not require gas purification and natural gas, biogas or synthesis gas can be used directly without the need of a reformer. SOFC can run on fuels such as natural gas, biogas and methanol, thanks to its ability to reform hydrocarbons within the cell itself. Solid oxide fuel cells typically operate at about 1000°C . Since the materials that could withstand high temperatures need to be used, these fuel cells are rather expensive. More durable and cheaper SOFCs should be built. Research is going on to develop SOFCs that can operate at $550\text{-}600^\circ\text{C}$.

Conversion via Metal Hydrides

The coupling of hydrogen and metal hydrides serves various hydrogen conversion methods, aside from its use as a storage medium. The combination of hydrogen with a metal (or an alloy) is an exothermic process, which means that heat is released. Using different types of metals with different characteristics and making use of the heat and temperature properties of reactions, metal hydrides can be utilized for various applications, such as heat storage, heating/cooling, pumping and hydrogen purifications.

Hydrogen Utilization

Hydrogen as an energy carrier has many applications. Hydrogen enables the use of renewable energy sources instead of fossil fuels for almost all purposes: as a fuel for surface and air transportation, as a fuel for heat production and even as a fuel for direct electricity production in fuel cells or indirect electricity production through gas and steam turbine driven generators. Additionally hydrogen is the only energy carrier which makes it possible to power an aircraft using solar energy. Generally one can differentiate between three main areas for the use of hydrogen which are mobile, stationary and portable applications.

Mobile Hydrogen Applications

All the means of transport known today could be powered by hydrogen. Technologies are being developed to use hydrogen in both fuel cells and internal combustion engines, including methanol systems. Hydrogen fuelled internal combustion engine vehicles are viewed as a near term, lower cost option that could assist in the development of hydrogen infrastructure and hydrogen storage technology. A key advantage of this option is that hydrogen fuelled internal combustion engine vehicles can be made in large numbers when demand warrants. The use of fuel cells in cars has some distinctive advantages:

- 1) There is only water emitted from the exhaust.
- 2) It operates without noise and without vibrations.
- 3) It is more efficient than a combustion engine.

Efforts to convert vehicles to hydrogen operation began in the mid 1920s with the work of a German engineer Rudolf Erren, who converted numerous engines to run on hydrogen for a variety of applications including trucks, buses and submarines (Hoffmann 1981). Large amount of research work has been done on the use of hydrogen as a fuel for cars, trucks and buses starting in 1970s. This work has been mainly aimed towards conversion of the existing internal combustion engines to run on hydrogen and studying the problem of hydrogen storage in vehicles. Three concepts, based on compressed hydrogen, liquid hydrogen and metal hybrid storage have been developed, tested and successfully demonstrated.

Hydrogen Driven City Buses

For buses the two different concepts of internal combustion engine and fuel cell could be used as well. Compared with diesel buses they both have the advantage of greatly reduced pollutant emissions. A Canadian fuel cell manufacturer, Ballard, demonstrated one of the first PEM fuel cell powered buses in 1993 (Howard & Ballard 1986). The bus was driven over 2,000 km in Vancouver, Los Angeles and Sacramento. Since then Ballard has built several more buses using more advanced fuel cell stacks. Ballard plans to introduce a commercial fuel cell bus, which will be in the range of 550 km. Daimler-Benz introduced its first hydrogen fuelled PEM city bus NEBUS (new electric bus) demonstrator. The engine consist of ten 25 kW fuel cell stacks by Ballard. Compressed hydrogen is carried in seven 150 lt, 300 bar roof-mounted cylinders. The range of the bus is 156 km (Hydrogen & Fuel Cell Letter 1997).

Hydrogen Powered Automobiles

Worldwide all the big motorcar producing companies such as Daimler Chrysler, Opel and Ford are developing test cars with fuel cell drive systems. BMW presented hydrogen powered cars very early but they are still concentrating on combustion engines. Recently Daimler Chrysler wanted to bring up a serial A-class model with fuel cells for sale. It has not been decided yet whether to use hydrogen or methanol as fuel. Presently the missing fuel station infrastructure is an obstacle to the broad market introduction of fuel cell cars.

Marine Applications of Hydrogen

Hydrogen/oxygen fuel cells particularly low temperature fuel cells such as PEMFC have characteristics which make them ideal for powering submarines: Since they do not need air they can operate underwater, provided that both fuel (hydrogen) and oxidant (oxygen) are stored on-board. They do not produce any emissions or waste products except water and can therefore maintain zero buoyancy. Since there are no moving parts they operate quietly and reduce sonar temperature. They reject heat at low temperature and generate very low thermal signature. They are very efficient proving longer cruising range and lower "indiscretion" time. Hydrogen and oxygen storage on-board may pose a problem due to weight and volume constraints. Liquid hydrogen and oxygen seem to be the best option, although metal hydrides for hydrogen storage have been considered as well (Brighton et al. 1992).

In 1989 Perry Technologies, Florida completed a small submarine equipped with Ballard's fuel cell. The German Navy has decided to equip their next generation of submarines with hydrogen fuel cell power plants and Siemens has developed reliable and efficient fuel cells exclusively for submarine applications (Strasser 1992). Australian and Canadian navies are experimenting with hydrogen fuel cells for their submarines. Fuel cell power plants may also be used for surface ships and boats, both as main propulsion engines and as auxiliary generators. As geothermal energy potential is abundant in Iceland, the government is considering production of hydrogen from geothermal energy and using it in the fishing boats instead of diesel oil which they have to import (Arnason et al. 1992). This would also help the country to meet the proposed United Nations restrictions for CO₂ emissions.

Trucks and Trams

The use of hydrogen and fuel cells in trucks has not been tested yet, because on long-distance rides diesel engines work very efficiently. However the use of fuel cells in delivery vehicles operating in cities is very interesting because these vehicles are usually part of a fleet and have only a limited daily mileage. In the evening they could be refilled in the depots.

Hydrogen Powered Airplanes

Liquid hydrogen has numerous advantages as a fuel for commercial subsonic and especially for supersonic aircraft (Brewer 1991). The most important advantage of liquid hydrogen is its high energy content (142 MJ/kg), which is 2.8 times higher than the energy content of conventional jet fuel. A liquid hydrogen powered aircraft would therefore have to carry one third of the fuel mass of a conventional aircraft. This means more payloads, smaller engines and higher fuel utilization. A subsonic hydrogen fuelled passenger aircraft will need on average 16 per cent less fuel to complete the same flight than a comparable conventional aircraft. This advantage will be even higher in a supersonic aircraft (28 per cent).

Stationary Hydrogen Applications

The most important stationary application of fuel cells and hydrogen is the co-generation of electric power and heat in a fuel cell heating and power station. The advantage of making use of both products, electric power and heat, is the very high overall system efficiency thus making the best possible use of the primary energy sources.

Hydrogen Application in Buildings

Hydrogen can be used for space heating and cooling, and water heating in the same fashion as natural gas is being used today, with minor modifications to the burner and fuel supply. In addition, instead of flame combustion, hydrogen can be used in catalytic combustors directly heating and humidifying the air. Since no other emissions are generated, these heaters can safely be used indoors. Another option for space heating and cooling, as well as refrigeration, using hydrogen would be hydrogen/hydride refrigeration systems.

Another way of providing heat in domestic applications would be to use the waste heat from residential/commercial fuel cell power systems. The fuel cells are very efficient in generating electricity, yet there is a significant amount of heat that may be recuperated and used for space and water heating. In this case the efficiency of the fuel cell may be raised to 70% to 80%.

The Fraunhofer Institute for Solar Energy Systems in Germany has developed, designed and tested several appliances based on the principle of catalytic combustion of hydrogen, which are now deliverable to customers (Ledjeff 1990). These appliances are: a catalytic hydrogen stove, an absorption refrigerator with catalytic H₂ burner and a modular H₂ eliminator system. The Solar Wasserstoff Bayern demonstration plant includes the following hydrogen appliances:

*Two gas fired heating boilers for variable natural gas/hydrogen mixtures, 20 kWth each, one using air and the other using oxygen as oxidants.

*Catalytic heater, 10 kWth boiler output, fuelled with natural gas and variable mixtures of natural gas/hydrogen and air as oxidant. The heater is integrated into the building heating system.

*Catalytically heated absorption type refrigeration unit, with rated refrigeration capacity of 16.6 kWth, with hydrogen as fuel and air as oxidant. This unit supports the existing chilled water circuit.

Hydrogen Application in Electricity Generation

Hydrogen fuel cells are very efficient devices which can produce both electricity and heat. Fuel cells can be used for centralized or individual electricity generation. Several fuel cell concepts are currently being developed and some such as phosphoric acid fuel cell plants are already in the demonstration and commercialization phase. Phosphoric acid Fuel Cell (PAFC) is the most advanced fuel cell type available today. Numerous demonstration plants have been constructed and are operating in the USA, Japan and Western Europe ranging from several kilowatts to megawatts. Fuel cells offer the possibility of decentralized power generation and may alleviate the need for establishing a massive grid infrastructure. This method of electricity generation and supply is very suitable for the biggest and fastest developing electricity markets such as heavily populated urban areas in developed countries and scarcely populated developing countries. In the former case, decentralized, zero emission electricity generation may be the only option for the expansion of energy services since building new power plants is physically impossible. In the later case, developing countries do not have a developed electrical grid and developing one for small power requirements but large distances would be economical.

Efficient hydrogen use in electricity generation will become very important in solar power plants, where hydrogen serves as an energy storage medium. During periods when the available solar energy is higher than the demand surplus energy can be used in electrolyzers to produce hydrogen and during periods when demand is higher than available, electricity can be produced from hydrogen via fuel cells. Another way to generate electricity from hydrogen is combustion of hydrogen in gas turbines or generation of steam, which can then be used in conventional steam turbines.

Portable Power Generation

A great variety of possible applications for fuel cells and hydrogen can be found in the energy supply of portable devices. Mobile phones, laptops, walkman, camcorders and many other things could be powered by hydrogen and by fuel cells in the size of batteries. Many participants in the fuel cell industry are developing small capacity units for a variety of portable and premium power applications ranging from 25 watt systems for portable electronics to 10 kilowatt systems for critical commercial and medical functions. Most of these portable applications will use methanol or hydrogen as fuel. In addition to consumer applications, portable fuel cells may be well suited for use as auxiliary power units in military applications. Having a look at a computer powered by a fuel cell, one can see that the operation time far exceeds the operation time of computers powered by conventional accumulators. Fuel cells which are even smaller, so called micro fuel cells could be integrated in mobile phones. Prototypes with an operation time of fifty hours have already been presented. Portable applications with higher power ratings are in the development stage as well. In the USA the lighting appliances on some construction sites in remote regions are already powered by fuel cells. Provided there is a big enough tank these systems work for weeks and they are cheaper to run than batteries with equivalent capacities.

Vision for Hydrogen Applications

Hydrogen will be available for transportation, power generation, industrial process heaters and portable power systems. It is expected to be an indispensable fuel for commercial and government fleets, personal vehicles and trucks. In order to generate electricity and thermal energy for domestic and industrial use, Hydrogen can be combusted directly or mixed with natural gas in turbines and reciprocating engines. Regarding mobile and stationary applications, it can be used in fuel cells. Furthermore it can be also used in portable devices such as laptops, mobile phones and any other electronic equipment.

Obstacles and Proposed Solutions for Hydrogen Applications

In order to realize the vision for the hydrogen applications, some obstacles need to be dealt with.

Hydrogen Storage

Mobile, stationary and portable applications require technological solutions. Regarding the transportation applications, hydrogen storage which is both practical and affordable is not available. This obstacle seriously prevents investment in infrastructure development.

Customer Opinion

Customers need to approve the hydrogen technologies and fuel cell vehicles which are still in the early stage of development. The hydrogen fuel infrastructure which seems to be limited in the early years will be spread out gradually. Hydrogen fuelled vehicles have quite a lot of advantages such as reduced emissions and safe energy compared to conventionally fuelled vehicles. The customer needs to be convinced of these benefits to increase its detected value. However these social benefits need many years to be realized after the market introduction.

Research and Development

Low cost and long lasting fuel cell stacks and systems are needed to be developed for transportation and stationary applications. For transportation applications research should be made on reformer in order to enable near term end use of hydrogen prior to the development of a larger hydrogen delivery system. Hydrogen storage research should focus on systems that are safe, small size and cost effective. Codes and standards should be developed to ensure the safety of the storage system designs. Combustion technologies and after treatments should be improved to optimize the power output and thermal efficiencies while reducing the emissions. Lean, premixed combustion is considered to be the best technology to control emissions in stationary turbines. Better strategies should be developed to make hydrogen and hydrogen enriched hydrocarbon fuels more popular.

Demonstration Studies

Strong coordination between the government and industry is needed in order to implement hydrogen energy technologies. Stationary, mobile and portable applications should be increased in order to evaluate the potential of hydrogen as a long term energy solution. The costs and benefits of infrastructure requirements for transition to hydrogen economy could be achieved through technology demonstrations and hydrogen pilot projects. Demonstrations on alternative hydrogen energy technologies and their commercial uses including the related performance should be increased significantly. Conventional conversion devices should be demonstrated in stationary, transportation and mobile applications.

Public Policies for Encouragement of Hydrogen Use as a Fuel

The major goal is to convince consumers to use hydrogen energy devices for transportation, electric power generation and portable electronic devices such as laptop computers and mobile phones. After identifying the cost and the performance of hydrogen energy systems it should be focused on customer awareness and acceptance. The major consumer demands are safety, affordability, convenience and environmental friendliness. The customer preferences need to be well understood and integrated into related hydrogen system design. Additionally, incentives such as price parity and cost sharing demonstrations should be applied in order to convince the public to use hydrogen applications. Stationary hydrogen customers should be treated equally and distributed generation options should be made valued for their ability to utilize waste heat and have high efficiencies.

Conclusion

Today's hydrogen conversion products, have started introducing hydrogen energy economy around the world but most of the products have not yet been manufactured in large quantities, since cost, durability and reliability issues need to be solved first. Consumers are not convinced to buy hydrogen conversion products since conventional fuels and conventional devices are practical and cheaper. Therefore, there is a need of policies of Government to improve the marketing of hydrogen conversion products, after more durable, reliable and cost-efficient fuel cells, engines and other hydrogen conversion products are manufactured.

The most difficult would be the initial penetration of hydrogen energy technologies into the existing energy markets. As any new technology, hydrogen energy technologies are in most cases initially more expensive than the existing mature technologies. Neither hydrogen, nor equipment for hydrogen production and utilization are mass produced, since there is no demand for them and there is no demand since they are expensive. The only way for hydrogen energy technologies to penetrate into the major energy markets is to start with those technologies that may have niche markets and penetrate them with governmental or international subsidies. Once developed, these technologies may help reduce the cost of other related hydrogen technologies and initiate and accelerate their market penetrations.

Interrelation and interdependence between hydrogen technologies has also impact on the market penetration of hydrogen technologies. For instance, without economically feasible technologies for hydrogen

production, storage, delivery and refuelling, it is not possible to introduce hydrogen powered airplanes into the market. Therefore, the design and implementation of a hydrogen economy must be considered as a whole system from production to end-use.

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