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Design and Development of a Dual-Fuel (Hydrogen + Gasoline) Power System for an Extended Range Electric Vehicle

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Abstract

Hydrogen is an ideal vehicle fuel for use not only in fuel cells, but also in spark-ignition internal combustion engines. The combustion of Hydrogen fuel offers vastly superior tail-pipe emissions when compared with gasoline and can offer improved performance. Hydrogen is ideally suited for use in an extended range electric vehicle architecture where engine efficiency can be optimized for a single engine speed. Hydrogen ICE's are significantly more cost effective then an equivalent sized hydrogen fuel-cell making them a better near term solution. Dual-fuel capabilities are an integral step between the hybrid vehicles of today and the hydrogen economy of tomorrow offering the refuelling flexibility of gasoline and the clean burning characteristics of hydrogen.

Keywords: hydrogen, series HEV, ICE, battery, power management

1 Introduction

In recent decades there has been growing global concerns over the supply and use of fossil fuels in vehicles. This attention has ushered in a new era of automotive research and brought to light an inherent need for a cleaner renewable energy source for fuelling the next generation of automobiles. With many technologies vying for international attention few possess the necessary characteristics to replace crude oil as the main personal transportation fuel. While no clear winner has yet to emerge many experts are predicting that a hydrogen based infrastructure could be the future of automotive propulsion.

Hydrogen is the most abundant element in the universe accounting for 75% of all elemental matter by mass. It is also the second most abundant element in the salt water that makes up earths oceans accounting for approximately 11% by mass. [1] Although elemental hydrogen is rare on earth it can be produced by a number of methods and from a wide variety of sources, such as electrolysis of water and reforming of hydrocarbons. Hydrogen can then be stored on-board the vehicle as either a gas (up to 10000 psi), as a cryogenic liquid or using a metal hydride system.

With regards to vehicle propulsion specifically, hydrogen can be used in both a Fuel Cell (FC) and an Internal Combustion Engine (ICE) as a means of energy conversion. In its simplest terms a Fuel Cell uses hydrogen and air to create electrical energy which can be used to power an electric motor. An ICE on the other hand is used to combust hydrogen capturing stored chemical energy and converting it into mechanical rotational energy. Both systems offer unique benefits and trade-offs. While ICE systems tend to cost less they also tend to be less efficient than a fuel cell system.

The hydrogen infrastructure/economy is still many years away from being a reality. However, there is a significant opportunity in the near term to develop an intermediary vehicle technology to help promote the development of a hydrogen infrastructure while retaining the cost effectiveness and re-fuelling flexibility of the existing fossil fuel infrastructure.

Hybrid vehicles were first popularized in North America with the introduction of the Toyota Prius in 2001 which has since gone on to sell nearly 160,000 units in 2008. [2] The Prius, which utilizes a parallel hybrid architecture uses both an ICE and electric motor to power the wheels. In 2010 General Motors is set to release North America's first series hybrid vehicle, known as the Chevrolet Volt. The Volt, a series hybrid, uses an electric motor to power the wheels and an ICE mated to an electrical generator to recharge the batteries.

This paper illustrates the design and development of a novel dual-fuel power generation system for a series hybrid electric vehicle. For test purposes the power generation system was integrated into a dune buggy chassis as seen in 3D CAD model of the vehicle shown in Figure 1. The dune buggy was chosen as it was readily available and easy to reverse engineer as it was comprised mainly of simple mechanical systems.

Figure 1 - Dual Fuel E-REV Prototype

2 H_2 Fuel Cell vs. H_2ICE

The potential for a hydrogen economy has left many automakers and researchers pondering how to best use one of the most abundant resources in the universe. Hydrogen based fuel cells and Internal Combustion Engines both use hydrogen in two distinct manners to generate power on-board a vehicle.

In short a hydrogen Fuel Cell relies on an electrochemical reaction between hydrogen and a catalyst which separates an electron from the hydrogen atom. The electrons become the source for the Fuel Cells DC current and are used to power an external load such as an electric motor. Oxygen then combines with the electrons returning from the load and the h+ ions to form water. The by-products of the system are simply water and latent heat.

Internal Combustion Engines on the other hand burn a mixture of hydrogen and air in an enclosed chamber. The combustion of the air/fuel mixture creates pressure which acts on a mechanical piston creating mechanical rotational energy.

Currently there is no clear indication as to which technology will be most widely accepted by customers. In order to compare hydrogen fuel cells to ICEs for vehicle use the following parameters will be analyzed:

- Cost
- Efficiency
- Power Density
- Fuel Economy
- Vehicle Mass

To aid in the comparison between Fuel Cells and Internal Combustion Engines, two commercially designed vehicles of relative size will be compared. The hydrogen ICE vehicle known as the Ford H_2RV uses a supercharged 2.3 litre ICE with a peak power output of 110 HP with an additional 33 HP from an electric motor used for power assist. The vehicle can reach 60 mph from rest in 11 seconds. In addition the vehicle achieves a combined fuel economy of 45 MPG gasoline equivalent. Ford company officials predicted that the vehicle could be ready for mass production by 2005, but the vision never materialized. [3]

The Honda FCX is one of the first production ready Fuel Cell vehicles. The latest edition boasts a 100 kW hydrogen PEM fuel cell stack and is powered by a 134 HP electric motor. Honda predicts that the FCX could see mass production as early as 2018.

The car boasts modest performance with an acceleration time from 0-60 mph in 11 seconds. The Li-Ion battery pack and regenerative braking allow for a significant improvement in the vehicles overall energy efficiency.

Table 1 – H_2 Fuel Cell vs. H_2ICE [4-7]

Parameter	Ford H_2RV	Honda FCX
Engine	110 HP 2.3l Supercharged ICE, 33 HP Elec. Motor Total: 143 HP	134 HP Electric Motor
Architecture	Parallel Hybrid Electric Vehicle	Fuel Cell Electric Vehicle
Hydrogen Fuel Type	5000 PSI Gaseous Hydrogen	5000 PSI Gaseous Hydrogen
Features	- Electric Transmission - Regenerative Braking - Li-Ion Battery	-100 kW Fuel Cell - Regenerative Braking - Li-Ion Battery
Vehicle Mass	1551 kg (3420 lbs.)	1625 kg (3582 lbs.)
Acceleration	11 s.	11 s.
Fuel Economy	5.23 l/100km 45 MPG	3.41 l/100km 69 MPG
TTW Emission Reduction	CO_2 - >99%	CO_2 – 100% NO_x – 100%
Efficiency	52% Indicated Energy Eff.	60% Indicated Energy Eff.
Cost	$30-40000 est.	$3,000,000

Based on the data presented in Table 1, it is evident that the two vehicles are very similar in terms of their driving performance. While the H_2RV was all but abandoned by Ford the Honda FCX project is still in full swing with a select number of lease units on sale to the general public as of 2008. While the performance of the two vehicles is comparable the FCX produces significantly better fuel economy, emissions, and has a higher energy conversion efficiency. Recent developments in direct injection ICEs have lead to an increase in energy conversion efficiencies in hydrogen fuelled engines allowing them to eclipse 60% in vehicles such as the BMW Hydrogen 7. Such an improvement would certainly help modernize the Ford vehicle.

The H_2RV pulls far ahead of the FCX when it comes to vehicle cost and near term feasibility. The cost of the FCX is almost entirely driven by the expense of the fuel cell stack. With the cost of a prototype vehicle stack estimated at $3000/kw mass production (~500,000 units per year) could ultimately see that value drop to $225/kw. [8] This still remains high when compared to developmental cost of only $30 per kW for a typical ICE. [9] The cost of Fuel Cells will have to drop significantly closer to $30/kW before they become feasible for mass production.

Thus, in the near term forced injection ICE hybrids are a more likely choice for commercial hydrogen vehicles. They will allow for the continued advancement of a hydrogen infrastructure and hydrogen generation strategies while still drastically reducing emissions and increasing efficiency. The hope is that the cost of fuel cell production will one day become competitive with ICEs and replace them yielding zero TTW emissions.

3 Design Methodology

The design cycle being used for this project is highlighted below in Figure 2. The cycle illustrates a method for retro-fitting an Extended Range Electric Vehicle (E-REV) power generation system to an existing vehicle architecture. The purpose of the design cycle is to carefully define the requirements of the architecture in terms of its component driven characteristics, such as:

- Range
- Acceleration
- Fuel Economy

} *Performance*

- Energy Conversion
- Drive train Losses

} *Efficiency*

- Charge Times

} *Charging*

These characteristics can be easily quantified and evaluated throughout the design process, allowing for feedback to earlier design stages and subsequent re-design.

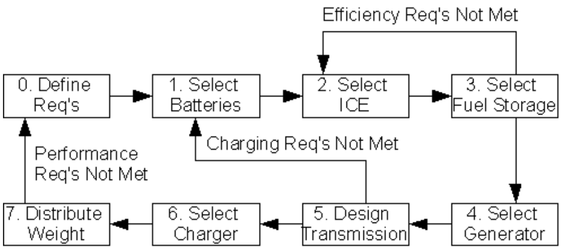

Figure 2 – E-REV Design Cycle

The design cycle is particularly useful in the design of an E-REV power generation system due to the high degree of dependence among components.

4 Vehicle Operation

The operation of the power generation system during a typical extended range (>65km) trip is detailed in the following steps:

- *Re-fuelling* –Vehicle receives full electrical charge overnight, the driver refills the H_2 tank from their in home electrolyzer/methane reformer prior to leaving
- *Charge Depletion Mode* – The vehicle travels, depleting its initial electrical charge, until it reaches 40% SOC
- *Regenerative Braking*, the battery is being recharged by the regenerative capabilities of the electric motors which are providing resistance to travel in effect assisting in slowing the vehicle.
- *H_2 Recharging Mode* – The H_2 system is initiated restoring the batteries SOC to 80% during which the vehicle may continue to drive (40-80% SOC = 4.8 kW)
- The process continues until the H_2 supply is too low at which point the gasoline system is initiated
- *Gasoline Recharging Mode* – The process continues until the gasoline supply is too low and the driver must refuel the vehicle either by charging the batteries or by refueling with H_2 and/or gasoline.
- Finally, the vehicle returns home, where it can be plugged-in and recharged overnight

The power generation system architecture for this build is outlined in Figure 3. There are three unique electrical systems on-board the vehicle including: 120/240 VAC input the battery charger, 48 VDC from the batteries to the electric motors and 12 VDC to the vehicles accessories and power electronics. A 5 VDC system is also being considered in the future for integration of sensitive micro-controllers for improving vehicle and engine control. DC voltages are stepped down using DC/DC converters from the main 48 VDC power source.

Hydrogen is compressed and stored in a gaseous state at 7000 PSI. The hydrogen is regulated twice to near atmospheric pressure (40 psi) prior to entering the ICE. The second regulator is heated by the vehicles coolant system in order to help reduce loses. The pressure is continuously monitored and used to initiate the switch to the gasoline fuelling system when levels become low.

The engine timing is automatically adjusted as needed using a stepper motor and PLC which advances the spark timing of the carburetted ICE from 20º Before Top Dead Centre (BTDC) to 10º BTDC for hydrogen. Backfire in the engine is controlled using an Exhaust Gas Recirculation (EGR) system which reintroduces exhaust gases into the intake to reduce the heat of combustion.

The electric generator is a 15 kW peak Brushed DC Electric Motor which is connected to the engine via a belt drive. When the ICE is running it turns the generator at approximately 5000 RPM which generates 50 VDC at 200 amps.

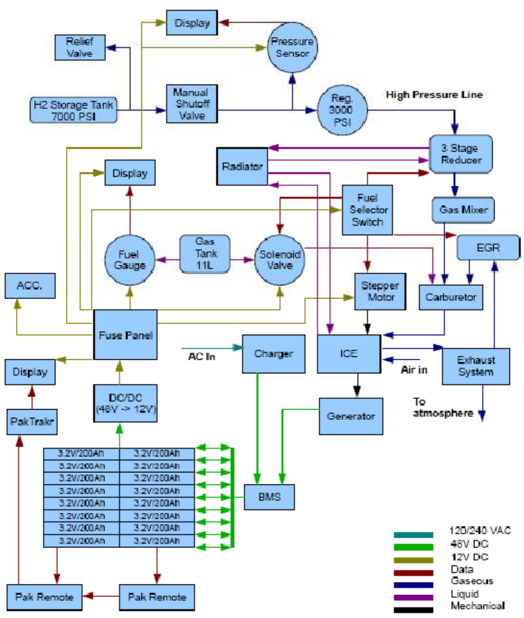

Figure 3 – Dual Fuel E-REV Architecture

This energy is channelled directly to the battery pack and is used to recharge the battery pack from 40-80% SOC while the vehicle is in motion.

The 48V 200Ah $LiFePO_4$ battery array is managed with a custom designed Battery Management System (BMS) which balances the charge on each cell and monitors the pack for over and under voltage. Balancing is provided to the pack during charging, idle and discharging to ensure that the individual cells always remain balanced. The BMS does not limit the input or output current from the pack which is particularly useful with high output $LiFePO_4$ cells.

Driver controls include a variety of switches for controlling power distribution to various system components, fuel controls, and gauges for monitoring the battery pack and fuel sources.

5 Test Platform

The conversion of the vehicle from an SI ICE to E-REV is highlighted in Figure 4-10. Figure 4 illustrates the $LiFePO_4$ battery system which is comprised of 32 cells. Each set of two cells are wired in parallel to increase the output of the pack from 100 Ah to 200 Ah while maintaining 48 VDC nominal. The cells are connected with copper and zinc plated bus bars. The BMS is missing from the photo.

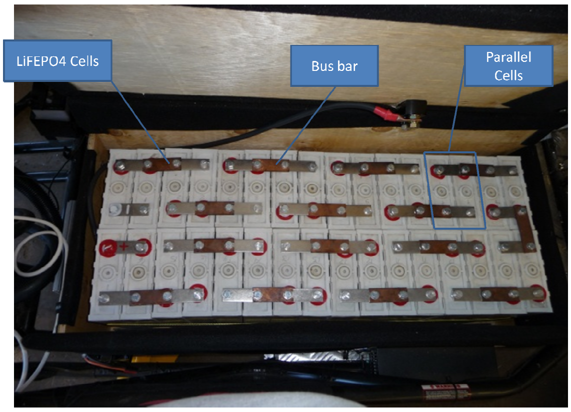

Figure 4 – Vehicle LiFePO4 Battery System

Figure 5 shows the vehicle control systems and a portion of the drive train electronics, motor controllers etc. Of greatest importance is the fuel control module which allows the driver to select which fuel is being used and will automatically switch to gasoline when the hydrogen pressure becomes too low. The output from the batteries is wired directly through the main safety stop, which if flipped cuts all electrical power to the vehicle.

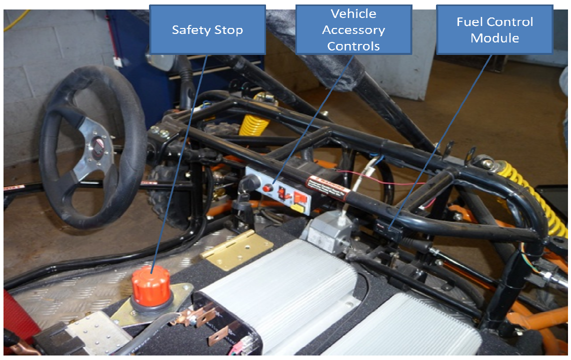

Figure 5 – Vehicle Control Units

Figure 6 illustrates the mounting of the 48-12V DC/DC converter and the battery charger which receives input from a standard 120/240 VAC outlet. Charge times from a 120 VAC outlet is approximately 6.95 hours from 0% SOC to 100% SOC. The battery charger outputs a maximum of 60V at 18A regardless of the input voltage. It is internally controlled to detect over voltage and will turn itself off when the pack is fully charged.

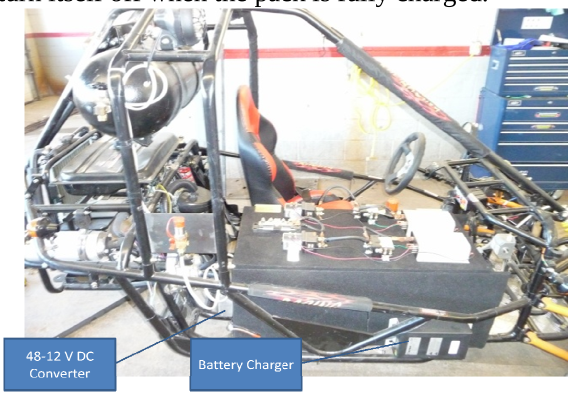

Figure 6 – Vehicle Battery Accessories

Figure 7 shows the mounting of the generator which is located at the rear of the vehicle. The shaft of the generator, which is a 15 kW brushed DC motor is aligned parallel to the output shaft of the ICE. Attached to the shaft of the generator is a 3" steel pulley which is driven directly by the ICE with a composite belt. To eliminate the need for an idler/tensioner the generator mounting plate includes a ¾" pickup to tension the belt. The efficiency of the belt drive has been theoretically determined to exceed 95%.

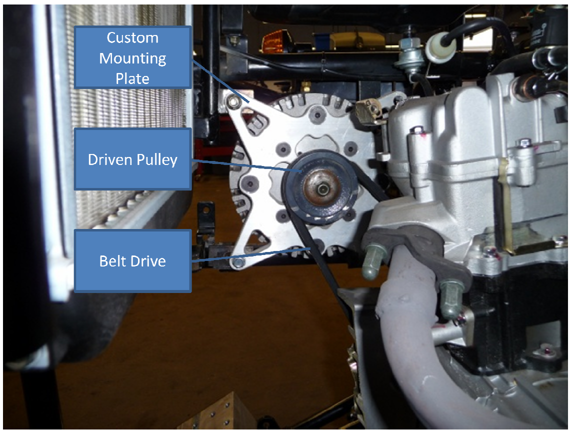

Figure 7 – Generator Driven Pulley Setup

Figure 8 shows the remainder of the belt drive system connecting the ICE and the electric generator. Mounted to the output shaft of the ICE by a spline coupling is the 6” drive pulley. The belt drive system has a 1:2 ratio in which the system steps up the rotational speed to ensure that the proper voltage is obtained from the generator. The ICE is operated at a constant 2500 RPM for both hydrogen and gasoline. The CVT that was originally connected to the motor has been removed and the housing cut off.

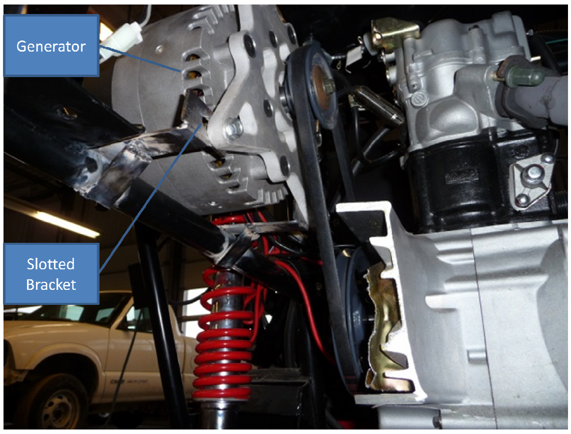

Figure 8 – Generator Belt Drive

The fuel delivery system is illustrated in Figure 9. The fuel delivery process begins by receiving a supply of compressed hydrogen gas (200 Bar) through the fill valve which is shown in Figure 10, with the red cap. The hydrogen then enters the tank (Figure 10). When the ICE operation cycle commences the fuel flows back from the hydrogen storage tank to the three stage regulator. The regulator is heated by the vehicles coolant system and has an inlet and outlet feed that connects it with the radiator. The high pressure hydrogen travels through stainless steel piping to the regulator where it is reduced from 200 Bar to 4 Bar. The hydrogen then exits the regulator through a braided rubber hose. Before it reaches the intake system the flow rate is managed via a variable mechanical valve. The hydrogen is then injected into the intake tract using a specially designed diffuser.

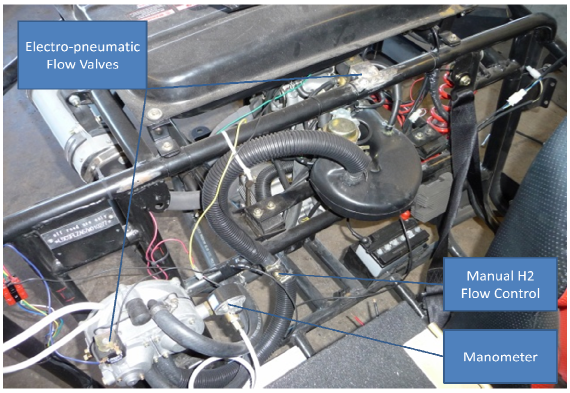

Figure 9 – Fuel Delivery System

Control of the fuelling lines is maintained by the fuel control unit (Figure 5) and two electro-pneumatic flow valves that are installed in line with the gasoline and hydrogen fuel lines. A manometer is used to monitor the pressure of the hydrogen system at the regulator. This data is sent back to the fuel control unit which incorporates a digital fuel gauge and changes from hydrogen to gasoline operation when the hydrogen pressure becomes too low.

Figure 10 - Fuel Storage

6 Challenges

A number of design and operational challenges have been identified during the design/construction process of the dual-fuel E-REV power generation system.

There is a high degree of risk from hydrogen leaks occurring within the fuelling system. This risk is especially prevalent during hydrogen combustion, but is present any time the main valve to the hydrogen tank is open. A hydrogen leak in an open vehicle such as a dune buggy is not particularly dangerous due to the relative weight of hydrogen compared to air. However, in an enclosed vehicle the hydrogen might become trapped which increases the chance of a fire or asphyxiation. As such a Safety Integrated System (SIS) has been proposed for detecting and mitigating the effects of a hydrogen leak.

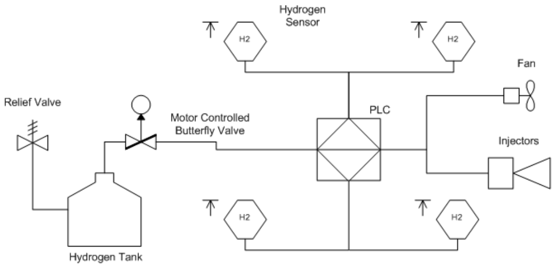

Figure 11 - Hydrogen Leak Detection System

The leak detection system, shown in Figure 11, includes three key elements:

1. Hydrogen Detection Sensor Array
2. PLC
3. Motor Controlled Butterfly Valve, Fan and Electronic Fuel Injectors

When a leak is detected by the hydrogen sensors a signal is sent to the PLC. The PLC instantaneously activates the fan to begin clearing the hydrogen from the vehicle. If the hydrogen is not quickly vented then the engine power is reduced until it stops and the tank is isolated from the rest of the system by an electro-pneumatic valve.

The second operation challenge is overcoming pre-detonation/backfire in the engine during the combustion of hydrogen. Hydrogen is prone to backfire in ICEs due to its high laminar flame speed, low auto-ignition energy, and small quenching gap. Due to hot spots and latent heat in the combustion chamber the hydrogen gas combusts while the intake valve is still open. Several design changes must be made in order to effectively control the problem. The first solution is to increase the engine timing from 20º Before Top Dead Centre (BTDC) to 10º BTDC. [10] The second solution is to increase the engine speed above 3000 RPM. [11] Finally, an Exhaust Gas Recirculation System can be installed to reduce the heat of the combustion chamber by mixing the air/hydrogen mixture with burnt exhaust gases.

7 Results

The conversion of the carburetted SI ICE Dune Buggy to a dual-fuel (hydrogen + gasoline) E-REV has yielded a number of interesting results in terms of the vehicles performance and emissions. By storing hydrogen and gasoline fuel in addition to the battery array the range of the vehicle has increased significantly.

The range of the vehicle before and after the conversion can be seen below in Figure 12. The initial range was composed solely of the gasoline combustion portion, which yielded slightly more than 160 km on average. For the E-REV conversion of the Dune Buggy the range of the vehicle is a combination of the all-electric range, the hydrogen combustion portion and the gasoline combustion portion. This yielded approximately 65, 43 and 160 km of range respectively for a total range of more than 260 km; equating to an increase of 81.25%. The conversion and subsequent range increase was accomplished with a mass increase of only 23.4%. The vehicles gross weight was increased from 478 to 590 kg. Components such as the batteries, generators and hydrogen tank made up the majority of the increased mass.

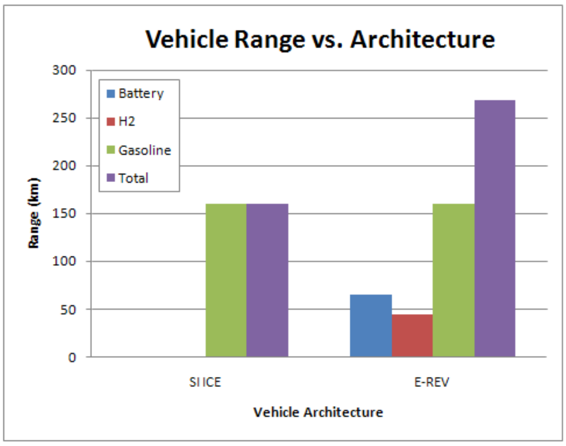

Figure 12 - Vehicle Range Before vs. After Conversion

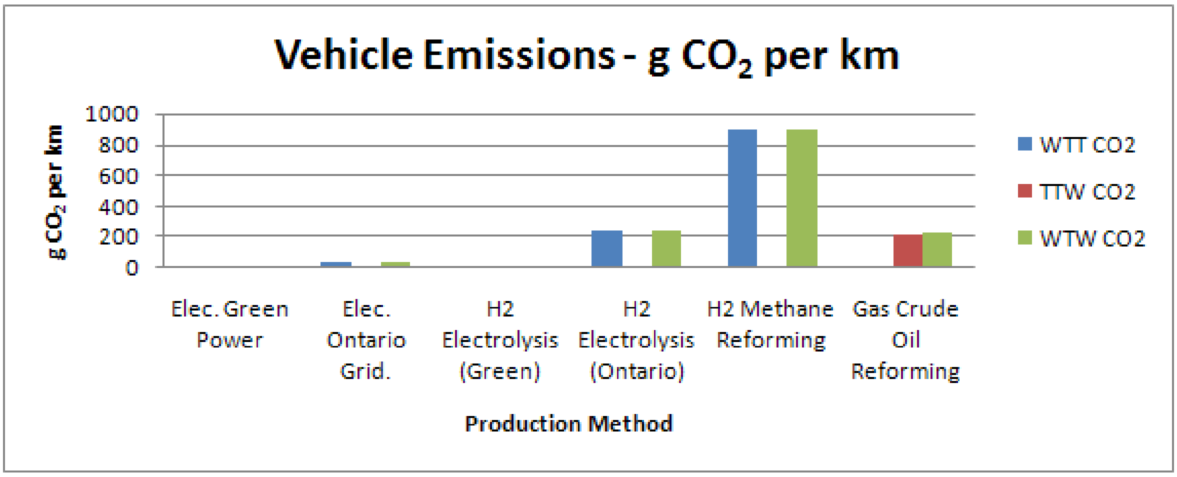

Figure 13 - Vehicle CO2 Emissions per km

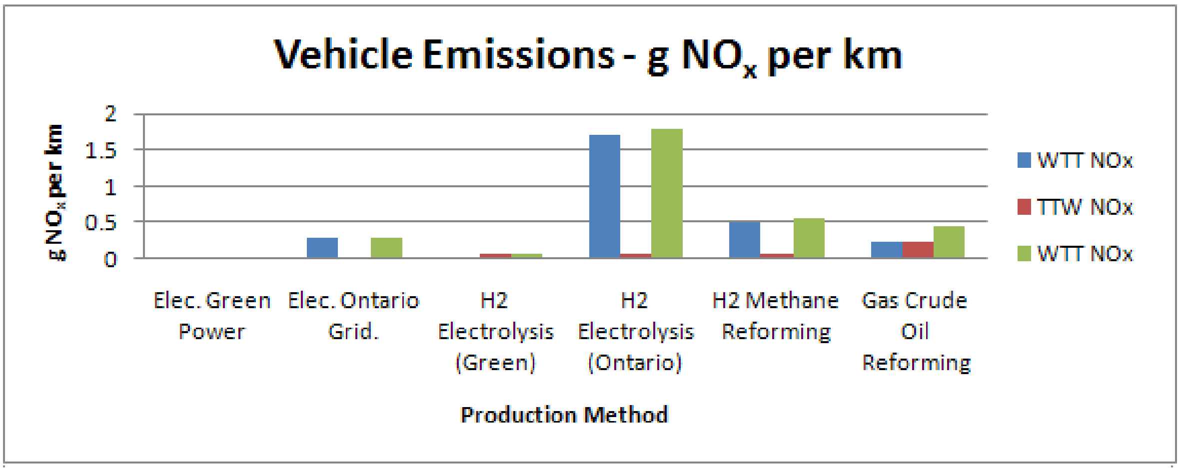

Figure 14 - Vehicle NOx Emissions per km

The emissions of the vehicle have been calculated for each of the three operational modes based upon a number of power production methods. The pure electric operation of the vehicle (<65 km) is calculated for electricity from green power such as nuclear, solar, hydro, and wind as well as for electricity from the standard peak time Ontario, Canada grid. [12] The Ontario Power distribution is 52% Nuclear, 21% Hydro, 18% Coal, 8% Gas, 1% Wind For hydrogen combustion three production methods have been considered which includes: electrolysis from green power and the Ontario grid and from methane reforming. The electrolysis process is assumed to consume 50 kWh per kg. The hydrogen and electrical operational modes are compared to the baseline gasoline combustion supplied by crude oil reforming.

From Figure 13-14 the emissions on a per km basis have been calculated for the well-to-tank (WTT) and tank-to-wheel portions of the operating lifecycle for CO_2 and NO_x emissions respectively.
From the figures we can see that the electric fuelling (from green power) and operation of the vehicle is the lowest emitting in terms of both CO_2 and NO_x. Hydrogen operation is superior to gasoline operation when green power generation methods are used for electrolysis. However, if conventional electricity (Ontario) or methane reforming are used then it is nearly equivalent to gasoline emissions. When green power is used hydrogen operation yields a 200g/km reduction in CO_2 emissions and a 0.35g/km reduction in NO_x emissions.

In addition to an improvement in emissions and range a number of other performance improvements have been made as a result of the conversion from an SI ICE to an E-REV. For instance, the top speed of the vehicle has increased from 85 km/h with the SI ICE to slightly more than 125 km/h in the E-REV. This yields an improvement of 47% from the baseline. The E-REV would be capable of reaching speeds much higher, but for the purposes of this study and the limited testing facilities available at the time of construction the voltage was capped at 48V nominal.

The overall fuel economy of the vehicle has also improved. The initial fuel economy of the SI ICE dune buggy was 6.7 litres/100 km. However, for the E-REV the combined fuel economy of the three fuel modes is 5.45 litres/100 km. This represents an improvement of 22% from the baseline.

The costs associated with refuelling the vehicle have also been determined for grid electricity, hydrogen generation and gasoline. To calculate the prices the following assumptions were made: $0.055 per kWh of electricity (Ontario Average), $2.75 per kg H_2 and $1.35 per litre of gasoline (typical price Ontario 2008). The result is approximately $0.01 per km on all-electric power, $0.048 per km on hydrogen produced electrical energy and $0.088 per km on gasoline produced electrical energy.

8 Conclusion

In conclusion, a novel dual-fuel E-REV power generation system has been developed for the conversion of a SI ICE off-road vehicle. Initial results indicate a significant improvement in vehicle range, acceleration, fuel economy and TTW emissions. A summary of the vehicle performance results can be found in Table 2 below. These improvements have come at the consequence of a significant increase in costs due to the expensive nature of the $LiFePO_4$ batteries, BMS, and hydrogen fuel delivery equipment.

The dual-fuel E-REV power generation system provides a number of important benefits when compared to conventional vehicles and parallel hybrids. Such benefits include zero emissions travel for short duration trips, improved overall emissions and fuel economy, and a reduced reliance on fossil fuels.

Table 2- Vehicle Results

Specification	Value
All Electric Range	65 km
Consumption Rate	183.77 Wh/km (295 Wh/mile)
MPG Equivalent	1.89 l/100km (124.2 MPG)
H_2 Range	43 km
MPG Equivalent	6.18 l/100 km (38.1 MPG)
Gasoline Range	165 km
MPG Equivalent	6.67 l/100km (35.2 MPG)
Total Range	268 km (68% ↑)
Total Fuel Economy	5.45 l/100km (43 MPG) (22% ↑)
Top Speed	125 km/h (47% ↑)
Corrected Ah Rating	152.4 Ah
Useable Energy	7.3 kWh
Charge Time (Charger)	6.95 h
Charge Time (Generator)	0.73 h
Vehicle Mass	590 kg (23.4% ↑)
Capital Cost	Substantial Increase ↑↑↑
Fuel Costs	Elec: $0.01/km H_2: $0.048/km Gasoline: $0.088

Furthermore, the architecture offers a chance to explore the use of hydrogen and promote the generation, distribution, and storage technologies

required to increase the validity of a hydrogen economy.
The hydrogen ICE has proven to be more feasible in the intermediate term than hydrogen fuel cells due to their cost benefits and ease of integration into SI ICE vehicles.

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