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# Evaluating the Necessity of Production and Competing Ability of a New Energy: Approaches to Expansion of Hydrogen Fuel

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**ABSTRACT:** Stable economy leads to increasing the economical productions, participation of more people in development and lack of probable limitations of production resources in short term and pollutants in long term. Stable development considers the energy as the main factor in economic, producing and service activities, which is needed in developing processes and expansion of producing systems in order to achieve a higher yield along with lower pollution and price. Over a period of time, economic and environmental restrictions have led to producing the energy via various resources and newly-made energies have generally been considered as available alternatives for previous fuels with different rates. In spite of all globally changed approaches and made attempts to decrease the usage of fossil fuels, transportation is still the main concern of green theorists. Three goals are focused in this paper, i.e. "hydrogen fuel burning features", "hydrogen natural features" and "price of the new fuel", and the necessity of expanding this energy is studied according to accomplished studies in this field. Findings show that producing, storing and transferring costs of hydrogen in a nutshell "the price of hydrogen" has decreased due to increasing demand and mass production of the fuel, and this gives a chance to hydrogen to compete with current fuels, and world energy system consequently the world economy would experience a stable situation.

**KEYWORDS:** Pollution of the Environment, Hydrogen Efficiency, Economic Limitations.

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## 1. INTRODUCTION

Energy industry has undergone great progress in environment-friendly technologies. Hydrogen is one of these cases; an available fuel that possess exceptional standards in energy production and harmonizes with the environment. In the present era that peripheral impacts of using fossil fuels, including global warming, pollutants distribution and running out of the fuel, has raised serious concerns, hydrogen can attract particular attention because of its considerable capabilities and its environment-friendly characteristics. Thanks to naturally high capacities and heat transferability rate, hydrogen is used in various areas, such as methanol production, cooling systems in power plant generators cooling the generators, which is the most typical usage of hydrogen, brings about increasing the efficiency and decreasing the production costs. High purity of hydrogen is required to achieve mentioned goal, because it increases the security energy (fuel and electricity) in spaceships, office and residential buildings (heat and electricity) and public transportation system. Therefore massive investments are made in different countries. Recently some countries have set up and completed big projects in this area; for instance, hydrogen industries in the United States produce 9 million tons hydrogen annually, which provides required fuels of 20 to 30 million hydrogen-based vehicles and 5 to 8 million houses. According to a strategic project in Europe, which is supposed to develop hydrogen technology and fuel cells, a plant is expected to be built by 2015 in order to produce one gigabyte electricity; and 0.4 to 1.8 million hydrogen-based vehicles are expected to be manufactured by 2020. Current hydrogen market is more than 40 milliard dollars per day, from which 49% is used in ammoniac production, 37% in petrochemical refining, 8% in methanol production, and 7% in other cases (Konieczny, 2008). An empirical study has shown that adding approximately 10% to 15% of hydrogen gas capacity to civil gas system, not only leads to no problems, but also decreases the amount of distributed carbon dioxide considerably. In another example in Montreal, adding 5% to the gas capacity, which equals 15% of hydrogen, to fuel system of natural gas-based vehicles to optimize the engine performance, reduced the azote oxides and organic volatile substances from the exhaust pipe after the engine checkup. Another governmental project, which was set up and completed in Netherlands, a hydrogen distributing and using network was established as civil fuel. Plastic pipes were used for transferring in this system (Ansari nick and Ahmadpour, 2008). Hydrogen can be produced from various sources, and this is its key advantage. Hydrogen fuel cells are capable of reducing the spread of greenhouse gases through different practical cases. If the required hydrogen is produced from renewable resources, the most amounts of greenhouse gases will be reduced. However, hydrogen has improved and increased the flexibility of consumption patterns all over the world as a fuel, this is worth mentioning that there is still no boom for hydrogen as energy in business, and hydrogen usage is mainly restricted to oil and petrochemical industries and some other similar companies that produce chemical substances. Fuel cells are the only cases in which hydrogen is directly used as a material to provide energy; burning hydrogen in the cells leads to producing electricity and nowadays this approach is considered as a strategic project in automobile manufacturing industry. More economical and competitive energy systems, which require more manpower and have less unpleasant environmental influences, are always expected to be provided. A scattering of activities along with political and economical limitations is the obstacle in the path of facilitation of this globally useful energy. Numerous steps, including the necessity of producing the new fuel, competitive features of the new fuel in comparison with existing fuels, availability of required substructures to expand the usage of the new fuel, safety of consumption, and predicting the demand level of the fuel, need to be taken in order to replace a kind of energy with another and benefit from a variety of energy. Currently, technological advances in production and transferability of the fuel for decreasing the price are needed to benefit from hydrogen. On the other hand, considering the existing technology, it is not feasible to use hydrogen in all areas, like fossil fuels. That is why fossil fuels, particularly oil and gas, are considered as the least expensive and most appropriate source of energy yet.

## 2. LITERATURE REVIEW

Several studies have been carried out to evaluate hydrogen as a kind of energy in the country as well as abroad, some of which are mentioned below. In 2009, Bae and Cho used dynamic Countable Generic Equilibrium (CGE) to evaluate the economical effects of hydrogen fuel in South Korea. They concluded that if the government does not intervene in development of hydrogen fuel, this fuel is sufficient for only 6.5 percent of the total demand in the country by 2040; and if the subsidy of this energy is increased 10%, 20%, and 30%, respectively, demand for hydrogen will increase 9.2%, 15.2%, and 37.7%, respectively by 2040. Also, Lee et al. (2011) studied the economical and environmental aspects of hydrogen in South Korea. Considering the production approaches, capacity and distribution, they used Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methods. Finally, they concluded that obtained hydrogen from reforming of natural gas and naphtha can compete with other fuels for buses. In a study by Ramazani in 2002, different scenarios of developing hydrogen energy were studied and the minimum costs and less effective expenses of hydrogen, in comparison with fossil fuels, were concluded. Muhammadifar et al. (2003) have conducted another research, in which economic process of liquefying the hydrogen with different capacities was analyzed. Their results show that producing liquid hydrogen with lower capacities is not cost-effective economically, and in spite of increasing the general expenses of investment, increasing the hydrogen production capacity reduces the production costs of every single kilo of liquid hydrogen. In another paper, which is conducted by Mousavifar in 2004, global demand for energy in the future, role of new kinds of energy and hydrogen is studied. Also, some common methods for producing hydrogen (biomass, hydroelectric, solar, etc.) is discussed in this study on the basis of economic approach from the cost and initial energy viewpoint. Ansari nick and Ahmadpour (2008) evaluated the equipment and technologic limitations in hydrogen fuel and studied its role in the market. In 2009, Shiroudi et al. carried out another study in this field; they offered their results, which were obtained from technical and economical analysis of two different systems of energy, i.e. photovoltaic – the system of water electrolysis – and photovoltaic – the system of natural gas reformer, in order to provide the required energy of an office building in Taliqan site. They used HOMER software and concluded that although the life cycles of both systems are equal, the cost of producing electricity through gas reforming is less than water electrolysis.

In this paper, according to accomplished studies, “natural characteristics of hydrogen”, “characteristics of hydrogen fuel” and “economic indices of hydrogen fuel” are discussed, and expansion and development of hydrogen is concentrated on the basis of mentioned approaches as well.

## 3. DEVELOPMENT OF ENERGY INDUSTRY TOWARD HYDROGEN: INCLINATION TO HYDROGEN ECONOMY

Considering the human’s increasing demand for energy, rapid economic growth, economic restrictions in different geographical areas all over the world, necessity of raising the environmental standards and consequently raising the living standards, substituting a new kind of energy for another, but not as an absolute substitution, has taken place as a transition from solid fuels to gas ones. This transition, which has started with the wood and undergone a transformation from the coal, into the petrol and natural gas, will experience a new situation with the advent of the hydrogen. The transition from the wood energy to the coal, then to the petrol, and from the petrol to the natural gas has been short-term transitions. Production systems and technologies made the distribution and consumption of each of mentioned fuels feasible in a period of about 60 years (World Resources Institute, 2009). The era of gas energy has started with methane consumption and finally will end with carbonless fuels (hydrogen). Therefore, some activities are required to be done in order to fulfill hydrogen economy and mentioned transition; these activities can be listed as follow: defining the entire perspective, making huge investments in studying and developing the required substructures and technology, defining related standards and rules in consuming the new energy, and public education.

### 3.1. An Approach to Natural Characteristics of Hydrogen Fuel

Hydrogen is a light and volatile gas. Small molecules of $H_2$ easily leak from chinks and cracks as well as joints and valves, and they evaporate immediately after leakage. Expansion causes heat, so pipe or tank leakage brings about fire. Hydrogen permeates four times faster than methane and ten times faster than petrol steams. It is a very dense liquid whose density is more than all other fuels, unlike its gas form. Other natural characteristics of hydrogen are presented in table 1.

Table 1: Characteristics of Hydrogen ($H_2$)

| | |
|---|---|
| The most abundant element in the nature (impure) | Quick changing from liquid into gas in a normal temperature |
| A tasteless, colorless and odorless element in natural temperature and pressure | Requiring great pressure as a liquid to be stored in a tank |
| A flammable element, and highly active chemically | High permeability and dissolvable in metals that make them friable |
| The least amount of density among other elements and 14.5 times lighter than the air | Capability of quick combining with oxygen |
| Boiling point 20.27 and melting point 14.02 degree Kelvin | Liquefying in -253 degree centigrade, and low density in this temperature |
| It does not pollute the underground water | Non-pollutant, low solvability |

Source: research findings

In order to store hydrogen in a tank, a peripheral cooling system and a very high level of insulation is required, and this increases the weight of the fuel tank. Developing studies led to discovering a particular rock, named “Zeolite”. Since zeolite is porous, it can play the role of a molecular sponge and trap (store) hydrogen gas in a semi-liquid form without any heavy cooling system in the fuel tank. There are approximately 50 different kinds of zeolite with various chemical combinations and crystal structure in nature (Evenon and Young University, 2004). The best kinds of zeolite are able to store hydrogen as much as 2% or 3% of their weight. Provided that some crystals of zeolite are produced that are able to store hydrogen 4% to 7% of their weight, a zeolite tank of hydrogen will be able to compete with an ordinary petrol tank. Hydrogen distribution and storing technologies suffer from shortages in some areas and are not developed as much as they need. Conducted research and studies in hydrogen storing is not sufficient and the storage capacity of hydrogen is not high. Different methods of storing hydrogen are presented in table 2.

Table 2: Methods of Storing Hydrogen ($H_2$)

| General Usage | Method |
|---|---|
| Small Amount | Carbon Nano-Pipes |
| Large mounts | Metal Hybrids |
| Small Amounts, Short-Term Storage | Compressed Gas |
| Large Amounts, Long-Term Storage | Liquid Form |
| Large Amounts, Long-Term Storage | Underground Establishment |

Source: research findings

There is no pure hydrogen in nature. Impurity and variety of sources has led to various methods to produce hydrogen. The pure hydrogen is needed to be produces to generate energy, although new technologies have solved the purity problem. Required sources for producing hydrogen are rather inexpensive and available; for instance, water, natural gas, coal, petrol and methyl alcohol. Special characteristics of hydrogen caused many operational problems, some of which are not solved yet, considering all technological advances. Hydrogen can be considered as a joint factor of physical energy, renewable resources and chemical energy. In fact, it is also the best kind of fuel and an ideal fuel for new kinds of clean energy-generating machines, like fuel cells. Briefly, the consequence of evaluating the expansion of hydrogen fuel from the view point of hydrogen natural characteristics approach is the necessity of conducting some studies in order to control the natural characteristics of hydrogen and increase the safety standard in consuming this fuel.

### 3.2. Characteristics of hydrogen fuel

The main characteristic of hydrogen as a fuel refers to its environmental features; comparing to other fuels, hydrogen is more compatible with the environment. Burning features of hydrogen, including efficiency and produced heat, are more capable of competing, comparing to other fuels. It can be burned in combustion process as well as used in fuel cells. Some special features distinguishes hydrogen from other fuels, these features are shown in figure 1.

Fig.1: Characteristics of hydrogen fuel

| | | |
|---|---|---|
| Produced heat due to combustion per weight unit more than any other fuel | **$H_2$** | High Efficiency and Clean Combustion |
| Changing blending rate with the air to burn in a wider area | | Reversibility of production cycle |
| Producing steam, water and nitrogen oxide after the combustion | | The highest energy capacity per weight unit of the fuel |
| Distributing the least pollutants | | Capability of being burned in internal combustion engines and hydrogen cells |
| Reducing the greenhouse effect | | Energy of 1 kg hydrogen = Energy of 3 kg petrol = Energy of 2.5 kg gas |

Source: research findings

Currently available fuels are compared with hydrogen in table 3 on the basis of two indices, i.e. special energy and density in order to evaluate hydrogen and compare it with other common fuels as well as justifying the necessity of developing the new fuel. Results show that hydrogen has the most amount of special energy per kilogram in kilowatt/hour. Comparing with natural gas, petrol and methanol, this superiority is significantly considerable.

Discussing the burning characteristics of hydrogen, it is worth mentioning that, as shown in table 4, comparing the combustion process of three common and mass-producing fuels with hydrogen, the new fuel, i.e. hydrogen gas has priority over coal, petrol and natural gas.

Table 3: Comparing the currently available fuels with hydrogen

| Fuel | Specific energy (kWh/kg) | Energy density (kWh/dm$^3$) |
|---|---|---|
| Liquid hydrogen | 33.3 | 2.37 |
| Hydrogen (200 bar) | 33.3 | 0.53 |

| | | |
|---|---|---|
| Liquid natural gas | 13.9 | 5.6 |
| Natural gas (200 bar) | 13.9 | 2.3 |
| Petrol | 12.8 | 9.5 |
| Diesel | 12.6 | 10.6 |
| Coal | 8.2 | 7.6 |
| Methanol | 5.5 | 4.4 |
| Electricity (Li-ion battery) | 0.55 | 1.69 |

Source: Edwards et al., 2008.

Table 4: Comparing the characteristics of combustion process

| | **Heat Power** | **Flame Speed** | **Combustion Temperature** | **Expansion*** | **Flammability*** |
|---|---|---|---|---|---|
| Coal | 7260 | 0.4 | 2000 | 0.147 | 0.841 |
| $CH_4$ | 11900 | 0.35 | 1745 | 0.088 | 1 |
| $C_8H_{17}$ | 10400 | 25 | 3500 | 1 | 0.434 |
| $H_2$ | 25000 | 2.65 | 2332 | 0.057 | 0.676 |
| $X^* = X/X_{MAX}$ | | | | | |

Source: Shiva and Zarrabi, 2003.

The expansion index is defined on the basis of dangers that are posed when the fuel gets to its combustion temperature. And flammability index is defined on the basis of the fuel volume increase when it changes its form from liquid or compressed gas into a normal form. Mentioned indices are less than a unit. These numbers are obtained from the best quality of mentioned fuels and balanced amounts are measured by the real amount and maximum amount.

Comparing coal, petrol, gas and hydrogen, in a fixed volume, hydrogen fuel has the least amount of pollutants. In 2003, Shiva and Zarrabi conducted a study and showed that the combustion process of hydrogen fuel is much cleaner than all other studied fuels. The findings of mentioned study are shown in table 5.

Table 5: Quantity of Pollutants in combustion products

| * | **$CO_2$** | **$SO_2$** | **$NO_X$** | **Dust and inflammable materials** |
|---|---|---|---|---|
| Coal | 1.893 | 0.012 | 0.008 | 0.1 |
| $CH_4$ | 2.75 | 0.03 | 0.0075 | 0 |
| $C_8H_{17}$ | 3.09 | 0.010 | 0.0115 | 0.85 |
| $H_2$ | 0 | 0 | 0.016 | 0 |
| *Kg Pollutants / fuel in kg | | | | |

Source: Shiva and Zarrabi, 2003.

Two most common fuels, which currently provide the most required energy in transportation, i.e. petrol and natural gas, are compared with hydrogen in table 5 on the basis of their chemical and physical characteristics. It is shown that hydrogen is rapidly emitted in the air and its boiling point, density and molecular weight is much less than petrol and gas fuels. Also, hydrogen has the highest heat power, steam rate and flame speed. High flammability is another considerable feature of hydrogen. A complete list of characteristics of hydrogen is shown in the table.

Table 6: Physical and chemical properties of three fuel options

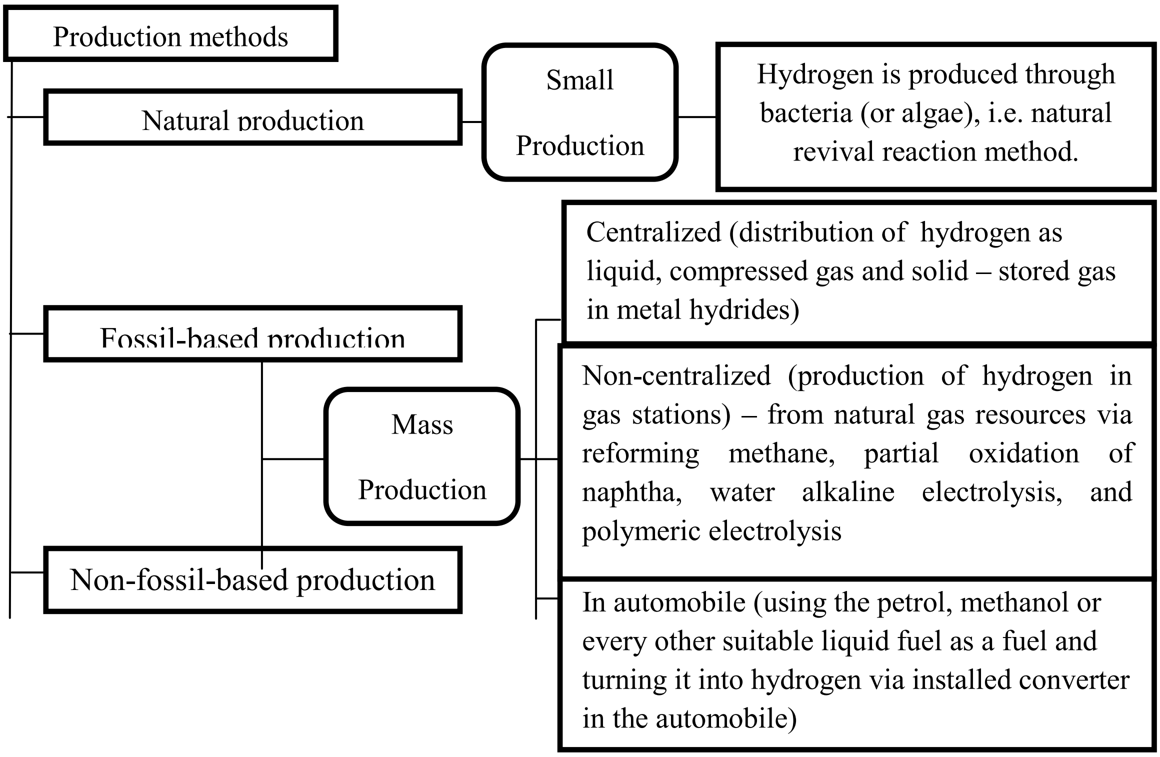
| | $H_2$ | Methane | Gasoline |
|---|---|---|---|
| Molecular weight (g/mol) | 2.016 | 16.04 | 110 |
| Mass density ($kg/N_Am^3$) at P = 1 atm = 0.101 MPa, T = 0 C | 0.09 | 0.72 | 720-780 (liquid) |
| Mass density of liquid $H_2$ at 20 K ($kg/N_Am^3$) | 70.9 | - | - |
| Boiling point (K) | 20.2 | 111.6 | 310-478 |
| Higher heating value (MJ/kg) (assumes water is produced) | 142 | 55.5 | 47.3 |
| Lower heating value (MJ/kg) (assumes steam is produced) | 120 | 50 | 44 |
| Flammability limits (% volume) | 4-75 | 5.3-15 | 1-7.6 |
| Deniability limits (% volume) | 18.3-59 | 6.3-13.5 | 1.1-3.3 |
| Diffusion velocity in air (m/s) | 2 | 0.51 | 0.17 |
| Ignition energy (m J) | | | |
| – At stoichiometric mixture | 0.02 | 0.29 | 0.24 |
| – At lower flammability limit | 10 | 20 | n/a |
| Flame velocity in air (cm/s) | 265-325 | 37-45 | 37-43 |
| Toxicity | Nontoxic | Nontoxic | Toxic above 50 ppm |

Source: balat, 2008.

### 3.2.1. Producing Hydrogen

Methods of producing hydrogen can be classified into three types: natural producing, fossil-based producing, and non-fossil-based producing. Produced hydrogen through natural producing method is not considerable and researchers are studying this field in order to produce more hydrogen via this method. In this method, hydrogen is produced through bacteria (or algae), i.e. natural revival reaction method. In fossil-based and non-fossil-based methods, hydrogen is produced and distributed through different systems, i.e. centralized mass production of hydrogen – distribution of hydrogen as liquid, compressed gas and solid (stored gas in metal hydrides) – non-centralized production of hydrogen in gas (fuel) stations – from natural gas resources via reforming methane, partial oxidation of naphtha, water alkaline electrolysis, and polymeric electrolysis – and production of hydrogen in the automobile – using the petrol, methanol or every other suitable liquid fuel as a fuel and turning it into hydrogen via installed converter in the automobile. These points are clarified in figure 2.

Fig 2: Production methods in business viewpoint

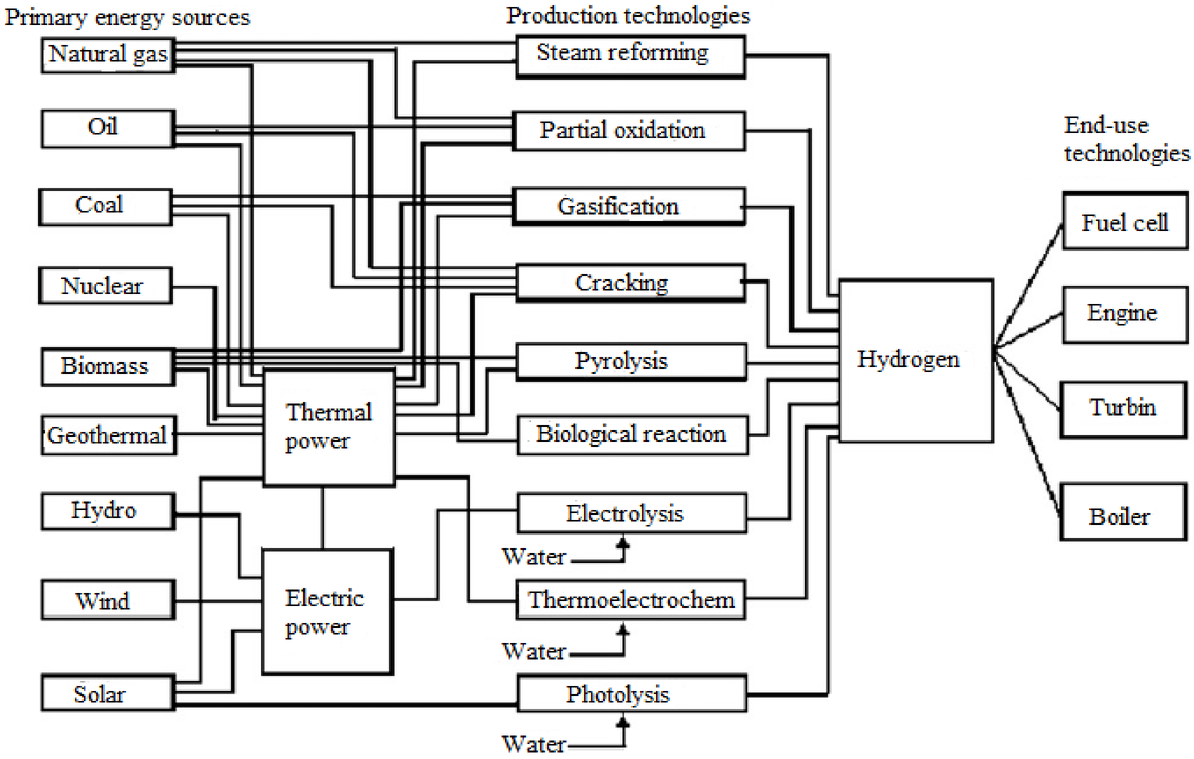



Source: research findings.

Commercial sale of hydrogen is less than 10% of its production all over the world, which is estimated as 20 million tons per year; it means that 90% of produced hydrogen is consumed at its production place. Nowadays, hydrogen is mostly produced through fossil resources. The production through non-fossil resources include producing hydrogen from water and biomass through particular methods, such as water electrolysis, photo-electrochemical, hydrogen sulfide, biochemical, water thrombolysis, gasifying biomasses, pyrolysis, and radiolysis. Currently, hydrogen is produced on the basis of fossil fuels all over the world and about 48% of produced hydrogen is produced from natural gas through reforming method; and the rest is obtained from the steam of produced natural gas from the petrol (30%), from the coal (14%) and the rest 4 % from the water electrolysis (Taheran, 2008).

Regardless of probability of different methods to produce hydrogen, there are some technological challenges in the way of hydrogen production all over the world. These difficulties have led to a situation in which hydrogen is not able to compete with other fuels in production cost. In one hand, the production cost of hydrogen is more than other fuels and on the other hand, the demand for hydrogen is low enough to be considered as an obstacle in production capacity. Furthermore, current technologies, which are used to produce hydrogen, produce carbon dioxide as well. More studies and development are required in advanced methods of hydrogen production and technologies of hydrogen production need to be practically shown. Water electrolysis is a typical method in hydrogen production, which is considered as an efficient method due to its high electricity consumption. High requirement of hydrogen plants to electricity has made hydrogen automobile industry look for a better substitution to produce hydrogen, industrially. Using new kinds of energy, like wind, can be an eminent resource of energy to produce liquid hydrogen. It is a new idea to use produced electricity of wind power plants in order to electrolyze water and produce hydrogen, which is a promising start to increase the benefit and put the process of production to consumption into practice.

Fig 3: Production methods




Source: Andrews & Shabani, 2012; U.S. Department of Energy, 2003.

If the required hydrogen by green (eco-friendly) automobiles, is produced from wind electricity, a renewable and stable process will be obtained, which is an endless clean fuel for automobiles.

The amount of input and waste of energy for production largely depends on the applied method. The method of water electrolysis, whose energy is provided by water power plants and method of gasifying through biomass are of the best. These two methods require an initial input energy as approximately 0.1 to 0.2 kilowatt/hour for every single kilowatt/hour of produced hydrogen. If the same electrical energy is provided by electricity power produced through photo-voltaic cells by the water electrolysis machine, approximately a kilowatt/hour initial input energy is required for every single kilowatt/hour of produced hydrogen. The optimum performance is when the hydrogen is produced through natural gas and electrical energy by "Kavearner" method through stream reforming. In such a condition, approximately 3 kilowatt/hour of initial energy is required for every single kilowatt/hour of output hydrogen; 66% of this energy is provided by natural gas and 34% by electricity power (Moussavifar, 2004).

Table 7 shows a comparison between electricity and hydrogen productions, economically. Numbers in the table show that generally the required capital (in dollars) to produce electricity is more than hydrogen, and also it is hydrogen that incurs more dollar expenses per gigajoule. In table 7, the expense (in \$/GJ) contains maintenance cost and capital gains, 25 years of capital lifetime, and the cost of 2 dollars for every single GJ coal and 1 dollar for every single GJ uranium. Also the capital is based on the capacity of every kilowatt production of hydrogen or electricity. In the method of producing electricity from solar energy, the energy is stored from morning until night, and then the produced electricity is measured. And in producing electricity from coal, carbon captivation and storage (CCS) method is conducted.

Table 7: Investment cost, load factor and efficiency for production of electricity and hydrogen

| | | **Nuclear** | **Thermal solar** | **Coal CCS** |
|---|---|---|---|---|
| Hydrogen | Capital ($/kW) | 2100 | 1500[b] | 900 |
| | Efficiency HHV (%) | 42 | n.a | 60 |
| | Load factor (%) | 90 | 22 | 80 |
| | Cost[a] ($/GJ) | 12 | 24 | 7 |
| Electricity | Capital ($/kW) | 1500 | 4200[b] | 1500 |
| | Efficiency HHV (%) | 48 | n.a | 35 |
| | Load factor (%) | 80 | 70 | 70 |
| | Cost[a] ($/GJ) | 10 | 21 | 13 |

Source: Hedenus et al, 2010.

In this table: (a): The cost in USD/GJ is calculated given an annual operation and maintenance costs of 4% of the capital investment, a lifetime of 25 years of the capital, and the fuel costs 2 USD/GJ coal and 1 USD/GJ uranium (which is substantially higher than current costs but assumed to reflect longer term costs if uranium scarcity were to drive up prices; the fuel cost only plays a minor role in the overall economics of nuclear power).

(b): The capital cost is per kW hydrogen and electricity production capacity, respectively. For electricity generation, as solar energy is stored from day to night and the electricity generation is leveled out, thus the specific capital cost is higher.

Probable challenges and advantages of some methods to produce hydrogen are briefly shown in tables 8 and 9.

Table 8: overview of the challenges and research needed for hydrogen production technologies

| **Distributed Natural Gas Reforming** | **Bio-Derived Liquids Reforming** | **Coal and Biomass Gasification** |
|---|---|---|
| *Challenges* | | |
| • High capital costs<br>• High operation and maintenance costs | • High capital costs<br>• Feedstock quantity and quality | • High reactor costs<br>• System efficiency<br>• Feedstock impurities<br>• Carbon capture and storage |
| *R&D Needs* | | |
| -Improve catalyst efficiency and reduce costs.<br>-Develop low-cost, efficient separation/purification.<br>-Combine unit operations to increase cost effectiveness.<br>-Optimize operations to meet variable demand.<br>-Develop flexible, modular reformer designs using low-cost materials. | -Increase hydrogen yield and efficiency.<br>-Develop catalysts to enable use of low temperatures or the liquid phase.<br>-Develop low-cost, efficient separation/purification.<br>-Develop flexible, modular reformer designs using low-cost materials.<br>-Identify best feedstock candidates by region. | -Improve catalyst tolerance of impurities.<br>-Develop more efficient and robust components for entire system.<br>-Reduce cost of biomass feedstock storage, preparation, and handling.<br>-Increase quantity of affordable biomass.<br>-Develop biomass/coal co-fed gasifies. |

Source: The U.S. Department of Energy, 2009.

Table 9: overview of the challenges and research needed for hydrogen production technologies

| **Thermochemical** | **Water Electrolysis** | **Photo electrochemical** | **Biological** |
|---|---|---|---|
| *Challenges* | | | |
| • Longer-term technology<br>• Effective and durable materials of construction | • Low system efficiency and high capital costs<br>• Integration with renewable energy sources | • Effective photo catalyst material<br>• Low system efficiency | • Efficient microorganisms for sustainable production<br>• Optimal microorganism functionality in a single organism |
| *R&D Needs* | | | |
| -Develop robust, low- | -Develop long-lasting | -Develop durable, | -Develop |

| | | | |
|---|---|---|---|
| cost materials for solar receivers, chemical cycles, reactors, and thermal storage.<br>-Optimize thermal and chemical storage system designs to address variable solar power availability and lower total costs. | membranes and corrosion-resistant interconnects.<br>-Balance storage and production rate capacity for variable demand.<br>-Develop efficient water conditioning systems. | effective photo catalysts and electron transfer catalysts.<br>-Automate system control, increase equipment reliability, and minimize energy losses. | microorganism functionality for efficient and sustainable production.<br>-Identify and characterize new microbes.<br>-Design manufacturing processes for high-volume production at low cost. |

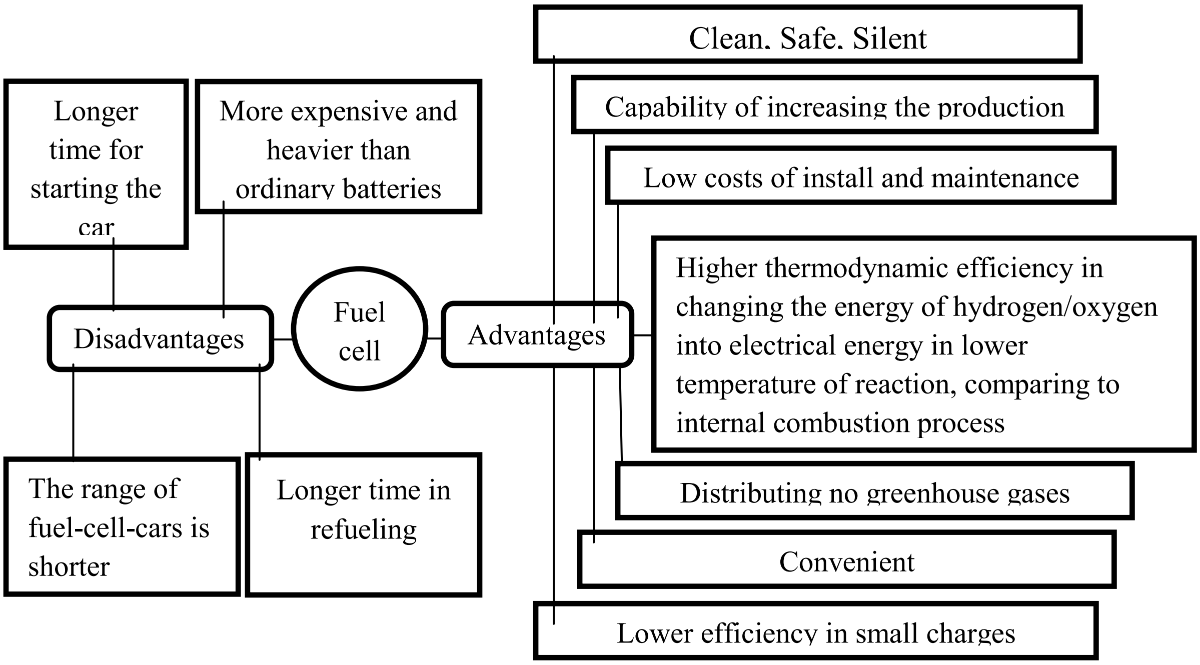
Source: The U.S. Department of Energy, 2009.

**3.2.2. Fuel Cells**

This is a system to turn the chemical energy of the fuel into electrical energy whose fuel is hydrogen or other gases, which contain hydrogen, like natural gas and methanol. Water and heat are peripheral products of fuel cells. Therefore, it is directly fed by hydrogen or another chemical compound that contain hydrogen (like natural gas) through an analyzed reformer, which responds this requirement. There are various cells on the basis of the kind of resources that contain hydrogen. There are three main utilizations for fuel cells, i.e. fixed, portable and transportation area. Fuel cells have some considerably typical features, including cleanness, modularity, safety, low install and maintenance cost, distributing no greenhouse gases, convenient usage, and silent application, which have made them popular in different areas. If the utilization of fuel cells to produce electricity is compared with internal combustion process, found differences will encourage the production of fuel cells.

For instance, the thermodynamic efficiency of changing the energy of hydrogen/oxygen into electrical energy is much higher when the temperature of chemical reaction is low, and also the efficiency of changing the electrochemical energy increases in lower charges, so fuel cells have higher efficiency in small charges. Also it is possible to make a set of small fuel cells with higher efficiency by a fuel cell with high charge. Mentioned features can be considered as advantages of fuel cell technology. Purity of hydrogen in the cell is a vital factor in vehicles; because the applied platinum catalyst in fuel cells can be easily polluted by impurities of hydrogen, which affects the efficiency of the catalyst. Therefore, the applied technologies in hydrogen production have to produce pure hydrogen or accompany it with purification processes.

Fig 4: Advantages and disadvantages of fuel cell




Source: research findings

On the other hand, fuel cells have some disadvantages as well; weight and price of fuel cells are more than ordinary batteries, inventor technologies are not absolutely clean and bring about some pollution, the range of fuel-cell-cars is shorter and time of refueling and starting the car is longer for them, comparing to ordinary automobiles.

Table 10: Summary of fuel cell types and their present characteristics

| **Type of electrolyte** | **Operating temperature (°C)** | **Applications** | **Electrical power range (kW)** | **Electrical efficiency (%)** |
|---|---|---|---|---|
| Proton exchange membrane | 60-110 | Mobile, portable, low power generation | 0/01-250 | 40-55 |
| Alkaline | 70-130 | Space, military, mobile | 01-50 | 50-70 |
| Direct methanol | 60-120 | Portable, mobile | 0/001-100 | 40 |
| Phosphoric acid | 175-210 | Medium- to large-scale power and CHP | 50-1000 | 40-45 |
| Molten carbonate | 550-650 | Large-scale power generation | 200-100000 | 50-60 |
| Solid oxide | 500-1000 | Medium-to large-scale power and CHP, vehicle auxiliary power units, off-grid power and micro-CHP | 0/5-2000 | 40-72 |

Source: Edwards et al., 2008.

The second approach yields this result that the new kind of energy is quite capable of competing with other current fuels and its suitable features guarantee an appropriate standing in this area, provided that more studies support it.

### 3.3. Economic Features of Hydrogen Fuel (Price)

Nowadays, there are many economic reasons to develop new systems of energy and discover new kinds of fuels with economically and environmentally improved indices, like hydrogen. Providing the required energy of a society from the same source of energy may jeopardize the stability, and political issues may lead to serious problems of a country.

Fig 5: Economic aspect of appealing to the new kind of energy

1. The war and other political strategies and boycotts, which are related to current fuels
2. Higher price, considering the pollution of current fuels
3. Being cost-effective economically
4. Creating economic superpowers
5. Stable resources of energy is the prerequisite of stable economy
6. Limitations and economic growth development
7. Changing the living welfare
8. Decreasing the efficiency of manpower, due to pollution
9. Economic limitations, like sudden high inflation
10. Requirement to reversible oil dollars that causes crisis in developing countries

Source: research findings.

Figure 5 shows the reasons that why a new movement toward benefiting from a variety of energies and developing hydrogen as a fuel seems vital, economically. Investment expenses for most required technologies to produce hydrogen are considerably higher than other fuels. The price of hydrogen is an important factor that reduces the ability of hydrogen to compete with other fuels in the market. Hydrogen pricing is a fundamental factor in creating demand for this fuel. Different studies, which have been conducted in order to increase the ability of hydrogen to compete with current fuels, show three various ways to achieve mentioned goal. Firstly, involved specialist need to continue their research and complete their studies in order to reduce the production cost, store and transfer through developing production methods, identify new materials, reduce the number of necessary components, deign simple systems and move toward mass production, identify and improve related materials with operational steps, stabilize processing steps, reduce the need for manpower and maintenance costs or increase the lifetime of equipment. Increasing the investment and developing production capacity, reduces the cost of producing every single kilogram of hydrogen. For instance according to conducted studies, producing liquid hydrogen in low capacities is not cost-effective. Secondly, if the cost of environmental destruction is regarded in pricing process of other fuels, the price of hydrogen will be reasonable and it will be able t compete with other fuels. A basic fact in a stable energy system and its consequent stable economy is that the price is set in a way that covers following definition (Andrews and Weiner, 2005):

**Stable Pricing** = Price of Lifetime + Costs of Environmental Distraction + Fine of Ending the Resources + Cost of Radiation Distribution – Encouraging to Resources Renewability

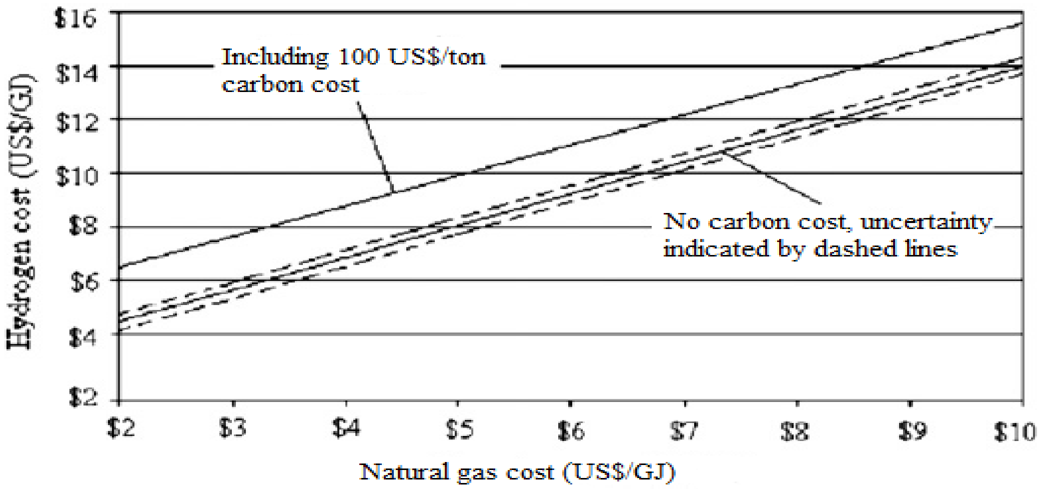
Thirdly, people lean to pay more money for green automobiles. Therefore, it is possible to roughly rely on people's money to compensate the expenses in initial steps and up to mass production.

So far, the price of hydrogen production, the price of hydrogen storage, and the price of transferring hydrogen have been tree special fields that attracted the attention of researchers and projects. In other words, price of the new energy is a function of mentioned expenses:

$$P(H_2) = F(C_{Production}, C_{Storage}, C_{Transfer}) \quad (1)$$

In production field, producing hydrogen by steam reforming of methane is the most economical method, among all current commercial processes.

Fig 6: The cost of hydrogen production from natural gas using SMR

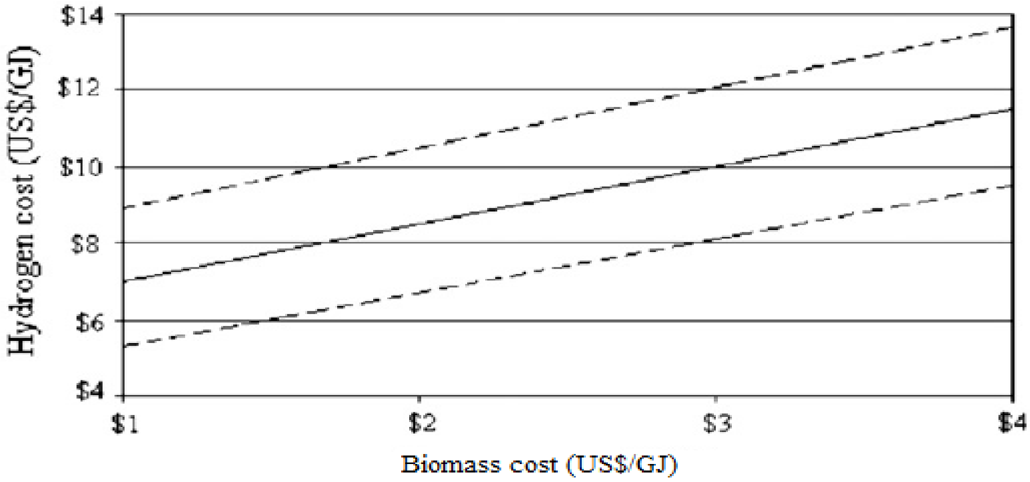



Source: Balat, 2008.

In this method, the initial amount of natural gas in large projects of hydrogen production 52% to 68% affects the reducing the price of produced hydrogen, and in small projects, it equals up to 40% in capital expenses. in this method, if the price of gas equals 6 dollars per GJ, the price in large projects will equal 1.25 dollars per kg and in small projects as 3.5 dollars per kg of produced hydrogen (Balat, 2008).

Following figures compare the price of producing hydrogen through three different resources, i.e. hydrogen, coal and biomass. In these figures, considering the produced carbon during the process of hydrogen production affects the expenses significantly. In Iran, producing hydrogen through natural gas costs 3 to 7 dollars and through electrolysis method as 6 to 10 dollars. It is expected to cost 3 to 10.5 dollars per kilogram (Shiroudi et al., 2009).

Fig 7: The cost of hydrogen production from biomass




Source: Balat, 2008.

In storage field, considering different discovered methods, different costs are offered. The price varies on the basis of the storage tank size and duration of hydrogen storage. Produced hydrogen is stored as gas (in cylinder reservoirs in a pressure as much as 41 Mpa or in underground tanks – the space between mineral floors or rock crystals – like empty tanks of petrol or gas. 15% of total energy is devoted to press hydrogen), as liquid (storage as a cryogenic liquid in a temperature of -253 centigrade, which requires 40% of hydrogen combustion energy) and as solid (combination of hydrogen with metals and metallic alloys as hydride, e.g. using ammoniac hydride in a temperature under zero, and absorbing hydrogen as 2% to 7% of its weight) (Pedro and Putsches, 2008). Five methods, including compressed gas and liquid hydrogen in different periods of time are compared in table 11. The table shows that storing hydrogen as compressed gas in a short time, i.e. 1 to 3 days, is the least expensive method.

Table 11: A summary of the hydrogen storage costs for stationary applications

| Storage system/size (GJ) | | Specific TCI ($/GJ capacity) | Storage cost ($/GJ) |
|---|---|---|---|
| Compressed gas | | | |
| *Short term (1-3 days)* | 131 | 9008 | 4.21 |
| | 147* | 16600 | 33 |
| | 13100 | 2992 | 1.99 |
| | 130600 | 1726 | 1.53 |
| *Long term (30 days)* | 3900 | 3235 | 36.93 |
| | 391900 | 1028 | 12.34 |
| | 3919000 | 580 | 7.35 |
| Liquefied hydrogen | | | |
| *Short term (1-3 days)* | 131 | 35649 | 17.12 |
| | 13100 | 7200 | 6.68 |
| | 130600 | 3235 | 5.26 |

| | | | |
|---|---|---|---|
| *Long term (30 days)* | 3900 | 1687 | 22.81 |
| | 391900 | 363 | 8.09 |
| | 3900000 | 169 | 5.93 |
| Metal hydride | | | |
| *Short term (1-3 days)* | 131-130600 | 4191-18372 | 2.89-7.46 |
| *Long term (30 days)* | 3900-3900000 | 18372 | 205.31 |
| Cryogenic carbon *(1 day)* | | 4270 | 26.63 |
| Underground *(1 day)* | | 7-1679 | 1-5 |

*This value is based on storage in pressurized tubes in a specific application and may not be appropriate for extrapolating.

Source: Padro & Putsche, 1999; balat, 2008.

In the field of transferring the hydrogen energy, all available distribution systems are expensive and low demand for such systems has increased their price. Undoubtedly, technological advances will increase the ability of competition for this fuel in future. Currently, road transportation is the least expensive way to transfer hydrogen as liquid for every single kilogram per 1000 kilometers (Hawkins, 2006). The noticeable point in transferring hydrogen is that its density is lower than natural gas, so if the same way is used to transfer both fuels, the required pumping for transferring the new energy is 3 times more than the natural gas. Furthermore, hydrogen reacts with the ordinary metallic pipes, which are used to transfer the natural gas (Harris, 2004).

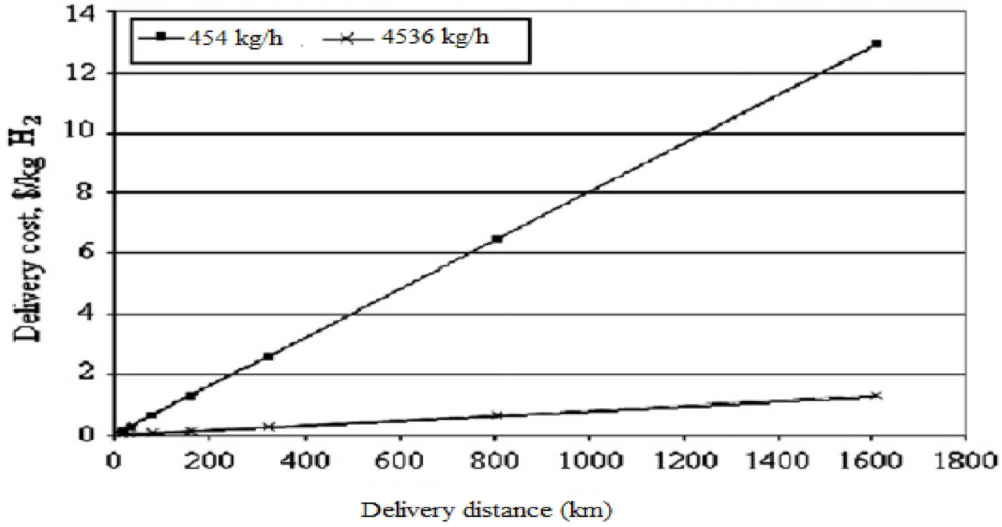
Four different methods of transferring hydrogen are compared in table 12. Regardless of mentioned expenses, provided that current fuels are replaced with hydrogen in future, the cost of changing current gas (fuel) stations into hydrogen stations as much as 50000 gallons petrol will equal 1.4 million dollars monthly. This amount for CNG and LNG costs 0.9 and 0.6 million dollars, respectively, and for methanol, ethanol and LPG equals 0.2 million dollars (Agnolucci, 2007).

Table 12: Cost of hydrogen with different technologies ($/kg/100km)

| | **Pipeline** | **Liquid (by road)** | **Liquid (by the ship)** | **Tube trailer** |
|---|---|---|---|---|
| Marginal Cost | 0.1-1 | 0.3-0.5 | 1.8-2 | 0.5-2 |

Source: Hawkins, 2006.

Fig 8: Cost of pipeline delivery with distance at different pipeline capacities




Source: Hawkins, 2006.

The third approach confirms the fact that the price of hydrogen, which is under the influence of production, storage and transferring costs, is able to compete with current fuels in mass production, and developing studies will reduce the cost.

## 4. Conclusion

Helping to stable development of energy through reducing social and environmental risks caused by increasing consumption of fossil fuels all over the world, increasing the stability and variety of energies through developing the fuel cell technology and decentralizing the production of electricity, possibility of constant and more effective consumption of renewable sources of energy through fuel cells, protecting the resources of fossil fuels and using more efficient resources, helping to create and develop the market of natural gas and move toward a wiser economy through providing a chain in the global market of fuel cell technology along with key technologies focusing on competitive aspects in economic field, are some advantages of developing the hydrogen production and consumption.

Along with all mentioned advantages, new studies are required to complete the process of hydrogen production, develop the moving and fixed storage systems, increase the technical and economical efficiency of transferring systems, and importantly, improve the safety of hydrogen fuel and create the culture of consuming the new energy. This prepares a competitive ground for hydrogen to be considered as a suitable substitution for current fuels, especially in transportation area. Production, storage and transferring costs are justifiable only in mass production projects.

Considering the availability of great resources of natural gas in Iran, there is a good opportunity to produce hydrogen. In another hand, the availability of substructures of natural gas distribution in Iran has paved the way for substructures of hydrogen in transportation and electricity production. Installing an inventor can turn the natural gas into hydrogen. Currently, most amount of hydrogen is produced by fossil fuels, especially natural gas. Availability of such natural resources enables the country not only to import fossil fuels directly, but also to benefit from hydrogen production.

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**ETHICAL CONSIDERATION**

Authenticity of the texts, honesty and fidelity has been observed.

**AUTHOR CONTRIBUTIONS**

Planning and writing of the manuscript was done by the authors.

**CONFLICT OF INTEREST**

Author/s confirmed no conflict of interest.

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