國立交通大學

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氫能源的現況與展望

The Status and Trend of Hydrogen Energy

研究生：裘惟立

指導教授：虞孝成 教授

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研究生: 裘惟立 Student: Willie Chiu

指導教授: 虞孝成 教授 Advisor: Dr. Hsiao-Cheng Yu

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摘要

能源是經濟的基礎。石化能源在近代發展迅速，也造成了許多問題，尤其是石化能源的有限資源和環境影響。1970 年代已經歷過油價的上漲，現在有限的石油資源和石油需求增加又再一次的造成了高油價。排放二氧化碳所造成的全球暖化影響了我們的環境。解決這些問題須要尋找新的替代能源。氫做爲替代能源可以解決這些問題。氫和燃料電池在這會做不同關點的探討。

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Student: Willie Chiu Advisor: Dr Hsiao-Cheng Yu

Institute of Management of Technology

National Chiao Tung University

Abstract

Energy is one of the fundamental building blocks for our economy. Through out the history, rapid advances in energy sector only occurred in the past two centuries. Fossil fuel energy appeared in 20^{th} century dominated through out the century and continued into 21^{st} century. Two main issues of fossil fuel energy are the finite resources and the impacts on our environment. Fossil fuel will eventually faces depletion as we continue to harvest resulting consequences in energy supply reduction and zero production of oil related products such as plastics. In 1970s, high oil prices made people realized their energy dependency. In 2007, oil prices raised even higher than 1970s, but not due to decrease in oil production. Carbon dioxide emission is tide with global warming and climate changes. This is an environmental problem caused by using fossil fuel energy resulting severe weather conditions. To find resolutions to these problems, alternative energy and renewable energy are being researched. Hydrogen energy as an alternative energy is one possible resolution. Different aspects of hydrogen energy and fuel cell presented in this paper allow us to have a better insight on the possibilities of hydrogen energy.

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Willie Chiu

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Chapter 1 Overview

Energy is one of the most important sources in the history of human development since their relation is directly linked together. Energy was defined in the eighteenth century as the ability to do work. Work is the amount of effort put into a task. Even before the existence of definition, energy had been used by human to perform task. The primary energy source in the ancient time was the muscle power from human or animal, wind, fire, and water. Muscle power was used in variety tasks such as building houses and farming. Wind was used for windmill and to sail boats, water was used in watermills, and fire on woods was used for heating and cooking purposes.

Energy and ways of utilization started to develop in the 1800. Steam engine was invented by Watt and later applied into ships or steamboat, railways, and motors. Steam engines become widespread in Europe and U.S. and were the biggest energy utilization method. Moreover, one of the fossil fuel energy sources was commonly used in this time, which was coal, prospering the coal mining and other coal related industries. Later, the introduction of combustion engine proved to be superior then steam engine. Thus, steam engine gradually phased out.

As combustion engine spread widely, especially the introduction of diesel engine in the late 1800s stimulated development of automobile, the demand of petroleum started and continued to the current days. During the process of searching and extracting crude oil, people noticed another fossil fuel energy source called natural gas. In the early time of crude oil extraction, natural gas had little use. Thus, burning them was the way to handle this gas. In the mid 20th century, people started using natural gas for space heating and become one of our energy sources.

1.1 Environmental Issues

Coal, petroleum and natural gas are the three fossil fuel energy commonly used today. They brought us the convenience and improved our well being especially in the developed nations. However, issues arouse when using these resources and their impact on the environment is one of the major issues. Although coal usage dropped drastically after mid 20th century, coal caused a lot of problems environmentally. Coal is considered a dirty energy due to the experiences learned in the early time uses, from mining, handling and burning of coal. When burnt, hazard gases are produced such as smoke, tar, soot, SO_2, CO_2 and NO_2…etc. When it was widely used in cities, it caused smog and fog. This situation was well known in early London, causing many respiratory diseases. As a result, regulation on air quality was introduced during the coal period to reduce the smoke problem. This is not a problem anymore as coal is not used widely nowadays as it was replaced by natural gas for space heating purpose.

Petroleum and natural gas are currently utilize the most and are cleaner than coal. Still, petroleum combustion causes many environment concerns. Hot topics on being green or being environmental friendly, arose in the early 21st century due to the concern of consequences. When oil is burnt in a power plant to produce electricity, several byproducts are also formed, including carbon dioxide, carbon monoxide, sulfur dioxide, nitrogen oxide, and mercury compounds. All of these had consequences, directly or indirectly, toward environment and human health.

Sulfur dioxide aggravates respiratory and cardiovascular diseases, making difficulty in breathing to asthma patients. It is also a source of acid rain formation, which can damage trees, building, and affect our water sources. Sulfur dioxide can travel for long distances that impact wider area, thus become a global problem without country boundary restriction. Nitrogen oxides result in the formation of ground level photochemical ozone, or smog, this is a hazardous condition as it causes respiratory problems. Nitrogen oxides cause formation of acid rain, react to form other chemical that affect respiratory system and water sources. Similar to sulfur dioxide, nitrogen oxides pass through long distances and require regional attention rather than local.

Road vehicle were the main causes of carbon monoxide and have serious health impact. With high concentration level, it is poisonous to human, affect heart disease, and central nervous system. Mercury compounds are heavy metals highly toxic to human through inhaling or intake from mouth. A wide range of symptom when inhaled includes, not limited to, tremor, nerve related problems, impaired cognitive ability, kidney problems, respiratory problems, and death. All of these problems have been reduced by technology research and governmental regulation. However, complete reductions are not possible thus leaving these byproducts in existence. Moreover, potential mechanical failures in reduction methods add greater pollutants into the air. Besides the health concerns due to these pollutants, some of them cause climate change that result in global worming.

1.2 Climate Changes

Intergovernmental Panel on Climate Change, or IPCC, defined climate change as changes in average or variability of climate state in a period of time, decades or longer. The cause of climate change can be natural activities or human activities. Currently, we are more concerned with the human activities since possible regulation and reduction methods serve promising resolutions.

During the period of 1995 to 2006, temperature are recorded as warmest since 1850. The rate of temperature increased in recent 50 years with an average of 0.13 °C per decade. This rate is faster than 100 years period with overall average of 0.74°C, or 0.074 °C per decade. Temperature increases faster in the North Artic region, land and ocean also showed increase in the temperature. Although unclear in whether the raise in sea level is due to natural variation or a long term trend, sea level raised faster in recent 10 years compared to time period of 50 years. Recent 10 years average of 3.1 mm per year compared to 1.8 mm per year of 50 years time period. Ice region and frost land also decreased recently. More frequent activities of cyclone in the North Atlantic region are also observed (Climate Change 2007, 2007).

There are many causes of climate change, either naturally or due to human activities. Green house gas is one of the important factors, having high influences on the radiative forcing, a measure on the balance of entrance and exit of energy in Earth atmosphere through absorption and emissions of radiation. Therefore, different amounts of green house gases alter the energy balance of atmosphere, resulting climate changes in temperature aspect. Within all the green house gases, carbon dioxide is created the most by human activities, contributing to 77% of green house gases and faster emission rate in the recent years. These emissions were coming from mostly industrial activities, energy sectors, and transportations. In 2004, within all types of the green house gases created by human activities, 56% were carbon dioxide due to fossil fuel usage. Besides carbon dioxide, methane, nitrous oxides, and halocarbons are all green house gases caused by human activities and all of them have increased compare to earlier records. Overall, IPCC statistical analysis supported that a likelihood of positive relation between human activities and global warming (Climate Change 2007, 2007).

Despite the effort to control and mitigate the green house gases emissions, the emissions continued to rise and fossil fuel continued to dominate in the near future. This results a temperature rise of 0.2 ℃ per decade. If climate change continues, different impacts are likely to occur around the world. Ecosystem structure might change and possible regional shift might occur. The result is negative impact on animal diversity. Crop productivity can increase or decrease depending on the region. Colder region has higher crop productivity while warmer region decrease in productivity. Costal areas are very likely to face coast corrosion and flood due the rising sea level. This affects society in costal area, making them vulnerable to economy changes and production that dependent on climate (Climate Change 2007, 2007).

Rain precipitation and heat wave frequency increases, causing various problems such as crops damages, changes in water quality, and increasing water demand…etc. Climate changes also impact on wide population's health. Malnutrition, injury, and death increases when extreme weather condition occurs more frequently. Colder area benefited from decrease in cold climate related injuries or death; however, the overall health consequences are negative. All in all, climate changes impact our world and human being in various ways, and people started to be aware of such issues. International organization and resources are invested into these matters to seek out accurate information and develop mitigate methods as responses. While effort of reducing negative environment impact from the use of energy is necessary, the problems are only mitigated, not solved. Therefore, finding alternative renewable energy and new energy structure are as important. With massive R&D investment involved, different renewable energy possibilities are being investigated and people view hydrogen as an ideal element to form a new energy structure (Climate Change 2007, 2007).

1.3 An Alternative Energy: Hydrogen

Hydrogen is the most abundant and lightest element in the universe. This element does not commonly occur by its own, but combined with other elements forming different compounds since hydrogen is high reactive. When by its own, its physical state at one atmospheric pressure is gas with two hydrogen atoms together forming H_2. As of hydrogen abundance, it makes up three quarters of universe. The Milky Way galaxy and stars were formed by hydrogen gas when rotating and compressed by gravitational forces. Besides gas, hydrogen occurs in wide range of compounds such as water, hydrocarbon, organic matters, and acids…etc.

Hydrogen was first noticed by Theophrastus Bombastus von Hohenheim (1493-1541), an alchemist and physician in the Renaissance period. When doing reaction with acid and metal, he found a gas released. Then in 1766, British scientist Henry Cavendish identified hydrogen in its distinct property, and flamed this gas yielding water, led the understanding of water composition from hydrogen and water. First hydrogen balloon was introduced in 1783, and in 1788, this gas was being named as hydrogen from Greek word hydro and genes meaning water and born of. In the 1800s, electrolysis and fuel cell effects were discovered. The separation of water into hydrogen and oxygen then combined the two gases to form water. With continuous research and findings in this area, hydrogen was forecasted as energy of the future in late 1800s and 1900s.

Before realizing the potential of hydrogen roles in energy, it has been used in different industries. Chemical production is common when hydrogen used to produce ammonia, methanol, hydrogen peroxide and many other chemicals. Hydrogen is used in the production of plastic related product, used in the production process of glasses, electronics and metals. Lastly, hydrogen usage in space program as space shuttle rocket fuel is also well known.

Hydrogen exists in many different compounds, including current major energy source fossil fuel. Chemically known as hydrocarbons, these compounds contain hydrogen and carbons. After the distillation of crude oils by breaking them into components, hydrocarbons are formed with different hydrogen to carbon ratio. C_xH_x

is a way to represent hydrocarbons, where the subscript x represents the different numbers of carbon and hydrogen within a hydrocarbon. High hydrogen to carbon ratio has lower numbers of carbon compare to low hydrogen to carbon ratio. Therefore, this ratio determined whether hydrocarbons are considered clean or not.

In an environmental standpoint, the higher the hydrogen to carbon ratio is, the cleaner the hydrocarbons can reach. By combusting lower portion of carbon in fossil fuel, there will be less carbon dioxide emitted into the air resulting decreases in green house gas and climate changes. From the ratio prospective, fossil fuel gases or natural gases are the cleanest energy when combusted as they have higher ratios. Here are the chemical symbols for those gases listed from higher ratios to lower ratios, methane CH_4, ethane C_2H_6, propane C_3H_8, and butane C_4H_{10}. From here, we can see that methane has the highest ratio and considered to be cleanest fossil fuels. However, carbon component still exist producing carbon dioxide. If we can remove the carbon part from hydrocarbons, then no carbon dioxide would be formed during the combustion process. Figure 1 listed out the carbon numbers of hydrocarbons, their names, and applications. Notice pure hydrogen is not considered as hydrocarbons, however, by listing it into the figure allowed a comparison of carbon numbers (Dell, R.M., 2004).

Carbon Numbers	Common Name	Applications
0	Hydrogen	Industries usage, potential energy usage
1-4	Natural gases	Liquefied petroleum gas
5-8	Petroleum	Vehicles fuel
7-11	Naphtha	Organic chemicals
10-16	Kerosene	Jet fuel
14-20	Diesel oils	Diesel fuels
20-50	Lubricating oils	Wax, lubrication

20-70	Fuel oils	Ships, factories, heating
Above 70	Bitumen and others	Roads pavement

Figure1 Summary of hydrocarbons and their applications comparing to hydrogen

There are two energy accounts that supplied desired energy to people. One of them is energy saving account and the other one is energy income account. The energy from saving account is fossil fuel that took years of formation from decayed organic matters under the earth surface. The energies of income account are various current energies happening around the world such as wind, sun radiation, water, and tidal that unlike fossil fuel energy, can not be stored through natural processes. Just recently, more people started to exploit the energy current account from solar energy, wind and water current. However, major energy source we uses are still coming from the energy saving accounts (Hoffman, Peter, 2001).

As an analogy, a son received a great fortune accumulated by his parents and ancestors, so he has an abundant storage account. He can still choose to work and earn money, so that his current account is active. However, the effort of using current account is much greater than exploiting the storage account. Similarly, exploiting energy current account requires greater efforts than using fossil fuels. Moreover, people could not find efficient ways to exploit and store those energies in the past. Recently, more ways of exploiting current energy has been introduced and generally known as renewable energy that turns wind, solar, water current into electricity. Therefore, converting these current energies into usable energy (electricity) becomes feasible with continuous research and development. However, there is still a storage problem due to the property of electricity, where we have to consume it instantly when being produced. Most renewable energies provide fluctuating and random energy supplies. For example, electricity generated by wind requires the flow of air, if the air is stable, then we have no electricity to use. To solve the unpredictable patterns of energy supply from renewable energy, we need to store the energy. Technology of storing electricity in large quantity is still very limited. Hydrogen, then, can be a natural storing element that is possible to solve the storage problem.

A problem related to the energy saving account is energy security. Using the analogy above, if the son continues to use his saving account, then he will eventually use up all his wealth and consequently suffers for money resource. Same applied to energy as we will harvest all the stored energy leaving people to suffer in lack of energy. Moreover, some of the energy supplier countries were political unstable, adding more risk in the market. Energy security issue was noticed early as oil depletion is not a hard concept to grasp.

This issue becomes more serious recently due to the dynamic situation. In 2008, news on crude oil price breaking historical record high becomes more common. People questioned on the supply and demand of crude oil. OPEC stated that current quantity of oil supplied can meet the demand; the rise in price is due to market speculation. Another perspective argued that the oil demands are rising due to the fast economic growth in some developing countries such as China and India. Unlike environmental problem caused by energy, rising oil price impacted regular people's life in a direct way through the prices increased in daily goods and petroleum for car. Hydrogen has the potential to be part of future energy system that discards fossil fuel energy and relies on renewable energy sources.

Hydrogen is not an energy source, instead acts as an energy carrier. Our energy sources are coming from primary energy such as fossil fuels or woods. Hydrogen as a carrier is a secondary energy. Another well known secondary energy is electricity. We can not directly harvest electricity from the natural. Instead, we use primary energies to produce electricity, for example, burning fossil fuel in a power plant. Hydrogen, too, have to be manufactured from primary energy sources, currently, natural gas are used the most to produce hydrogen. However, manufacture hydrogen can come from wide range of primary sources, giving countries more chances in producing their own energy compare to currently only few countries has fossil fuel resources (Hoffman, Peter, 2001).

In summary, ideal hydrogen production using renewable sources does not produce carbon dioxide that influences global warming, serve the purpose of storage and transfer as an energy carrier, and a possible replacement of fossil fuel. In the earlier vision, hydrogen can be burnt similar to fossil fuel in a combustion engine. Just recently, rapid advancement in fuel cell technologies turned people's attention away from the combustion methods. Fuel cells become a popular topic serving the function of engine in transportation, producing only little pollutants from some of the fuel cells. In the future, advancement in fuel cell using pure hydrogen as a fuel will produce zero carbon dioxide emission or other pollutants.

Hydrogen economy is a term refers to a society that uses hydrogen as their main energy resources. An ideal hydrogen economy can be pictured as using renewable energy sources such as solar energy or wind energy through water electrolysis splits water into hydrogen and oxygen. Then hydrogen will be used in different sectors like transportation, commercial, residential, and stationary powers without the environmental problems caused by the current fossil fuels. Moreover, the finite resources will not be applicable toward hydrogen energy (The Hydrogen Economy: A non-technical review, 2006).

Chapter 2 Hydrogen Technologies

2.1 Hydrogen Production

2.1.1 Production through Current Sources

Current and near future production of hydrogen will rely on the primary energy source, mostly fossil fuel especially natural gas. Renewable resources and nuclear power as energy sources still have technological and social opposition problems. Therefore, fossil fuel because of higher availability, cost advantage, and convenience is still the practical way of producing hydrogen energy. During the production process, carbon dioxide is emitted and possible ways to reduce them do exist.

Natural gas is being used widely to produce hydrogen currently. Through the process of steam reforming and water-gas shift, hydrogen can be produced most efficiently. Since methane is the major feedstock in producing hydrogen through steaming reforming, SMR or steam methane reforming is commonly used in describing this process. In chemical reactions, natural gas methane combined with water to form hydrogen. Here are the equations:

Steam reforming $CH_4 + H_2O \rightarrow 3H_2 + CO$

Water-gas shift $CO + H_2O \rightarrow H_2 + CO_2$

In the first equation, synthesis gas is generated as a mixture of hydrogen and carbon monoxide. Besides hydrogen, synthesis gas can be prepared to produce other chemicals such as ammonia, methanol, and other organic chemicals. Water-gas shift combine carbon monoxide and water to produce extra hydrogen. This reaction process requires intensive energy, operating at 850 °C to 950 °C and high pressure. Thus, require high fuel usage and decrease the efficiency of hydrogen production plus carbon dioxide emission. There are 4 mole of hydrogen produced during the processes and the efficiency can reach 60% to 70% (Dell, R.M., 2004).

Another way of hydrogen production using natural gas is partial oxidation. The reaction combines a fuel such as natural gas with oxygen or steam to produce hydrogen and carbon monoxide. Here is the equation.

$$CH_4 + O_2 \rightarrow 2H_2 + CO_2$$

This is an exothermic reaction meaning no extra external generated heat. Reaction can go with or without catalysis. Without catalysis, it requires higher temperature environment about 1100 °C to 1500 °C and can use heavy oils to generate hydrogen. With catalysis, temperature drop to 600°C to 900°C, but usually use light hydrocarbon (with less carbon) in the reaction. If pure oxygen is used in the reaction, it requires extra infrastructure to store the oxygen. On the other hand, if using air, nitrogen will dilute the products, requiring larger air purification system (Hydrogen Production and Storage, 2006).

Stem iron process is an old practice and serve as another way of producing hydrogen using iron oxide. There are multiple steps process, requires high temperature, and additional steps in stem reforming. Thermal decomposition thermally breakdown fossil fuel into carbon and hydrogen, the carbon during the process become carbon black through a very high temperature of 1400 °C. This process was intended to produce carbon black and hydrogen as byproduct. Carbon black is used in the tire, rubber, ink, paint…etc (Dell, R.M., 2004).

A Norway company Kvaerner Engineering invented a process using natural gas to manufacture hydrogen and carbon black called Kvaerner process. This process uses hot plasma to break down natural gas at temperature of 1600 °C. Company claimed to have very high conversion rate from natural gas to hydrogen and carbon black with low required energy input. They also claimed that any kind of fossil fuel can be decomposed using this method, but natural gas production cost the least. As Norway as many oil fields with existence of natural gases, it’s not hard to imagine one of the reason Kvaerner Engineering invented the method (Hoffman, Peter, 2001).

Coal is another primary energy source to generate hydrogen through the gasification processes, which is an old practice for coal processing. This process is considered as clean coal technology through improvements in handling the waste products. When coal is supplied with air, the reaction will produce carbon monoxide. This can then further processed to form hydrogen (Dell, R.M., 2004). Another gasification method is to supply with steam and water-gas reaction occurred as following chemical reaction:

$C + H_2O \rightarrow CO + H_2$

Then with water-gas shift reaction generating more hydrogen.

$CO + H_2O \rightarrow H_2 + CO_2$

Since there is a cheaper and cleaner option for making hydrogen from the natural gas described above, gasification method becomes less used. However, if the demand for hydrogen increases for energy uses, then various methods of producing it from primary energy sources need to be considered. After the gasification process, synthesis gas temperature is around the range of 540 °C to 1040 °C and the besides desired hydrogen, other various containments are formed such as HCl, H_2S, HCN…etc. To remove these containments in scrubbing process, synthesis gas temperature is lowered to 22 °C. Then the gas is reheated to 315 °C to 371°C in WGS reactor to perform water gas shift shown in the equation above. After, to obtain hydrogen, gas separation from CO and CO_2 are performed. Then final removal of containment in hydrogen gases to meet the requirements of usage (Dell, R.M., 2004).

2.1.2 Production through Renewable Sources

Water is an abundant resource existed on earth. With its chemical structure of H_2O, it can be a source to produce hydrogen by splitting the hydrogen and oxygen apart. One of the ways is through electrolysis process. Around 1800s, after the electrical battery, electrolysis was discovered by William Nicholson and Sir Anthony Carlisle. An industry based on electrolysis grew in the 1920s, and then gradually replaced by steam methane reforming as it is a cheaper way of producing hydrogen (Romm, Joseph J, 2004).

Although hydrogen production from natural gas dominated the hydrogen market, electrolysis industry still exist to meet the high purified hydrogen requirements in the demand market since electrolysis can produce 99.9995% purity of hydrogen and oxygen. Also, as natural gas gradually increase in price, the electrolysis option returned into production for price consideration. The industry tends to exist in places where the price of electricity is cheap, such as Canada with good hydropower resources to produce electricity.

The electrolysis of water by splitting them into hydrogen and oxygen requires two electrodes, one positive and one negative. Positive electrode is known as anode, which is responsible for oxidation reaction. While cathode, the negative electrode is where reduction reaction taking place at. To separate water, the two electrodes are immersed into water and apply direct current. Then the gaseous oxygen occurs on the anode and gaseous hydrogen occurs on the cathode. Ideally, voltage of 1.229V is required to split water at 25 $^{\circ}$C with 1 atmospheric pressure. However, in reality it may take more to split the water due to the electrical losses, For example, ohm resistive losses on the electrode or over potential at the positive and negative electrodes. Early electrolysis has electricity to hydrogen efficiency of around 60%. Current large commercial electrolysis cells can reach 75%, and smaller cell with best practice can reach 85% (Dell, R.M., 2004).

Extra infrastructures are needed for commercial production. A system to convert alternating current to direct current and connection to the electrodes are required. The hydrogen and oxygen produced must be collected through pipelines. Heat removal and drying gas system need to be implemented. There are two types of commercial electrolyzer, one is unipolar known as tank type and the other one is bipolar known as filter press.

Unipolar electrolyzer is designed with alternating anode and cathode with separator in a pool of electrolyte, potassium hydroxide is a common type. The advantages of unipolar electrolyzer are its relatively cheaper, fewer parts for construction, and easier for maintenance. On the other hand, it cannot sustain high temperature due to its structure and require more space for installation. Bipolar electrolyzer has a positive side and a negative side in one electrode. Each side is faced to a different cell. Space requirement for bipolar electrolyzer is smaller and can withstand higher temperature, but harder maintenance and construction sophistication are the drawbacks. Due to the material handling difficulties, a new method for electrolyzer using solid polymer electrolyte was introduced by General Electric Company. The conversion efficiency is similar to the traditional electrolyzer, however, at high pressure, it can generate more efficiently with less cost. It is also more responsive to abrupt change in power supply, making it reliable for safety application such as oxygen generation in space and nuclear submarine (Kroposki, B. et al., 2006)

Utilizing multiple renewable energy sources to decompose water into hydrogen is an ideal clean picture for future energy structure. Electrolysis requires electricity in the form of direct current, and this electricity can be produced by renewable energy sources. By combining electricity generation part and hydrogen production part, an ideal picture of hydrogen economy system is formed. With previous discussion on electrolysis, here are brief discussions on some of the renewable energy sources for electricity generation.

Water usage existed for a long time dating back to the Roman period. It also played an important role during the industrial revolution in Britain. Hydroelectricity was first built in Wisconsin, USA with output of 12 kW followed by increased construction around the world since then. There are two major systems of hydroelectricity depending on the electricity output. Large output capacity is around MW to GW, this system usually involved large civil engineering works on dam construction, and the source of water from high altitude mountains and reservoirs. Smaller output capacity ranging from kW to MW often does not require the construction of dam, but employ a process of diversion using water flow. The sources of water are coming from river flow in altitude difference terrains, such as mountain or falls (Dell, R.M., 2004).

Hydraulic head is a key component in a hydroelectricity system that creates altitude difference. Examples of hydraulic head can be dam, reservoir, or smaller structures utilizing river water flow. Depending on the placement of hydraulic head, potential power generation is different. Hydraulic head in the higher altitude have higher potential than the lower altitude ones. Another component is powerhouse that utilizes the water source to generate electricity. In a powerhouse, water turbine, generator, and system of transferring water into the house called penstock are required. Water flow control system need to be implemented to manage the inflow and outflow of water. Water flow is a very important factor in hydroelectricity; therefore this system is mostly employed in countries with suitable mountainous terrains.

Tidal energy is also a renewable energy related to water, but somewhat different from hydro energy as energy is obtained through the rise and fall of ocean level. The natural mechanism behind tidal energy and hydro energy is different. Hydro energy depends and the water evaporation and precipitation, transferring water from low altitude ground to high altitude mountain region. Ocean movement in tidal energy is caused by the gravitational forces from the moon. During full and new moon, the ocean level movements are the strongest, while in first and last quarters of moon cycle has a smaller tide. Tidal movement also occurred around 12 hours each day providing potential energy generation (Dell, R.M., 2004).

Range of area is a key factor that determines the amount of energy produced by tide. So placing barrage in the junction parts of river and ocean is suitable. Incorporating reversible turbines, the rise and fall of tide can be captured as potential energy around 3 to 5 hours. Then the electricity generated can be feed into electrical grid or to produce hydrogen through electrolysis of water. There are many structures around the world to exploit the tidal energy, for example, in France, Canada, China, and Russia.

Marine currents are caused by the tidal movement and can be a potential renewable energy source. Slower currents cannot be used to generate electricity, but strong marine currents are ideal in capturing the energy. Underwater turbines are installed in the flow of currents with diameter up to 20 meter. The turbine is attached with a generator to produce electricity. Since the power of water flow is strong, the turbine must be designed to withstand such flow. Depending on the size of turbine design, additional support and material strengthen is required. This is a relatively new technology with little experiences that poses some difficulty for countries to construct such scheme. However, the construction is more economical then tidal energy or hydro energy, which requires building dams or barrages.

Another type of energy related to water is wave. As wind blow on the ocean surface, waves are created and travels toward shoreline. Waves carry a lot of energy that can be potentially harvested, estimating of 1000 TWh per year in the European shore. The system to convert wave energy can be placed in three general locations, shoreline, near shore, and off shore. Shoreline and near shore location are being researched the most since the proximity of the system influences the maintenance and installation efforts. The first wave energy system called oscillating water column is suited for shoreline with hollow structure. This created a space filled with air with Well turbine between the air flows, generating electricity as turbine connected to a generator. Another shoreline system is called Tapchan. This structure consists of narrowing channel and reservoir. Channel allows wave to splash into and transfer them into reservoir. Reservoir stores this water and directs them into turbine to generate electricity. Offshore systems are currently under development, allowing further potential to harvest the wave energy (Dell, R.M., 2004).

Wind energy has been used in human history for a long time especially for irrigation system and grain grinding. Historical records have shown the usage of wind through windmills in Persia and Europe in the early time. Holland further developed the use of windmills to drain water out in order to use the remaining land. As steam engine invented, windmills soon been replaced by it. However, as more advancement into electricity usage, wind energy was back into people's eyes as it can generate electricity. The system was first invented in early 1900s and continues in advancement toward currently known wind turbines system.

Traditional wind turbines have three blades and a horizontal axis design, following a box called Nacelle connected behind. Within the Nacelle is gearbox and generator that turn wind kinetic energy into electricity. Wind turbines are connected together to form wind farm. To prevent the interruption between each turbine, turbines installation is spaced 5 to 10 rotor diameters. The energy wind provided is about three folds in relation with wind speed. Thus, an increase in wind speed can dramatically increase the energy collection.

Several considerations need attention when installing the wind farm. Wind turbine currently can be operated at a range of wind speed between 4 to 20 ms^{-1}, any speed out of the range cannot be captured by the wind turbines. The height above the ground should also be considered when installing wind turbine as wind speed is slower at the ground level. Another issue is the existence of wind. Wind occurrence can be due to season changes, time bases, altitude, location, and terrain. Turbulence also occurs to disrupt the energy generation efficiency as the blade faces multiple pressures. Buildings, hills, and trees…etc are some of the reasons for turbulence. Therefore, careful analyses including the above parameters are needed before the actual installation.

Notice current wind farm is usually built inland. Another alternative for harvesting wind energy is by building wind turbines off shore. The wind is usually stronger off shore with wider open space, would not interfere with local residents' life, and reduce the use of land resources on the continent. However, the cost and maintenance is high. Denmark, Sweden, and United Kingdom have all built this type of off shore wind farm and expected to grow in the future (Ivy, Johanna, 2004).

Solar energy is one of the most important resources on earth and consider as an unlimited resources given that sun will function long enough that poses no concern currently. Ideally, the energy provided by sun is more than enough to meet the current energy demand worldwide. However, we still cannot efficiently collect solar energy. Energy produced by sun through fusion reaction can be divided into heat and light and we can utilize this energy directly on heating purpose or generate electricity from the sun light(Hoffman, Peter, 2001).

Discovered in 1800s, Edmund Becquerel, a French physicist found out when semiconductor materials receive sun light, it will produce low DC electricity. Albert Einstein further explained such effects and become the current photovoltaic technology. Photovoltaic literally means light electricity as photo is light in Greek and volt represents a pioneer in electricity named Alessandro Volta. Different types of silicon materials can be used in photovoltaic cells, such as crystalline, gallium arsenide, cadmium telluride and organic compounds…etc. When n-type semiconductor and p-type semiconductor are brought together with one receiving the light, a voltage is developed between the two semiconductor junctions, creating electricity known as photovoltaic effect. Generally, phosphorous is put onto a p-type semiconductor forming an n-type layer. Then above n-type layer is an anti reflection coating to form a common solar cell. Low voltage is generated through these cells of about 0.6V. Therefore, multiple cells are packed together to form a solar panel that generate greater voltage output for practical uses.

For further application and practical uses, solar panels need to be connected and arranged in a parallel way. Combined with other support system to fully utilize solar energy, this system is called solar array. Some of the support systems include inverter, transformer, electricity storage devices, and control system on energy flow. Also, a tracking system is important in solar array as daily sun movement and seasonal changes affect the amount of energy collected by solar panel. By tracking the sun movement, solar panel should be arranged from horizontally to degree of tilting depending on the needs. The arrangement should also take into the consideration of energy demand fluctuation, for example, constant demand yearly or various demands as season changes.

Recent conversion rate from sunlight to electricity is about 18% to 25% depending on the types of silicon used in solar panel. Some of the factors affecting conversion rate includes light wavelength, recombination, temperature, resistance, and sunlight reflection. The wavelength of light affects the amount of electron flows in the band gap, since only certain wavelength of light provide enough energy to the silicon, conversion rate becomes low as other wavelength cannot be utilize in silicon. An estimation of 55% waste occurs due to this result. Reflection is another factor, simply because when reflecting sunlight off the solar panel, the light reflected cannot be utilized for electricity generation. Due to the materials property in solar panel, light cannot be fully absorbed. Therefore, to increase the efficiency, a triple junction and multi-junction solar panels are introduced with different silicon materials combined to absorb wider range of light wavelength. Recent conversion rate can reach above 40%, however, this type of panel is expensive which process improvement and production growth might solve the issue. Besides traditional silicon materials, organic photovoltaic devices and dye-sensitized solar cells are under development. There are also other ways of using solar energy such as photo thermal, photo electrochemical, and solar decomposition through bacteria to generate hydrogen other than electrolysis. These methods are still being researched while electrolysis can be readily available. If successful, they would serve as another opportunity for the renewable energy in solar sector (Dell, R.M., 2004).

By combining the renewable sources' electricity generation and water electrolysis processes, we can have a pollution free infrastructure of hydrogen production. Figure 2 shows a general process flow of clean hydrogen production.

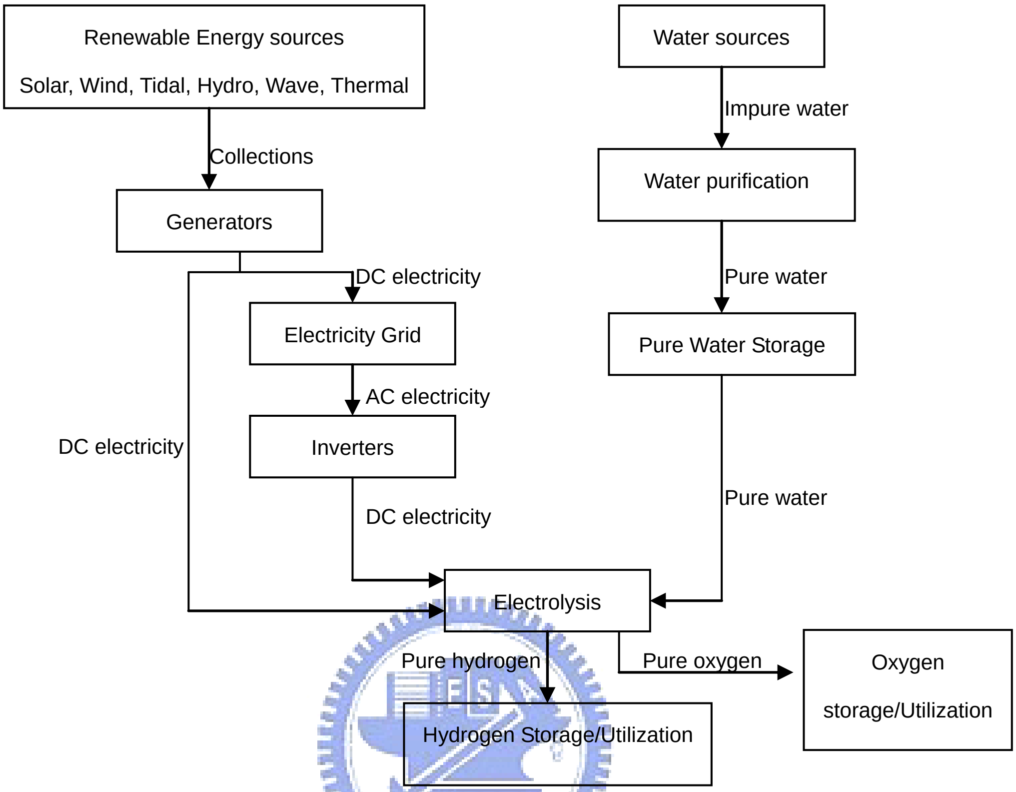

Figure 2 General process flow of renewable hydrogen electrolysis production

This is a process flow diagram using electricity from renewable energy sources and electrolysis of water to produce hydrogen. Due to the electrolysis requirements, water should be purified for the uses. Electricity generated thorough renewable energy is transferred directly for electrolysis uses or feed into electricity grid system for both electrolysis and electricity demand. Then, the pure hydrogen product is manufactured to store or for immediate usages (Kroposki, B. et al, 2006).

2.2 Hydrogen Storage

As an energy carrier, hydrogen by itself acts as a chemical storage device for energy. Although with a potential to replace current fuels, unlike fossil fuel or natural gas, hydrogen due to its properties requires dedicated research and technology to store it. In this section, types of hydrogen storage and some of the methods of storing hydrogen will be discussed.

There are several purposes for hydrogen storages, resulting in different types of storage needs. Large quantity hydrogen stationary storage is needed mostly for centralized hydrogen production plant where large quantity of hydrogen is produced for no immediate uses. This is also critical for energy security and emergency at national level. Small quantity hydrogen stationary storage is demanded by industrial plant using hydrogen in their production process or backup, and hydrogen refueling stations for vehicles based on fuel cell engine or other related hydrogen utilization vehicles. The stationary storage may be less restrictive in requirements than storage for vehicle purposes. Besides stationary storage types, storage for mobile purpose should be developed. Large mobile hydrogen storage system is mostly used for hydrogen transportation by land, on ocean and in air. Small mobile hydrogen storage system is similar to current vehicles gasoline tank, where the primary purpose is an energy reservoir for transportation to travel a desired long distances.

With multiple methods of storing hydrogen, the new ones are still in development phase while others exist in the commercial market. With common pressure and room temperature, pure hydrogen is in the form of gas. 1 kg of hydrogen takes about 11 m^3 of area. So the criteria of hydrogen storage density should be on temperature, pressure, gravimetric, hydrogen repulsion, and reversibility.

2.2.1 Air Compression Storage

High pressure gas cylinder with steel materials is a common way to store hydrogen, withstanding pressure up to 20 MPa, causing a relative low density in hydrogen storage; with composite materials, cylinder can stand pressure up to 70 MPa. This composite cylinder is usually made of carbon fiber shell that has lighter mass, however, compressing hydrogen in such high pressure requires extra energy. The volume of composite tank is still large if trying to apply to vehicles with appropriate hydrogen density (Hydrogen Production and Storage, 2006).

Another way is using glass micro sphere, filling in hydrogen operating at 35 Mpa to 70 Mpa and temperature of 300 °C. Then the glass sphere is cooled and placed into vehicle vessel and reheat to 200 °C to 300 °C releasing the hydrogen for energy uses. However, this way have many difficulties needed to resolve. For all compression storage, electricity consumption to maintain pressure at 20 Mpa requires about 7% of hydrogen energy content. Energy demand rises with higher compression. Also, cylinders design is not compact as single container that limited the vehicles' driving distances (Hydrogen Production and Storage, 2006)

2.2.2 Cryogenic Storage

Liquid is a possible hydrogen physical state under cryogenic condition with temperature about - 253°C. Hydrogen can also be injected into other liquids that are able to store. Cryogenic hydrogen in liquid state is usually referred as liquid hydrogen, LH_2. It has a density of 80 kg m^{-3}, giving a much higher density then at gaseous state of 30 m^{-3}. Although liquids are generally easier to transport than gas, liquid hydrogen might poses some problem due to its liquid existence at extremely low temperature, resulting a need in good storage equipment. Even with insulation, liquid hydrogen can only stored within few days. Moreover, the cost of liquefying hydrogen requires large energy input, equivalent about 30% of the liquid hydrogen produced. Currently, transportation and usage of liquid hydrogen existed in nuclear power plant and space program. For liquid hydrogen to become a method of storage, further improvement on efficient liquefying procedure, better insulation, and ways to capture the boiled hydrogen is required to make liquefied hydrogen in the hydrogen economy theme (Hydrogen & Fuel Cell: Review of National R&D Program, 2004).

2.2.3 Metal Storages

Hydrogen can also be stored in solid state, but not by pure hydrogen as it requires even lower temperature than liquid hydrogen. By combining hydrogen and metals to form metal hydrides, an alternative method for hydrogen storage is formed. The metal should be able to absorb and release hydrogen during storage and demand cycle without deteriorating the metals. There are many types of metal suitable for absorbing hydrogen to for hydride, including elemental metals, alloys, intermetallic compounds, and complex hydrides. Alloys and intermetallic compounds are studied the most. Some of the criteria for selecting alloys as follows: hydrogen reversibility, temperature, pressure range, reaction kinetics, stability, and hydrogen cycles. With these conditions, a good metal hydride storage should have high hydrogen proportion, safe of air exposure or other hazardous condition, process of releasing hydrogen should be under a similar earth temperature and pressure environment (Prospects for Hydrogen and Fuel Cells, 2005).

Metal hydrides are performing chemisorption as hydrogen atoms bond to the metals. Another way of hydrogen interaction with materials is physisorption or hydrogen interacts and stores on the high surface area of the materials that are usually carbon or boron nitride nanostructures. Due to the weak bonding of physisortpion between hydrogen and nanostructures, the required pressure and temperature are less than chemisorption. Carbon nanofiber and nanotubes can hold some quantity of hydrogen, but previous reports on the capability of holding large quantity was viewed as error measurements. Other high surface area materials include zeolites, metal oxide framework, and clathrates hydrates that are capable of storing hydrogen in very low temperature. Further research in this area needs to be conducted in order to determine their potential as hydrogen storage methods (Zuttel, Andreas, 2007).

Chemical hydrides can serve as hydrogen storage devices. They are reactive to water and thermal energy in releasing hydrogen. Some of the water reactive chemical hydrides are LiH, NaH, MgH_2. Example of the chemical equation for LiH is

$$LiH + H_2O \rightarrow H_2 + LiOH$$

Some of chemical hydrides releasing hydrogen through thermal decomposition are ammonia borane and other ammonia borane family. Chemical hydrides have high storage ability, but the release of hydrogen is irreversible reaction. Therefore, after they release the hydrogen, the byproduct needs to reprocess in the factory to generate back to hydride (Hydrogen & Fuel Cell: Review of National R&D Program, 2004).

2.3 Hydrogen Distribution

2.3.1 Pipe Distribution

Hydrogen distribution becomes important when production of hydrogen in remote areas with long distances to destination result in difficulty to supply to the end users. One of the options to send gaseous hydrogen is through pipeline. This method already existed in the current time and can be dated back to early 1900. In Germany, pipelines are established for chemical processes. Made out of bitumen, plastic, s, the length of pipeline grew from initial of 24 km to a network of 210 km pipeline with few that crosses Rhine River. As a whole, the length of hydrogen pipeline in North America is about 700 km and Europe with 1500 km with materials based on steel and carbon steel. The major organizations using current systems are chemical companies and scientific research centers such as national laboratory or NASA.

This is currently the economic way of transferring hydrogen. However, still there are issues related to pipeline distribution. The construction of new pipeline is expansive and current existence of hydrogen pipeline is relatively small compare to natural gas pipelines. Using current natural gas pipeline system causes problem as the pipeline are not design for hydrogen uses, especially in its material due to the attack from hydrogen and pressure. Since hydrogen has low volumetric density, requirements to pressure them in pipeline and re-pressure is needed for a given distance causing energy loss and increase costs. Also, the flow rate has to be faster with energy requirement about 4.6 times comparing to natural gas in order to provide the same amount of energy from natural gas. Therefore, transferring hydrogen for a long distance through pipeline is not economical compare to natural gas pipeline. Hydrogen leakage detection and prevention system should also be developed due to the hydrogen property that is prone to leak. Similar to other hydrogen technologies, further research into hydrogen pipeline distribution are required for an economic acceptable way transferring hydrogen to refueling station and end users (Winter, Carl-Jochen, 1988).

2.3.2 Ground Distribution

Distributing hydrogen via truck or other transportation means are highly related to the hydrogen storage technology. Currently, hydrogen can be transferred as compressed air. However, this method is expensive and can only travel a short distance of about 300 kilometers. Hydrogen metal storages are possible to travel on truck. Since this method did not exist in the past, further research into the development and feasibility are needed (Hydrogen Distribution and Delivery Infrastructure, 2008).

Liquid hydrogen has been demanded in nuclear energy sector use in nuclear bubble chambers, space program…etc. Therefore, transportation of liquid hydrogen existed. The process of liquefying hydrogen is expensive, consuming large amount of energy. Current large cryogenic hydrogen production requires 36 MJel per kilogram of hydrogen, with prediction of energy requirement reduced to 26.5 MJel per kilogram of hydrogen. The current energy input is about 31% of produced hydrogen energy content. With decrease in energy requirement, energy input is 21% of liquid hydrogen output (Hydrogen Distribution and Delivery Infrastructure, 2008).

Also, depending on the electricity efficiency during the liquid hydrogen production, this might further increase the energy input. For example, 50% electricity efficiency raises 21% to 42% of hydrogen energy output. Liquid hydrogen is produced as a very low temperature of -253 °C, it will boil off to gaseous hydrogen if temperature is not maintained. Liquid hydrogen transportation requires energy to maintain the low temperature, good insulators, and a system to recapture the boiled off hydrogen for uses in truck or ships when transferring the hydrogen. Overall, if research continues to improve the production process, the cost could be reduced with benefits of economies of scale providing the opportunities for hydrogen distribution system(Dell, R.M., 2004).

Chapter 3 Fuel Cell

3.1 Fuel Cell Overview

Fuel cell becomes a well known term in recent year due to its potential of replacing traditional combustion engine. Fuel cell can convert the fuel into electricity which can be used in wide range of applications. The discovery of fuel cell effect dated back to around 1839, when Sir William Groove discovered the electricity generation through reversing water electrolysis. In 1889, Charles Langer and Ludwig Mond tried to create such effect and termed their system fuel cell. Then in 20th century, further development in fuel cell continues. In 1950s, NASA developed fuel cell system that can generate electricity and applied to space mission in 1960s. In late 20th century, energy issues arose causing acceleration in fuel cell research in search for possible resolution.

Benefits of fuel cells are low impact on environment, high efficiency in energy power, high reliability, low noise during operations, and wide range of potential applications. Fuel cell, depending on the fuel used, can be low to zero carbon dioxide emission. When fueled with pure hydrogen, the products are electricity, water and heat. With hydrocarbon fuel, low carbon dioxide emission existed. Compare to other traditional method of generating electricity such as burning fossil fuel, the efficiency of energy conversion is relatively high with about 40% to 50% for fuel to electricity. Unlike combustion engine with mechanical movements, the operations of fuel cell create no noise providing a pleasant sound volume environment. With high reliability and high power quality, fuel cell can serve as power backup in organization preventing any harm caused by power shortage. Besides power backup, there are multiple applications for fuel cell in stationary, transportation, and small mobile devices (Fuel Cell 2000, 2008).

3.1.1 General Fuel Cell Mechanism

Fuels for fuel cell are not necessarily hydrogen. It can be other high hydrogen concentration matters. Pure hydrogen, however, provide more advantages to fuel cell in generating electricity with greater efficiency and less harm toward environment. By supplying hydrogen and oxygen, fuel cell creates electricity and water. Fuel cell has two electrodes, a negative anode and a positive cathode. Between the electrodes is electrolyte. Hydrogen is supplied to anode and oxygen supplied to cathode. Hydrogen through chemical reaction and catalyst is split into proton and electron. Electrons passed through circuit creating electricity while protons passed through electrolyte reunite with electrons, and combined with oxygen in the cathode to form water with heat. Figure 3 shows what was described graphically (Rayment, Chris, 2003).

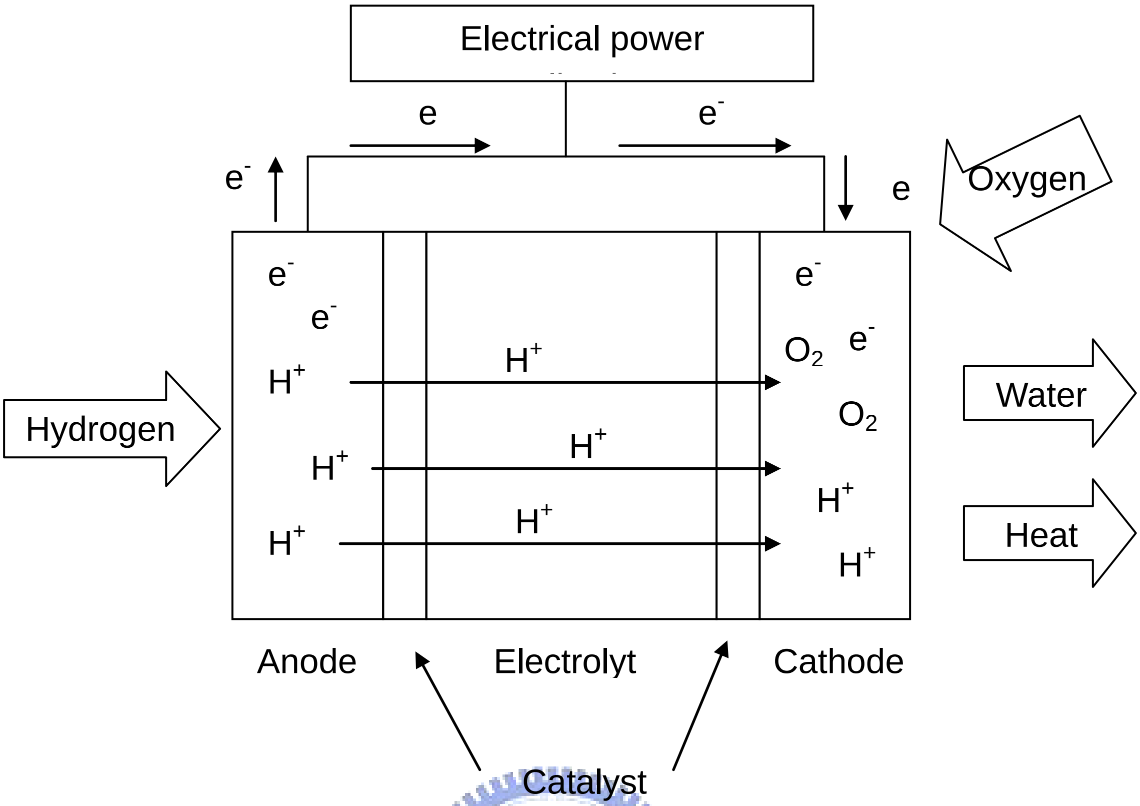

Figure 3 General fuel cell working process

3.1.2 Types of Fuel Cell

Different types of fuel cells existed with varying operating temperature, pressure, fuel used, materials and their design. There are generally six major types of fuel cell design introduced as follows.

Alkaline Fuel Cell

Alkaline fuel cell abbreviated as AFC, was the first available fuel cell technology and with portability. The biggest application of this type of fuel cell was in space program for water and electricity generation purposes. Potassium hydroxide is used as electrolyte in AFC, and the electrode are made of less precious metals giving an advantage over other fuel cell. Some of the materials of electrode can be sintered nickel, Raney metals, and rolled electrode. Operating temperature is in the range of 100 °C to 250 °C, but through advancement, it reduced to the range of 23 °C to 70 °C. Due to the chemical reaction in alkaline fuel cell, they have high efficiency about 60%. However, it can be easily poisoned by carbon dioxide, requiring usage of pure oxygen that results a less favored condition for applications operating in regular environment. The purification of oxygen is costly, and the available operation hours of 8,000 hours might not meet the demand for large scale usage of 40,000 hours, adding more disadvantages to ACF (Prospects for Hydrogen and Fuel Cells, 2005).

Direct Methanol Fuel Cell

Direct methanol fuel cell (DMFC) is relatively new as it was developed during the 1990s. Unlike other types of fuel cell, the fuel requirement is methanol following the name of the fuel cell. When supplied methanol entered to anode with presence of water, it separates into hydrogen ion, electron and carbon dioxide. The disadvantages of DMFC are low efficiency, low power density, and the methanol fuel is toxic. The efficiency rate is in the range of 15% to 20%. Through further development, DMFC efficiency might improve toward 40%. The operating temperature range is between 50 °C to 120 °C. Due to its small and medium physical size and low temperature operation, potential commercial application on mobile power supply for cell phone and notebook computer is currently under research in some manufactures (Prospects for Hydrogen and Fuel Cells, 2005).

Proton Exchange Membrane Fuel Cell

Proton exchange membrane fuel cell is also known as polymer electrolyte membrane fuel cell (PEMFC) or polymer electrolyte fuel cell (PEFC). Instead of using electrolyte solution, PEMFC uses polymer electrolyte that is solid and immobile.

Nafion is the most popular polymer electrolyte produced by Dupont. The fuels for PEMFC are hydrogen and air containing oxygen, with water formed after the process. Some of the advantages include low operating temperature of about 80 °C, quick start up time, high power density with small physical volumes, and manufacture ease due to solid polymer electrolyte compare to liquid solution electrolyte. Disadvantages can be expensive platinum metal used as catalyst that is vulnerable to carbon monoxide. PEM fuel cell is one the best potential fuel cell for uses in vehicles and transportation due to the advantages mentioned. It can also be used in stationary powers giving a possibility in mass commercialization (Rayment, Chris, 2003).

Phosphoric Acid Fuel Cell

As named, phosphoric acid fuel cell (PAFC) uses phosphoric acid as electrolyte and platinum catalyst operating at around 150°C to 220°C. With around 200 units used mostly in stationary power, this fuel cell is considered a mature type as it was the first commercialized fuel cell. One of the advantages of this fuel cell is its high efficiency up to 85% combining the electricity and heat created for uses. If only electricity is utilized, the efficiency dropped to about 40%. Another advantage is its relative high tolerance to impurity compared to PEMFC so less requirement in designing system preventing impurities. On the other hand, precious metal platinum as catalyst making this fuel cell costly. Given a fixed size, PAFC is less powerful than other types of fuel cell, resulting large volume and size design. The large size of PAFC then is used mostly as stationary power applications(Prospects for Hydrogen and Fuel Cells, 2005).

Molten Carbonate Fuel Cell

Molten carbonate fuel cell (MCFC) developed in 1960s and consumes natural gas as its fuel. Unlike other fuel cell, molten mixtures used in electrolyte with two carbonate salts, lithium carbonate with potassium carbonate or sodium carbonate. This fuel cell operates at high temperature around 650 °C, allowing it to use natural gas directly without extra fuel processing. Natural gas due to heat decomposes into hydrogen internally serving as fuel for MCFC. MCFC has high efficiency rate about 60%, when combined with heat utilization, it can reach up to 85%. However, because of its high temperature, durability is lessened. Also, it would take a long start up time to reach the required temperature, making it suitable for constant operations instead of short consecutive power generation. In an environmental perspective, the emission of carbon dioxide is another disadvantage requiring emission capturing system for an extra cost (Hydrogen & Fuel Cell: Review of National R&D Program,2004).

Solid Oxide Fuel Cell

Solid Oxide Fuel Cell (SOFC) uses ceramic compounds with a solid physical state in electrolyte. This fuel cell's efficiency in generating electricity is up to 70%, the highest efficiency in all major fuel cell types. With cogeneration by using both electricity and heat produced from SOFC, efficiency reaches 85%. SOFC operates at high temperature around 800 °C to 1000 °C contributing to both benefits and drawbacks. One of the benefits operating at this temperature is saving the material cost of expensive metal catalyst. Moreover, the extreme hot environment allows fuel to be reformed within the fuel cell saving the cost from external fuel production. Besides, SOFC is more tolerable to sulfur and carbon monoxide. The disadvantages are slow startup time, good method of keeping the high temperature environment, and economical materials that can be durable in such temperature(Hydrogen & Fuel Cell: Review of National R&D Program,2004).

3.2 Fuel Cell for Stationary Usages

Primary purposes of stationary fuel cells application is for power and heat generation. When combined heat and power generation with proper usage, a high efficiency rate of 85% making a good justification of using stationary fuel cell system. Due to these characteristic, stationary fuel cells apply to power generation and power backup in various places and remote places. Some of the fuel cells suitable for stationary applications are PAFC, PEMFC, MCFC, and SOFC. Stationary fuel cells provide power for residential uses and various commercial uses such as in hospital, office building, and schools. An important feature fuel cell has in stationary energy sector is distribution generation (Fuel Cell 2000,2008).

A general term refers to the on-site or near-site power generation to power consumption places is called distribution generation system. Fuel cells can be one of them as it can be placed in proximity of demanded unit such as school or residential building. Distribution generation systems have some benefits compared to traditional electric grid in supplying electricity. The long distances of electricity transfers in electric grid system have energy loss potential due to various reasons such as weather condition and grid system condition. Distribution generation reduces all of this potential risks loss due to the closer installation to power demand units. Distribution generation also provide a more reliable energy system as electric grid system may experiences small to large area failure due to natural disasters, accidents, or strategic attacks. Fuel cell serves as distribution generation system is designed in a modular way. Modular arrangement allows additional fuel cells add into the system compare to inflexible large power plant, providing benefits of better energy rush demand control, easier energy demand development planning, and preinstalled capability (Pehnt, Martin, 2008).

3.3 Fuel Cell for Transportation Usages

Fuel cell application for transportation is probably an area most sought into. From small electric power bicycle, scooters, to large boat, airplane, and submarine, almost all types of transportation fuel cell can be applied to. However, within all these, road vehicles especially cars are being focused by automobile industry, energy industry and government.

As crude oil price reaches historical record high every often in 2008, and expected to be depleted sometimes in future if oil demand increases or even remained in the same level, awareness and concern for alternative car system becomes high in our society. Although this is not the primary reason why automobile companies looked into fuel cell car dated back to early 1990, this situation surely adds more justification toward alternative car system such as fuel cell. Car companies foresight fuel cell cars as a potential future.

Within many benefits, the efficiency of fuel cell is 2 to 3 times comparing to traditional combustion engine powered vehicle. The petroleum conversion rate of combustion engine is about 16%, while fuel cell vehicle can achieve 45% conversion rate. Using fuel cell is environmentally friendly with zero to near zero carbon dioxide emission. The fuel cell car has an electric power-train with single gearbox design allowing better acceleration data, and no gear change feeling during the acceleration. Instead of combustion engine with mechanical parts, electric motor used in fuel cell car reduces the noise. This can be viewed as both benefits and disadvantage. The benefit is a better acoustic environment, while it might be dangerous for people to recognize the presence of vehicle through sound, which is potentially a source of traffic accidents (Stobart, Richard, ed., 2001).

DMFC and AFC are some fuel cells with potential in the transportation industries;

however, PEMFC is currently the most applied fuel cell toward car by automobile companies. PEMFC uses pure hydrogen as its fuel, smaller size, lower operating temperature, and membrane electrolyte make it suitable for current car application. Compressed cylinder to store gaseous hydrogen is also currently the major hydrogen storage on board. Most of the car companies are developing fuel cell cars, with few intended for market. Other transportation with more fuel cell researches is buses, and forklift. Transportation is an urgent sector that requires alternative ways to power the vehicles as condition on crude oil prices and production become harsh.

3.4 Fuel Cell for Portable Usages

Besides stationary power and transportation application, fuel cells have potential roles in portable power supply application especially in consumer electronic component and military devices usage. The power generated from portable fuel cell is only few watts, a relative small amount compare to stationary fuel cells but served the intended purposes. Even with the small size fuel cell application, the size can be divided further into small power units and micro fuel cell units. With this difference in sizes, their usages are also different.

PEMFC with small power unit sizes are ideal for one or two people to carry depend on the amount of power and length of supply time desired. The unit size is best suitable for outdoor activities such as camping, night market, and outdoor parties…etc (Fuel Cell 2000, 2008). Another possible demand market is in military. During military operation with more electronic devices, time length of power demand increases. Battery might serve the function but in shorter time that did not meet the time demand. The problem arises when fuel supply becomes limited and hard to product hydrogen during military operations. One possible solution is making the fuel cell disposable. Once the fuel used up, the small fuel cell power units will no longer be used. A nonreversible chemical reaction is in placed to supply the required hydrogen fuel, usually with chemical and metal hydrides such as $NaBH_4$, with up to 10 times of power supplied compared to same sized battery (Dell, R.M,2004).

Current battery for portable electronic devices served its function acceptable. However, with increasing power demand for these electronic devices requires better power supply solution. For example, cell phone with additional side function beside communications such as multimedia function like TV, movie, music, game entertainment, photographic and video recording, larger screen, better graphic interfaces…etc. that demands more power for performing these functions. Micro fuel cell devices might serve a better battery function by providing higher power storage and length of time. DMFC is currently the fuel cell used for developing this type of micro unit, as methanol in liquid form has ease in fuel replacement.

Fuel cells are important devices to utilize hydrogen energy. The many benefits make fuel cell a potential role in future energy sector, especially true in hydrogen energy sector. Six major types of fuel cell were discussed with each of them more suitable in certain applications. These applications generally fall into three categories, stationary power application, transportation applications, and mobile applications. The transportation sections are heavily researched on as alternative transportation devices are required due to crude oil issues.

Chapter 4

Industry Application Development, Demonstrations, and Cases

4.1 Industry Application Development

Automobile companies are one of the most active players in hydrogen related industry. Besides the environmental benefits in reducing carbon dioxide, fuel cell vehicles have several advantages over traditional combustion engine cars previously mentioned. Within a wide range of car companies, fuel cell vehicles by Toyota and Honda are being discussed due to its initiative in market ready fuel cell vehicle. Also, more diverse lists of car companies with their most recent fuel cell vehicles are in Figure 4.

Toyota started to develop its fuel cell vehicle in 1992 and abbreviated the prototype model FCHV that stands for fuel cell hybrid vehicle. Initial prototypes were developed during 1996 to 2001. In December 2002, a market ready FCHV based on FCHV-4 prototype were introduced, followed by further refinement in 2005 with maximum range and speed of 330 km and 155 km/h. There are two major systems in this FCHV, fuel cell stack and hybrid system. This PEM fuel cell stack uses pure hydrogen with 90 kW of outputs. Hydrogen is stored in high pressure tank with 35 Mpa of pressure. The hybrid system uses battery, electric motor, and power control unit to reduce and recover energy during vehicle operation. This system was first employed to Toyota Prius that is successful in reducing petroleum usage thus reduce carbon dioxide as well. With the success, Toyota continues the hybrid system with FCHV (Toyota FCHV, 2008)

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In June 6, 2008, Toyota announced more advancement in FCHV, know as FCHV-advanced. Areas of advancement are longer cruise distance, more efficient fuel cell stack, and operating climate. Fuel cell performance increased by 25% result more fuel efficiency and longer distances drive. Combine with fuel cell efficiency with higher pressure gas tank of 70 Mpa and slightly more gas tank capacity, cruising range is about 830 km with 15 test cycles. Vehicles operating climate now can reach negative 30 degree Celsius, solving one of the previous fuel cell problem of operation in cold temperature. FCHV advanced will start small release in later 2008 mostly for test drive (Toyota Develops Advanced Fuel Cell Hybrid Vehicle, 2008).

Honda also started fuel cell vehicle early and released first and second prototype (FCX-V1 and FCX-V2) in 1999. Additional prototypes were released from 2000 to 2004. Then in 2005-2006, FCX car was put on auto show as a concept vehicle and Honda announced production of concept FCX in several years (Honda FCX Clarity, 2008). This should less be a surprise as they leased their older version of FCX to a family in Los Angeles as world's first fuel cell vehicle retail. (Honda Delivers FCX Fuel Cell Vehicle, 2005).

Finally, in June 16, 2008, Honda announced production of FCX clarity and the first 5 customers receiving the cars at the day including the Los Angeles family trading their older generation FCX to FCX clarity. Major components of this car are V flow fuel cell stack, compressed hydrogen tank storing 4.1 kg of hydrogen at a pressure of 5000 psi, lithium ion battery, power unit, and electric motor of 100 kW output. FCX clarity has driving range of 450 km, maximum speed of 160 km/h, and capable of starting at negative 30 degree Celsius. Honda planed to produce about 200 units of FCX clarity in the next 3 years leasing them to partial areas in Japan and United States. Although retail process of customer selection criteria and 3 years $600 per month leasing are not similar to common car retail, this is still a next step toward commercialization of fuel cell car (Honda Announces First FCX Clarity Customers, 2008).

Automobile Companies	**Vehicle Model**	**Year**	**Fuel cell size**	**Range**	**Maximum Speed**
Audi	A2	2004	PEM 66 kW	220 km	175 km/h
BMW	Series 7	2000	PEM 5 kW	300 km	140 km/h
Daihatsu	MOVE FCV-K2	2001	PEM 30 kW	120 km	105 km/h
Daimler Chrysler	EcoVoyager	2008	PEM 45 kW	483 km	185 km/h
ESORO	Hycar	2001	PEM 6.4 kW	360 km	160 km/h
Fiat	Panda	2007	PEM 60 kW	200 km	130 km/h
Ford Motor Company	Airstream	2007	HySeries Drive	491 km	137 km/h
GM	Provoq	2008	PEM 88 kW	483 km	160 km/h
Honda	FCX Clarity	2007	PEM 100 kW	450 km	160 km/h
Hyundai	i-blue concept	2007	PEM 100 kW	600 km	165 km/h
Kia	Sportage	2004	PEM 80 kW	300 km	150 km/h
Mazda	Premacy FC-EV	2001	PEM 85 kW	N/A	124 km/h
Microcab Industries Limited	Microcab	2008	N/A	160 km	45 km/h
Mitsubishi	Grandis FCV	2003	PEM 68 kW	150 km	140 km/h
Morgan	LIFECar	2008	PEM 22 kW	402 km	137 km/h
Nissan	Effis	2003	N/A	N/A	N/A
Pininfarina	Sintesi	2008	Four PEM 20 kW	N/A	222km/h
PSA Peugeot Citroen	H2 Origin Delivery Van	2008	PEM 10 kW	300 km	N/A
Renault	EU Fever Project	1997	PEM 30 kW	400 km	120 km/h
Suzuki	Mobile Terrace	2003	N/A	N/A	N/A

Toyota	FCHV-adv	2008	PEM 90 kW	830 km	155 km/h
VW	Space Up Blue	2007	PEM 45 kW	250 km	120 km/h

Figure 4 Summary of automobile companies' fuel cell vehicles

Source: Fuel Cell Vehicles, Fuel Cells 2000

Automobile companies developed fuel cars on the demand side while hydrogen energy infrastructure and refueling stations are on the supply side. The current hydrogen refueling stations are decentralized infrastructure. The hydrogen production, storage, and distribution are all done in refueling stations. Some of the energy companies are pursuing this market such as shell. Shell group formed Shell Hydrogen in 1999 and pursuing the retail of hydrogen through refueling stations. Shell Hydrogen involved in many region that is active in hydrogen demonstration projects, such as U.S., Europe, and Japan. They cooperated with many organizations and provide refueling stations in demonstration projects at Iceland, California, Washington D.C., Tokyo, Amsterdam, and Luxemburg. In addition, a concept for placing hydrogen refueling stations at home to resolve the lack of hydrogen fueling infrastructure is formulated (Shell Hydrogen, 2008). Honda is developing prototype using natural gas conversion into hydrogen while CSIRO in Australia is experimenting solar power hydrogen home refueling stations. Many of these developments are under the many hydrogen and fuel cell demonstration projects around the world.

4.2 Hydrogen Energy Demonstration Projects

In order to bring hydrogen and fuel cell technology one step forward into real commercial market and practical uses, several demonstration projects are conducted in different countries. A lot of these demonstration projects include a concept called hydrogen highway, which is a term refer to building hydrogen supply station along the road or highway for fuel cell vehicles to travel longer distances. Active projects countries include but not limited to, California USA, Japan, British Columbia Canada, Scandinavian countries Norway, Denmark, and Sweden. In addition, there are more demonstration projects related to hydrogen energy and fuel cell mostly located in Europe, North America, and Asia shown in Figure 5. Two demonstration projects are selected for further discussion.

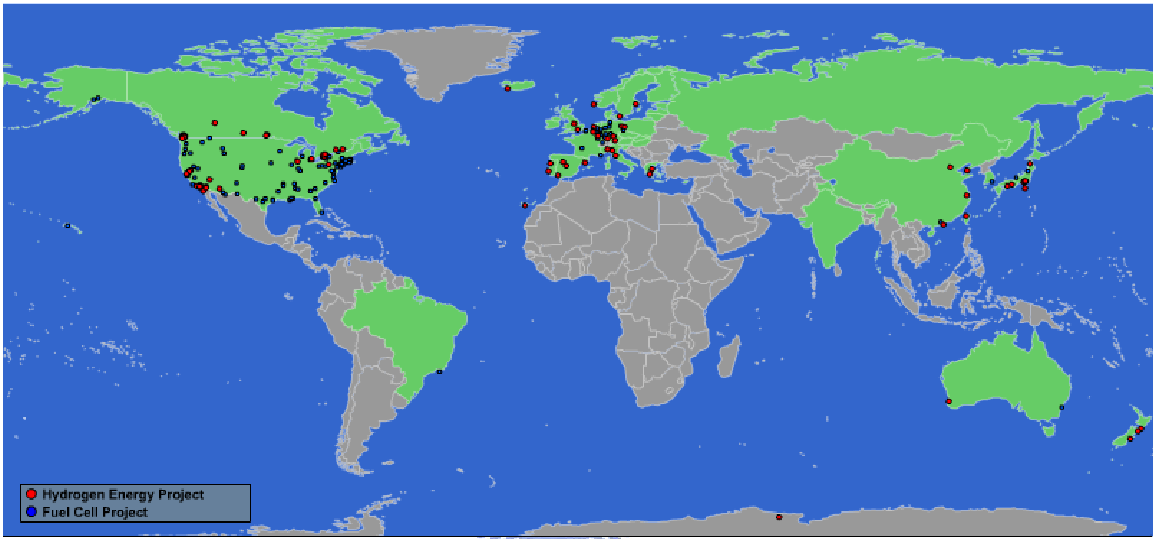

Figure 5 Location of the hydrogen and fuel cell demonstration projects

Source: Hydrogen Demonstration Projects Atlas, International Partnership for the Hydrogen Economy

4.2.1 California Fuel Cell Partnership

California Fuel Cell Partnership (CaFCP) is a fuel cell demonstration project in California. Started in 1999 jointly be government agencies and other members; currently with a total of 31 members divided in to full member and associate members ranging from automobile companies, fuel cell companies, energy companies, and research institutions. Figure 5 listed out the CaFCP full members.

Automobile Companies	Daimler Chrysler, Ford, General Motors, Honda, Hyundai, Nissan, Toyota, Volkswagen
Fuel Cell Company	UTC Power
Energy Companies	Chevron, Shell Hydrogen
Government Agencies	National Automotive Center, California Air Resources Board, South Coast Air Quality Management District, California Energy Commission, U.S. Department of Energy, U.S. Environment Protection Agency, U.S. Department of Transportation

Figure 6 CaFCP Full Member List as of 2008

Headquarter located in West Sacramento, primary purposes CaFCP existed are demonstration of fuel cell vehicles, demonstration of hydrogen infrastructure, possible realization of commercial market, and increase public awareness. From 2004 to 2007, CaFCP followed the main guideline detailed in enhancing public awareness, demonstration support on hydrogen related infrastructure hydrogen, and education for fire fighters communities on hydrogen standards and fueling. From 2008 to 2012, target goals are standardize fueling infrastructure with enhanced customer refueling experiences, provide information gathered during the past years of demonstration, and working toward commercialization by identifying opportunities and risks. Moreover, CaFCP planned to support more fuel cell vehicle and buses into the demonstration infrastructure. Figure 6 represents the hydrogen refueling stations in California, the main hydrogen infrastructures for the fuel cell vehicles to travel. There are 25 stations in operation with 9 more stations installation plans (California Fuel Cell Partnership, 2008).

Figure 7 Hydrogen refueling stations in California

Source: Hydrogen fueling stations, California Fuel Cell Partnership

4.2.2 Japan Hydrogen & Fuel Cell Demonstration Project

Japan Hydrogen & Fuel Cell Demonstration project or JHFC is Japan's efforts in developing alternative energy in hydrogen and fuel cell sectors. As name suggested, the purpose of the project is to conduct demonstration in hydrogen infrastructure and fuel cell vehicle resulting real data collection and clarification. The project is separated into two phases where each phase aims to achieve planned demonstration objectives.

Phase 1 was conducted during 2002 to 2005, with results in clarifying the high efficiency of fuel cell vehicle and well to wheel efficiency. Well to wheel efficiency covers the energy of the whole system, begging from the mining of primary energy, production, transportation, toward fuel cell vehicle usages, so we have a complete understanding of the overall energy efficiency of hydrogen infrastructure. Phase 2 began in 2006 and intended to end in 2010. Some of the goals for this period of time are collecting data for setting standard regulation, clarify remaining issues, identify trend of hydrogen infrastructure, conformation on reduction of harmful environmental effects, and enhance public awareness.

This project is supported by Japan's Ministry of Economy, Trade and Industry (METI) with variety of companies' participation in the demonstration. Figure 7 shows the listed companies. Being partly a fuel cell vehicle demonstration, refueling infrastructure is important, and most of the refueling stations were constructed in Tokyo region, 2 in Osaka region, and 1 in Chubu region. Figure 8 shows a rough location of hydrogen refueling stations in Tokyo and JHFC Park. JHFC Park consists of hydrogen refueling station, garage for fuel cell vehicle, a maintenance room and a show room. These facilities are primarily for studies and tests of hydrogen infrastructure, it also allows visitors to obtain related information, tours and experience FCV riding, enhancing public relation and awareness (JHFC Demonstration Project, 2008).

Automobile Companies	Toyota, Nissan, Honda, Daimler Chrysler, GM Asia Pacific, Hino, Suzuki, Mazda, BMW
Energy Companies	Cosmo Oil, Nippon Oil, Showa Shell, Tokyo Gas, Toho Gas, Osaka Gas, The Kansai Electric Power, Japan Energy
Other Related Companies	Iwatani International, Japan Air Gases, Taiyo Nippon Sanso, Nippon Steal, Kurita Water Industries, Sinanen, Itochu Enex, Babcock Hitachi, Kurimoto

Figure 8 Companies Involved in JHFC

Figure 9 Hydrogen Refueling stations in Tokyo Region

Source: Moving Our Future Forward, Japan Hydrogen & Fuel Cell Demonstration Project,

4.3 Iceland's Efforts in Hydrogen Energy

Iceland is an island located in the Northern Atlantic Ocean formed by volcanic activities. Due to its high altitude, about 10% of the island is covered by glacier. Similar to the rest of the world, fossil fuel dominated the Iceland energy sector in the first part of 20th century. Then with advantages in geothermal and hydroelectric alternative energy, about 70% of energy demand in Iceland is fulfilled by these two renewable energies in the form of electricity and heat from geothermal energy. About 90% of buildings are connected to geothermal hot spring for heat in various purposes. However, the transportation sector, agriculture, and boats in fishing sector still depend on fossil fuel energy. With Iceland government vision on developing hydrogen alternative energy and reducing the dependency on the fossil fuel energy due to risk of transporting them to the island and rising high price, Iceland is making efforts in developing Hydrogen energy.

Several opportunities are present for Iceland early transition into hydrogen society. The abundance of geothermal, hydroelectric, and water resources allow foreseeable hydrogen production. Iceland possesses know-how especially in electrolysis using heat and electricity by geothermal and hydroelectric power. Heat reduces the energy needs in electrolysis which provides an opportunity for Iceland. If more advances in these types of technology, Iceland is able to produce self sustained hydrogen energy entirely based on renewable energy. Combining the used and unused, Iceland renewable energy supplies an estimation of about 50 TWh of power annually. The hydrogen needed for transportation and fishing industry in 2030 is estimated at100,000 metric ton, requiring 5 TWh of energy for the amount of hydrogen production. So a 10% energy requirement for hydrogen production using renewable energy seems a feasible picture for Iceland (Sigfusson, Thorsteinn I., 2007).

Hydrogen is a potential energy for fulfilling Iceland government vision in domestic fuel production, and result the formation of Icelandic New Energy Ltd in 1998. The corporation was jointly ventured by Iceland energy companies, Iceland government, University of Iceland, and the Technology Institute of Iceland by holding 51% shares. The rest 49% is owned by international corporations consisting Daimler Chrysler, Norsk Hydro and Shell. The main goal of Icelandic New Energy is to replace fossil fuel with hydrogen fuel and form world’s first hydrogen economy. In order to reach the goal, professors in University of Iceland outlined three stages of actions. First stage employs hydrogen fuel cell buses into public transportation. Second stage is to promote fuel cell vehicles for family or personal uses. Last stage is primarily on testing hydrogen and fuel cell uses in maritime environment especially in fishing sector.

Started in March 2001, Ecological city transport system or ETCOS uses the first stage ideas to test hydrogen fuel cell buses in public transportation. The main goal for this project is to obtained experiences and data from bus operation and hydrogen infrastructure. ETCOS seeks European Union's financial support under the Fifth Framework Programme of the European Union. Some the reasons for this support are the Iceland environment for hydrogen test ground with government support, similar transportation system compared to other countries, and provide initial hydrogen application experiences for other countries interest in adaptation (Sigfusson, Thorsteinn I., 2007).

Being the Icelandic New Energy company's main focus, ETCOS was divided into two parts with 2 years length each. The first two years was centered on preparation, such as building refueling station, facility for marinating the operations…etc. After the preparation, 2 years of hydrogen fuel cell buses was implemented for practical experiences.

In October 2003, 3 buses started to operate in Reykjavik, the capital city of Iceland. Joining the public transportation system in Reykjavik, the buses operated in regular but routes. About 180 km of operation, the buses was maintained and tested for its performance. With the previous 2 years of preparation, Hydrogen fueling stations were implemented for bus drivers to fuel in daily manner. This is the first hydrogen fueling station using electrolysis under light source, capable of storing 50 kg of gaseous hydrogen under 440 bar pressure. The refueling station is surrounded by walls prohibit for entry; however, partial walls are being transparently built allowing people to see the stations structure and operations. Station neighbor didn't file complaint or protest for the proximity of hydrogen refueling stations, which can be an advantage toward future hydrogen refueling station construction when explaining to neighborhood. ETCOS project ended in August 2005, but more projects have started for example, HyFLEET CUTE and SMART H2. HyFLEET CUTE is a hydrogen fuel cell buses demonstration around many cities in Europe and in Beijing China organized by European Union. Icelandic New Energy Ltd. now enters into the second stage of three stages actions. SMART H2 is an Iceland demonstration project on various powered vehicles including fuel cell vehicles, and fuel cell boat. This project also tests for the hydrogen infrastructure for these vehicles (Icelandic New Energy Promoting Hydrogen in Iceland, 2008).

Chapter 5 Issues, Challenges and Discussions

5.1 Hydrogen Safety Issues

Safety is a primary concern in risk associated technologies of potential damages to properties and harmful effects toward human beings. This is especially true in energy sectors as fuels contain energies that can cause damages when undesired energy release is encountered. Without exception, hydrogen as an energy carrier does have safety issues needed to be addressed. Just like gasoline and natural gas, hydrogen has potential to cause hazardous conditions. The different properties of hydrogen in comparison to natural gas and petroleum result different methods in hydrogen risk handling. Also, due to the hydrogen properties, it has advantages and disadvantages over the traditional fuels.

Hydrogen gas disperses faster and easy leakages into the space of about 3.8 times more than natural gas. Hydrogen is lighter than air, so it can quickly rise to the top of environment. These properties are advantageous in an open and out door environment as hydrogen will quickly move away and rise from the leakage facilities point causing difficulty in building up flammable volume concentration. As a result, people near the facilities will less likely to be harmed from hydrogen compare to natural gas or petroleum that stays near the leakage facilities. These properties become dangerous in closed environment as they will quickly build up concentration starting from the ceiling and down. So a good ventilation system is a must when operating hydrogen facilities indoor (Hydrogen Safety Fact Sheet, 2008).

Hydrogen gas have higher leakage rate and people are unable to detect using their senses since hydrogen is colorless, odorless, and tasteless. Natural gas has the same properties, so mercaptan, additives that injected into natural gas for odor detection. However, hydrogen cannot use the same techniques as some of the fuel cell only accept pure hydrogen, additives to hydrogen would shorten the life of fuel cells. A solution is to design advanced sensors that detect hydrogen presence and alarm such existence to people (Mathis, David A., 1976).

Hydrogen can be ignited and causes fire hazard conditions. The flammability limits is the required concentration of gaseous mixtures between combustible gases oxidizing gases, usually oxygen or air, to be able to cause flame. The flammability limits of hydrogen gas are from 4% to 75% compare to natural gas of 5% to 15%. Although the 75% upper limits of hydrogen seems dangerous, the lower limits might be the potential problem as it is the minimum required hydrogen concentration in air for possible ignition (Hydrogen Safety, 2008). The energy for hydrogen gas ignition required is 0.02 mJ, which is a very low energy requirement. Lower concentration of hydrogen gas needs higher energy ignition similar to natural gas of about 0.30 mJ. However, electrostatic spark from human body with 10 mJ of energy is enough to ignite hydrogen gas and natural gas. Handling these kinds of energy fuel needs extra attention as they are all highly flammable (Hydrogen Safety Fact Sheet, 2008).

When flame occurs from hydrogen gas, it has a different and dangerous property. The flame is hard to detect by human eyes under daylight or any light source. Unlike regular fire emits lights in visible light spectrum, hydrogen flame burns at ultra violate region in light spectrum. Hydrogen flame also emits lower heat, which might cause more burning injuries since people might not realize they are approaching a fire since they cannot see or feel the heat. On the other hand, lower heat emission lowers the possibility of fire spreading over other flammable objects and also allows fire fighters to separate flammable materials from the fire (Hydrogen Safety, 2008).

Hydrogen can be explosive under certain conditions. For hydrogen gas to be explosive, oxidizer gas such as oxygen needs to be presented. A concentration of 10% or more for pure oxygen or concentration of 41% or more for regular air with combination of hydrogen gas in concentration of 18% to 59% is required of explosive condition. However, gasoline is more dangerous since a 1.1% to 3.3% concentration would cause a potential explosion. Overall, hydrogen safety is acceptable from the past experiences of industrial usage. However, situation might be different if hydrogen usages are massively introduced to common commercial usage or home usages. Closed spaces create dangerous environment for using hydrogen, so ventilation system and detection system should be installed. Government should put efforts into generating codes and standard for common hydrogen usages and place more efforts into hydrogen safety education(Hydrogen Safety Fact Sheet, 2008).

5.2 Challenges and Barriers

Hydrogen energy is one of the multiple paths in searching for alternative solution to current energy situation regarding cleanness to the environment and energy security. Other paths are competing forces to hydrogen energy, including biofuels, plug-in hybrid electric vehicle, compressed natural gas, and synfuel…etc. All of these forces can be a threat to hydrogen energy as they provide some benefits hydrogen energy cannot achieve. However, they also have disadvantages giving hydrogen energy some chances. Overall, hydrogen energy should mitigate its own disadvantages to be competitive in the alternative energy market.

5.2.1 Hydrogen Infrastructures

As described in chapter 2, hydrogen can be produced by wide range of sources from fossil fuel to renewable resources and some of the production methods are still under development. Natural gas, coal and fossil fuel are the cheapest way of producing hydrogen but pose some problems. During the production process, carbon dioxide will be released contradicting to the cleanness of using hydrogen. Although there are processes of capturing the carbon dioxide and store them underground, there are technologies enable vehicle to use natural gas directly. Therefore, hydrogen through natural gas production seems redundant. Natural gas only serve the purpose of helping society transition in hydrogen by supplying lower price hydrogen, long term sustainable production still depends renewable resources.

Using renewable resources such as solar or wind energy to produce hydrogen is the goal of hydrogen economy due to environmental benefits, energy security, and sustainable production by using energy current account. However, compare to traditional production methods, the cost becomes high and reduced the incentive for people to choice hydrogen fuel over petroleum. Moreover, current available method of renewable hydrogen production is water electrolysis; this method has acceptable efficiency in energy conversion rate, but lower efficiency rate compare to direct electricity usage from the same renewable production. This is one of the arguments commonly used in pure electrical battery vehicle when compared to fuel cell vehicle. If hydrogen conversion efficiency is higher, then we can save more infrastructure cost such as lower amount of solar panel or wind turbine. Other renewable hydrogen production methods are mostly in research stage, further studies for marketable hydrogen production need to be demonstrated.

Vehicle onboard hydrogen storage technology is commercially available as pressurized gaseous hydrogen tank storage and being the current major choice for automobile companies' fuel cell vehicle. However, this method is costly around \$600/kg H_2 and requires extra energy to keep the pressure, which poses difficulty for introducing economical fuel cell vehicle. Other on board hydrogen storage methods are in development phase with possibility of better benefits such as metal hydride. Selection and standardize the onboard storage method is important as it affects how hydrogen infrastructures are being built (The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, 2004).

To build massive centralized hydrogen production units, massive hydrogen storage technology and distribution technology needs to be mature. However, currently massive hydrogen storage technology is not available except storing them underground by using depleted natural gas mine. Hydrogen distributions using vehicle or pipeline have many problems need to be solved. Hydrogen pipeline existed in Europe and America, but the distances are shorter than natural gas pipelines. To build a hydrogen pipeline distribution infrastructure needs lots of investment due to the hydrogen property and materials required. Also, the gaseous hydrogen needs to be re-pressured when travel through certain distances, adding more cost toward the system. Overall, hydrogen infrastructure faces problem mainly in technical difficulties and cost of building such infrastructure (Dixon, Robert K, 2007).

A quick way to solve the costly and almost non existence storing and distribution hydrogen infrastructure is through decentralized infrastructure, which combines hydrogen production, storage and delivery all in one location and provide hydrogen for vehicles when they arrive to refuel. This onsite refueling station produces hydrogen mostly through natural gas steam reforming and electrolysis. As mentioned, although with smaller amounts, steam reforming produced green house gas carbon dioxide; cost of controlling carbon dioxide emission is even higher than centralized infrastructure. Overall, the cost of decentralized units of hydrogen production is more than 50/GJ H2, while centralized production can achieve 10-20/GJ H2 in the future. So decentralized hydrogen production becomes expansive in the long run. Moreover, centralized infrastructures have more production method choice than decentralized units. In the long run, centralized infrastructure showed more economical, while decentralized units serve a quick hydrogen supply introduction in energy transition phase especially in fuel cell vehicles.

5.2.2 Fuel Cell Technologies

Fuel cell technology with wide range of applications can operate efficiently and environmentally using hydrogen as fuel. Fuel cell can possibly play an important role in future hydrogen economy. Despite these benefits, if fuel cell cannot reach economical prices, customers would not have incentive to purchase this technology. As price becomes a barrier to fuel cell introduction, cost reduction is a primary goal for fuel cell improvement. Stationary fuel cell has to reach $ 1,500 per kilowatt or below to be competitive. Fuel cell for vehicle usages needs to reach $50 to $100 per kilowatt in order to compete with hybrid vehicles.

Several areas of fuel cells need further research. Material science is an important area where reduction of material cost and alternative material are important since many types of fuel cell uses precious metals as electrodes that raise the cost of fuel cell. Other areas of research includes increasing the power density of fuel cell, improve the production process and implement mass production in reaching economies of scale, and reduce system complexity. To drive down the cost of fuel cell, these areas needs to be further developed. Besides these needed improvement for cost down purpose, fundamental research in fuel cell will add extra benefits. New types of fuel cell with new materials, increase containment tolerance from carbon monoxide and sulfur, and new improved overall fuel cell system through balance of plant concept. Innovative concepts are needed for further improvement or new fuel cell concepts for reaching further benefits.

Another fuel cell matter is its reliability of providing power supply. Fuel cell can provide high power quality, however, long term power supply performance and reliability needs to be tested. Some of the areas need to be researched on include the endurance and lifetime of fuel cell, durable in installed environment, and grid connection. If reliability can be justified with the power quality supplied by fuel cell will assist fuel cell into commercial market applications (Rayment, Chris and Sherwin, 2003).

5.3 Government Policies

Hydrogen economy faces fundamental problems known as chicken and eggs dilemma. Hydrogen supply would not occur if hydrogen demand does not exist. On the other hand, hydrogen demand would not start to increase if hydrogen supply is not available. This was also the case for fossil fuel infrastructure 100 years back, and we managed to reach current massive fossil fuel economy. Although we can allow hydrogen energy to follow fossil fuel development pathway, the length of time of such development stretch out in the future. To realize faster hydrogen development, government can step in with multiple energy policies to stimulate transition from current fossil fuel economy into sustainable hydrogen economy.

Tax on transportation and energy related issues can influence the market price, supply and demand. The goal of these taxes is usually intended to reduce the harmful effects the sector caused to the environment, and usually refer as to internalize the external cost or social cost. Some of the taxing methods include fuel tax, vehicle tax, or tax on carbon dioxide emission. Not only these kinds of taxes can directly influence the mitigation of carbon dioxide and other environmental harmful effects, but also indirectly influence the alternative energy sectors. By raising the taxes further, people will either reduce the usage of taxed infrastructure, or switch to alternative vehicle and structure finding economical benefits and environmental benefits. However, the switching behaviors only occur if the infrastructures of alternative energy sectors are readily available to the customer. So these taxing policies help hydrogen energy sectors and other alternative energy sectors to accelerate their market share, but only under the circumstances of acceptable availability of infrastructures in those sectors.

On the other side of tax policies are tax incentives. Reducing the tax on companies and customers is another method government policy can affect the energy industry. This is a direct method of assisting manufactures primarily in lowering the cost of hydrogen fuel cell vehicle and infrastructure. Thus, a faster introduction with competitive price would increase hydrogen vehicles market share. Some policies can be performance-based tax incentive and credits for alternative fuel selection. By creating tax incentive, faster mass production occurs and drives the cost down further, leading society toward alternative energy. Moreover, tax incentive is a direct policy assisting method that allows companies and customers to realize the supportive position from government to the hydrogen sector.

Tax and tax incentive directly influence the price on the market. Other policy might indirectly influence the market direction, such as setting regulatory standards. Environmental standards in technology or performance help to reduce carbon dioxide emission. Standards can be set on emission quantity, energy efficiency, or requiring technologies that mitigate the environmental problem. Failure to meet the standards result consequences such as fine penalty. Government or intergovernmental organization can initiate voluntary agreement on the commitment of reduce environmental problem or even toward developing alternative energy structures. Most of these polices have passive influence on developing hydrogen economy since companies might put extra efforts in improving original fossil fuel infrastructure to meet the regulation. However, a stricter regulatory standard might inspire more organizations into considering alternative energy sectors.

Government policy should also be aimed toward research and development. State initiated and funded R&D projects accelerate the advancement in alternative energy resulting a faster entry and growth in market. Projects should be funded toward academic institution and research organization aiming at break trough of key barriers of hydrogen energy. Hydrogen energy information dispersion should also be considered in government policy agenda. As more people notice such information, hydrogen information exchange on opportunities, risk, and other important messages allow better understanding of hydrogen energy in a society. Information allow public to judge and express their attitudes toward hydrogen energy, which benefits in all sorts of decision makings. Generally, government is an important factor in hydrogen infrastructures due to government policies toward taxation, regulation settings, R&D researches, and education support transformation into hydrogen economy (Steenberghen, Therese., 2008).

5.4 Public Perceptions

Public perception is one of the key factors for the success of hydrogen infrastructure. Historical view can justify the influential power of public perception, for example nuclear power. Nuclear power was thought to be a clean energy source using uranium fission to create electricity. The abundant uranium resources made nuclear power a sustainable energy for a long period of time. However, after several nuclear accident and the radio active by products, public perception viewed nuclear power as dangerous and unclean. The construction of new nuclear power plants grew slowly after then, or even complete stop in some countries.

Public opposition becomes exceptionally strong when nuclear plants are being built near their community. Locally Undesirable Land Uses, LULU, is a term refer to this situation where negative impacts brought by building infrastructure, such as landfill and nuclear waste site, to local community. The infrastructures bring overall benefits a greater society, however, causes harm to the local community. Although the opposition commonly being viewed as a reaction of not in my backyard, a short future sighted and selfish behavior, several factors involved in such opposition behaviors. Distances between community and infrastructure is the main factor influencing the community perception and opposition. The further apart the distances are, the less opposition occurs, until zero opposition when certain distances reached. Other important factors are risk perception and trust. The higher the risk perception due to lower trust in technology and host organization, the stronger is the opposition. Social economic and prior knowledge are also influencing factors. The construction also lowered the land and house property ranging from $3000 to $15,000 per mile. These factors explained some of the rational behind the negative perception (O'Garra, Tanya, 2008).

From O'Garra et. al, surveys were conducted in London by selecting community near the refueling stations as they are expected to bare the cost of hydrogen refueling stations. 800 surveys distributed with 346 responded. Beside general survey method, contingent behavior method was used by asking hypothetical situations, building hydrogen refueling station in the next 3 months, for consequent behaviors of length of time dedicated to opposition. Result showed that 10% of respondent are opposing, 25% respondent support the idea, while 59% said need more information. 33 opposition respondents were asked on their time spent on opposition, about 65% of them willing to spend 1hours to 3 hours, 25% spent more time from 10 to 30 hours and 10% spend 0 to 15 minutes. As we can see, the opposition effort among the respondent tend to be low to moderate, about 75% will spent up to 3 hours in opposition. From this survey we can see that there are more support than opposition, however, there a large amount of people need more information, contributing to the uncertainty of the report (O’Garra, Tanya, 2008).

Another survey study by Heinz, B. and Erdmann G. on general public perception on hydrogen energy was conducted. Total of 3552 of people were surveyed across different European countries’ cities. Total of eight cities under Hyfleet CUTE project of hydrogen bus demonstration includes Amsterdam, Barcelona, Berlin, Hamburg, London, Luxemburg, Madrid, and Reykjavik. More than 300 people were conducted in each city as interviewer read the questions and mark respondent answers. Internet survey was conducted toward students in Berlin University. All respondents were given extra information on the hydrogen energy after the survey. First question is regarding the search of alternative fuel for vehicle, 72% of respondents strongly agreed and 18% agreed, only 1% object the question. The mean value is 4.6 as 5 represented strongly agreed and 1 represented strongly disagreed. When asked of replacing traditional bus to hydrogen fueled bus under the choice of support, indifferent, oppose, and need more information, respondents results 68%, 7%, 1%, and 21% respectively. From this study, we can see a very strong public attitude in supporting alternative fuel (90%) and relative strong attitude toward supporting hydrogen bus (68%) (Heinz, B., 2008).

According to the above two and other surveys, the general attitudes toward hydrogen energy related to vehicle usages are generally positive. Some survey indicated numbers of people needing more information regarding hydrogen that might influence the attitude structure either toward stronger positive attitude, similar positive attitudes, or more opposing forces. Some literature concerned over negative hydrogen public attitudes due to 1937 Hindenberg accident in New Jersey. Hindenberg accident refers to a zeppelin fueled with hydrogen gas caught on fire resulted in several human death. With some clarification, the hydrogen is not the main cause of fire, but the chemical painted on the airship's balloon. Not affected by Hindenberg accident, surveys showed positive attitudes in hydrogen energy probably because of the effective clarification, forgetfulness due to the length of historical events, or not knowing the events at all. Hydrogen bomb might also be associated with hydrogen energy due to the word hydrogen. However, hydrogen bomb mechanism is completely different from hydrogen energy. Other negative association might occur due to the lack of information and clarification. To maintain such public positive attitudes, continue efforts in hydrogen safety and hydrogen education are necessary to justify a transition toward hydrogen economy.

5.5 International Organizations in Hydrogen Energy

Stepping toward hydrogen economy is mega scale in terms of capitals, geographical locations, and technologies. Political issues and social issues are also concerns for hydrogen economy. Not only should individual countries actions in searching for the hydrogen energy possibilities, but also the international organizations efforts in hydrogen energy. In searching for alternative energy, two international organizations have dedicated efforts in hydrogen energy, which are International Energy Agency (IEA) and the International Partnership for the Hydrogen Economy (IPHE). In addition, other international organizations have also involved in the field such as World Bank and United Nations.

International Energy Agency was founded around 1970 from the oil crisis originally aimed at oil emergencies. IEA has added more objectives as time goes on, including energy security, economic development and environment protections. Within a wide range of energy related activities by IEA, they involved in hydrogen energy and fuel cell through technology collaboration. Common participants of technology collaboration are governments, research institution, universities, and energy companies. Collaboration is established base on the implementing agreement, a legal contract created by IEA providing standards and rules for participants to follow. Within the many implementing agreements, hydrogen energy related collaborations are hydrogen implementing agreement and implementing agreement on advanced fuel cell (International Energy Agency, 2008).

Hydrogen implementing agreement started in 1977, just a few years after the formation of IEA. Main objectives are to promote hydrogen as an energy and research on the hydrogen technologies. There are currently eight research tasks being conducted mostly on the hydrogen infrastructures, and they have already completed 17 tasks in the past. 2 more tasks will be researched on in the future. Countries participants from government, universities, and companies are listed in the box 1 (Hydrogen Implementing Agreement, 2008).

Australia, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Italy, Japan, Korea, Lithuania, New Zealand, Norway, Spain, Sweden, Switzerland Netherlands, Turkey, United States of America, United Kingdom.

Box 1 Countries involved in hydrogen implementing agreement

International Partnership for the Hydrogen Economy (IPHE) was established in November 2003. The goal of IPHE is to organize international efforts in developing, demonstrating, commercialization of hydrogen and fuel cell related topics. Several member countries or partner have joined IPHE which is listed in box 2. Terms of reference laid out the general objectives, structure and framework of IPHE and being signed by member countries. IPHE has two committees, Steering committee and Implementation-Liaison committee. Steering committee is responsible for overall framework of IPHE. Implementation-Liaison committee is responsible for reviewing, guiding the various projects, other hydrogen related works, and report to Steering committee. Overall, from these international organizations, indications on countries efforts in developing hydrogen energy technologies and collaboration with other countries was demonstrated (International Partnership for the Hydrogen Economy, 2008)

Australia, Brazil, Canada, China, France, Germany, Iceland, India, Italy, Japan, New Zealand, Norway, Korea, Russia, United Kingdom, United States of America, European Commission

Box 2 Partners in IPHE

Chapter 6 Recommendations and Conclusion

6.1 Recommendations

Taiwan is an island located west of china with high energy demand. Over 90% of energy is imported making Taiwan vulnerable to world energy price fluctuation that leads to inflation. To mitigate the energy situation in Taiwan, Taiwan's government should actively pursue alternative energy options such as hydrogen energy. Two advantages Taiwan has are renewable energy and small geographical location. Taiwan has abundant renewable energy sources such as solar, wind, geothermal, ocean energy, and these renewable energies can be converted into hydrogen for transportation. Small land size allows Taiwan to quickly build up hydrogen infrastructure around the country.

In order to realize hydrogen as part of the Taiwan's energy sector, Taiwan with the lead of government should actively pursue renewable energies to provide electricity around the island. When renewable energies are in excess supply, these can be converted to hydrogen for road vehicles and fishing boats. Taiwan government should form a special division for renewable energy with active policies to encourage and coordinate companies, research centers, and universities involvement. A platform should be available for exchanging information and data to avoid redundancy. Renewable energy division should also inform the public about the possibilities of hydrogen energy and other alternative energy through internet, traditional media, schools, and brochures. Government should set up hydrogen and fuel cell demonstration projects to test the feasibility and allow more exposure to the public. Fuel cell cars and buses can be obtained from major car companies while Chinese

Petroleum Company can develop hydrogen refueling station. Overall, Taiwan should consider hydrogen energy as one of the alternative energy possibilities for the next energy generation.

6.2 Conclusion

Energy and environment problems are gradually reveling consequences toward our society. Many warnings have been made through out the history. However, these problems are public interest that individuals might careless compare to other issues that directly impact them. Crude oil prices continue to reach historical record high, while demands from developing countries continue to rise. Carbon dioxide as a green house gas continues to contribute to global warming and climate changes.

North Pole ice cap melted at rates faster than expected, glaciers also experienced faster melting rate. Majority or all ice cap melted was predicted to happen in 2100, with dynamic conditions, years have been shorten to 2050 and then in year 2030. In 2007, North Pole experienced largest ice melt rate, about 60% of ice were melted. 2008 news reported a 50% chance of complete ice free environment for North Pole in summer suggested by scientist from National Snow and Ice Data Center in Colorado. Although complete melt of ice have no immediate harm, the situation clearly gives a message to the society on the seriousness of climate changes (Duke, Alan, 2008).

Hydrogen as an energy carrier might not solve the problem completely, but sure serve as a resolution toward the energy and environment problems. Just like using electricity, hydrogen is a clean energy with many applications. However, it is a secondary energy manufactured from primary energy. So the overall energy system still emits carbon dioxide if hydrogen is produced from fossil fuel. An overall clean energy system can be achieve if hydrogen is produced from clean renewable energy such as solar or wind power. These kinds of renewable energy fluctuate in providing energy supplies, so hydrogen can serve as a massive energy storage medium to handle the fluctuating energy supplies and demands. Combined with fuel cell technology, hydrogen can be used in many applications while currently transportation sector is the most aggressive developers.

Hydrogen energy and fuel cells face many difficulties, and many of them are problems associated with technologies. There are multiple ways to produce hydrogen, while the cheapest way is still from manufacturing natural gas or fossil fuel. Researches on cost down of clean hydrogen production methods are needed. Hydrogen storage and distribution still faces many technological challenges, so the hydrogen infrastructure based on centralized production, storage and distribution is currently not possible. Decentralized on site production and refueling stations are currently available, but the price tends to be higher with lesser hydrogen production choices. Fuel cells needs improvement in durability and other technological break through for better performance. In addition, dynamic public perceptions, policies, standards, and safety issues are also important for the success of hydrogen energy infrastructure.

Hydrogen was once used in early 20th century for street lamps, but later replaced by electricity and fossil fuel. In the future, as society largely uses hydrogen energy, hydrogen economy is formed. Hydrogen economy can ideally reach zero carbon emission and combined with renewable energy can assist sustainable development. Many barriers existed in the pathway of hydrogen economy, but hydrogen energy has long term advantages worth the efforts in pursuing. Building a new energy infrastructure requires collaboration between government, research institutes, universities, private sectors, individuals, and international organizations. As one of the promising alternative energies, hydrogen economy is worthy for further explorations.

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