CHAPTER 1

INTRODUCTION

This chapter highlights the global problem arise from using fossil fuels which later bring the idea of hydrogen economy as part of the solution. However, there are several hurdles and challenges that need to be overcome in realizing the hydrogen economy including the problems in hydrogen storage. Several techniques are discussed including the use of material such as carbon nanomaterial as the hydrogen storage medium for onboard vehicles.

1.1 Fossil fuels: Benefits and current problems

Malaysia has been blessed with a huge amount of fossil fuels such as oil and gas. These natural resources are the resources of energy to supplement the industrial sectors, transportation and electricity demand. The exploitation of the oil and gas has made Petroliam Nasional Berhad or PETRONAS, the national agency that manages the oil and gas, as a significant contributor to the nation's manufacturing sectors, which is almost 29% of the country's gross domestic product (GDP) (Ariff, 2007). Its manufacturing activities constitute roughly one-third of the Group revenue. For example, crude oil and natural gas account for one-fourth and one-sixth of PERONAS' revenue, respectively.

Based on Malaysia External Trade Statistics reported in July 2008, the total exports of crude petroleum, natural gas and refined petroleum products contributes 17.18% of Malaysia total exports or RM114.01 billion (Matrade, 2008). This has increased significantly as compared with the previous year that is 13.13% of total exports or RM79.48 billion. Detail of the exports breakdown can be referred to Table 1.1.

Table 1.1 Malaysian major export products 2007 and 2008 (Matrade, 2008)

Products	RM Billion	
	2008	2007
Transistors, valves	89.82	96.47
Automatic data processing equipment	46.30	55.53
Fixed veg. Fats,oils,crude, refined not soft	45.61	30.41
Petroleum oils, crude	44.09	33.52
Natural gas	40.73	26.16
Parts & accessories for office machines	36.47	36.75
Petroleum products	29.19	19.80
Telecommunication equipment parts	26.18	28.83
Electrical switcher relays,circuits	13.78	14.06
Others	291.33	263.62
Total Exports	**663.49**	605.15

Source: Department of Statistics Malaysia

Therefore, these two precious resources have enhanced the country's economic growth substantially in all sectors like manufacturing, business and commerce, housing development as well as tourism. In addition, it has also improved the living standard of local people including in education, health and lifestyle.

Unfortunately, like any other countries in the world, the extensive utilization of the resources creates problems such as air pollution and global warming. This is because in transportation, an internal combustion engine of a vehicle like a car for example is not perfect. Besides carbon dioxide and water, it also produces other poisonous gases such as carbon monoxide, sulphur dioxide and nitrogen dioxide. Apparently such pollutants could harm the respiratory system and causes other related health problems. In global warming, the elimination of greenhouse gases like carbon will slowly increase the temperature of the earth. Consequently, there will be a dramatic climate change that affects everyone on the planet. For example, when the ice caps melt, the sea level will rise significantly which will cause flooding and destroying all coastal cities in existence today (Brain, 2008).

Another major problem of fossil fuel is environmental pollution. The process of transporting and storing oil has a big impact on the environment whenever something goes wrong. For instance, an oil spill, pipeline explosion or well fire can create a huge mess and disruption. Besides pollution and global warming, an economic dependence could have been created since some countries import oil from oil-rich countries as they cannot produce enough oil to meet demand. In other words, if the oil producers decide to raise the oil price, the rest of the world has little choice but to pay the higher price.

Apart from the problems, the growth in population coupled with rising per capita energy demands means that the amount of energy required will increase at a greater rate than can be sustained using prevalent technologies and fuels. In Malaysia the energy demand is increasing in all sectors like industrial, transport, residential and commercial areas as well as agriculture and forestry. For example by referring to Table 1.2, it is expected that in industrial and transport sectors in Malaysia, the energy demand will be increased by 36.3% and 37.9%, respectively from year 2005 to 2010 (Economic Plan Unit, 2006). Other sectors' energy demands are also increasing over time.

According to PETRONAS, Malaysia's crude oil reserves of 5.25 billion barrels will last for another 20 years at current rates of extraction (Ariff, 2007). In other words, if there is no more new oil and gas resources to be found, the government has to find other alternative fuels apart from implementing efficient use of energy. Therefore, in 1999 renewable energy (RE) is added as the fifth fuel of Malaysia in addition to oil, gas, coal and hydropower with a target of RE to be 10% of the total energy by 2010 (Wan Daud, 2006). Efforts in promoting RE continues where in the 9^{th} Malaysian Plan (2006-2010), the sources of fuel will be diversified through greater utilization of renewable energy and emphasis will be given to further reduce the dependency on petroleum products by increasing the use of alternative fuels. During the plan period, two projects with a combined grid connected capacity of 12 MW was implemented under the Small Renewable Energy Power Programme (SREP) and a roadmap for the development of solar, hydrogen and fuel cells was formulated. In addition, to promote the wider application and utilization of photovoltaic technology in buildings, the Malaysia Building Integrated Photovoltaic Technology Application Project (MBIPV) was also launched (Economic Plan Unit, 2006).

Table 1.2 Commercial energy demand by sector 2000-2010
(Economic Plan Unit, 2006)

Source	Energy (Petajoules)			Energy (% of Total)		
	2000	2005	2010	2000	2005	2010
Industrial[1]	477.6	630.7	859.9	38.4	38.6	38.8
Transport	505.5	661.3	911.7	40.6	40.5	41.1
Residential and Commercial	162.0	213.0	284.9	13.0	13.1	12.8
Non-energy[2]	94.2	118.7	144.7	7.6	7.3	6.5
Agriculture and Forestry	4.4	8.0	16.7	0.4	0.5	0.8
Total	1,243.7	1,631.7	2,217.9	100.0	100.0	100.0

Notes: [1]Includes manufacturing, construction and mining

[2]Includes natural gas, bitumen, asphalt, lubricants, industrial feedstock and grease.

Hence, identifying renewable energy resources such as solar, wind, biomass, biodiesel, biogas and hydrogen as potential fuels are crucial in order to replace the oil and gas in the future. The next topic is focusing on hydrogen as an alternative energy and types of storage method for onboard vehicles.

1.2 Hydrogen economy

Hydrogen is the most abundant of all elements in the universe. Named by Antoine Lavoisier, hydrogen was first recognized as a distinct substance by Henry Cavendish in 1766. On earth, hydrogen occurs in combination with oxygen in water (H_2O) and also present in organic matter such as living plants, petroleum, coal, etc. In the atmosphere, as the lightest of all gases, hydrogen gas (H_2) is present as a free element with a capacity of less than 1 ppm by volume. H_2 can combine with other elements (sometimes explosively) to form compounds (Los Alamos National Lab, 2003). However, unlike coal, solar energy, biomass energy, wind energy, nuclear energy and geothermal energy, hydrogen is not a source of energy but rather a fuel (Tarara, 2001). There are two main uses of hydrogen that are fuel for transportation and for storing excess electricity. The term hydrogen economy was coined by John O'Mara Bockris, who is a professor from University of Pennsylvania in 1970 (US Department of energy, 2009).

Hydrogen economy is defined as a hypothetical future economy in which the primary form of stored energy for mobile applications and load balancing is H_2, and in particular, H_2 replaces fossil fuels in automobiles. Based on the US National Hydrogen Energy Roadmap 2002, several segments that cover production, delivery, conversion, storage and utilization need to be considered in order to design and implement a hydrogen economy system (Abraham, 2002).

In hydrogen production, a better system is required to lower overall costs, improve efficiency, and reduce the cost of carbon sequestration. Currently, global hydrogen production is 48% from natural gas, 30% from oil, 18% from coal and 4% from water electrolysis (National hydrogen association, 2009). Among these methods, partial combustion of natural gas in a natural gas combined cycle (NGCC) power plant offers the most efficient chemical pathway and the greatest off-take of usable heat energy.

For hydrogen delivery, development of better components for existing delivery systems such as hydrogen sensors, pipeline materials, compressors, and high-pressure breakaway hoses are essential to manage cost, safety and reliability issues. Conversion plays an important role in converting H_2 into useful forms of electric and thermal energy. This involves the use of fuel cells, reciprocating engines, turbines, and process heaters (Abraham, 2002).

The most crucial segment that is still under research and development is hydrogen storage. Lots of effort needs to be done to improve existing commercial technologies by lowering the cost, increasing the performance and developing advanced materials. This issue will be further discussed in this chapter.

Finally, the utilization or end-user application is taken into account where consumers should be able to use hydrogen energy for transportation, electric power generation, and portable electronic devices. Key consumer demands include safety, convenience, affordability, and environmental friendliness.

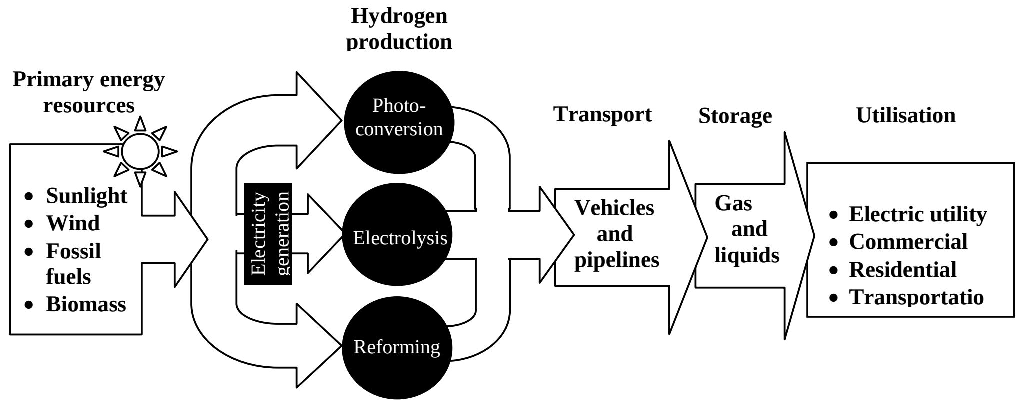

Figure 1.1 The components of hydrogen economy system (Cleveland, 2004)

These interrelated and interdependent segments or components are clearly shown in Figure 1.1 (Cleveland, 2004). In addition, customer education and the development of codes and standards are included in order to accomplish the hydrogen economy implementation (Abraham, 2002).

1.3 The advantages of hydrogen economy

There are several advantages of implementing hydrogen system. The following section details out each of the advantages.

1.3.1 Elimination of the use of carbon-based fossil fuels

The primary purpose of hydrogen economy is to eliminate the use of carbon-based fossil fuels and thus reduce carbon dioxide emissions. This is because the use of hydrogen could reduce the pollution problems that the fossil fuel economy creates today. For example hydrogen in a fuel cell is completely a clean technology where no byproduct will be formed during the combustion except water. Moreover, there are also no environmental dangers like oil spills to worry about with hydrogen (Brain, 2008).

1.3.2 Elimination of greenhouse gases

If hydrogen comes from the electrolysis of water, then hydrogen adds no greenhouse gases to the environment. There is a perfect cycle where electrolysis produces hydrogen from water, and the hydrogen recombines with oxygen to create water and power in a fuel cell.

1.3.3 Derivation from diverse domestic resources

Hydrogen is derived from natural gas and oil, nuclear and renewable resources. For instance, hydrogen can be extracted chemically from hydrogen-rich materials such as natural gas, water, coal or plant matter (Tarara, 2001). The processes of extraction including steam reforming, off-gas clean up, photo-processes, electrolysis and hydrolysis. For instance, electrolysis produces hydrogen from water, and the hydrogen recombines with oxygen to create water and power in a fuel cell.

1.3.4 Elimination of economy dependence

Hydrogen also provides energy independence to countries without oil resources. This will eliminate economic dependence to countries such as the Middle East and its oil reserves.

1.4 Hydrogen: mass energy density vs. volumetric energy density

H_2 has high energy content or mass energy density, which is the amount of energy obtained when it reacts completely with oxygen to form water. This can be seen in Table 1.3 where the amount of higher heating value (HHV) and lower heating value

(LHV) of H_2 is the highest among any HHV and LHV of other fuels. This is because H_2 has the highest energy-to-weight ratio of any fuel since it is the lightest element and has no heavy carbon atoms.

Table 1.3 Heating values of comparative fuels (Lanz, 2001)

Fuel	Heating value at 25°C, 1 atm (kJ/kg)	
	Higher	Lower
Hydrogen	141.86	119.93
Methane	55.53	50.02
Propane	50.36	45.60
Gasoline	47.50	44.50
Diesel	44.80	42.50
Methanol	19.96	18.05

Thus, H_2 is a suitable fuel for transportation. Since 1960s, H_2 has been used extensively in the space program where weight is crucial (Lanz, 2001). Another comparison of mass energy density of fuels can be seen in Figure 1.2. It can be seen that hydrogen can release about 2.5 times more energy than other conventional hydrocarbon fuels (Tzimas et al., 2003).

Since it has a high mass energy density, combustion of hydrogen in a fuel cell is more efficient than an internal combustion engine. The internal combustion engine is said to be 20-30% efficient, while the fuel cell is 35-45% efficient (not accounting for losses in the actual production of hydrogen, which would result in an overall efficiency of about 25%) and together with the electric motor and controller, the drive train overall efficiency approaches 24% with low idling losses. However, H_2 has poor volumetric energy since it has a lower density compared with other fuels (see Figure 1.3). It can be seen that hydrogen (either in liquid or high pressure) has the lowest volumetric energy value among other fuels. In other words, large storage volume and pressure are needed to generate sufficient energy. Hence, hydrogen storage for transportation is indeed a great challenge which needs to be overcome by scientist and researchers.

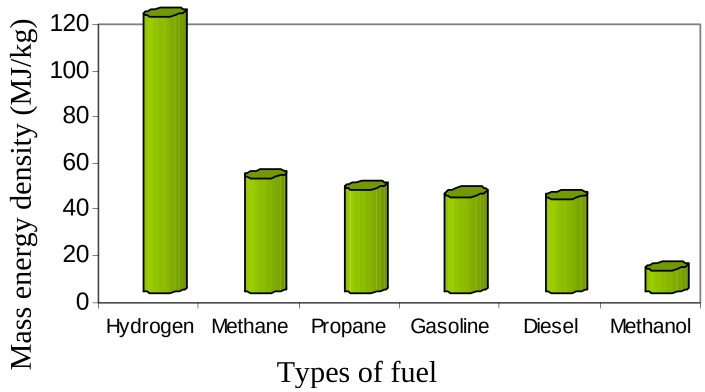

Figure 1.2 Mass energy density of fuels (Tzimas et al., 2003)

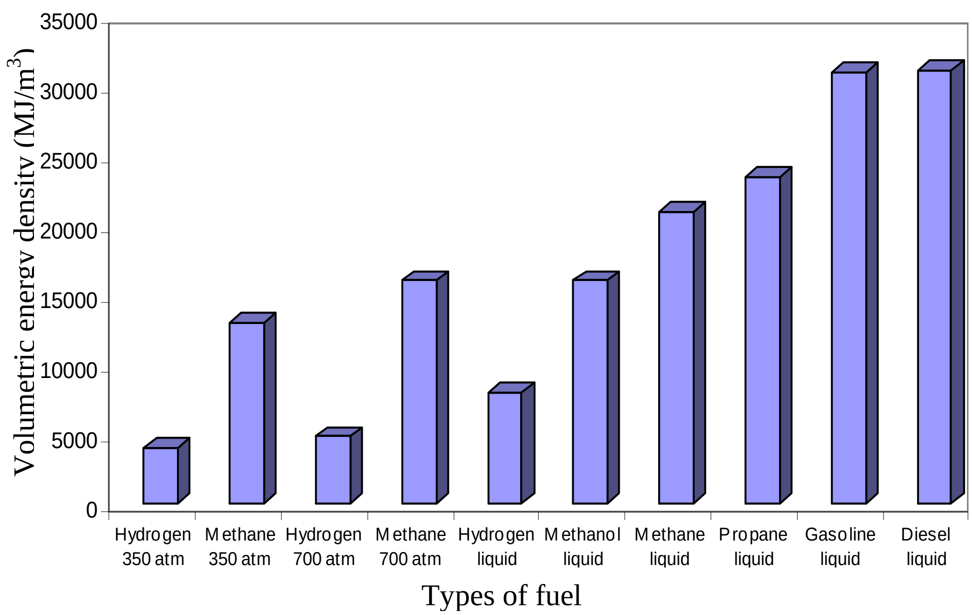

Figure 1.3 Volumetric energy density of typical types of fuel (Tzimas et al., 2003)

1.5 Hydrogen storage and the technological hurdles

The Hydrogen Program under U.S. Department of Energy (DoE) has stated that for an onboard vehicle, a light-duty fuel cell vehicle must carry approximately 5-13 kilograms of hydrogen on board (depending on the size and type of vehicle) to allow a driving range of more than 300 miles (483 km). The perfect hydrogen storage is still under research since none of the storage methods have achieved the similar volume of typical gasoline tank as in Figure 1.4. All current volumes of storage methods are way up higher than the targeted value which should be achieved by year 2015. Specifically, the DoE has set up new prospective targets for hydrogen storage in 482 km vehicle range as in Table 1.4 (Tzimas et al., 2003).

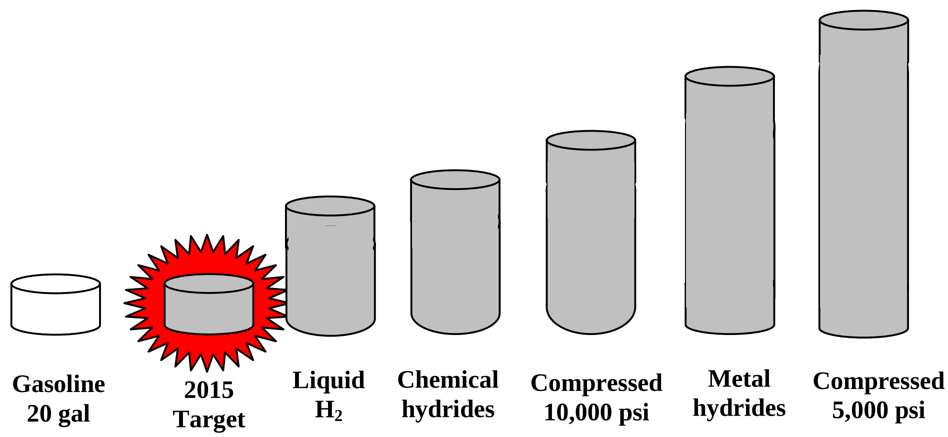

Figure 1.4 Relative volume needed for hydrogen storage to achieve more than 300 miles (Hydrogen.gov, 2009)

Vehicle range will be an important factor to consumers, especially as hydrogen refueling infrastructure begins to develop. Fuel cell vehicle with ranges of 300-400 miles (483 to 644 kilometers) will be needed, requiring roughly 5 kilograms of hydrogen to be stored on-board (Abraham, 2002). The key of challenges for sufficient hydrogen storage in onboard vehicle has been described by DoE as below (US Department of Energy, 2006):

Table 1.4 DoE hydrogen storage target by year 2010 and 2015 (Freedom car and fuel partnership, 2005)

Storage parameter	Target year	
	2010	2015
Gravimetric capacity (Wh/kg) / Specific energy (H_2/kg)	2.0 / 0.060	3.0 / 0.090
System weight (kg)	83	55.6
Volumetric capacity (kWh/L) / Energy density (kg H_2/L)	1.5 / 0.045	2.7 / 0.081
System volume (L)	111	62
Storage system cost ($/kWh)	4	2
System cost ($)	666	333
Refueling rate (kg H_2/min)	1.5	2.0
Refueling time (min)	3.3	2.5

1.5.1 Weight and Volume

Current weight and volume of hydrogen storage are too high for onboard vehicle that requires compact and light weight storage system as in conventional petroleum fueled vehicle.

1.5.2 Efficiency

The energy required to get hydrogen in and out is an issue for reversible solid-state materials. Life-cycle energy efficiency is a challenge for chemical hydride storage in which the by-product is regenerated off-board. In addition, the energy associated with compression and liquefaction must be considered for compressed and liquid hydrogen technologies.

1.5.3 Durability

Materials and components are needed that allow hydrogen storage systems with a lifetime of 1500 cycles.

1.5.4 Refueling Time

There is a need to develop hydrogen storage systems with refueling time of less than three minutes, over the lifetime of the system.

1.5.5 Cost

Low-cost materials and components for hydrogen storage systems are needed, as well as low-cost, high-volume manufacturing methods.

1.5.6 Codes and Standards

Applicable codes and standards for hydrogen storage systems and interface technologies should be established. Standardized hardware and operating procedures, and applicable codes and standards are required as well.

1.5.7 Life cycle and Efficiency analysis

More analyses of the full life-cycle cost and efficiency for hydrogen storage systems are required.

1.6 Pro and Cons in different types of hydrogen storage

Hydrogen, in comparison, is quite difficult to store or transport with the existing current technology. Although it has good energy density by weight, it requires a larger tank to store due to its poor energy density by volume. A large hydrogen tank will be heavier than the small hydrocarbon tank used to store the same amount of energy (provided that all other factors remaining equal). Increasing gas pressure will improve the energy density by volume that is by making the container tank smaller but unfortunately the tank gets heavier. Alternatively, the gas can be compressed but this will require energy to power the compressor. Subsequently, higher compression means more energy lost due to the compression step.

Hydrogen can be stored as physical storage and chemical storage. For physical storage, the gas is compressed at high pressure such as compressed hydrogen and glass microspheres or the gas is cooled at cryogenic temperature (liquid hydrogen). Chemical storage covers both reversible and irreversible reaction. Reversible chemical storage is when hydrogen is stored in a material based such as on the surface of the solid (physical adsorption) or within solids (chemical absorption). Hydrogen can be released and refilled without physically removing the storage medium from the vehicle. The case of irreversible chemical storage system involves releasing hydrogen via onboard chemical reaction with the storage material and replenishing the hydrogen off-board. The different types of hydrogen storage can be summarized in Figure 1.5. The details of each type of hydrogen storage will be explained in the following section.

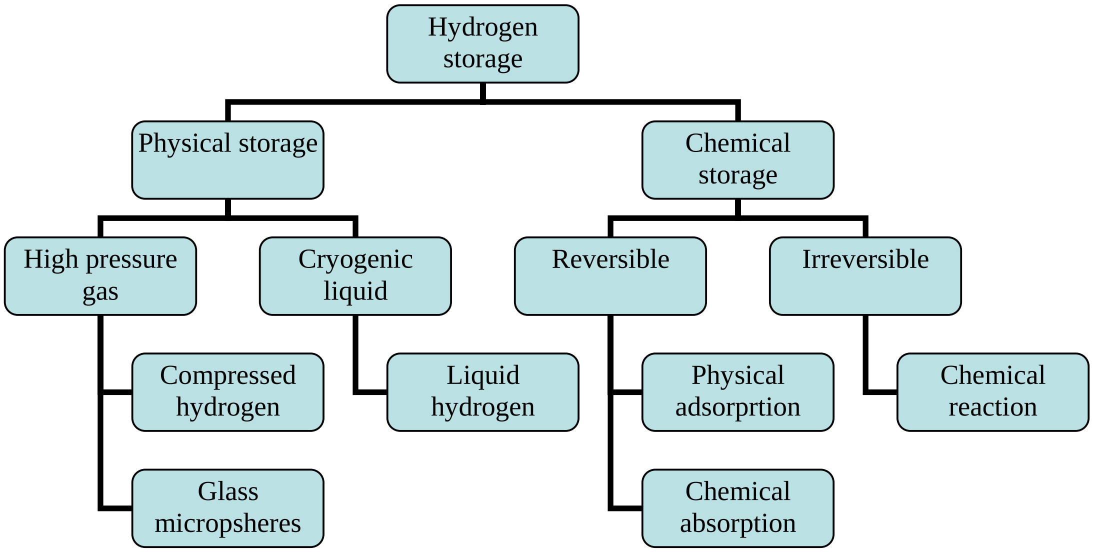

Figure 1.5 Types of hydrogen storage

1.6.1 Compressed hydrogen

The most conventional way to store hydrogen is by compressing the gas at high pressure between 200 to 350 bar or sometimes even up to 700 bar. By increasing the gas pressure, the volumetric energy density can be improved where storage efficiency is estimated between 10-12 wt%. This technology is well in hand to a field demonstration vehicle with ready availability of gas at almost any desired flow rate.

Although the system is relatively simple, extra external energy is required to power the compression. In addition, the mass of container tank is heavier since thicker liner of the tank is required to overcome the small, energetic molecules of hydrogen which tends to diffuse through the liner, thus leads to the embrittlement or weakening of its container. As a result, the heavy tank could reduce the fuel economy of the vehicle. For example at 250 atm, the tank is four times bulkier than liquid hydrogen and 15 times bulkier than the energy equivalent volume of gasoline

(Cleveland, 2004). Moreover, for mobile application, safety concerns associated with high pressure should be considered.

1.6.2 Glass microspeheres

Glass microspheres storage method is achieved when hydrogen at a pressure of 700 bar and temperature of 200-400°C permeate a glass sphere of 2-500 microns in diameter and wall thickness of 1 microns. The spheres are then cooled, locking the hydrogen inside the glass ball. A subsequent increase in temperature will release the hydrogen trapped in the spheres. Using this method it is intrinsically safe against catastrophic hydrogen release and resistant to poisoning by atmospheric gases (Async, 2002). Unfortunately, glass microspheres method has low volumetric storage efficiency with maximum practical fill pressure of about 410 bar due to pumping cost. On top of that, pressurizing of the gas will result in broken glasses. The defect of the perfect sphere shape glass will affect the storage performance.

1.6.3 Liquid hydrogen

The first successful test of liquid hydrogen (LH_2) was in one engine of a modified B-57 aircraft during the late 1950s (Cleveland, 2004). Later, LH_2 has been use in air and space craft including the first rocket that was launched in the 1960s. The storage capacity of LH_2 is about 20 wt%. Therefore, it is well suited for aircraft where the mass energy density of hydrogen is higher that is 120 MJ/kg in comparison to jet fuel that is 45 MJ/kg. The mass energy density value counterbalance is roughly four times greater than the volume of storage tank.

However liquid hydrogen is cryogenic and boils at 20.268 K. Cryogenic storage cuts weight but requires large liquefaction energies. The liquefaction process needs an intensive energy since it involves pressurizing and cooling steps. This makes the cost of the storage relatively expensive. Besides that, the liquefied hydrogen has lower volumetric energy density than gasoline by approximately a factor of four, due to the low density of liquid hydrogen. In addition, LH_2 must also be well insulated using super insulated tank to minimize boil off. Ice may form around the tank and help corrode it further if the liquid hydrogen tank insulation fails.

1.6.4 Physical adsorption

In adsorption hydrogen attaches to the surface of material either as hydrogen molecules (H_2) or hydrogen atoms (H). Sorptive processes typically require highly porous materials to maximize the surface area available for hydrogen sorption to occur, and to allow for easy uptake and release of hydrogen from the material. This category of materials-based storage technologies includes a range of carbon-based materials such as carbon nanotubes, aerogels, graphitic nanofibers (including metal doped hybrids), as well as metal-organic frameworks, conducting polymers and clathrates. If structures can be tailored at the nano-scale, hydrogen storage could be enhanced.

The big advantages of physiosorption for hydrogen storage are the low operating pressure, low cost of material, low volume of storage and relatively simple design of the storage. However, the significant drawbacks are that gravimetric and volumetric energy densities are small as well as low operating temperature are necessary. Also, handling and contamination problems might exist during the refueling process.

1.6.5 Chemical absorption

In absorption, hydrogen molecules dissociate into hydrogen atoms that are incorporated into the solid lattice framework such as intermetallic hydride and complex hydride. A simple metal hydride such as $LaNi_5H_6$, incorporates hydrogen into its crystal structure but its gravimetric capacity is too low (~1.3 wt%) and its cost is too high for vehicular applications. However, some hydrides provide low reactivity (high safety) and high hydrogen storage densities (above 10% by weight) such as sodium borohydride, lithium aluminum hydride and ammonia borane. Complex metal hydrides such as alanate (AlH_4) materials have the potential for higher gravimetric hydrogen capacities in the operational window than simple metal hydrides (US Department of Energy, 2006).

In simple crystalline metal hydrides, absorption occurs by an incorporation of atomic hydrogen into interstitial sites in a crystallographic lattice structure of metallic alloys (US Department of Energy, 2006). The metallic alloys absorb hydrogen at low pressure and ambient temperature to create hydrides. The advantages of this technique are that the volumetric energy density is high, hydrogen can be safely delivered at constant pressure (10 atm), the gas released from the tank is extremely pure and the hydrides can be repeatedly charged. However, the mass energy density or percentage of hydrogen in total hydride weight is low that is about 1-2 wt% weight. Furthermore, the tank is very heavy that is around 1250 kg which is not suitable for onboard vehicles. Another drawback is that since the impurities are left behind, the tank's lifetime and ability to store hydrogen is reduced. In addition, many potential systems such as hydriding and dehydriding kinetics and heat management are also issues that need to be overcome.

1.6.6 Chemical reaction

Hydrogen can be strongly bound within molecular structures as chemical compounds containing hydrogen atoms such as chemical hydride. The chemical reaction route for hydrogen storage involves displacive chemical reactions for both hydrogen generation and hydrogen storage. One good example is sodium borohydride. The hydrogen generation reaction is not reversible under modest temperature/pressure changes. Therefore, although hydrogen can be generated on-board the vehicle, getting hydrogen back into the starting material must be done off-board.

1.7 Hydrogen storage in GNF

Carbon materials are known to be one of the most potential hydrogen storage materials. This is due to their low cost, low density, pore structure, excellent chemical stability and various structural forms. In addition, the structures can be modified using different preparation, carbonization and activation conditions (Thomas, 2007).

An investigation of adsorbing H_2 onto carbon material has begun as early as 1967 (Dillon et al., 2001) using coconut shell charcoal as the adsorbent. Consequently, extensive researches have been done in developing activated carbons (ACs) for H_2 storage purpose. However, although a typical AC has a wide pore size distribution, but only a small fraction of the pores over are strong enough to interact strongly with H_2 molecules at room temperature and moderate pressure. Thus, ACs are ineffective in storing H_2. Today, scientists and researchers have focused on synthesizing carbon nanomaterials such as SWNT, MWNT and GNF which are believed to be potential materials for H_2 storage due to their smaller pore sizes that can attract H_2 molecules at room temperature (Dillon et al., 2001).

Among carbon nanomaterials, GNF has been identified as the most suitable material to store H_2 due to several reasons (Baker, 1998):

1. GNF consists of platelet and herringbone structures, which result in slit-shaped pores where the interlayer spacing between graphenes is 3.4 Å. This spacing is sufficient enough to allow H_2 with kinetic molecular diameter of 2.9 Å to accommodate the spacing and preventing other bigger gas molecules to access through the pores.
2. GNF consists of micropores in majority. Therefore, the adsorption volume could provide a high storage capacity.
3. No cryogenic condition is needed since GNF can retain H_2 at room temperature since the presence of delocalized π-electrons between the graphite platelets creates a strong interaction of solid (carbon) and gas (H_2).
4. For desorption, H_2 molecules are released in a reversible manner at room temperature once the pressure is reduced below a critical level.

Moreover, the fast adsorption and desorption kinetics make the material suitable for fast recharging and discharging of hydrogen (Thomas, 2007). In addition, the dynamic hydrogen molecular diameter is determined as 0.4059 nm. Thus, the most effective micropores should have capillaries of not exceeding a few molecular diameters of the dynamic hydrogen molecular diameter (Hong et al., 2007; Schlapbach et al., 2001). Although CNT possesses similar characteristic as GNF, but due to its long individual rope that can be up to 100µm, closed pore and encapsulation problem, GNF often to be seen as the better storage. In addition, a theoretical study described in (Async, 2002) also strengthen the potential of GNF to store hydrogen as compared with other materials (refer to Figure 1.6).

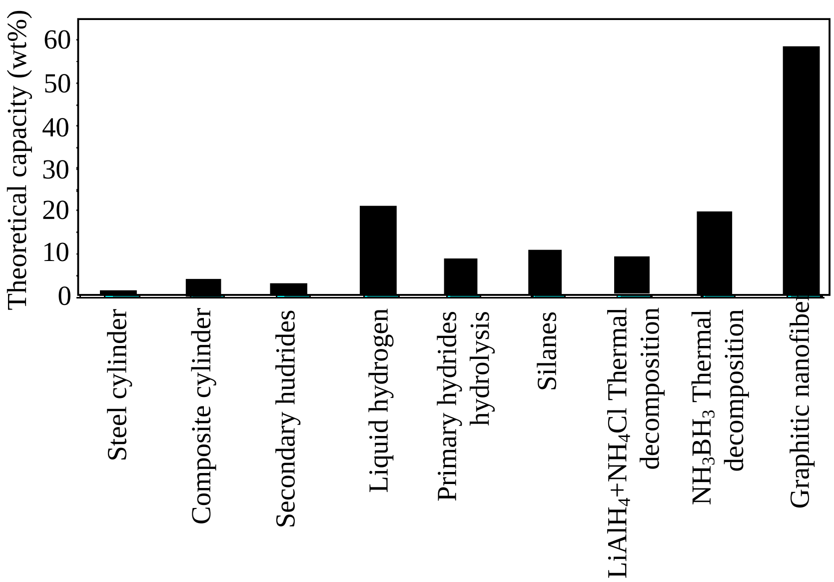

Figure 1.6 Theortical capacities for different hydrogen storage methods excluding ancillaries (Async, 2002)

1.8 Summary

Hydrogen is indeed one of the most potential alternative fuels to replace oil and gas in the future. It provides solution to most of the current problems occurred in the usage of the fossil fuels. This chapter gives a clear view on what hydrogen economy is and types of hydrogen storage that already exist in the market (i.e. high pressure and cryogenic tanks) or still under research and development (i.e. material based storage). The next chapter describes more detail on carbon based material specifically carbon nanomaterials which consists of carbon nanotubes and graphitic nanofibers. The discussion includes the preparation, mechanism properties and applications of the materials.

1.9 Problem statement

The current automobile technology in Malaysia is now moving to the use of natural gas vehicle (NGV). Apart from creating less air pollution, natural gas is comparatively cheaper than diesel and petrol. However, like other fossil fuels, natural gas is declining in time. To overcome such problem, hydrogen is preferred as potential fuel to replace natural gas in the future. A transition to hydrogen as a major fuel in the future could significantly change energy economy, reducing air emissions and expanding domestic energy resources.

The current technology of the hydrogen storage system for onboard vehicles is using compressed hydrogen at high pressure (350 bar). However, this method is thought to be expensive and unsafe (due to the high pressure). For sufficient hydrogen storage the system requires an inexpensive, safe, low-weight tank, comparable in volume to a conventional gasoline tank with capability of quick loading and unloading hydrogen fuel.

1.10 Aim and objectives

1.10.1 Main aim

The aim of the research is to investigate the feasibility of carbon particularly graphitic nanofibre (GNF) in adsorbing hydrogen at lower pressure compared to conventional compressed gas storage in onboard vehicle using gravimetric measurement.

1.10.2 Specific objectives

The objectives of the study are as follows:

1. To develop and optimize carbon nanomaterials particularly GNF by applying the Taguchi method as the design of experiment for process optimization purpose.
2. To characterize the developed GNF.
3. To test the developed GNF in its ability for hydrogen adsorption and desorption studies using gravimetric measurement.
4. To predict hydrogen adsorption isotherm using Neuro-fuzzy system at different surface area of adsorbent.

1.11 Scope of study

1. Synthesis and optimization of catalysts of iron (III) oxide (Fe_2O_3) and nickel oxide (NiO), CNT and GNF by applying the Taguchi method as the design of experiment.
2. Characterization of the developed catalysts, CNT and GNF using Raman spectroscopy, X-ray diffractometer (XRD), transmission electron microscope (TEM), high resolution of transmission electron microscope (HRTEM), scanning electron microscope (SEM), field emission scanning electron microscope (FESEM), surface area analyzer and ultrapycnometer.
3. Investigation of pure hydrogen adsorption and desorption capacity using developed GNF.
4. Predicting of hydrogen isotherm data using programming using an assumption free model that is Neuro-fuzzy System and verification of results between model simulation and experimental data.