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COMPARISON OF HYDROGEN FUELED POWER SOURCES

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1.0 INTRODUCTION

Hydrogen made from electrolyzed water or ammonia produced from this hydrogen are prime candidates to replace fossil fuels. These fuels can be made from renewable energy sources, which will reduce carbon based air pollution and greenhouse gases that contribute to global warming. They can be used as the power source in vehicles, rotating machinery, and electrical generation without creating pollution associated with conventional hydrocarbons. Hydrogen fuel can be used in conventional Combustion Turbines (jet engines), Internal Combustion Engines (ICEs) or one of several types of Fuel Cells including Proton Exchange Membrane (PEM), Solid Oxide (SO), Phosphoric Acid (PA), Molten Carbonate (MC), or Alkaline applications. Hydrogen, ammonia or a combination of ammonia/hydrogen can be used as fuels directly in an ICE system. All fuel cell systems require purified hydrogen.

The hydrogen (H_2) fuel industry is extremely complex and diverse covering everything from H_2 liquid fueled rockets to small computer devices. This paper narrows its focus to the advantages and disadvantages of these systems in applications for the 80-250 kW (120 to 375 hp) electrical range for mobile and stationary applications:

- Polymer Exchange Membrane - PEM - Fuel Cell electrical generation
- Hydrogen Internal Combustion Engines - HICEs
- Ammonia Internal Combustion Engines - AICEs
- Hydrogen/Ammonia Internal Combustion Engines – H/AICEs

There are advocates for the use of each of these hydrogen fueled power systems. This paper discusses each of the above applications with an objective dialogue describing the strengths and weaknesses of each use. [1][2][3][4]

It contains the collective thoughts of Ted Hollinger, of the Hydrogen Engine Center; William (Bill) Ayres, of Renewable Solutions, LLC ; and David Toyne & Jay Schmuecker who have designed and installed a solar hydrogen and ammonia generation system that powers a tractor.

2.0 POWER OPTIONS

2.1 FUEL CELL ELECTRIC POWER [5]

Fuel cells require hydrogen (H_2) and oxygen (O_2). The H_2 may be produced from fuels which contain carbon; or from the electrolysis of water. The most common hydrogen fuel is derived from methane/natural gas (CH_4) and O_2 is typically supplied from the air

Fuel Cells combine hydrogen and oxygen electrochemically to produce Direct Current (DC) electricity that is converted to Alternating Current (AC) and used to drive electric motors to power vehicles and rotating machinery.
There are many types of fuel cells [4], with the two major fuel cell categories, PEM and High Temperature. An excellent comprehensive analysis of the fuel cell market with a breakdown of manufacturers and end users is available in a 2014 review from E4Tech at http://www.fuelcellindustryreview.com/

2.1.1 POLYMER EXCHANGE MEMBRANE (PEM) FUEL CELLS

PEM systems provide the highest volume of commercialized fuel cells and are usually in the small (1 kW) to medium (100 kW) size range with the current largest use in small stationary power production. The stationary sector represents a large potential number of units for fuel cell technologies, providing markets across all types of uses including small-scale grid-connected combined heat and power units for residential use and to off-grid backup power systems providing uninterruptible power supplies to critical infrastructure.

One of PEM fuel cells most important attributes is that they provide an extremely fast start up and operate at low temperatures between 50^o to 100^o C (106^o to 212^o F). However, a major weakness is that they require extremely high quality H_2 and O_2 and are easily poisoned by carbon monoxide (CO) and other atmospheric gases. The oxygen needed to combine with hydrogen in the fuel cell reaction is provided from air. Care is needed to filter and purify the air to remove airborne particulates or gases that can contaminate, degrade or poison the system.

These pollutants bind tightly with the platinum used in the fuel cell catalyst and quickly decrease efficiency or poison the cell stack. Currently, fuel cell manufacturers are investing in a large amount of research to develop a replacement for platinum that is more tolerant to these poisons.

2.1.2 HIGH TEMPERATURE FUEL CELLS

High temperature fuel cells operate in a range of 600^o to $1{,}100^o$ C ($1{,}112^o$ to $2{,}012^o$ F) and help to internally reform hydrocarbon based fuels to hydrogen and CO_2. High temperature fuel cells are more tolerant to impurities that poison PEM cells. However, small amounts of sulfur contamination in the hydrogen gas can destroy the electrolyte and greatly reduce stack life. The high temperature operation can also be beneficial by allowing the waste heat to be used to produce useful heat and additional electricity.

High temperature systems are best suited for large stationary electrical generation from conventional methane sources. Since these systems are large consumers of hydrogen, they are installed where natural gas pipelines are available. Newer installations provide 1,000 kW systems (1MW) or larger built from a base 250 kW to 350 kW stack module..

2.2 INTERNAL COMBUSTION ENGINES (ICE)

Over 100 years of development and refinement have been invested in the manufacture and operation of the internal combustion engine and development of the petroleum refining industry. Hundreds of millions of engine sales have allowed this industry to provide economical low cost manufacturing. An economy of scale provides production cost advantages due to automobile manufacturing industry size. Current global engine manufacturing exceeded 200,000,000 units per year in 2011[16]. Global parts inventory and millions of trained maintenance service men provide economical maintenance of this well-known power source, particularly in the transportation arena.

ICE units operate on low cost sources of high-density fuels primarily gasoline and diesel fuels. (See chart below.) An efficient global gathering, refining and distribution network is in place worldwide, which allows fueling this industry. These advantages provide for a very economical and robust system, which cannot be challenged easily by alterative fuels.

Fuel Energy Density Comparisons*

	Energy Content (LHV)		Octane Number	300 Mile Range - Tank Size (30 mpg gasoline equivalent)[1]	500 km Range - Tank Size (12.75 km/litre gasoline equivalent)
	Btu/gallon	MJ/liter		Gallons	Litres
Diesel fuel	129,500	36.10	8 - 15	8.8	34.5
Biodiesel	118,300	32.98	25	9.6	37.8
Gasoline	114,100	31.81	86 - 94	10.0	39.2
LPG (propane)	84,300	23.50	120	13.5	53.1
Ethanol	76,100	21.21	109	15.0	58.8
Methanol	56,800	15.83	109	20.1	78.7
NH3	41,700	11.62	130	27.4	107.3
CNG (3600 psi)	41,000	11.43	120	27.8	109.1
Hydrogen (10 kpsi)	16,000	4.46	130	71.3	279.5
Hydrogen (5 kpsi)	6,500	1.81	130	175.5	688.1
Lithium Ion Batttery	3,870	1.08	NA	98.3	385.2

[1]corrected for optimal engine efficiency due to increased compression ratio

* Data provided by the Ammonia Fuels Association

No renewable alternative fuel (except biodiesel) has the ability to be used in a mobile power system with the ability to be refilled quickly, drive 350 miles and do so in any weather condition. Because of these advantages high-density energy hydrocarbon fuels will likely be the fuel of choice for mobile vehicles for many years to come unless events like global warming require the use of other fuels.

2.2.1 HYDROGEN INTERNAL COMBUSTION ENGINES

Hydrogen can be used as an ICE fuel. Hydrogen gas is extremely light and requires large storage volumes or high pressure storage vessels. In our farm tractor the hydrogen is stored at 3,000 psi. Toyota's new fuel cell car the Marai uses 10,000 psi tanks.

High compression ratios in ICE systems are used to increase combustion efficiency, since H_2 has a low energy density. The hydrogen fueled tractor engine has a compression ration of 13.5 to 1. Hydrogen burns extremely fast and requires precise ignition controls; combustion is controlled with modern electronic Engine Control Units (ECUs). The gaseous hydrogen is injected into the spark-ignited combustion chambers. It combines with oxygen to produce an exhaust composed of only water vapor.

2.2.2 AMMONIA INTERNAL COMBUSTION ENGINES

Ammonia (NH_3) can provide stored H_2 to fuel AICEs. Once started the engine operates efficiently on ammonia alone; however, ammonia is a little more difficult to combust by itself when an engine is cold. Providing small amounts of hydrogen gas that is made from ammonia can be mixed with the pure ammonia and provides an easier start. Ten to twenty percent of a hydrogen/ammonia fuel mixture is optimum to start the engine. Ammonia is stored as a liquid at low pressures in the range of 100 to 200 psi and vaporized prior to combustion.

A natural direction of the development for these types of engines is to vaporize the ammonia into a small storage chamber and regulate it into the inlet manifold header controlled by an ECU. This will put precise amounts of the ammonia gas into the engine combustion chamber.

2.2.3 HYDROGEN/AMMONIA INTERNAL COMBUSTION ENGINES

Hydrogen and ammonia ICE engines store hydrogen and ammonia separately as a fuel source. This is the method used the Raphael Schmuecker Memorial Solar Hydrogen System tractor. The hydrogen is injected into the cylinders alone when starting the engine, after a few minutes when the engine has warmed slightly ammonia is added. The liquid ammonia is vaporized and mixed with the intake air, and the combination is ignited by spark plugs. During shutdown, the ammonia is turned off for a minute and the engine run on hydrogen only to burn off any residual ammonia vapor, and then turned off.

3.0 FACTORS

Below is a listing of important factors and the advantages and disadvantages associated with the above power production options.

3.1 VEHICLE EFFICIENCY

When considering PEM fuel cell efficiencies, looking at engines at low and high loads should be considered. PEM system "tank to wheel" efficiencies at low loads are approximately 45%; however, heavy load operation reduces efficiencies. The New European Driving Cycle test measures efficiencies under high, medium and low operating conditions and shows average PEM fuel cell operational efficiency values of about 36% (17)(18).

The shaft output efficiency of a hydrogen fueled ICE is about 40% and that of a Hydrogen/Ammonia engine about 35%. For comparison, gasoline fueled engine shaft output efficiency is about 35%, with a newer Toyota ICE system at 38%.(8) Newer turbo diesel combustion technology is 40% to 45% efficient.

PEM and ICE systems are similar when comparing overall output efficiencies and both drive train efficiencies vary depending on driving conditions and loads.

3.2 COST

Fuel cell power plants are more expensive than ICE systems. The membrane and precious metal catalyst materials (typically platinum) in PEM fuel cells are expensive. A substantial amount of research is being done to replace or decrease the amount of catalyst used, helping to reduce these costs. If lower cost catalyst materials are not discovered, mass-produced fuel cell costs will continue to be expensive because of the limited supply of catalyst materials. At this time, Fuel Cell powered vehicles are typically leased, since they are still in early commercial development and there are still unknowns about operating lifetime.

The United States Department of Energy (DOE) issued a statement and future estimates for fuel cell costs, "The cost of an 80-kWnet automotive polymer electrolyte membrane (PEM) fuel cell system based on next-generation laboratory technology and operating on direct hydrogen is projected to be $55/kW when manufactured at a volume of 500,000 units/year. The expected cost of automotive PEM fuel cell systems based on current technology, planned for commercialization in the 2016 time frame, is approximately $280/kW when manufactured at a volume of 20,000 units/year." (7) Current production is in the low hundreds of units with costs of $10,000/kW to $20,000/kW.

Based on financial, and not lifetime factors, ICE powered vehicles can also be either purchased or leased. ICEs are mass-produced and as a result the price of mass-produced hydrogen or hydrogen/ammonia engines will be competitive with other ICEs. Internal Combustion Engine Electrical Generators are already at the $55/kW cost level due to the development and mass production of these units over the last 100 years.

3.3 DRIVE TRAIN

A fuel cell driven vehicle uses inverters to convert DC to AC, which drive an electric motor that provides rotary motion. This may or may not drive the wheels through a transmission. The ICE output is rotary motion that is transmitted to the drive wheels through a transmission.

An ICE, powered by hydrogen, ammonia, or a combination of hydrogen and ammonia can also be used to power or charge batteries for a conventional “Hybrid” system requiring a smaller ICE and a more overall efficient system.

3.4 EXHAUST NOISE

Naturally aspirated PEM fuel cells reduce noise emissions to an average 60 decibels or about the volume of a normal conversation. Since fuel cells do not rely on combustion and have few moving parts, they are very quiet in stationary electrical generation applications. And because noise pollution is all but eliminated, fuel cells can be sited indoors or outdoors without being obtrusive. This provides an advantage of being able to operate indoors quietly.

However, in performance applications where cars are required to accelerate quickly, or carry heavy loads, PEMs require an electric compressor (super charger) needed to offset the low density H_2 fuel and is very loud operating at high speed (12,000 to 14,000 rpm).

3.5 EMISSIONS

The fuel cell only emits water vapor and excess air. ICEs fueled by hydrogen or hydrogen/ammonia also emit water vapor, excess air and extremely small amounts of NO_X that are well below emission limits.

3.6 CARBON EMISSIONS

There are no carbon emissions from fuel cells or ICEs when hydrogen or ammonia fuel is used. If the hydrogen and ammonia are made from renewable power sources, there are no carbon emissions in the generation as well as the utilization of the fuels.

3.7 VEHICLE ACCELERATION

While fuel cell powered vehicles may accelerate quicker from a standing cold start, traveling velocity decreases faster than an ICE powered vehicle. They are slower than ICEs due to fuel cell stack limitations for high load losses. The Hyundai Tucson fuel cell car has a 0-60 mph time of 12 seconds [(9)(10)] while a conventional BMW Hydrogen 7 ICE is 0-60 mph acceleration rate is 9.5 sec. [(11)]

3.8 ENGINE TUNING

Fuel cells do not need to be tuned, however, maintenance is required for air filters to remove particulates for the O_2 side of the fuel cell and CO scrubbers for incoming H_2 gas. Additional monitoring of stack efficiencies is also necessary because stack decay is a normal part of the fuel cell life.

Hydrogen gas has extremely high flame front speed during combustion in hydrogen fueled ICE and requires precise tuning of the spark and combustion. This is done with the use of modern Engine Control Units (ECUs). The ignition tuning of the spark and combustion is less critical in ICEs fueled with hydrogen/ammonia. Normal engine maintenance includes changing air filters and lubricating oil. However without carbon in the fuel, the oil change intervals can be greatly increased.

3.9 VEHICLE PERSONAL SPACE HEATING

An ICE uses energy from the engine (waste heat from the radiator fluid) to heat the vehicle occupant space.

At this time, electrical fuel cell power has to be diverted to provide electrical heat for vehicle occupants.

3.10 HYDROGEN GENERATION

In years to come, hydrogen itself may become one of the most important fuels for cars since its combustion does not produce carbon dioxide, but there are technical infrastructures and economic problems to be addressed which include manufacture, storage and distribution.

Today, hydrogen is primarily produced from the reforming of natural gas (CH_4) and used as a chemical feedstock to manufacture hydrochloric acid, ammonia, and methanol. Another major use is for hydro-treating petroleum fractions to remove sulfur and also hydrogenation of oil fraction to upgrade hydrocarbons.

Conventional reforming of natural gas to produce H_2 produces CO_2 green house gas emissions and renewable sourced H_2 is being advocated for the future. Renewable energy electrical production to supply power to electrolyzers to manufacture H_2 is gaining traction globally and has the ability to supply H_2 economically in the future.

Currently, it requires about 45 kW hours to produce 1 pound (194 SCF) of hydrogen (equivalent to .45 gallons of gasoline) at 200 psi and then compress it into storage at 3,600 psi. With newer hydrolyzers and ever more efficient equipment, this amount is expected to continue to decline.

3.11 HYDROGEN PURITY

Fuel cell powered vehicles require very pure hydrogen, since any of several contaminants will damage the stack. Special precautions are needed to assure that hydrogen made from fossil fuels is purified so it can be used in fuel cell applications. Very low parts per million of CO and sulphur will poison fuel cell catalysts.

Hydrogen suitable for use in fuel cells can also be made by electrolysis of purified water using renewable power sources. These sources do not involve any carbon emissions in either the generation or utilization of the fuel and the hydrogen is extremely pure.

PEM fuel cell vehicle hydrogen quality is covered under the Proposed International Standardization Organization ISO 14687-2 and SAE J2719.

California has its own Standards covered under California, Title 13 CCR Section 2292.7. There does exist hydrogen specifications for several industries but vehicle standards will require “A” Standard Propellant (99.995%) or “B” High Purity Propellant (99.999%).

A major advantage for HICE, AICE, and H/AICE systems is that they are extremely hearty and tolerant of most conventional contaminants that poison fuel cell stacks. Lower purity hydrogen, and ammonia fuels can be used in internal combustion engines without major issue.

3.12 HYDROGEN COSTS

It is important to note that it is hard to estimate the commercial hydrogen costs for fuel cell vehicles because it is highly subsidized. Industrial Propellant Grade “A” Hydrogen fuel is $4.00 per gallon gasoline equivalent while “B” Grade High Purity is $14.00 per gallon gasoline equivalent. Estimates for future electrolysis H_2 production using $0.03 kW, off peak electricity to operate an electrolyzer could produce “B Grade” hydrogen for about $4.00 per gallon of gasoline equivalent.

Using the example above of 45 kW hours to produce 1 pound of hydrogen and compress it to 3,600 psi, the equivalent gasoline price using $0.03 electrical power would be $2.97 per gallon.

Making ammonia using H2 from the above method and adding existing nitrogen from the air through a modified Haber-Bosch method would produce ammonia at an estimated cost of $1.73 per gallon, with a gasoline equivalency of $4.75 per gallon.

3.13 HYDROGEN STORAGE

Hydrogen gas has good energy density by weight, but poor energy density by volume versus hydrocarbons, hence it requires a larger pressurized tank for storage. A large hydrogen tank will be heavier than the small hydrocarbon tank used to store the same amount of energy, all other factors remaining equal. Increasing gas pressure would improve the energy density by volume, making for smaller, but not lighter as the container tanks become much heavier by volume because of the extra strength required to handle the higher pressure. [15]

The newer fuel cell cars are using Type IV carbon-composite technology in hydrogen tanks at 350 bar (5,000 psi) and 700 bar (10,000 psi).

Hydrogen can be stored as a gas in pressure vessels up to 10,000 psi, or as a liquid at temperatures near absolute zero. Higher pressures and liquid storage increase the cost of H_2.

Hydrogen stored as liquid ammonia, rather than as compressed hydrogen gas, consumes much less volume than gaseous hydrogen, and at lower storage pressures. Ammonia can be stored at about 200 psi, making the storage tanks much more economical.

As demonstrated in our Tractor, a 60 gallon ammonia tank, containing 50 gallons of ammonia, pressurized to 200 psi, contains about the same energy as 40 pounds of hydrogen stored at 3,000 psi in two 21 inch X 10 ft long composite tanks. This is over 5 times the energy density of the stored hydrogen gas.

3.14 AMMONIA GENERATION

Today most ammonia is made from reforming natural gas. As a result of this chemical process, large amounts of CO_2 are emitted into the atmosphere. As conventional fossil resources decrease, the cost of conventional hydrocarbon based hydrogen and ammonia will increase.

However, where hydrogen is available from renewable sources, ammonia can be made using solar or wind power to drive compressors and gas pumps. This ammonia can be considered to be a “green” fuel since it is using renewably generated hydrogen and creates no CO_2 as it is being formed or from the electricity generated to run the process.

3.15 EXPECTED LIFE

While life expectancy of PEM fuel cell systems continues to improve, five years of continuous duty is considered good. The stack itself will need to be replaced as membrane and electrolytes degrade over time. The costs of upgrading or replacing a fuel cell stack will be approximately 50% of a new fuel cell system cost. The electric motors and inverters used in fuel cells have longer life expectancies.

ICEs have been the main source of automotive power for over 100 years, and have demonstrated long lifetimes and easily repaired. When ICE repairs are needed, they can be rebuilt and seldom is a new ICE needed. With clean fuels such as hydrogen and ammonia, the service life of the engines is expected to be substantially extended over conventional gasoline powered ICEs.

3.16 MAINTENANCE PERSONNEL

There are larger numbers of personnel who are experienced maintaining and repairing ICEs. The hydrogen or hydrogen/ ammonia fueled ICEs do not require any sophisticated maintenance knowledge.

As fuel cells are new technology, there are a limited number of personnel or repair locations with the special training and equipment needed to maintain fuel cell powered vehicles. Cleanliness during the repair process is a critical factor.

3.17 REPAIR PARTS

ICE repair parts are readily available. Most of the parts used in hydrogen or hydrogen/ammonia engines can be sourced from conventional gasoline parts suppliers. They are mass produced and relatively inexpensive. Even new engines designed specifically for hydrogen and/or ammonia would be based on existing technology and would fit into existing production capacities.

Most repair parts for fuel cells are not stocked locally and are not mass-produced. This increases the cost and limits supply. Equipment downtime increases since parts need to be shipped longer distances or adequate spares inventoried.

3.18 SERVICE INTERVAL

With fewer moving parts, fuel cell powered vehicles may not need to be serviced more than annually, depending on the incoming air quality.

With the exception of the need to change the engine lubricating oil, an ICE powered vehicle does not need to be serviced more frequently than one that is fuel cell powered. Air filters and oil need to be changed, however because hydrogen fueled engines do not contaminate engine oil with carbon, oil change intervals can be dramatically extended.

3.19 SAFETY

Hydrogen gas is extremely flammable and cannot be seen, smelled, or easily monitored when released. Its flammability range is very large: from 4% to 75%. However, because it is very light, it quickly rises and dissipates when released. There is consensus that hydrogen is safer to work with than gasoline. An excellent paper from DOE discusses the differences and shows a comparison to fuel tank fires with gasoline and hydrogen. The video frames in the paper dramatically show how hydrogen is much safer then gasoline. [(13)]

Ammonia when released as a gas or a liquid changing into a gas; also rises because it is lighter than air. When ammonia comes in contact with water vapor, they rapidly combine. Personnel safety is critical because when significant amounts of ammonia come in contact with the eyes, skin, or mucous membranes, it will cause rapid dehydration and severe burns as it combines with body moisture. A comprehensive discussion can be found on the NH3 Fuel website. [(14)]

One very positive safety characteristic of ammonia is that it has a very distinct, strong odor that can be identified at very low levels, higher then 5 PPM. Therefore, if there is a small leak, it can be identified long before you are exposed to a concentration that is harmful so personnel can immediately move away from it before harmful levels are reached.

Both hydrogen and ammonia can be safely used in an exterior environment. Enclosures that may have hydrogen or ammonia leakage should be continuously vented so that any leaking materials will rise. Ammonia flow levels for commercial and transportation use are much lower than that which is encountered fertilizing corn cropland.

When combined hydrogen and ammonia are used as fuels, the engine is started and shut down using only hydrogen. The ammonia is turned on and off while the engine is operating with hydrogen alone. This reduces the residual ammonia remaining in the engine combustion and intake chambers. The ammonia and hydrogen fuel mixture valves are opened and closed using the same ECUs that are used for combustion control.

Care must be taken around fuel cells because of the hydrogen and high DC voltages generated.

Hydrogen fueling of fuel cells and hydrogen fueled ICEs is the same. Conventional fueling procedures similar to those used in agriculture are needed for ammonia.

4.0 CONCLUSION

There are short and long-term benefits in using hydrogen fuel cells, hydrogen ICEs, hydrogen/ammonia and ammonia ICEs powered installations. In all instances hydrogen must be available as the fuel source. The availability of hydrogen fueling stations is needed as fossil fuel costs increase and as global warming is accepted. Initially, most hydrogen will be made from fossil fuels until renewably generated hydrogen is available economically for fuel cells for the generation of ammonia.

If the problems of cost to manufacture and requirements for super clean hydrogen can be solved, the best long-term solution will be fuel cells. At best it will take several years to bring them into general use and the personnel trained to support them. Ideally, the usage of ammonia to provide the hydrogen would make refueling and fuel storage more efficient. PEM fuel cells are unable to use ammonia-based hydrogen easily at this time.

In the short term, Internal Combustion Engines can be readily modified to burn clean fuel combinations of hydrogen and ammonia. Minimal engine modifications are required to allow the use of these fuels, and existing personnel with conventional mechanic skills could easily be trained to support them. Likely, the most effective use would be as hybrid type vehicles.

Hydrogen and ammonia fuels can be made cleanly using renewable solar power, wind power, and hydro-electric power. The hydrogen fueling station infrastructure is required for either type of "engine" system.

EXTERNAL LINKS

1) http://www.worldometers.info/world-population/
2) http://esa.un.org/unpd/wpp/Publications/Files/Key_Findings_WPP_2015.pdf - Page 1
3) http://www.eia.gov/forecasts/steo/report/global_oil.cfm
4) http://energy.gov/eere/fuelcells/fuel-cell-technologies-office
5) https://en.wikipedia.org/wiki/Fuel_cell - Comparison_of_fuel_cell_types
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