Analyzing the Physical and Chemical Properties of Hydrogen Gas as an Alternative Energy Storage for the Future Transportation Sector*

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I. INTRODUCTION

The evolution of technology has spawned numerous opportunities that lead to energy efficient transportation systems. Energy utilized for transportation systems throughout the globe has experienced tremendous growth over the past several decades. Passengers travel mainly by automobiles for short and long distances. Many of these conventional vehicles run on fossil fuels that are non-renewable, natural, sources of gasoline. Although producing fossil fuels are much cheaper than reproducing other elements, a major worldwide problem is the pollution from increasing fossil fuel emissions. Figure 1 demonstrates the amount of energy consumed by certain vehicles and sectors. 75% of the total energy is mainly consumed on the Highway where over 40% of the U.S. population owns a vehicle. The remaining 25% of the energy that is not consumed on road is utilized for agricultural, industrial, and constructional purposes. Thus, many scientists are seeking for a more alternative method to reduce such cause of pollution.

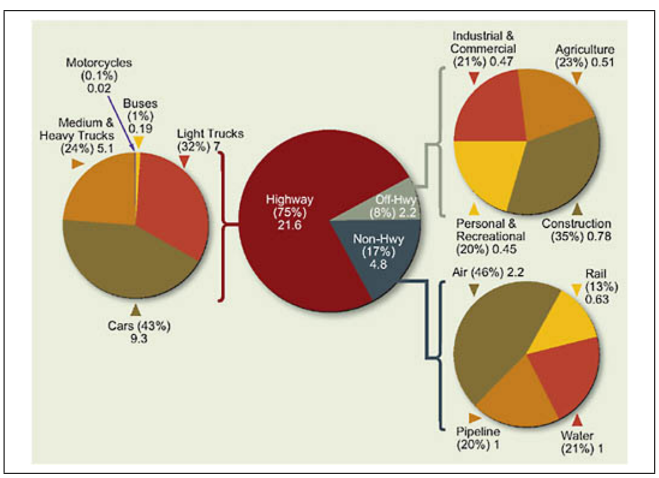

Fig. 1. U.S. Transportation energy consumption by mode and vehicle in 2003 [20]

Mobility is a socio-economic reality that is a necessity now and for the growing future. As an alternative method, for a more fuel-efficient energy storage system, hydrogen comes to mind. Many studies have shown that hydrogen can be an alternative fit for the transportation industry because it is a common element and comes in abundance. The development of hydrogen fuel cell cars raises attention for the near future. Recent developments in hydrogen power electric vehicles are sustainable and environmentally friendly [5]. Like fossil fuels, hydrogen can come from various sources: renewable or non-renewable. The main attraction of this element as fuel is that it gives off zero emissions of CO_2 in the atmosphere when driven. However, hydrogen comes in many ways that emit greenhouse gas (GHG) emissions in the atmosphere during production. One of the many ways to produce hydrogen is from natural gas reformation or gasification which mixes the chemicals of hydrogen, carbon monoxide, and carbon dioxide in order to create natural gas with high temperature steam [24]. Carbon monoxide is then reacted with water to produce an abundance of hydrogen. Figure 2 demonstrates the route for hydrogen production from fossil sources while capturing CO_2 emissions [16].

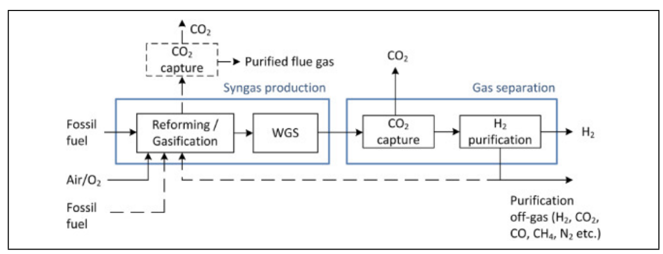

Fig. 2. The route for hydrogen production from fossil fuel sources with CO_2 capture. Solid black lines represent gasification or reformation processing. The dash black lines represents other streams or processing such as methane reformation processing [16].

Around 60% of the CO_2 is captured from the overall process [16]. Another way to produce hydrogen is through electrolysis where an electric current splits water into hydrogen and oxygen. Hydrogen is then also considered renewable as long as the electricity is produced by renewable sources, such as solar or wind [24]. By examining the GHG emissions from various transportation sectors, it is found that the production of hydrogen creates 33% fewer GHG emissions than petrol [24].

Hydrogen fuel cell vehicles (FCV) run on an electric motor generated by electricity. As that happens, a chemical reaction between hydrogen and oxygen forms and is pulled in from the outside to produce only water and heat, thus reducing CO_2 emissions in the atmosphere. Hydrogen is a clean alternative for storing energy in transportation systems because it reduces greenhouse gas emissions by creating water as a discharge. Although hydrogen FCV has many benefits in the economy and the environment, there are also various aspects that need improvement before executing hydrogen FCV into the near future. This approach addresses a fundamental question in the research: Under what safety circumstances is compressed hydrogen gas a more sustainable energy storage for the near future?

Before discussing the safety of hydrogen, the status of hydrogen needs to be further discussed by looking at the economic and environmental impact it will have in comparison to other energy stored vehicles. These other energy storage vehicles, are common amongst the transportation industry, which are conventional, hybrid and electric cars.

The future of the 21st century significantly relies on an eco-friendlier energy production in replacement with todays energy storages. The amount of energy use for transportation in the world has experienced tremendous growth over the past decade [20]. Due to an excessive amount of vehicle ownership, the worlds global energy market is more than 1.5 trillion dollars and heavily relies on fossil fuels [5]. Thus, the rise for a sustainable future transportation system is further discussed by analyzing the issues of one of the most dominant transportation sectors in the world other, the United States. These issues solemnly discuss the amount of increase energy consumption due to growth of vehicle ownership.

Due to high intake of energy produced by fossil fuels in the transportation sector, it remains to be a major source of GHG emissions. An investigated approach between hydrogen and some fossil fuels, such as gasoline and methane, are further analyzed to show how hydrogen is safer for the environment since it does not emit any GHG emissions. Although hydrogen is considered one of the most promising fuels in replacing fossil fuels in the future of the transportation sector, certain safety circumstances must be considered before substantially moving forward. By looking at the main hazards associated with storing hydrogen in addition to a deeper analysis on the effects and conditions of hydrogen cells during refueling, the production of hydrogen FCVs are more likely to be widely accepted in the near future as an alternative energy storage for the transportation sector.

II. Economic and Environmental Analysis of Conventional, Hybrid, Electric and Hydrogen Fuel-Cell Vehicles

Utilizing actual data, an economic and environmental comparison is performed in four types of vehicles; conventional, hybrid, electric and hydrogen fuel cells. The beauty of hydrogen FCV is that they can be produced in many ways that do not always use conventional fuels, such as oil or gas, thus reducing economic dependence on oil producing countries [21, 26]. Using mathematical procedures, which includes economic indicators such as; pricing of the vehicles and their driving ranges are compared. Environmental indicators such as GHG and pollution emissions are also addressed in addition to the vehicles optimal relationships [26]. Nonetheless, it is safe to conclude that the statistics of hydrogen FCV outweigh the conventional, hybrid and electric vehicle through process of elimination given in the data [14].

A. Economic Characteristics of the four vehicles

Utilizing actual data, an economic and environmental comparison is performed in four types of vehicles; conventional, hybrid, electric and hydrogen fuel cells. The beauty of hydrogen FCV is that they can be produced in many ways that do not always use conventional fuels, such as oil or gas, thus reducing economic dependence on oil producing countries [21, 26]. Using mathematical procedures, which includes economic indicators such as; pricing of the vehicles and their driving ranges are compared. Environmental indicators such as GHG and pollution emissions are also addressed in addition to the vehicles optimal relationships [26]. Nonetheless, it is safe to conclude that the statistics of hydrogen FCV outweigh the conventional, hybrid and electric vehicle through process of elimination given in the data [14]. The economic characteristics of each vehicle focuses on their price range, fuel cost, and driving range. Figure 3 demonstrates the economic characteristics of each of the four vehicles in which a 40-L tank is assumed for conventional and hybrid vehicles in order to calculate driving ranges [14, 17].

Type of car	Fuel	Price (thousands US$)	Fuel consumption[a] (MJ per 100 km)	Fuel price (US$ per 100 km)	Driving range (km)	Price of battery changes (changes times price) during life cycle[b] of vehicle (thousands US$)
Conventional	Gasoline	15.3	236.8[c]	2.94	540	1 × 0.1
Hybrid	Gasoline	20.0	137.6	1.71	930	1 × 1.02
Electric	Electricity	42.0	67.2	0.901	164	2 × 15.4
Fuel cell	Hydrogen	100.0	129.5	1.69	355	1 × 0.1

Fig. 3. Lists of the economic characteristics for four vehicles [20].

Although the price of hydrogen cars is much more expensive than others, it consumes about 129.5 MJ/100km of fuel, which is much less than conventional (236.8 MJ/100km) and hybrid (137.6 MJ/100km). The table also shows that the refueling prices for hydrogen ($1.69) is much less than both hybrid ($1.71) and conventional ($2.94), thus indicating that hydrogen is an inexpensive fuel when consuming and refueling [18]. The only downfall is the driving range that hydrogen has in competition with conventional and hybrid. Hydrogens driving range is 355 km total for a given full tank, leading in front are conventional vehicles (540 km) and then hybrid being first with 930 km [25]. The electric vehicle is not competitive in this sector because it is mainly generated through electricity rather than gas, thus weeding this type of mobility noncompetitive with the other three vehicles. In addition to the price ranges of the vehicles, Figure 4 shows the various forms of energy within a given parameter in years [17].

Within the year 2000, it shows the price of gasoline is about

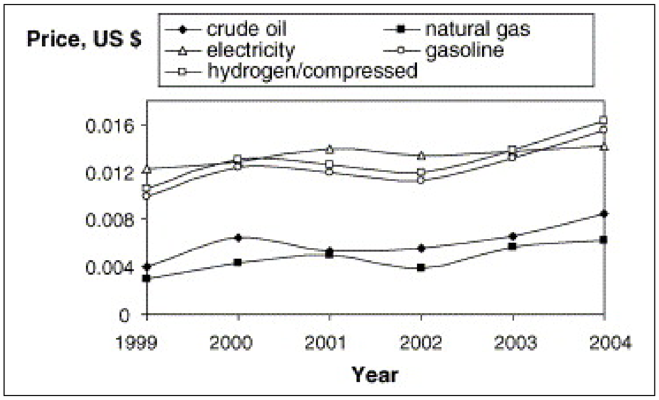

Fig. 4. Prices of selected energy carriers in MJ from 1999 to 2004 [17].

two times that of crude oil, whereas the price of hydrogen is also about two times that of natural gas. Thus, the efficiency of producing gasoline from crude oil and hydrogen from natural gas are similar [17, 27]. However, to utilize hydrogen in vehicles, it must be compressed, liquefied or stored. More chemical work must be done to utilize hydrogen as a FCV, thus the pricing of it is slightly higher than that of gas by about $.01. The issue with the given data is that it is more than a decade ago, in which the economic statistics have tremendously changed throughout the time. Thus, it is uncertain whether the cost of each energy source has risen or dropped within comparison. Crude oil and natural gas are much cheaper than hydrogen, but it does take a huge toll on the environment, emitting carbon dioxide (CO_2). For future studies, a more latest approach on comparing the economic characteristics of the four vehicles during the late 2010s would be a more relevant data to compare these statistics with.

B. Environmental Characteristics of the four vehicles

The environmental impact of each vehicle is measured by examining the air pollution (AP) and GHG emissions during production stages. The main gases in GHG emissions are CO_2, CH_4, N_2O and SF_6 [28]. In figure 5, it shows the impact that each vehicle has on the environment by assuming that GHG and AP are proportional to the vehicle mass [26].

Type of car	Curb mass (kg)	GHG emissions (kg)	AP emissions (kg)	GHG emissions per 100 km of vehicle travel[a] (kg per 100 km)	AP emissions per 100 km of vehicle travel (kg per 100 km)
Conventional	1134	3595.8	8.74	1.490	0.00362
Hybrid	1311	4156.7	10.10	1.722	0.00419
Electric	1588	4758.3	15.09	1.972	0.00625
Fuel cell	1678	9832.4	42.86	4.074	0.0178

Fig. 5. Environmental impact associated with vehicle production stages [14].

Hydrogen FCV, during production, is seen to be emitting the most GHG and AP emissions than all three of the other vehicles compared. That is because more energy is utilized when trying to produce various sources of hydrogen using natural gas, whether it be liquid, compressed or gas. Also, utilizing a mathematical approach,
For conventional vehicles:

$$AP = m_{car}AP_m(1)$$

$$GHG = m_{car}GHG_m(2)$$

For hybrid vehicles:

$$AP = (m_{car} - m_{bat})AP_m + m_{bat}AP_{bat}(3)$$

$$GHG = (m_{car} - m_{bat})GHG + m_{bat}GHG_{bat}(4)$$

For fuel cell vehicles:

$$AP = (m_{car} - m_{fc})AP_m + M_{fc}AP_{fc)}(5)$$

$$GHG = (m_{car} - m_{fc)})GHG_m + m_{fc}GHG_{fc}(6)$$

Where m_{car}, m_{bat}, and m_{fc} are the masses of the cars. AP_m, AP_{bat}, AP_{FC} are air pollution emissions per kilogram of conventional vehicle. GHG_m, GHG_{bat} and GHG_{fc} are greenhouse gas emissions per kilogram of conventional vehicle. These equations were the given approach to calculate the environmental impact associated with each vehicle production. The GHG emissions for hydrogen is 9832.4 kg, which is doubled that from conventional vehicles in which emits 3595.8 kg of GHG during production stages. For AP emissions, hydrogen is leading with most at 42.86 kg, electric with 15.09 kg, hybrid with 10.10 kg, and conventional being the least with 8.74 kg [14]. However, a very interesting study published by the Pembina Institute, compared the total carbon dioxide emissions of fuel cell vehicles using hydrogen produced by various sources of methods, Figure 6 [30].

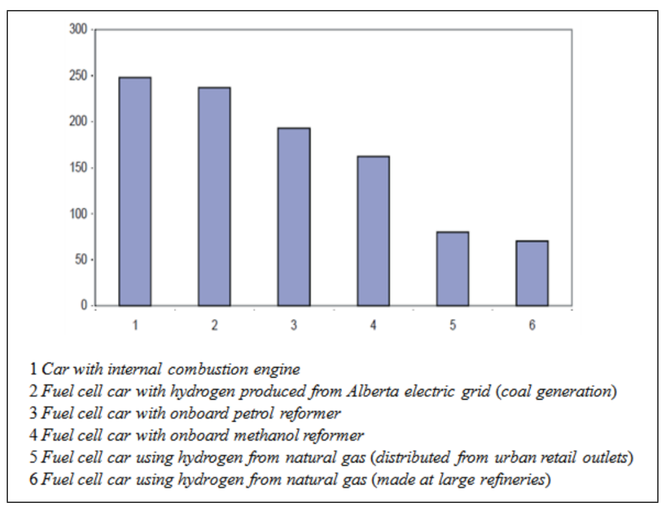

Fig. 6. Graph comparing carbon dioxide emissions in kilograms per 1000km of cars, using different types of fuel sources [22].

These results clearly show that fuel cell car using hydrogen from natural gas emits only about 75 kg/ 1000km of CO_2, which is much less CO_2 in the atmosphere as compared with

cars having internal combustion engine (250 kg/1000km) during production [22, 29, 30]. A further investigation for the AP and GHG emissions of the four vehicles should also be considered in the future for much more accurate environmental data.
The analysis of the four types of vehicles show that each are compatible in improving the economy and environment. However, with the given statistics using various sources in measuring the economic and environmental characteristics of the four vehicles, hydrogen is calculated as the best alternative energy storage for the future. With little AP and GHG emissions during production stages and no emissions during fuel cell usage; fuel-cell technology offers a promising future in the transportation industry.

III. An investigated approach between hydrogen and some fossil fuels

An investigated approach of some fossil fuels is further discussed to demonstrate the negative affect it has on the environment in comparison to hydrogen. There are high fossil usage and consumptions in the transportation sector, in which increases emissions of AP and GHG. Hydrogen comes from a variety of foundations that can chemically separate hydrogen from its source, which is nearly an infinite amount of supply and no additional environmental impact costs [23]. Whereas gasolines sources of energy are from crude oil, where theres only a finite number of supplies left in the world and additional environmental impact costs. In this content, it is important to focus on that environmental impact cost that is the main reason for the earths average temperature increment [4]. The contribution of CO_2 and other compounds contribute to about 76% of the greenhouse effect (GHE). As seen on figure 7,

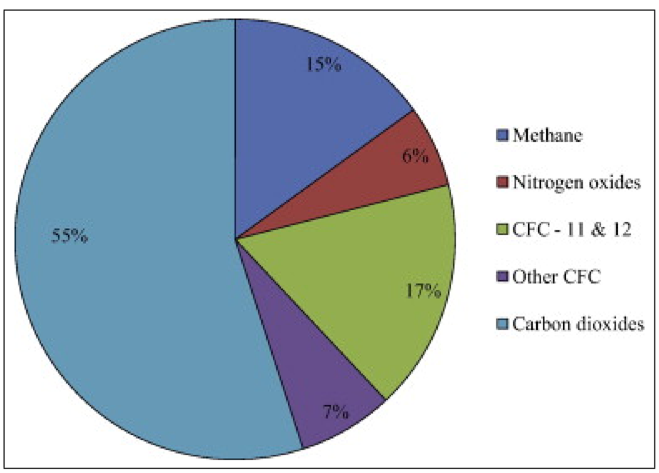

Fig. 7. Percent contribution provided by different greenhouse gases to the earth's average temperature rise [4, 32].

Carbon dioxide (CO_2) contributes about 55%, methane (CH_4) contributes about 15%, and nitrogen oxide (N_2O) contributes to about 6% of the GHG emissions to the earths average temperature rise [31]. In figure 8 shows that about 73% of CO_2 sources are from fossil fuels, mainly emitted from the transportation sectors [32].

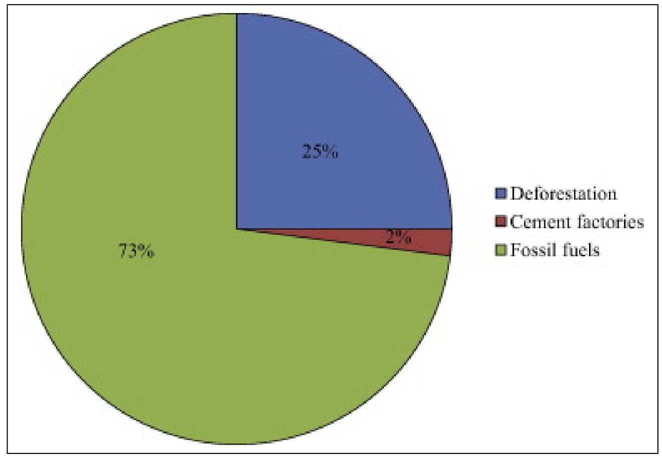

Fig. 8. Main CO_2 sources [4, 32].

Figure 9 is a bar graph that compares the densities of hydrogen, natural gas, propane and gasoline vapor relative to air being 1.0.

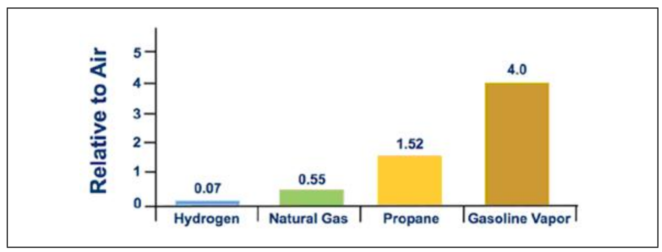

Fig. 9. Bar graph of hydrogen and some fossil fuels relative to air [21].

As shown, hydrogen is about 14 times lighter than air, this means that when hydrogen is released from its tank and exposed to air, it will typically rise and disperse rapidly. In comparison with gasoline vapor being 4.0, hydrogens vapor density is .07, which means that hydrogen is about 57 times lighter than gasoline vapor [21]. When gasoline vapor is released during the combustion of fossil fuels, it creates a more toxic odor when discharging since its density is much heavier than most gases. In relation to density, the chemical compounds diffusion coefficients are also important in determining the compounds toxicity. figure 10 analyzes gasoline and hydrogens physics and chemical compounds much closer using various papers;

With low density and high diffusion coefficient causes buoyancy relative to air, thus hydrogen is a safer compound as an alternative source because it can easily disperse rapidly when exposed to air. The specific heat causes the fuel to be safer because it slows down the temperature increases for a given heat input [3]. Each of these given factors relates to the flame emissivity, if the density is low, diffusion coefficient is high, and the specific heat is high, then the flame emissivity is low. Flame emissivity is the strength of the flame which emits thermal radiation. Thermal radiation of the flame increases

Property	Gasoline	Methane	Hydrogen
Emission and Toxicity	CO2, CO, NO***	CH4***	H2O vapor*
Density' (kg/m^3) (w.r.t air = 1)	4.40***	0.65**	0.084*
Diffusion coefficient in air' (cm^2/s)	0.05***	0.16**	0.610*
Specific heat' (J/g K)	1.20***	2.22**	14.89*
Ignition limits in air (vol%)	1.0-7.6*	5.3-15.0**	4.0-75.0***
Explosion limit in air (vol%)	1.1-3.3*	6.3-14.0**	13.0-59.0***
Ignition energy in air (MJ)	0.24**	0.29*	0.02***
Flame emissivity (%)	34-43***	25-33**	17-25*
Safety factor	.53***	.80**	1.00*
** - safest; ** - less safe; *** - least safe*			

Fig. 10. Physical and chemical properties of hydrogen and gasoline. The highlighted parts demonstrate hydrogen being the safest. [3, 13, 18, 33]

if the diameter of the flame increases and ignition limit is high. The safety factor was calculated to compare the two fuel's safety aspects. The safety factor is a ratio of how reliable a vehicle is given the calculate data of both hydrogen and gasoline's properties. A factor of safety below one represents that the vehicle is unsafe for the environment, a factor of one means that it is safe, and a factor above one is absolutely safe for the environment [3]. It was reported that hydrogen is the safest fuel with a safety factor of 1.0 and gasoline having a safety factor of .53. Whats assumed in this table is that most of the properties are at normal temperature and pressure. Also, the ignition energy and flame temperature were calculated in Celsius from Sonal Singhs paper, which was then measured to Kelvins for absolute temperature measurements [3]. Nonetheless, given the data from various papers, it is safe to conclude that hydrogen is much safer for the environment. However, when it comes to hydrogen storage, such as refueling, certain hazards need to be addressed.

IV. Direct Dangers and Situations in Hydrogen Use

Although hydrogen is considered one of the most promising fuels in replacing fossil fuels in the future of the transportation sector, certain circumstances must be considered before substantially moving forward. Some of these concerns are from [1];

- Explosions
- Hydrogen embrittlement
- Hydrogen leakage
- High pressurization during refueling

In figure 11, a ranking of hydrogen and some fossil fuels safety were analyzed to demonstrate each fuels safety during ignition [3]. Hydrogen is safe in most of the characteristics that were listed, but is ranked unsafe for the ignition limit, ignition energy, and flame temperature [3, 4].

Particularly, hydrogen is not a dangerous fuel, although in areas where its ranked unsafe is because hydrogen has the widest explosion/ ignition mix range when reacted with air of all gases [22]. Figure 12 compares some of the fossil fuels and hydrogen with calculated statistics.

The ignition limit in air for hydrogen is 75.0 vol%, which is 10 times higher than that of gasoline (7.6 vol%) [3,

	Fuel ranking[a]		
Characteristic	Gasoline	Methane	Hydrogen
Toxicity of fuel	3	2	1
Toxicity of combustion (CO, SOx, NOx, HC, PM)	3	2	1
Density	3	2	1
Diffusion coefficient	3	2	1
Specific heat	3	2	1
Ignition limit	1	2	3
Ignition energy	2	1	3
Ignition temperature	3	2	1
Flame temperature	3	1	2
Explosion energy	3	2	1
Flame emissivity	3	2	1
Totals	30	20	16
Safety factor	0.53	0.80	1.00

Fig. 11. Ranking of gasoline, methane and hydrogen. 3 - least safe, 2 - less safe, 1 - safe [3, 33]

Property	Gasoline	Methane	Hydrogen
Density (kg/m^3)	4.40	0.65	0.84
Diffusion coefficient in air (cm^2/s)	0.05	0.16	0.610
Specific heat at constant pressure (J/kg K)	1.20	2.22	14.89
Flammable limit in air (vol%)	1.0–7.6	5.3–15.0	4.0–75.0
Flammable energy in air (MJ)	0.24	0.29	0.02
Flammable temperature (K)	501–744	813	858
Flame temperature in air (K)	2470	2148	2318
Explosion limit in air (vol%)	1.1–3.3	6.3–14.0	13.0–59.0

Fig. 12. Physical and chemical properties for safety consideration of three investigated fuels [4].

4, 33]. Higher ignition limit is dangerous because when hydrogen leaks from the storage tank, it reacts quickly with air, which is a wide range to react with. The ignition energy for hydrogen is .02 MJ, which is 12 times less than gasoline (.24 MJ). With lower ignition energy means that hydrogen takes less work to ignite during a leakage, which leads to a lower flame temperature in air. Hydrogens flame temperature in air is 2318 K, whereas gasolines flame temperature is 2470 K. Although the difference between the two gases are a little over 150 K, lower flame temperature causes less impact on the vehicle and the environment during explosions.

A. Explosions

A Hydrogen and Fuel Cell Vehicles Safety Evaluation was constructed to compare high pressured tank-mounting vehicles with gasoline vehicles. Figure 13 to 15 shows the states of flame at the time of maximum strength between gasoline and hydrogen fuel types [15]. For the sources of vehicle fires, the ignition of solid fuels was utilized to demonstrate a more natural fire. This scenario is mainly for what would happen if gasoline and hydrogen FCV come to a collision in which both reach their maximum flammability limit and temperature in air. For gasoline, in figure 13, shows

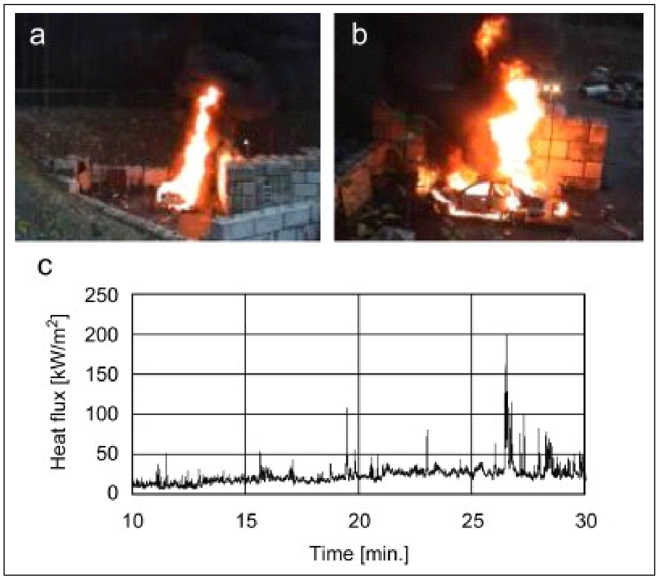

Fig. 13. Gasoline flame from a vehicle filled with 40-L tank. (a) back view, (b) side view, (c) graph of heat flux with respect to time [15].

an ordinary steel gasoline tank with 40-L of gasoline filled. Results show that after 14 minutes of ignition, gasoline vapor leaking from the seals of the gas tank burned and caused erratic flames. Therefore, various values of heat radiations were recorded, but the maximum value of the heat radiated was about 200 kW/m^2 at about 26 minutes. The duration of the flame was measured passed 30 minutes and seemed to increase in the image, but the literature did not specify how long the flame continued after 30 minutes. Figure 14

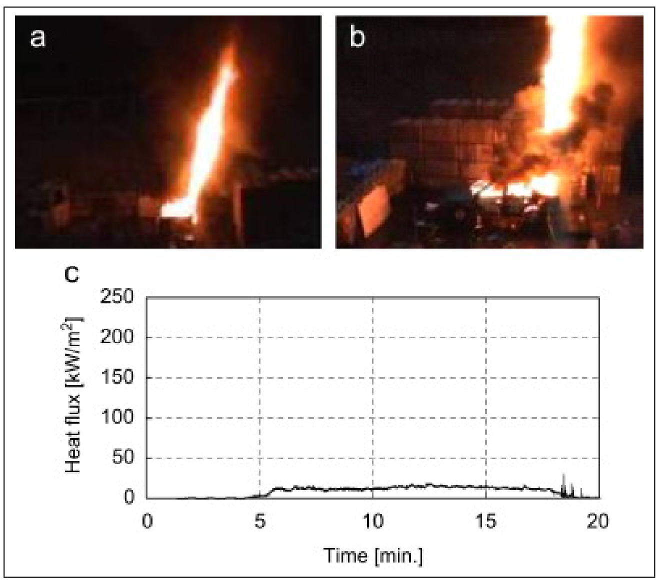

Fig. 14. Upward hydrogen flame from a vehicle with two 35MPa installed. (a) back view, (b) side view, (c) heat flux with respect to time [15].

demonstrates the case of mounting two 35 MPa high pressure hydrogen tank in the trunk of the vehicle in which hydrogen began to release upward and emit about 25 kW/m^2 of constant heat flux, much less than that of gasoline. The duration of the flame was measured to be about 16 minutes, but no conspicuous peak of heat radiation was measured [15]. If compared with the physical properties for safety, then the ignition limit is much lower during the spread of fire, small effect of the heat radiation in its surrounding, which is also known as the flame emissivity, and a constant heat flow of temperature in air compared to gasoline. Figure 15 shows

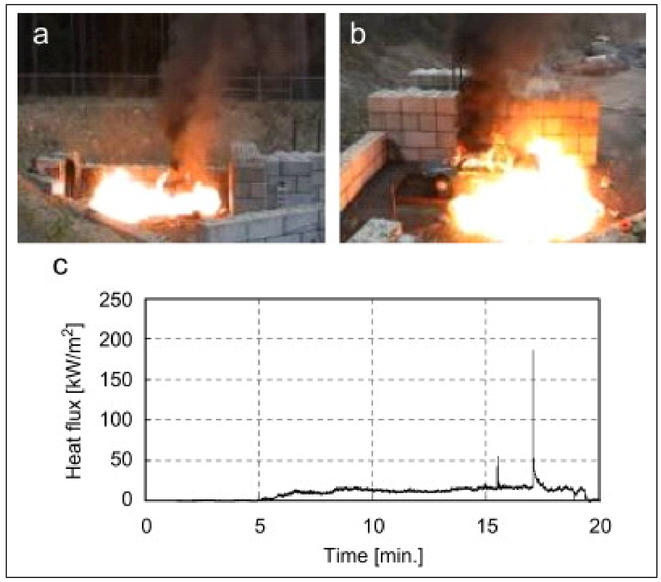

Fig. 15. Downward hydrogen flame from vehicle with two 35MPa installed. (a) back view, (b) side view, (c) heat flux with respect to time [15].

the same case for the hydrogen tank, where two 35MPa high pressure hydrogen tanks were mounted, however, hydrogen was released downward rather than upward. Because of that, the heat flux after 17 minutes of ignition radiated up to 190 kW/m^2, which is near to gasolines heat radiation, 200 kW/m^2. As seen in the given data, when hydrogen flame ignites downward, its flame limit in air is much wider in volume than gasoline. By comparing the images of gasoline and downward hydrogen flames, hydrogen covers a wide range of volume because of its reaction with air. However, its ignition time lasts much shorter than gasoline. In the literature, the ignition length for gasoline is uncertain, which does not give an accurate measurement in the difference between the two fuels.

B. Hydrogen embrittlement and leakage

Hydrogen fuel-cell cars suffer from many sudden failures in their parts and machineries because of unexpected effects hydrogen reacts towards metal used on vehicles. Although hydrogen is viewed as one of the promising alternative energy storages for transport, hydrogens chemical element has made many unusual distortions when reacted with metal fuel tanks such as steel, aluminum and magnesium causing a deformation known as embrittlement that can cause leakage in the tank [35]. It has been shown that during low temperatures inside storage tanks, hydrogen can penetrate through metal frameworks during corrosion since mild steel and most iron alloys tend to lose their tensile strength and risk mechanical failure [1]. In order to catch these deformations from letting hydrogen leak, a SEA Technical Information Report has been created to address the safety performance of hydrogen storage and through performance testing [35]. A durability test of the compressed hydrogen storage system (CHSS) was conducted by subjecting a prototype containment vessel to pressure cycling with hydrogen gas [35] that measured the effects of hydrogen embrittlement on mechanical work. Figure 16 demonstrates a schematic procedure of CHSS during (a) performance testing (pneumatic) and (b) durability testing (hydraulic) [35]. The performance (pneumatic) test

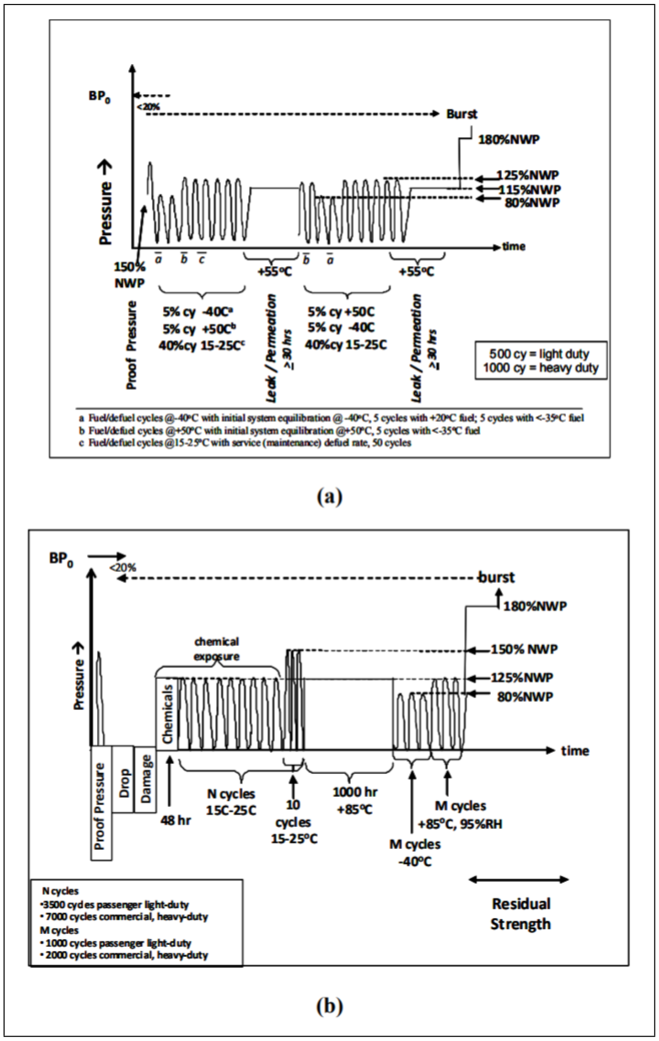

Fig. 16. Schematics showing protocols for (a) the expected service performance test (pneumatic) and (b) the durability test (hydraulic) [35].

is for evaluating the effect of hydrogen embrittlement using hydrogen gas. If the results show that the metal has accepted hydrogen embrittlement resistance, then the durability of the vessel can be evaluated from the hydraulics test [35]. Two temperatures, 223.15 K and 293.15 K are specified because hydrogen embrittlement depends on temperature and one of the two temperatures measured typically corresponds to the maximum embrittlement in most metals [35, 36]. It is expected, however uncertain, that the operating temperature for a hydrogen tank can reach 223.15 K, which is the critical temperature for embrittlement. Thus, the materials of the tank, their performance during compressed hydrogen fueling, and durability should be further tested for safety considerations in order to fully accept hydrogen as an alternative energy fuel.

C. High pressurization during refueling

Throughout the paper, hydrogen is concluded to be a clean alternative in replacing some common fuels such as gasoline in the transportation sector. When it comes to hydrogen storage tanks, hydrogen fueling stations usually store hydrogen in either high pressure buffer or cascade systems. Figure 17 shows a diagram of a typical hydrogen fueling station, where hydrogen is compressed using a multi-stage compressor and collects the hydrogen in the storage system [37]. The storage system comes in several sizes of large cylinders, typically from 50-L to a little over 100-L capacity [6]. The buffer storage system shown in figure 18,

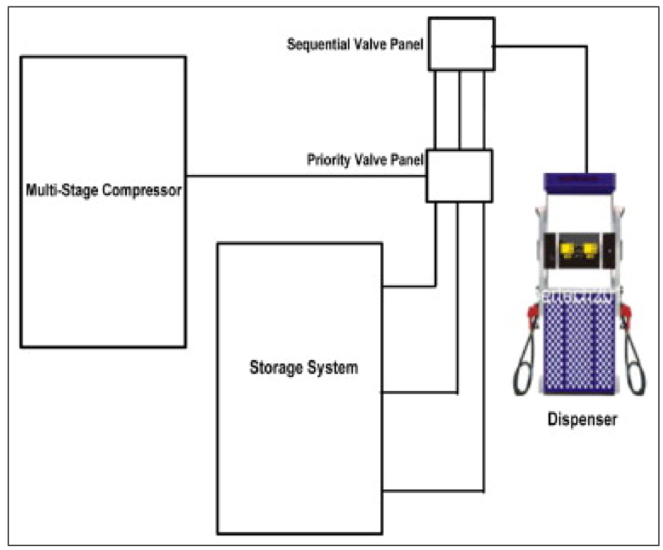

Fig. 17. A schematic diagram of a typical hydrogen fueling station [6].

operates in the range of 37-70MPa. In this type of storage, the reservoir temperature and pressure are assumed to be equal to 300K and 37MPa [6]. The cascade storage systems

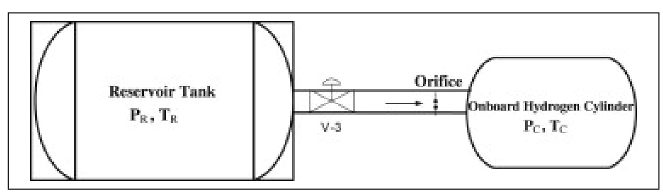

Fig. 18. A schematic diagram of the buffer storage system [6].

shown in figure 19 consists of three reservoirs that are divided into low, medium and high-pressure reservoirs. Each reservoir also contains large cylinders in which are put into ascending pressure. During filling, the hydrogen cylinder is first connected to the low-pressure reservoir until it reaches a pre-set level that switches the system to the medium-pressure reservoir and then the high-pressure reservoir to complete the fill [6]. During refueling, dangers such as over pressurization

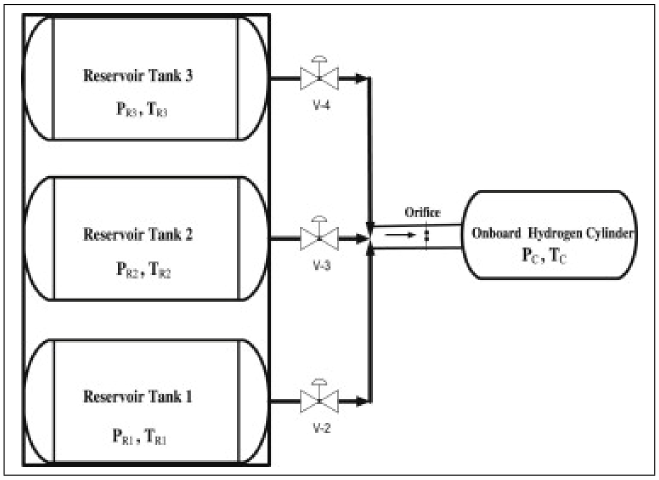

Fig. 19. A schematic diagram of the cascade storage system [6].

in the tank is likely to occur due to mass filling rate and initial pressure of the cylinder were considered [9]. During refueling, for a buffer in comparison to cascade storage system, the pressure of the fluid within the pores of the reservoirs are at instant and constant high-pressure. This can be dangerous for the material of the storage tank due to over pressurization that can cause cracks and leaks around the circumference of the tank. Also, as pressure rises, so does the temperature of the tank. Figure 20 shows various temperature rises each at initial pressure [9]. However, in the

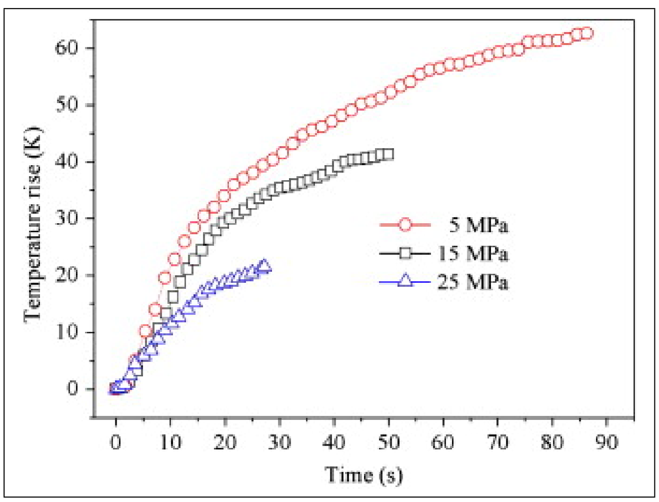

Fig. 20. Temperature rise with different initial pressure in the cylinder [9].

image it shows that 25MPa has the smallest temperature rise with respect to time. It indicated that the temperature filling process was determined by mass filling rate, the temperature of the gas, the initial pressure in the cylinder and the initial temperature in the cylinder. This showed that the ambient temperature has only a small effect on the temperature rise. Although high pressure intake on the storage tank can cause deformation and leakage, it takes a much longer time for the temperature of the tank to increase at a much higher-pressure reservoir than a low-pressure reservoir. Nonetheless, safety factors like over pressurization during refueling can cause serious dangers and fire hazards more commonly than gasoline since when hydrogen does leak out from the tank and is heated, it releases water vapor and heat. Hydrogen can be and has been handled safely and carefully many times, just like any other fuel. Hydrogen tanks have been put through a series of tests for performance, durability, and pressure. Although hydrogen is still a dangerous chemical to toggle with, at times the gas rather leaks out, burns, but hardly ever explodes [22]. Another issue that another literature mentioned that causes pressure and temperature rise during refueling is because the compressor hydrogen gas is not cooled at a given temperature. CHSS must be cooled to about -30 degrees to the hydrogen station before refueling to prevent a rise in temperature in the tank that causes embrittlement, leakage, or even explosions [18].

V. CONCLUSIONS

The future of alternative energy storage for vehicles is bright because the use of hydrogen in the economy provides various solutions to environmental situations. Hydrogen is as flexible as electricity in that it can be produced in both renewable and non-renewable sources of energy. However, the literature written focuses on the conditions that are needed to be accounted for when it comes to switching to hydrogen as an alternative energy storage using statistical analysis. By taking an economic and environmental investigation, hydrogen has the best air pollution emissions in comparison to conventional, hybrid and electric vehicles. It is also found that hydrogen fuel cell vehicles are simpler in design which accounts for its weight that is much lighter than most vehicles. Ergo, hydrogen is the preferred fuel for fuel cell vehicles because of efficiency that can increase the potential for a sustainable climate. The disagreement in this literature states that hydrogen is cost effective, but in the scope of various research paper, it is not because refueling hydrogen cost much more than refueling a traditional gasoline car. A comparison of hydrogen and fossil fuels were also discussed in this paper to get into an investigated approach about the environment. On the transition path from fossil to hydrogen fueling, the growth of the economy will surely prosper. But various gaps in the literature that compares the two fuel sources are addressed since many scenarios are being played out rather than tested. This limits the scope of what data is significant and what is assumed. However, it does provide a wide range of opportunities for future research. For future work, further studies on the replacement of fossil fuels with hydrogen fuels are required to show true environmental statistics. When thats the case, an accurate measurement of a more energy efficient transportation system that uses hydrogen fuel vs traditional fossil fuels can be utilized in further research and the future. This study will help consider the environmental considerations within the basis of introducing hydrogen into the economy as a modern transportation system. Using hydrogen is a clean alternative way to store as fuel in automobiles because it has a positive impact on the environment, but can lead to a series of hazards arising from hydrogen storage. These hazards can lead to a series of accident type problems like hydrogen embrittlement, leakage, over pressurization and explosions when hydrogen is not handled properly. For future work, further investigation on embrittlement of storage tanks and various temperatures should be considered during refueling and non-refueling times. Further investigation on the effects and conditions of hydrogen fuel cells caused by refueling should also be addressed before switching to hydrogen as a more ecofriendly path for future automobiles and the environment. Consequently, no disagreements within the literatures were addressed. Hydrogen is an important feedstock to progressing into a more sustainable future. Overall, studying the safety conditions of hydrogens physical and chemical properties will give the audience a much deeper perspective in accepting hydrogen as a replacement for fossil fuels to store energy for automobiles.

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