Review of the prospects for using hydrogen as a fuel source in internal combustion engines

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1 Introduction

Considering sustainable energy options such as hydrogen is of growing importance; it is obvious that power and heat production (including hydrogen production from them) using fossil fuels continues to threaten environmental stability both nationally and globally. Increasing energy demand, rapid technological development, increasing world population etc. are only a few of the numerous issues contributing to this concern. Previously, energy generation via fossil fuels has been a viable option, but presently the global picture does not allow for their use at the current rate [1].

The answer may lie in a sustainable hydrogen based energy to reduce the environmental effects of fossil fuel consumption, since:

- The simple reaction of going from two very basic molecules to a more complicated one means that on a chemical level hydrogen has the potential for excellent exergetic performance [2].
- If used appropriately, Hydrogen is an infinite fuel source. The hydrogen energy system could deliver a sustainable and reliable energy supply almost indefinitely.
- Hydrogen causes less of an environmental impact compared to conventional fuels, as it does not feature carbon in its chemical makeup. A wide array of options and applications is available due to the plethora of hydrogen energy resources.

Required time from design to implementation of the equipment is in many cases much shorter due to the simpler and smaller scale of the necessary equipment. This allows for improved scalability and elasticity when adapting to unpredictable changes in energy demand. Therefore, the high quality and environmentally non-damaging nature of hydrogen, as well as its non-toxic combustion products could mean that a safe and sustainable energy production method could be implemented. However, it should be noted that, the sustainable energy based hydrogen production processes are unlikely to yield significant reduction in hydrogen costs in the next one-to-two decades [3].

Constant debate hangs over hydrogen, heavily optimized hydrocarbon fuelled engines, electricity, biofuels, etc. as to what constitutes the best energy carrier as well as best engine power plant; with the factors to be taken into account including, but not limited to: tailpipe emissions relating to local pollution, cradle-to-grave primary energy use, greenhouse gas emissions, practicality, cost, etc. Clearly these are not easily ranked and ordered, making it very hard to predict the winner(s).

Shelef and Kukkonen [4] have compared electric vehicles, hydrogen ICE vehicles, and hydrogen fuel cell vehicles against conventional gasoline operated vehicles, on the basis of primary energy use and carbon dioxide emissions. Two decades have passed since this study, so the results will be in need of updating, but, Shelef and Kukkonen concluded that the wide flammability limits of hydrogen allow ignition and combustion of very lean mixtures, lowering peak cylinder temperatures and NOx emissions at a higher thermal efficiency, however the H2ICE vehicle would decrease primary energy use and greenhouse gas emissions compared to gasoline and natural gas vehicles.

A more recent study at Argonne National Laboratory concludes that by 2045, as consequence of recent and expected future developments in H2ICE technology, a H2ICE hybrid-electric vehicle would only consume 9% more than a H2FC Hybrid-electric vehicle [5]. This shows that the alleged difference in fuel economy between a H2FC HEV and H2ICE HEV is not only smaller than generally reported, but should also decrease over time. Both in terms of capital cost and fuel cost (owing to the high fuel purity requirements of the H2FC), H2FCs are presently much more expensive than H2ICEs. Furthermore, perhaps one of the most beneficial aspects of the H2ICE is their ability to operate and immediately switch between gasoline operation, hydrogen operation, and bi-fuel operation (a
simultaneous mixture of gasoline and hydrogen), which helps to lower the problem of the current small quantity of hydrogen fuel stations. This could be the significant feature to enable the implementation of a hydrogen infrastructure, where the experience gained with transport, fuelling and storage would directly translate to the eventual fuel cell vehicles.

The 2011 well-to-wheel study of the European Commission’s Directorate General Joint Research Centre, in cooperation with CONCAWE and EUCAR, concludes that H2ICE vehicles are available in the near term at a lower cost than fuel cell vehicles [6].

Although many papers on H2ICEs limit the introduction to why H2ICEs are attractive, it is important to be realistic and also pay attention to potential show-stoppers. The most important question is probably whether hydrogen can be justified as an energy carrier. Next to the attractive features listed above, it cannot be forgotten that there are enormous hurdles to overcome. Much of them are down to the low density of hydrogen, rendering distribution and storage difficult, costly and inefficient, as well as a tendency to decrease engine power output [7].

This review is a collection of information found from various sources, compiling relevant information on hydrogen infrastructure into one document, with unedited extracts taken directly from the sources in some cases. If the information collected here is found insufficient, all sources have been appropriately referenced for further reading. The most notable of these sources is the excellent review by Verhelst and Wallner [8], which features often, and it is suggested that their paper is read prior to reading this review.

2 Hydrogen Fuel Fundamentals

2.1 Properties of Hydrogen

Certain features of an H2ICE can be estimated, simply by using the physical and chemical properties of hydrogen and hydrogen–air mixtures. Verhelst and Wallner [8] summarise the chemical and physical properties relative to engines, beginning with a comparison between hydrogen, methane and iso-methane (which are taken here as representing natural gas and gasoline, respectively), shown in Table 1.

Hydrogen has a very low density at atmospheric conditions due to the size and weight of the molecule, which gives rise to a high mass diffusivity, as it is very mobile. The air-to-fuel equivalence ratios (λ) of the mixtures ranges from as rich as $\lambda = 0.14$ to as lean as $\lambda = 10$. This allows a wide range of engine power output through changes in the mixture equivalence ratio. The flammability limits (the experimentally determined upper and lower bounds of $\lambda$ required for fuel burn to take place, expressed in terms of volume percentage at 25 °C and atmospheric pressure) widen as the temperature rises, with the lower flammability limit being 2% volume at 300 °C.
Table 1 - Hydrogen properties compared with methane and iso-octane properties. Data given at 300K and 1 atm. [8].

<table>
<thead>
<tr>
<th>Property</th>
<th>Hydrogen</th>
<th>Methane</th>
<th>Iso-octane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight (g/mol)</td>
<td>2.016</td>
<td>16.043</td>
<td>114.236</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>0.08</td>
<td>0.65</td>
<td>692</td>
</tr>
<tr>
<td>Mass diffusivity in air (cm²/s)</td>
<td>0.61</td>
<td>0.16</td>
<td>≈0.07</td>
</tr>
<tr>
<td>Minimum ignition energy (mJ)</td>
<td>0.02</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Minimum quenching distance (mm)</td>
<td>0.64</td>
<td>2.03</td>
<td>3.5</td>
</tr>
<tr>
<td>Flammability limits in air (vol%)</td>
<td>4–75</td>
<td>5–15</td>
<td>1.1–6</td>
</tr>
<tr>
<td>Flammability limits (l)</td>
<td>10–0.14</td>
<td>2–0.6</td>
<td>1.51–0.26</td>
</tr>
<tr>
<td>Flammability limits (4)</td>
<td>0.1–7.1</td>
<td>0.5–1.67</td>
<td>0.66–3.85</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>120</td>
<td>50</td>
<td>44.3</td>
</tr>
<tr>
<td>Higher heating value (MJ/kg)</td>
<td>142</td>
<td>55.5</td>
<td>47.8</td>
</tr>
<tr>
<td>Stoichiometric air-to-fuel ratio (kg/kg)</td>
<td>34.2</td>
<td>17.1</td>
<td>15</td>
</tr>
<tr>
<td>Stoichiometric air-to-fuel ratio (kmol/kmol)</td>
<td>2.387</td>
<td>9.547</td>
<td>59.666</td>
</tr>
</tbody>
</table>

From the table, a number of important differences between Hydrogen and the other fuels can be seen. Firstly, there is a large difference between the higher and lower heating values of hydrogen compared to methane and iso-octane, due to water being the only combustion product of hydrogen. Secondly, the 0.02 mJ minimum ignition energy of a hydrogen–air mixture is an order of magnitude lower compared to the other mixtures. Due to the measuring technique, the minimum ignition energy is dependent on the spark gap (the distance between the two electrodes across which the spark pass between), and so the values vary for a varying gap. The table values are for a gap of 0.5 mm. A 2 mm gap would give a minimum ignition energy of 0.05 mJ.

Verhelst and Wallner go on to give the properties of hydrogen–air mixtures, at stoichiometric and at the lean limit, compared to stoichiometric methane–air and iso-octane–air mixtures, shown in Table 2 [8].

The low density of Hydrogen and hence its large volume fraction has the effect of reducing the engine power density. It also leads to important consequences on mixture properties such as the kinematic viscosity, thermal conductivity, etc. when combined with the wide flammability limits. The gas dynamics are also affected for engines operating under an external mixture formation (where the fuel is mixed with the air before reaching the cylinder, see later), due to the inconsistent density of the fuel entering the cylinder which changes the speed of sound. An increased ratio of specific heats results in an increased amount of compression work, but effected more so by injection strategy (see later).
### Table 2 - Mixture properties of hydrogen–air, methane–air and iso-octane–air. Data given at 300 K and 1 atm. (with the exception of the laminar burning velocity, given at 360 K and 1 atm.).

<table>
<thead>
<tr>
<th>Property</th>
<th>H2–air</th>
<th>H2–air</th>
<th>CH4–air</th>
<th>C8H18–air</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Volume fraction fuel (%)</td>
<td>29.5</td>
<td>9.5</td>
<td>9.5</td>
<td>1.65</td>
</tr>
<tr>
<td>Mixture density (kg/m^3)</td>
<td>0.85</td>
<td>1.068</td>
<td>1.123</td>
<td>1.229</td>
</tr>
<tr>
<td>Kinematic viscosity (mm^2/s)</td>
<td>21.6</td>
<td>17.4</td>
<td>16</td>
<td>15.2</td>
</tr>
<tr>
<td>Autoignition temperature (K)</td>
<td>858</td>
<td>&gt;858</td>
<td>813</td>
<td>690</td>
</tr>
<tr>
<td>Adiabatic flame temperature (K)</td>
<td>2390</td>
<td>1061</td>
<td>2226</td>
<td>2276</td>
</tr>
<tr>
<td>Thermal conductivity (10^-2 W/mK)</td>
<td>4.97</td>
<td>3.17</td>
<td>2.42</td>
<td>2.36</td>
</tr>
<tr>
<td>Thermal diffusivity (mm^2/s)</td>
<td>42.1</td>
<td>26.8</td>
<td>20.1</td>
<td>18.3</td>
</tr>
<tr>
<td>Ratio of specific heats</td>
<td>1.401</td>
<td>1.4</td>
<td>1.354</td>
<td>1.389</td>
</tr>
<tr>
<td>Speed of sound (m/s)</td>
<td>408.6</td>
<td>364.3</td>
<td>353.9</td>
<td>334</td>
</tr>
<tr>
<td>Air-to-fuel ratio (kg/kg)</td>
<td>34.2</td>
<td>136.6</td>
<td>17.1</td>
<td>15.1</td>
</tr>
<tr>
<td>Mole ratio before/after combustion</td>
<td>0.86</td>
<td>0.95</td>
<td>1.01</td>
<td>1.07</td>
</tr>
<tr>
<td>Laminar burning velocity =360 K (cm/s)</td>
<td>290</td>
<td>12</td>
<td>48</td>
<td>45</td>
</tr>
<tr>
<td>Gravimetric energy content (kJ/kg)</td>
<td>3758</td>
<td>959</td>
<td>3028</td>
<td>3013</td>
</tr>
<tr>
<td>Volumetric energy content (kJ/m^3)</td>
<td>3189</td>
<td>1024</td>
<td>3041</td>
<td>3704</td>
</tr>
</tbody>
</table>

(Note: There is some uncertainty with the autoignition temperature of the fuels, with hydrogen in particular. For hydrogen, values were found from 773 K [10] to 858 K [11], and methane values have been found between 810 K [12] and 868 K [13]. Some sources list the autoignition temperature for hydrogen as lower than that for methane; other sources list it higher. The uncertainty can be somewhat explained by the experimental procedure and the criterion used for defining the value, as well as the sensitivity of autoignition temperatures and the experimental apparatus [14]).

The laminar burning velocity (the speed at which an un-stretched laminar flame will propagate through a mixture of unburned reactants) of stoichiometric hydrogen–air mixtures is much greater than that of methane and iso-octane. 290 cm/s for hydrogen compared to 48 cm/s and 45 cm/s for methane and iso-octane respectively. However, if lean-burn strategies are used, the burning velocity can be much lower.

The high autoignition temperature of hydrogen allows for high compression ratios. When combined with the faster burn rate and the possibility of load control (changing the mixture richness at wide open throttle (WOT)), potentially high engine efficiencies can be achieved. However, heat losses from cylinder gases to the combustion chamber walls can be higher with hydrogen compared to conventional fuels, negatively affecting efficiencies. A more detailed analysis of how these factors effect engine efficiency is covered in the next section.

Finally, it is possible to calculate the maximum theoretical power density of engines with different fuel source, by combining the lower heating value of hydrogen, its density and the stoichiometric air requirement (this can be found later, in Table 3).

### 2.2 Engine Specifics & Mixture formation

Injection timing and duration have been found to be factors just as important as differences in the fuel properties; calculations have shown that improvements in efficiency of up to 4% can be gained when using an optimized injection strategy [15]. However, before evaluating the pros and cons of different mixture formation strategies, it is important to understand the principal correlation between...
the air–fuel ratio and oxide of nitrogen emissions that is applicable for all homogeneous mixture formation concepts.

For mixtures around stoichiometry (λ = 1), the high burning velocity and high adiabatic flame temperature point to high NOx emissions. Fig. 1 shows a typical nitrogen oxide emission as a function of the equivalence ratio for port-injection operation. As can be seen from the graph, combustion of hydrogen–air mixtures with fuel-to-air equivalence ratios of less than 0.5 results in extremely low NOx emissions. There exists a NOx production critical temperature of approximately 1800K due to the excess air available in the combustion chamber, and for these lean hydrogen-air mixtures, their combustion temperatures do not exceed it [16]. Increasing the equivalence ratio results in an exponential increase in nitrogen oxide emissions, finding a peak at a fuel-to-air equivalence ratio of 0.75, or an air-to-fuel equivalence ratio of λ = 1.3. At stoichiometric conditions, the NOx emissions are at around 1/3 of the peak value. The NOx emissions are affected by both oxygen concentration and gas temperatures, so although the highest burned gas temperatures occur around a fuel-to-air equivalence ratio near 1.1, but at this point oxygen concentration is low, so the NOx concentration peaks at 0.75 (λ = 1.3), as increasing oxygen concentrations initially offset the falling temperatures [17].

![Fig. 1. Correlation of air–fuel ratio and NOx emissions for homogeneous operation [18].](image)

As a result of this dependence of nitrogen oxide emissions on the air–fuel ratio, multiple operating strategies have been developed with the intention to achieve reasonable power densities while avoiding excessive NOx emissions.

The proper design of the mixture formation process is crucial for achieving high engine efficiencies while meeting more and more stringent emissions targets. The main classification of mixture formation strategies is based on the location of the formation of the hydrogen and conventional fuel mixture: External mixture formation refers to where hydrogen is introduced outside the combustion chamber (usually within the intake manifold), which contrasts with internal mixture formation, where the hydrogen is introduced directly into the combustion chamber.

Table 3 compares the theoretical power density of hydrogen and methane fuelled engines, which have both been normalised to an iso-octane-fuelled engine, representing a conventional gasoline fuel. Values for both port-fuel injection (PFI) (external mixture formation) engines and direct-injection (DI)
(internal mixture formation) engines are quoted. A large difference for Methane and Hydrogen can be seen, with a theoretical power density increase of 38% for hydrogen when switching from external to internal mixture formation. Clearly, the mixture formation strategy has a significant impact on the theoretical power output of the engine for hydrogen. The low density of hydrogen is what is causing the difference, as external mixture formation results in a significant decrease in mixture density compared to internal mixture formation as the hydrogen is arrives into the mixture at a much lower pressure. Generally, hydrogen injection systems for external mixture formation are operated at lower injection pressures (2–8 bar) compared to systems for hydrogen direct injection (5–250 bar).

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen</th>
<th>Methane</th>
<th>Iso-octane</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFI</td>
<td>86%</td>
<td>92%</td>
<td>100%</td>
</tr>
<tr>
<td>DI</td>
<td>119%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 3 - Theoretical power densities of hydrogen-, methane- and iso-octane-fuelled engines, for Port Fuel Injection (PFI) and Direct Injection (DI) mixture formation strategies.

An area of necessary research and development is the improvement of the hydrogen injectors for DI. The exposure of injectors to in-cylinder temperatures and pressure in combination with increased injection pressures for internal mixture formation systems still requires further injector development to reach production standards in terms of durability [19]. As an alternative to both of these strategies, cryogenic hydrogen has also seen a reasonable level of research [20-24]. This strategy poses new problems to the injection system however, due to extremely low temperatures required to maintain the hydrogen as a liquid (and related problems such as the freezing of the hydrogen injectors).

The two single most prominent mixture formation strategies for hydrogen engines are hydrogen port injection, hydrogen direct injection. The following sub-sections summarise the most common variations of these mixture formation concepts. However, first it is necessary to consider the if increased theoretical power densities outweigh the added complications of supplying high pressure hydrogen for DI, compared to the more manageable and low pressure hydrogen required for port injection.

2.2.1 Supplying pressurized hydrogen

A certain delivery pressure is required for the introduction of hydrogen into the engine. This is either via the intake manifold for external mixture formation, or directly into the combustion chambers for internal mixture formation. The style of on board storage as well as the pressure levels required for injection determine the most efficient way of providing the required pressure. The energy required to compress hydrogen is significant, regardless of whether it is performed off or on board the vehicle. The minimal work required for compression of hydrogen results from isothermal compression. With compressed hydrogen storage at pressure levels up to 700 bar, sufficient pressure is available for even high-pressure 100 bar injection systems. If no additional compressor is available however, the full amount of hydrogen stored in a compressed hydrogen tank cannot be utilized. For this example of a 700 bar storage tank and a 100 bar injection pressure, only 6/7 of the mass of hydrogen stored on board can be used. Considering most hydrogen tanks used in automotive applications are at a pressure of 350 bar, there is potential for significant wastage of fuel.

Liquid cryogenic hydrogen compression can be accomplished more efficiently as it is in the liquid state, so allows for cutting the compression work by a factor of 5–6 compared to gaseous compression. However, cryogenic pumps still have a number of questions concerning them in areas such as material selection and construction. Liquefaction of hydrogen in current large-scale processes requires about 30% of the energy content of the hydrogen, which clearly is rather inefficient. In order to avoid the
compression step of liquid hydrogen, ongoing research is performed on cryo-compressed hydrogen storage systems [25, 26].

2.2.2 Spark-ignition port injection & conversion engines.

Hydrogen port injection is the most common hydrogen mixture formation strategy. It is simpler than direct injection, and thus is often used in the conversion of conventional ICE engines to H2ICEs. Gasoline engines have been converted to hydrogen operation, employing a lean constant air–fuel ratio to minimise NO\textsubscript{x} emissions. By replacing the gasoline fuel injection system with hydrogen injectors, this strategy can be easily implemented [27-29]. Extremely low emission levels even without the use of any after treatment system can be achieved by using an equivalence ratio below the NO\textsubscript{x} emissions critical limit of $\lambda \approx 2$. Moreover, this operating strategy avoids many combustion anomalies such as autoignition and backfire, due to the reduced thermal load of the engine, the low combustion temperatures at this lean equivalence ratio, and the increase in required ignition energy for lean hydrogen–air mixtures.

Szwabowski et al [30] carried out a number of tests on the hydrogen powered ford P2000 vehicle. They used a constant air–fuel ratio of $\lambda = 1.8$ and a compression ratio of 14.5, and concluded an improvement in fuel economy by 18% over its gasoline counterpart, while still achieving emission levels low enough to meet the Transitional Low Emission Vehicles (TLEV) emissions standards, without EGR or any after treatment. Although this is positive, losses to power output were present.

If we assume a constant air-to-fuel equivalence ratio of $\lambda = 2$, it results in a theoretical maximum power output that is only about 50% of a regular gasoline engine. The use of a supercharger has been investigated into as a way of improving the loss in power (see Fig. 2) [31]. Multiple versions of hydrogen operated pickup trucks have also been fitted with superchargers, operating at equivalence ratios of around $\lambda = 2.5$, and compression ratios of up to 12:1 with boost pressures of approximately 0.8 bar [33]. A sudden decrease in efficiency was observed at $\lambda = 4.5$, due mostly to unburned hydrogen in the engine and a slower burn rate [34].

![Fig. 2 - Theoretical power density of a PFI H2ICE engine compared to stoichiometric gasoline operation as a function of equivalence ratio and charging strategy.](image-url)
A GM 454 spark-ignited PFI engine known as the Chevrolet Big Block was given an equivalence ratio that varied with respect to engine load, and its engine power was investigated. The equivalence ratio ranged between $2 < \lambda < 5$ and gave at least a 20% increase in engine power [35].

### 2.2.3 Spark-ignition direct injection

As a way of avoiding combustion anomalies common with external mixture formation strategies, as well as to increase the power density of the engine but still achieving low emissions, direct injection systems for hydrogen have been developed.

Direct injection (DI) can be characterised by at what point in the cylinder’s cycle the injection takes place. For example, early DI is where the hydrogen is injected during the early compression stroke, shortly after In-take valve closing. Late DI is where the injection is late in the compression stroke, as close as possible to the spark ignition. In addition to these, there is also the possibility of multiple injections per cycle [37-39].

The hydrogen must flow down a pressure gradient, so clearly the pressure inside the injection system has to exceed the pressure inside the cylinder in order for the hydrogen to enter the combustion chamber. Hence, as the pressure in the cylinder varies throughout its cycle, the variations on DI strategies such as early DI or late DI require different pressures depending on the pressures of the cylinder at the point of injection. Operating strategies with early DI require injection pressures in the range of approximately 5–20 bar, late injection strategies up to 100 bar and multiple injection strategies with injection pulses during the actual combustion event of 100–300 bar. Injection timing has important effects on the mixture distribution, and therefore on the combustion characteristics. For late injection, only limited time for mixing is available, so a non-uniform flame front at spark timing can result. With early injection, the injected fuel has sufficient time to mix with the air inside the combustion chamber and form an almost homogeneous mixture. The impact on NO$_x$ emissions behaviour is highly dependent on the engine load and the overall equivalence ratio.

The theoretical calculations above have already lead to the conclusion that DI operation gives higher power densities compared to PFI operation, for both hydrogen and gasoline. A comparison of indicated mean effective pressure (the average pressure over a cycle in the combustion chamber of the engine (IMEP)) as a function of the equivalence ratio was measured by Eichlseder et al [16], using a single-cylinder, 0.5 litre engine, and results are shown in Fig. 3. An IMEP of over 13 bar was achieved for DI, 15% higher than the peak IMEP in gasoline operation and more than 75% higher than the peak IMEP in hydrogen port-injection operation. However, for external mixture formation, the maximum achievable mean effective pressure is far lower than the values for gasoline because of the low volumetric density of hydrogen causing displacement of air during the injection into the intake pipe.
Fig. 3 also shows differences between the two mixture formation methods. As the quantity of air remains almost constant with a changing equivalence ratio for DI operation, a leaner equivalence ratio under the same IMEP is found compared with the external mixture formation. DI operation can achieve lower NOx emissions and higher engine efficiencies for the same engine load compared to PFI, since both of these quantities depend on the equivalence ratio. In another study, a single cylinder Ford research engine [19] demonstrated the impressive efficiency potential of hydrogen DI operation, with a peak thermal brake efficiency of more than 45% at 3000 RPM.

A compromise between optimizing engine efficiency and nitrogen oxides emissions has been encountered, which somewhat offsets the efficiency improvements found with DI operation compared to PFI. Multiple injection can be an effective tool to simultaneously achieve low NOx emissions and high engine efficiencies: results from a single-cylinder research engine point to a NOx emissions reduction potential of up to 95% when compared to single-injection, while still achieving reasonable engine efficiencies [37, 38, 39]. However, multi-injection strategies are more complicated, and pose difficult challenges in terms of pressure levels as well as required injector flow rates. Because of these problems, multiple injection strategies have been limited to fairly low engine speeds [39].

2.2.4 Compression Ignition

For further improvement in engine efficiencies, research has been performed on hydrogen DI operation on compression ignition engines for both stationary applications as well as automotive engines [42].

Stable compression ignition of hydrogen could be achieved employing induction air heating and supercharging without intercooling was shown to be possible in experimental investigations [42] on a single-cylinder research engine specifically designed for compression ignition. However, to avoid auto ignition, the load ranges were limited to a mid-part load. This led to the development of a multiple injection strategy where the first injection pulse delivered a small amount of fuel into the cylinder, compressing and igniting the initial mixture around top dead centre (the position of the piston when it is as far as possible from the crank shaft). This small injection pulse was used to generate a high
enough temperature in the combustion chamber in time for the injection of the second pulse which almost immediately converted in a diffusion type of combustion, inhibiting autoignition. This double injection pulse technique, with the first pulse spark ignited, and the second compression ignited, led to an indicated efficiency of the high-pressure cycle of 44% [42].

2.2.5 Problems

**NOx Emissions**
Carbon monoxide (CO), hydrocarbon (HC) as well as CO2 emissions are expected to be virtually zero due to the absence of carbon in the fuel, and so the emissions of H2ICEs are theoretically limited to oxides of nitrogen. [16]. However, traces of hydrocarbon and CO emissions are found in the exhaust gases, which are the result of combustion of the engine oil.

The oxides of nitrogen emissions of hydrogen engines strongly depend on the engine load, engine temperature and air-to-fuel ratio. Techniques for reducing NOx emissions include multiple fuel injections as discussed above, water injection or EGR as well as catalytic after treatment; either a conventional 3-way catalyst or lean NOx after treatment can to be employed depending on the engine operating strategy. NOx conversion efficiencies in excess of 99.5% were found from regular production-type catalysts [43].

Results on a 6-cylinder diesel engine converted to hydrogen external mixture formation operation and equipped with a NOx absorption 3-way catalyst showed impressive NOx emissions reductions of more than 90% with 3% of the hydrogen fuel injected into the exhaust [44]. An improved catalytic set-up with composing of a NOx storage-reduction (NSR) catalyst and an oxidation catalyst gave a NOx conversion of 98% [45]. Patents now exist where the need for the additional injection of the reducing agent into the exhaust removed by increasing the equivalence ratio from lean-burn operation to fuel-rich operation, and using EGR to purge the lean NOx trap [46, 47].

Water injection is another possible technique employed to reduce NOx emissions. Water injection reduces the cylinder temperatures, and was found to considerably reduce NOx emissions with only slightly negative impact on engine efficiency [48, 49]. However, although water injection is a very effective measure for NOx emissions reduction, its practical application will depend on an efficient way of supplying the liquid, e.g., by recovering and condensing it from the engine exhaust [50].

EGR has shown to be an effective technique for reduction of NOx emissions and autoignition, at the expense of engine efficiency. Research on a single-cylinder engine showed that the NOx emissions reduced by about an order of magnitude when EGR levels were increased from 0 to 35%, and the autoignition values decreased by about 85% [51]. EGR can be a valuable solution when stringent NOx emissions limits set by the EU and other governing bodies have to be reached, which can be more important than the resultant losses in engine efficiency when compared to unthrottled lean operation [31].

**Autoignition**
A rapid release of the energy generating high-amplitude pressure waves, commonly referred to as engine knock, is caused by certain volatile end-gas (the last part of the fuel-air mixture that has been introduced into the Cylinder but has not yet been consumed in the Flame-front reaction) conditions such as high pressure and temperature, causing it to spontaneously autoignite. The amplitude of the pressure waves of heavy engine knock can cause engine damage due to increased mechanical and thermal stress. The tendency of an engine to knock depends on the engine design as well as the fuel-air mixture properties [41].
A study [52] has been reported on attempts to predict the knock behaviour of hydrogen-fuelled engines. Good agreement when compared to experimental results was seen for variations in compression ratios, intake air temperatures, and air–fuel equivalence ratios. This suggests that the presence of knock strongly effects the operating regime of an H2ICE. However, based on work performed on a multi-cylinder hydrogen engine at compression ratios of up to 15.3:1, it was stated that knock, as has been observed on gasoline engines, was not observed in any of this hydrogen testing regardless of compression ratio [53].

**Backfire**

Backfiring is the process of fresh hydrogen–air charge combusting during the intake stroke in either the combustion chamber or the intake manifold. The hydrogen–air mixture is entered to the combustion chamber via the opening of the intake valve(s). When the fresh charge is autoignited at combustion chamber hot spots, hot residual gas or remaining charge in the ignition system, backfiring occurs. The main difference between pre-ignition and backfire is the point in the cylinder cycle at which the event takes place: Pre-ignition occurs during the compression stroke with the intake valves already closed, whereas backfiring occurs with the intake valves open. This causes combustion, followed by a pressure rise in the intake manifold, which damage or destroy the intake system.

Because most operation strategies with hydrogen DI start injection after the intake valves close, the occurrence of backfiring is generally limited to external mixture formation concepts. Due to the lower ignition energy, the occurrence of backfiring is more likely when mixtures approach stoichiometry. Intake pressures for a backfiring cycle were measured on a single-cylinder hydrogen engine operation at 3200 RPM and an IMEP of 7 bar. Fig. 4 shows the backfiring traces, with a regular intake and combustion pressure trace for comparison. As the intake valves open, the fresh charge is ignited and combusts in the intake manifold, causing an increase of intake pressure of up to 3 bar. Once all the fresh charge is burned, the pressure in the intake manifold lowers compared to the regular trace, and the cylinder pressure at intake valve closing is increased. The peak cylinder pressure for this backfiring cycle is only around 30 bar and the IMEP is negative (for reference, the peak pressure in motored operation is approximately 21 bar).

Pre-ignition and backfiring are similar phenomena, with the occurrence of backfire present after pre-ignition: Pre-ignition heats up the combustion chamber, which ultimately leads to backfiring in the next cylinder cycle [54, 55]. Thus, any attempts to avoid pre-ignition also reduce the possibility of backfiring. Research has been conducted [56] to avoid backfiring by optimizing the injection strategy and intake design. Injection strategies that allow pure air to flow into the combustion chamber to cool potential hot spots before aspirating the fuel–air mixture were proposed. A model and procedure for backfire-free operation were found as a result of experimental and simulation work on a PFI engine. They were based on the realisation that the chances of backfire are greatly affected by the concentration of hydrogen residual in the intake ports in PFI hydrogen engines. Hence, the lower the concentration of the residual, the lower the backfire possibility. Based on this conclusion it is suggested to limit the end of injection in a fixed range based on engine operation conditions with an earlier end of injection at higher concentration hydrogen mixtures and a lower RPM [57].
Pre-ignition can have numerous causes. Resulting from pre-ignition is a typical premature combustion during the engine compression stroke with closed intake valves. Sources for the fresh charge to combust during the compression stroke include hot exhaust valves or other hot spots in the combustion chamber, residual charge of the ignition system, hot spark plugs or spark plug electrodes, and residual gas or remaining hot oil particles from previous combustion events [58]. In general, both high temperatures as well as residual charge can cause pre-ignition (Mazda claims Pre-ignition is not a problem in their Wankel rotary hydrogen engine [59], see later).

Operating conditions at increased engine speed and engine load are more likely to cause pre-ignition due to higher gas and engine temperatures. Also, due to the dependence of minimum ignition energy on the equivalence ratio, pre-ignition is more pronounced when the hydrogen–air mixtures approach stoichiometric levels.

An automotive-size single cylinder hydrogen research engine at an IMEP of 7 bar and engine speed of 3200 RPM was measured for the in-cylinder pressure trace as well as intake manifold pressure against crank angle for a combustion cycle in which pre-ignition occurred, and is shown in Fig. 5.

Measures to avoid pre-ignition include design of the ignition system with low residual charge, sodium-filled exhaust valves specifically designed crankcase ventilation, proper spark plug design, as well as optimized design of the engine cooling passages to avoid hot spots.
The Hydrogen Infrastructure

Fossil fuels are likely to play a major role in hydrogen production in the near future, due to their obvious benefits such as their high energy density, low cost, high availability, and a large and successful delivery and distribution infrastructure. Unfortunately, they are the main basis for atmospheric pollution and cause great damage to the environment of our planet, because the combustion of fossil fuels releases CO₂, NOₓ, SOₓ, and other air pollutants. It is generally agreed that the renewable energy-based processes of hydrogen production such as solar photochemical and photobiological water decomposition, electrolysis of water coupled with photovoltaic cells or wind turbines, etc. would be unlikely to yield significant reduction in hydrogen costs in the next two decades [3].

3.1 Production & Price

Successful conversion and implementation of hydrogen fuel into the transport sector relies on cost-effective production of low-carbon hydrogen. Hydrogen is already widely produced worldwide, primarily through steam-methane reforming (SMR) of natural gas or electrolysis. In the future, hydrogen could be produced from electrolysis using low-carbon electricity (from renewables or nuclear), or technologies such as SMR and coal gasification with added carbon capture and storage facilities [60-63]. For ICE vehicles, the purity of the hydrogen does not need to meet the same standards as for fuel cell vehicles, but it would be important to minimise the cost of the hydrogen. For liquid hydrogen storage, minimising the cost and maximising the efficiency of liquefaction plants is also important.

Presently, the largest proportion of the industrial hydrogen is produced from the steam methane reforming process, which releases large quantities of CO₂ into the atmosphere. It was estimated that the global warming potential of producing hydrogen using the SMR process is 13.7 kg CO₂ (equiv.) per kg of hydrogen produced [64]: a typical steam methane reforming hydrogen plant with a production rate of one million cubic meters of hydrogen per day produces 0.3–0.4 million standard cubic meters...
of CO₂ per day, which is normally vented into the atmosphere, and the figure above is found due to the low density of hydrogen gas. Coal gasification, another major production method, has much higher GHG emissions.

The claimed energy efficiencies for natural gas reforming, coal gasification and water electrolysis are 75%, 60% and 75% respectively [66]. The fact that fossil-based production of hydrogen is associated with the emission of such enormous quantities of CO₂ may diminish the environmental appeal of hydrogen as a clean fuel.

Gardner [67] comments on costs of a number of renewable methods of hydrogen production, including electrolysis, biomass conversion, and solar energy. He concludes that biomass is the pathway with the highest likelihood of commercial viability in the 2015–2035 timeframe, using either gasification or dark fermentation – a process that uses anaerobic microorganisms to directly produce hydrogen. Capital and running costs of the other techniques make the prices of production too great.

Analysts at the National Renewable Energy Laboratory (NREL), completed a resource assessment to determine if the solar and wind resources in the United States could produce enough hydrogen to meet their national vehicle fuelling demands [68]. They estimated the potential for hydrogen generation from photovoltaic (PV) and wind energy in the United States, and compared that to the country’s gasoline consumption from vehicles [69]. Geographical information system data on the fundamental solar and wind resources available across the country were collected, and then combined with PV, wind turbine, and electrolyser efficiencies, capacities and other factors to determine the amount of hydrogen that can be produced from these renewable energy sources. This graphical representation of the resulting hydrogen production potential from PV, wind, and combined PV and wind energy for each county can be seen in Figs. 6-8 [73]. It was assumed that 53 kWh were required for an electrolyser to produce a kilogram of hydrogen.

PVs combined with low temperature electrolysis were used for the solar electricity generation technology in this assessment because such a system provides a boundary for the greatest energy requirement for solar conversion to hydrogen. If PV shows potential, then technologies that use heat with electrical energy or heat alone, such as high temperature electrolysis [70] and thermochemical [71] cycles, will also show potential, as they need less electrical energy to split the water since some or all of the energy is provided as heat. Also, technologies that directly split water into hydrogen and oxygen photo-electrochemically should be more efficient in the future as hydrogen is produced directly from sunlight and water [72], although the cost this method is not well understood. Finally, high temperature electrolysis, thermochemical cycles, and photo-electrochemical conversion are longer term technologies, which may or may not be viable large scale technologies in the future.
Fig. 6 - Total kilogram of hydrogen per county, normalized by county area. This analysis shows the hydrogen potential from solar.

Fig. 7 - Total kilogram of hydrogen per county, normalized by county area. This analysis shows the hydrogen potential from wind.
3.2 Distribution & Storage

The preferred way to distribute hydrogen on a large scale is through the pre-existing gas pipelines, even if the end use requires liquid hydrogen that would be best made at the demand site. A study of the conversion of the natural gas system to hydrogen in 1972 [74] highlighted the problems in using the existing natural gas distribution system. Pure hydrogen embrittles many pipeline steels causing cracking. This means that existing high-pressure steel pipes could not be repurposed to transport hydrogen instead of natural gas. Research is being pursued on ways to inhibit embrittlement, but so far an effective method has not reached development stage. Also, the low density of hydrogen produces significant problems for using the existing natural gas pipelines; since hydrogen only has one third of the volumetric energy density of natural gas, in order to have the same energy output, the system must run at greater pressures, and therefore would require major investment in new pumps and compressors, and all end use equipment will have to be modified. Since hydrogen flows much more quickly than natural gas, a pressure increase of only around 25% is required to deliver the same energy using hydrogen compared to natural gas.

Although natural gas companies have the capacity to develop the pipeline distribution for the use of hydrogen, their interest is low because natural gas supplies seem plentiful enough to satisfy the demand well into the 21st century. Presently, hydrogen is transported either by train or truck, as a liquid or high pressure compressed gas. As demand is so low, the need to build a pipeline designed solely for hydrogen distribution is also low, so these methods are used even for long distance transport. If the demand for hydrogen were to grow significantly, a dedicated pipeline system will become necessary. The cost and the time required to implement it are major impediments slowing down the introduction of hydrogen as an automotive fuel.

Heat from the surroundings causes boil off at rates of a few percent per day. Besides the energy loss, venting of hydrogen gas is a safety issue. This continues to be an issue that seriously affects all
hydrogen applications, not only its use in ICEs. A recent technical assessment of compressed hydrogen in storage tanks at 350 and 700 bar concluded that this technology will not meet the targets for volumetric capacity and cost of the U.S. Department of Energy for transportation applications [75]. Hydrogen gas has one third the energy density of natural gas which necessitates a large fuel tank even for a short vehicle range. Compressing hydrogen to 200–300 bar is a standard commercial practice but the cylindrical or spherical steel bottles are bulky and heavy. Use of new materials can somewhat lower the weight but at a considerable additional cost. The high pressures pose refuelling and safety problems, deemed to be more serious than is the case with liquid H\(_2\). To store the equivalent of 19 l (5 gallons) of gasoline as compressed hydrogen requires a heavy tank larger than a 200 l drum.

The story doesn’t improve much when considering liquid hydrogen; storage has its own drawbacks owing to the low temperatures required. However, it does have a high mass energy density (3 times that of gasoline) which minimizes the weight penalty. Peschka [76] considers all aspects of liquid hydrogen. The volumetric energy density of liquid hydrogen is also low (one quarter that of gasoline). This fact and the need for thermal insulation result in a tank almost the size of a 200 l drum. Hydrogen liquefies at 20 K, requiring energy intensive compression and refrigeration. It takes almost as much primary energy to liquefy hydrogen as is contained in the liquid.

Hydrogen can also be stored as a solid in metal hydrides [77]. Metal hydrides suitable for use in vehicles typically store 0.5–2% of hydrogen by weight, making the storage unit very large and heavy. Hydride formation is reversible and exothermic, releasing heat when charged with pressurised hydrogen and releasing hydrogen when heat is applied. The hydrides must release hydrogen at relatively low temperatures for automotive applications, because the heat source is the engine exhaust. This low temperature restriction can only be met by a few hydrides, such as FeTi, which unfortunately have a low hydrogen storage capacity.

The conventional gasoline tank, and even the compressed gaseous hydrogen tank beat the hydride storage system easily in both size and weight. The hydride storage vessel must be able to accommodate a sizeable pressure of hydrogen gas, as well as the 25% volume expansion of the hydride that occurs during charging. The repeated charge/discharge cycles cause disintegration of the metal hydride into a powder of micron-sized particles with ensuing handling problems. The system is also very sensitive to passivation by oxygen-containing impurities in the hydrogen. The fuel must therefore be exceptionally pure hydrogen for longevity, which is expensive. Provided the hydrogen contains less than 50 ppm impurities, with concentrations of CO, CO\(_2\), O\(_2\), H\(_2\)O and hydrocarbons being kept to less than 10 ppm each, the material should be capable of sustaining around 2000 charge/discharge cycles. Slightly larger concentrations of Nitrogen can be tolerated, and the content of an inert gases, such as argon, can exceed 1%.

Alloys based on titanium-vanadium-manganese (TiVMn) have been developed and used [70], and are expected to lower the weight of the hydride storage, but probably by less than 20%. The energy expended in hydride formation is much smaller than the liquefaction energy, but this advantage is lost in the high energy costs of carrying the hydride storage around and fabricating it. Also, the metals used for hydride storage, Ti for example, are expensive.

The energy cost of the smaller applications, such as connecting the rods or valves, has been a barrier. The energy penalty is roughly equal for both liquid hydrogen and hydride storage - for a small, 150 km ranged vehicle it is around 35 kWh/kg of Hydrogen [78]. However, for an increased vehicle range, the penalty for liquid H\(_2\) storage remains almost constant, while that for hydride storage increases sharply as so much extra weight has to be hauled along. The comparison between metal hydride and liquid hydrogen storage may vary slightly depending on certain vehicle types and configurations, but
generally the energy penalty is substantially higher with hydride storage. This combined with the much higher purity of the hydrogen required making the fuel more expensive make metal hydride storage a much less cost efficient storage method. Table 4 compares the storage methods with a 19 litre gasoline tank, as this is the largest hydrogen storage system that could be accommodated in a 4-6 passenger automobile or minivan.

<table>
<thead>
<tr>
<th></th>
<th>Gasoline reference</th>
<th>Liquid hydrogen (at 20 K)</th>
<th>FeTi hydride (1.2% H2 by mass)</th>
<th>Compressed hydrogen (207-690 bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel, kg</td>
<td>14</td>
<td>4.7</td>
<td>4.7</td>
<td>4.7</td>
</tr>
<tr>
<td>Tank, kg</td>
<td>6.4</td>
<td>18.6</td>
<td>550</td>
<td>63-86</td>
</tr>
<tr>
<td>Total, kg</td>
<td>20.4</td>
<td>23.2</td>
<td>555</td>
<td>70-90</td>
</tr>
<tr>
<td>Volume, L</td>
<td>19</td>
<td>178</td>
<td>190</td>
<td>410-290</td>
</tr>
</tbody>
</table>

Table 4 – Comparison of on-board hydrogen storage against gasoline.

3.3 Safety

Experts maintain that safety issues can be resolved and that hydrogen can be made as safe as gasoline or natural gas, but it is impossible to extrapolate today’s experience using trained personnel and special precautions at hydrogen fuelling stations to future safe 'self-serve' stations for widespread public use. The unique properties of hydrogen require an adapted approach when laying out a safety concept for both hydrogen engine test cells as well as hydrogen-powered vehicles. The gaseous state of the fuel at ambient conditions in combination with the low density, wide flammability and invisibility of the gas as well as its flames require amended measures to guarantee a safety level equivalent to conventional fuels. With modern fail-safe sensors and alerting devices coupled with proper education of the public and personnel the desired safety level might be attained but the engineering of safe hydrogen vehicles and distribution will be challenging and expensive.

Verhelst and Wallner [8] note the limited number of publications in the area of hydrogen safety, but do provide a summary of the current safety aspects and best-practice recommendations, including sensors and detectors to the engine’s hydrogen supply system.

Regardless of the lack of publications, clearly the unique properties of hydrogen require an adapted approach when laying out a safety concept for both hydrogen engine test cells as well as hydrogen-powered vehicles. The gaseous state of the fuel at ambient conditions in combination with the low density, wide flammability and invisibility of the gas as well as its flames require amended measures to guarantee a safety level equivalent to conventional fuels.

With all of this section considered, one can conclude that the operation of the ICE itself on hydrogen fuel compared with gasoline – (i.e. efficiency, power and range loss, etc.) is not a serious impediment when compared with production, distribution, and on-board storage of the hydrogen fuel.

4 Research & Development

Hydrogen as a fuel in ICEs dates back as far as 1807, where François Isaac de Rivaz invented an internal combustion engine that used a mixture of oxygen and hydrogen for fuel [79]. Since then, institutions (mainly automotive companies) have been developing and improving the technology, mainly by automotive companies searching for a more sustainable and clean fuel source.

The greatest quantity of research came from the late 1990s through to the late 2000s, where large investments were coming from automotive companies, energy companies, governments, and
universities, meaning development of the technology moved at a swift pace. Companies such as BMW, Ford, Mazda and MAN all saw great opportunities with hydrogen as a cleaner fuel source for their vehicles. However, research slowed after this period – perhaps because many automotive companies chose to turn to hydrogen fuel cell research over H2ICE, perhaps because although the technology was improving at a fast pace, the infrastructure required to support the collection, storage and supply of hydrogen fuel on a large scale was not ready.

4.1 Automotive & Engineering Companies

1807 - François Isaac de Rivaz’s hydrogen and oxygen internal combustion engine [79].

1933 – Norsk Hydro operated a hydrogen powered ICE vehicle using on-board ammonia reformation [80]. Using the hydrogen as a booster, the engine achieved much better combustion of hydrocarbons, eliminated backfiring and gave a higher output with lower specific fuel consumption and achieved much better combustion of hydrocarbons with higher power output and lower specific fuel consumption.

1974 – Musashi institute of Technology introduced Musashi 1, the first Japanese hydrogen-fuelled vehicle using a 4-stroke engine in combination with liquid hydrogen storage [82].

1977 – The Musashi 3, a 2-stroke engine with direct injection was presented [83].

2000 – University of California converted a gasoline powered 427 Shelby Cobra to run on gaseous hydrogen, in an attempt to break the land speed record for hydrogen powered vehicles. (Unfortunately the record attempt did not run due to bad weather) [84].

Early 2000’s – Quantum Fuel Systems Technologies Inc. converted over 30 vehicles to hydrogen operation, including a Toyota Prius, where two compressed hydrogen tanks replace the conventional gasoline tank, leaving the interior of the vehicle unchanged. A turbocharger was used to increase the power output when the vehicle was operating on hydrogen. With a drivability similar to the gasoline counterpart, the vehicle has an estimated range of 100–130 km per fill while meeting SULEV emissions standards [85].

BMW

BMW have been perusing hydrogen ICEs since 1979 [86], when they developed the 520, a prototype vehicle featuring an engine that ran on either hydrogen or gasoline. Since then to 1996, they developed three generations of hydrogen powered vehicles, and in 2000 introduced the 5.0-liter V-12 750hL, the company’s fifth-generation hydrogen car.

In 2001, BMW produced its sixth-generation hydrogen concept car, the 4.4-liter V-8 745h. It had two fuel tanks - one for hydrogen and one for gasoline. When running on hydrogen, the 745h generated 182 horsepower, reached 62 miles per hour (100 kph) in 9.9 seconds and had a top speed of 134 mph (216 kph).

In 2004, BMW unveiled the H2R hydrogen-powered concept race car, which went on to set nine speed records for hydrogen-combustion vehicles at the Miramas Proving Grounds in France. The H2R’s 6.0-liter V-12 engine is based on the 760i’s gasoline-fuelled engine. This H2-powered high performer generates 232 horsepower (173 kW), helping it to achieve a top speed of over 187.62 mph.
In 2007 came the BMW Hydrogen 7 bi-fuel, a luxury sedan powered by a 6.0 L V12 engine, shown in Fig. 10. The engine is equipped with two separate fuel systems allowing the vehicle to operate on gasoline as well as hydrogen. Gasoline is injected directly into the combustion chambers, and hydrogen is injected into the intake manifolds of the naturally aspirated engine [87]. The vehicle is equipped with a cryogenic hydrogen tank located in the trunk of the vehicle in addition to the conventional gasoline tank. This tank, along with its associated control equipment, adds about 15% (220 kg) to the car's weight. The cryogenic tank holds about 8 kg of liquid hydrogen which allows an estimated range of 200 km in hydrogen operation and another 480 km on gasoline [88]. The car always starts in hydrogen mode, in an attempt to lower emissions by allowing the catalytic converter to warm up. Approximately 100 BMW Hydrogen 7 bi-fuel vehicles were built.

According to the manufacturer’s claims, the BMW Hydrogen 7 vehicle successfully completed the process of series development, meaning that the vehicle and all components have gone through the same design, manufacturing and quality control processes as any other BMW vehicle.
At low loads, the engine operates a lean combustion strategy in order to reduce NO\textsubscript{x} so that after treatment is not required. In hydrogen mode the engine can achieve more than 170kW, with torques higher than 340Nm. Gasoline is directly injected into the cylinder, but the hydrogen is port injected. This means the injected hydrogen displaces approximately 30% of the aspirated air. Therefore, without the help of turbo-charging, the engine in hydrogen mode only achieves 80% of the maximum power of the engine in gasoline mode.

The BMW bi-fuel hydrogen 7 series complies with both the current European and US emission standards, as shown in Fig. 11, however it still uses more fuel than many trucks, consuming 13.9 l/100 km for gasoline (petrol) and 50 l/100 km for hydrogen. Table 5 shows the consumption (l/100 km) and fuel economy (mpg) for both Imperial and US gallons.

![Fig. 11 - Measured tailpipe emissions of the new bi-fuel BMW 7 series compared with legislative emission limits](image)

<table>
<thead>
<tr>
<th></th>
<th>Gasoline (petrol)</th>
<th>Hydrogen</th>
</tr>
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<tbody>
<tr>
<td>l/100 km</td>
<td>Imp. Mpg</td>
<td>US mpg</td>
</tr>
<tr>
<td></td>
<td>13.9</td>
<td>20.3</td>
</tr>
</tbody>
</table>

Table 5 – fuel consumption for the BMW Hydrogen 7.

The difference in fuel consumption is largely due to the different energy density with gasoline (petrol) yielding 34.6 MJ/l and liquid hydrogen yielding 10.1 MJ/l. Based on these energy density figures, one would expect 47.6 l/100 km for hydrogen based on 13.9 l/100 km for gasoline (petrol); which is very close to the stated 50.0 l/100 km. It was also more expensive than its sister the 760Li, which is BMW’s biggest and most expensive sedan, with a base price tag of over $118,000, thus further diminishing its widespread appeal.
The BMW Hydrogen 7 Mono-Fuel demonstration vehicle was built based on the BMW Hydrogen 7 bi-fuel car to showcase the emissions reduction potential of a dedicated hydrogen vehicle. The main alterations to the vehicle were the removal of the gasoline fuel system including fuel injectors, fuel lines, charcoal filters for tank ventilation and fuel rail. Fig. 12 shows the location of the hydrogen bearing parts. The two high pressure fuel pumps were also removed, which reduce the parasitic losses on the engine. For stability reasons, the gasoline fuel tank remains in the vehicle because it is a structural element. The vehicles are equipped with improved catalyst setup consisting of two monoliths, the first for stoichiometric operation and the second for reducing the NOx peaks that occur when switching from lean to stoichiometric operation.

The car achieved drive-cycle NOx emissions that were approximately 0.0008 g/mi, which is equal to 3.9% of the SULEV limit [89]. It also achieved CO emission levels of a fraction of the SULEV limit. For non-methane hydrocarbon (NMHC) emissions, the cycle averaged emissions were actually 0 g/mile, which required the car to actively reduce emissions compared to the ambient concentration! The fuel economy numbers on the FTP-75 test cycle were 3.7 kg of hydrogen per 100 km, which, on an energy basis, is equivalent to a gasoline fuel consumption of 13.8 l/100 km (17 mpg). Fuel economy numbers for the highway cycle were determined to be 2.1 kg of hydrogen per 100 km, equivalent to 7.8 l of gasoline per 100 km (30 mpg) [89]. Although low emission levels have been achieved, for the catalysts to work properly, a significant reduction in engine efficiency in stoichiometric operation was found compared to lean operation. Measurements on a single-cylinder DI research engine revealed an efficiency loss of 4% with throttled stoichiometric operation compared to unthrottled lean-burn operation at 2000 RPM and an IMEP of 8 bar [15].

On a naturally aspirated engine, hydrogen with external mixture formation produced 18% less power and 36% less torque that the equivalent gasoline. While hydrogen with internal mixture formation
produced 17% more power and 15% more torque than that of the gasoline. At full load, 2000rpm, the internal mixture formation H2-ICE had an indicated efficiency greater than 33% [88].

**Mazda**

Mazda have made notable developments into the hydrogen energy sector, starting with the creation of their Wankel Rotary engine. It uses an eccentric rotary design instead of reciprocating pistons to produce motion. This provides a higher power to weight ratio compared to similar reciprocating engines, and so can be favourable for hybrid applications. A Wankel Rotary engine schematic is shown in Fig. 13 [90].

Amrouche et al [90] have reviewed the use of hydrogen-enriched gasoline in a Wankel rotary engine, with hydrogen percentages ranging from 0% to 10%, and find that the brake thermal efficiency of the original gasoline Wankel rotary engine was enhanced by about 28% over the baseline by adding 10% energy fraction of hydrogen in the gasoline fuel mixture, decreasing the brake specific fuel consumption and the exhaust temperature of the engine. The performance of the original gasoline Wankel engine as indicated by the Torque and Power are improved as the energy fraction of hydrogen increases in the fuel mixture at the conditions tested. Because the increase of the peak working chamber pressure and temperature, the NO, brake specific emissions are raised by 137% as the energy fraction of hydrogen increased from 0% to 10%. However, reductions in the brake specific emissions of HC by 85%, CO by 64% and CO2 by 6% occurred with increasing hydrogen fraction due to better combustion of the air/fuel mixture at the conditions tested.

Fig. 13 – Schematic of a Wankel rotary engine [90].
Since 1991, Mazda has developed several generations of hydrogen-powered vehicles; the HR-X, HR-X2, MX-5 Miata and the Capella Cargo, which all feature a wankel rotary engine. 2003 saw Mazda unveil the RX-8 Hydrogen RE. Fig. 14 shows a diagram of the vehicle and the positioning of its engine and fuel tanks. The hydrogen version of the RENESIS Wankel engine is equipped with an electric-motor-assist turbocharger that is used to maximize the effectiveness of forced induction throughout the engine speed range [91].

The most recent generation is equipped with two compressed hydrogen tanks with an operating pressure of up to 350 bar, giving the vehicle a range of approximately 100 km in hydrogen operation plus an additional 550 km on gasoline. A combination of lean and stoichiometric hydrogen combustion operation results in a 23% improvement in fuel economy compared to gasoline operation, but at the cost of significant reductions in power and range. The performance of the vehicle is reduced from 154 kW in gasoline mode, to 80 kW in hydrogen operation, with a torque of 140 Nm [92]. The maximum speed is reduced from 234 kph to 169 kph. In 2007 Mazda signed a ‘memorandum of understanding’ to provide around 30 RX-8 Hydrogen RE’s to HyNor – a national development project which promotes the use of hydrogen in the transport sector, with the ultimate plan being a roadway stretching 580km from Oslo to Stavanger, complete with hydrogen fuelling stations along the route [93] (see later).

In 2007 Mazda unveiled the Mazda Premacy RE hybrid, shown in Fig. 15. As in the hydrogen RX-8, the on-board RENESIS rotary engine can burn either gasoline or hydrogen, however in the Premacy, the rotary doesn’t directly move the vehicle; it instead powers a generator that charges a small lithium-ion battery pack which helps power an 110kW electric motor. The vehicle can accelerate to 60 mph in around ten seconds and reach a top speed of more than 100 mph. Driving range is about 200km, with the additional 400km from the gasoline. The hydrogen tank with 110 litres at 350 bar stores up to 2.4 kg hydrogen. Table 6 gives a brief history of Mazda’s hydrogen vehicle development.
1991 Developed first hydrogen rotary engine vehicle, HR-X
1992 Conducted test drive of golf cart equipped with fuel cell
1993 Developed second hydrogen rotary engine vehicle, HR-X2
    Developed MX-5 test vehicle equipped with hydrogen rotary engine
1995 Conducted Japan’s first public road tests of a hydrogen rotary engine vehicle, Capella Cargo.
1997 Developed Demio FC-EV
2001 Developed Premacy FC-EV, conducted first public road test in Japan
2003 Announced RX-8 hydrogen rotary engine development
2004 Received MLIT approval for public road testing of RX-8 Hydrogen RE
2006 Started commercial leasing of RX-8 Hydrogen RE in Japan (eight models have been delivered to date)
2007 Signed agreement to provide RX-8 Hydrogen REs to HyNor, a Norwegian national transportation project
2008 Commenced public road tests in Norway with RX-8 Hydrogen RE validation vehicle
2009 Commenced commercial leasing of Premacy Hydrogen RE Hybrid

Table 6 - History of Mazda’s hydrogen vehicle development [94].

Fig. 15 – The Mazda Premacy RE hybrid.

Ford
Ford Motor Company has been evaluating hydrogen since 1997 as an alternative fuel option for vehicles with internal combustion engines. In 2001, Ford presented the hydrogen engine-powered P2000 vehicle, with a 2.0 l Zetec 4 cylinder gasoline engine adapted to run on hydrogen. The aluminium intensive five-passenger family sedan was equipped with a highly optimized hydrogen port injection, 14.5:1 compression ratio and gaseous hydrogen fuel supply with an operating pressure of up to 250 bar. The hydrogen P2000 vehicle met SULEV standards for HC and CO and emitted 0.37–0.74 g/mile of NOx, while showing a metro cycle fuel economy improvement of up to 17.9% relative to gasoline [30]. In comparison to a gasoline fuelled vehicle the P2000 emits only 0.4% of carbon dioxide, which
results from engine oil present in the burn chamber. Harmful emissions during the EPA 75 drive cycle were further reduced due to better calibration to hydrogen (see Table 7), except the nitrogen oxide emissions.

An experimental study on a Ford 2.0 l Zetec engine demonstrated that emissions levels of oxides of nitrogen below 1 ppm can be achieved by combining exhaust gas recirculation and a 3-way catalyst [95,96]. Simulation studies also concluded that the indicated thermal efficiency of cooled EGR is slightly higher than that of a hot EGR strategy. By increasing the EGR percentage (whether cooled or hot), the indicated thermal efficiency increases firstly and then decreases due to the unstable combustion at high EGR rates. The indicated thermal efficiency is mainly influenced by the properties of the cylinder charge, combustion duration and phasing as well as the wall heat losses. The combination of these factors results in an increased indicated thermal efficiency with moderate EGR levels; however, higher EGR levels result in decreased indicated thermal efficiencies due to inefficient and unstable combustion [97].

<table>
<thead>
<tr>
<th>EPA 75</th>
<th>NMHC [g/km]</th>
<th>CO [g/km]</th>
<th>NOx [g/km]</th>
<th>CO₂ [g/km]</th>
</tr>
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<tbody>
<tr>
<td>Phase I FG</td>
<td>0.0052</td>
<td>0.0073</td>
<td>0.23</td>
<td>0.87</td>
</tr>
<tr>
<td>Phase II FG</td>
<td>0.0047</td>
<td>0.0051</td>
<td>0.46</td>
<td>0.87</td>
</tr>
<tr>
<td>Gasoline FG</td>
<td>1.22</td>
<td>5.99</td>
<td>0.87</td>
<td>180.24</td>
</tr>
<tr>
<td>Gasoline TP</td>
<td>0.037</td>
<td>0.58</td>
<td>0.019</td>
<td>195.15</td>
</tr>
<tr>
<td>SULEV TP Standard</td>
<td>0.0062</td>
<td>0.62</td>
<td>0.012</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 7 – Ford P2000 Vehicle Emissions (FG: Feedgas, TP: Tailpipe)

In 2003 Ford launched the H2RV research vehicle. The H2RV had a 2.3 l supercharged H2-ICE coupled with Ford’s modular hybrid transmission system (MHTS) [98].

In 2004 Ford developed a 6.8 l V10 supercharged H2-ICE F-pickup and an H2-ICE E-450 shuttle bus. To demonstrate a commercially viable hydrogen ICE-powered vehicle application, Ford installed the 6.8 l V10 H2-ICE in a fully engineered demonstration fleet of 30 E-450 shuttle buses. The 8–12 passenger shuttle bus with a 4.5 m wheelbase and an estimated gross vehicle weight of 6373 kg is equipped with a compressed hydrogen on board storage system that holds up to 29.6 kg of hydrogen at a pressure of 350 bar with a resulting vehicle range of 240–320 km. The target specified for the hydrogen-powered shuttle bus was to meet 2010 Phase II heavy duty emission standards [99-102]. They will be leased to customers for 2-3 years for US$250,000. The first delivery of eight E-450 hydrogen shuttle buses will be sent to Florida.

Ford’s development of hydrogen IC engines has tended to focus on traditional strategies, such as port injection with lean combustion. More recently their hydrogen engines have been fitted with superchargers in order to increase the power and torque. Ford say they intend to continue research into the next-generation hydrogen internal combustion engines, with plans to include features such as direct injection to improve power and fuel economy. However Ford’s research specifically in hydrogen fuelled IC engines has declined, as they have migrated to research in hydrogen fuel cell applications.

MAN

MAN have produced several H2-ICE buses for various hydrogen transport demonstration projects.
since the early 1990s. A 6-cylinder 12 l bus engine (MAN H 2866 UH01) converted to bi-fuel operation was shown to achieve 170 kW in gasoline operation and 140 kW in stoichiometric port-fuel injected hydrogen operation, which is approximately 82% of the gasoline power output, confirming the theoretical considerations. However, in order to avoid combustion anomalies, the compression ratio of the engine had to be reduced to as low as 7.5:1 [103].

With later engine conversions, significant improvements could be achieved by using solenoid-driven hydrogen injection valves instead of rotary hydrogen valves; the MAN H2876 UH01, a 12.8 l in-line 6-cylinder engine using these improved injectors with sequential injection, achieved a peak brake thermal efficiency of 31% in naturally aspirated stoichiometric hydrogen operation. The said engine uses a reducing catalyst with lambda control for emissions after treatment. Operated with slight hydrogen surplus, the engine can be operated well below Euro 5 emissions levels [104].

![Fig. 16 – MAN hydrogen ICE H 2876 UH01.](image)

The port injection results in compromises either in terms of power density with lean air–fuel ratio approaches or engine efficiency with stoichiometric concepts. A potential solution to this trade-off is combining lean-burn and stoichiometric operating strategies. This concept has been proposed based on engine research results [104] and has also been implemented in hydrogen demonstration vehicles [86]. At low engine loads, the engine is operated at variable lean air–fuel ratios, resulting in good engine efficiencies and extremely low engine-out emissions. Once a certain engine power demand is exceeded, the operating strategy is switched to throttled stoichiometric operation. This generation of hydrogen internal combustion engines were developed under the EU project HyFLEET:CUTE (see later).

MAN also produced a turbocharged engine, the H 2876 LUH01, which has a higher compression ratio of 12:1, a higher maximum power of 200 kW and a better thermal efficiency (40%). The MAN H2-ICE buses produce emissions well below Europe's future emission limits (see Table 8).
Table 8 - Exhaust gas emissions from MAN's H2-ICE buses used in HyFLEET:CUTE (all values measured according to the European Stationary Cycle (ESC 13-stage test))

<p>| | |</p>
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<tbody>
<tr>
<td>NOx</td>
<td>0.2 g/kWh</td>
</tr>
<tr>
<td>HC</td>
<td>0.04 g/kWh</td>
</tr>
<tr>
<td>PM</td>
<td>0.005 g/kWh</td>
</tr>
<tr>
<td>CO</td>
<td>Below measurable limits</td>
</tr>
</tbody>
</table>

**Revolve**

Revolve is an engineering services company providing technical and design services to the Transportation industry. They are UK's leading provider of Hydrogen fuelled vehicles to the Research and local Authority sectors, and a market leader in the vehicle applications of Hydrogen storage systems for both Fuel Cell vehicles and ICE's.

Their work included modifying the engine of a Ford Transit-vehicle to operate using compressed hydrogen gas fuel, as well as gasoline. The vehicle's 2.3-litre 4-cylinder petrol engine, has a belt-driven supercharger added, providing additional combustion air under pressure when the fuel mode switch is selected to hydrogen only [105].

The hydrogen fuel is stored in three tanks below the vehicle floor. This installation provides a storage capacity for 4.5 kilograms of hydrogen at 350bar (5000psi) and gives an estimated range between 95 miles for the urban cycle and 135 miles for open highway running [105].

Revolve Technologies collaborated with ITM Power plc in 2009 to provide the breakthrough refuelling solution by enabling vehicle operators to generate their own hydrogen fuel using a patented electrolyser which entered production at ITM's special facility in Sheffield.

![Image of Revolve's adapted Ford Transit vehicle at ITM's hydrogen fuelling station in Sheffield](image)

More recently they have made advancements in Hydrogen ICE's with the "H2ICED" technology, with the “D” corresponding to Diesel. Here a compression ignition is used, giving significantly improved thermal efficiencies over the spark ignition variants previously developed.
The higher compression of the diesel engine improves thermodynamic efficiency, with the engine’s existing turbocharger providing the optimum low speed boost, and running the system throttle-less is ideally suited to hydrogen’s wide combustibility range (like diesel itself) allowing the engine to achieve in excess of 40% thermodynamic efficiency [106].

At higher loads, the engine utilises larger quantities of diesel injection with the hydrogen to achieve the same torque curve as the diesel-only engine, meaning no performance degradation at all. The hydrogen naturally promotes incredibly clean combustion with particulate masses being in excess of a factor of 10 lower than diesel-only.

Alset Global is a technology and engineering company that develops and produces clean mobility solutions based on hydrogen for the automotive industry. They have developed an on-board hydrogen hybrid system enabling internal combustion engines to operate using hydrogen or gasoline, or a customized blend of hydrogen and gasoline/diesel fuel. Their goal is to create an affordable hydrogen fuel solution that can bring significant CO₂ reductions whilst remaining at a competitive price; an attempt to bridge the gap to the hydrogen economy whilst hydrogen fuel cells undergo their required years of research and development [107].

Alset’s bi-fuel system is unique in the way it is able to alter the hydrogen concentration fuel mixture automatically to adapt to the power demand of the vehicle using an the engine control unit, which contains the proprietary Alset Engine Operating Software (AEOS) that controls fuel compounding and the combustion process according to each particular driving situation. This system was integrated into an Aston Martin Rapide S, which competed in the ADAC Zurich Nurburgring 24-hour race in May 2013 [108]. Alset won the PMW Powertrain of the Year award for this achievement [109].

Four carbon fibre fuel tanks are stored on-board the vehicle, two in the passenger seat and two in the boot. Together they hold a total of 3.5kg of hydrogen at 350bar. (700bar is possible to allow for smaller packaging of the hydrogen, or for more hydrogen storage). The hydrogen adaptations to the vehicle add around 100kg to the weight, 70% of which is the fuel tanks.
The hydrogen injectors are fitted to the intake manifold, upstream of the regular gasoline injectors. The hydrogen is delivered to the fuel rail in constant flow, at between 4 and 5 bar [110].

The combustion process is central to getting the most out of the hydrogen fuel, and is where much of Alset Global’s intellectual property lies. The AEOS controls the fuel injection to adjust a fuel compound optimum for each driving situation, and the combustion process optimised to each fuel compound. In this process, the advantages of a liquid fuel with a high volumetric energy density and a gaseous
carbon-free fuel can be combined. This results in a mobility solution with the highest CO₂ reduction potential for the lowest cost, without sacrificing performance or driving range [110].

4.2 Government & Energy Companies

HYICE

- Starting date: 05/01/2004
- Ending date: 04/01/2007
- Cost: 7,716,741 Euro

HyICE (Hydrogen Internal Combustion Engine), launched in January 2004, was a three-year European initiative aimed at contributing to the development of a clean and economical hydrogen fuelled automobile engine. The total project cost was 7.7 billion Euro, 5 Euro of which was from EU funding. The project is coordinated by BMW Group Research and Technology, with the ultimate goal being to beat both gasoline and diesel engines on performance and efficiency with reasonable product cost. In the range of high-power vehicles, where hydrogen internal combustion engines can deliver even higher efficiency, HyICE technologies may present not just an intermediate, but also a long-term solution [111].

The first subproject involved the system applied for the mixture formation. For the two most promising concepts, direct injection (DI) and cryogenic port injection (CPI), the necessary knowledge concerning design and application has to be created [112].

As the first logical step, the project focused on the development of new components such as injectors and an ignition system as well as the preparation of computational fluid dynamics (CFD) tools for optimisation of the process of mixture formation and combustion. By bringing together representatives of the automobile industry and researchers from Europe and the USA, the project ensured the dissemination and exchange of important and valuable know-how [111].

A commercial CFD-solver has been adapted and improved to deal with the calculations of Hydrogen to support the development process also of future production engines. Through Investigations into new injection strategies, thus controlling the combustion process, a method was developed to significantly improve the noise behaviour which is of the utmost importance in a passenger car application. At a certain operating point with multiple injections, pressure rise as well as maximum pressure can be limited. High-pressure direct injection shows vast potential by optimising the mixture...
formation process. However, high-pressure DI also poses some challenges starting from pressure supply to injector stability. Nevertheless the investigations within HyICE proved high potential concerning the key issues of improving efficiency and avoiding NOx emissions [113].

On the other hand, the important advantage to low-pressure direct injection is the reduced complexity of the fuel supply and its components, thus making it closer to series-production readiness. As the lower density of hydrogen leads to more voluminous storage tanks, the concept is better suited to commercial vehicles such as city buses, hence the follow-up project HyICE:CUTE, where MAN has equipped a fleet of hydrogen urban buses with low-pressure DI Hydrogen engines [113].

The project then moved onto the task of the modification of the DI injectors for Hydrogen. The HyICE report [113] does not give much detail here about the results, but does mention challenges concerning the precise metering of the required fuel mass during a very short injection time of a few milliseconds.

In contrast to direct injecting hydrogen engines, for the cryogenic port injection (CPI) the low pressure range of a liquid Hydrogen tank is sufficient. This concept takes advantage of the external mixture formation of Hydrogen and air by making use of the coldness. At the same time the concept of liquid Hydrogen storage and CPI forms a technically straightforward system, therefore supporting the attempt to build economic Hydrogen vehicles. Within HyICE detailed experimental investigation in the mixture formation and the combustion process, as well as validation and adaption work on CFD tools have been combined into the development of a combustion system for CPI.

The project successfully established a research exchange between European and US research activities, which has proved to be beneficial for both parties.

The project resulted in the demonstration of engine concepts exceeding a specific power output of 100 kW/l and a peak efficiency of 42%. The report concludes that in the range of high-power vehicles, HyICE technologies can:

- Answer customer demand regarding both fuel efficiency and engine performance
- Enable the development of products which can be sold at a reasonable price
- Offer the chance of rapid dispersal of mass market Hydrogen vehicles, provided that the related infrastructure is available and that the political basic conditions are favourable [113].

**HYFLEET:CUTE**

- 2006-2009
- 43 million Euros.

HyFLEET:CUTE saw the operation of 47 Hydrogen powered buses (33 FC and 14 H2ICE) in regular public transport service in 10 cities on three continents. The project brought together 31 partners from industry, Government, academic and consulting organisations. Some of the worlds' leading automotive and technology development companies, major energy companies, policy developers and transport operators are collaborating to lead Europe into the development of the 22nd Century hydrogen-based transport system of the future [114].

HyFLEET:CUTE was established under and is financially supported by the European Commission’s 6th Framework Research Programme. The European Union’s Energy Policy aims at diversifying and security energy sources while reducing CO2 and other emissions harmful to the environment and human health. The main goals of the project were:
• Demonstration of hydrogen fleets with innovatory extensions of the Clean Urban Transport for Europe Project (CUTE) through testing Hydrogen powered Internal Combustion Engines Buses and hybrid fuel cells buses.
• Demonstration of innovative, cost-efficient and safe production, storage, distribution and fuelling systems of hydrogen.
• Exploring synergies between sector and technology pathways. Demonstration of the benefits for transport and stationary applications of using hydrogen simultaneously for both cases. Assessment and monitoring from a socio-economic, energy efficiency, environmental and safety perspective.
• Communication and dissemination [115].

HyFLEET:CUTE has seen the successful construction and operation of 14 Hydrogen powered ICE buses for the Public Transport fleet in Berlin, supplied by MAN. The first four buses were naturally aspirated, and the remaining five were turbocharged DI. The first buses in the fleet were used to play an important promotional role in the 2006 FIFA World Cup by carrying VIPs, journalists and members of the public visiting from around the world. These buses were conventionally aspirated ICE buses with a power of 150 kW. The final 8 buses were introduced into the fleet by March 2008 and, along with the original four buses, are in on-going, normal operations in Berlin. These buses are turbocharged technology and have a power of 200 kW [115].

LHNE (London Hydrogen Network Expansion) project.

• Jan 2013 - Jan 2016

The LHNE project is a government-backed initiative co-funded by the Technology Strategy Board to create the UK’s first hydrogen powered transport system across London and the South East.

The consortium, led by Air Products, will deliver a publicly accessible, state-of-the-art fast-fill 700 bar renewable hydrogen fuelling station network. LHNE will also deploy new hydrogen vehicles in London; including a number of Hyundai hydrogen fuel cell vehicles and Revolve hydrogen powered vans.

Creating this network is seen as particularly important because the major car manufacturers have confirmed that the hydrogen vehicles available for purchase in the UK from 2014/15 require 700 bar fuelling systems. The LHNE project will therefore upgrade the existing fuelling station located near Heathrow Airport to 700 bar and deliver a brand new fuelling station with this specification in London [116].

In addition, the project will increase accessibility to the dual pressure fuelling station at Millbrook Proving Ground in Bedfordshire, and the Transport for London station in Stratford. These developments will create the first network of 700 bar fuelling stations in the UK, ready to meet an increasing demand for hydrogen fuel. It is hoped that the functionality of this network will then be proved by a fleet of hydrogen vans, which will be operated by Commercial Group as part of their delivery network.

The LHNE consortium comprises of Air Products, Cenex, Commercial Group, Element Energy, Heathrow Airport Ltd and Revolve Technologies Ltd and the project is co-funded by a grant from the UK’s innovation agency, the Technology Strategy Board [117].
The StorHy consortium carried out concrete R&D work covering the whole spectrum of hydrogen storage technologies (compressed gas, cryogenic liquid and solid materials) with a focus on automotive applications. The main objectives of StorHy were to provide economically and environmentally attractive storage solutions for transport applications and reinforcing the competitiveness of the European car industry.

The project Conclusions:

Concerning pressurised-\( H_2 \) (CH\(_2\)) storage technology, the analysis shows that the highest gravimetric capacities are achieved by 700 bar high pressure vessels designed for the storage of larger hydrogen amounts corresponding to high internal volumes. From an economic point of view, preliminary results were obtained from a dedicated cost calculation model (see section 5 for the details of this). From an environmental point of view, it has been highlighted that high pressure vessels are made of materials with an average Cumulative Energy Demand (CED) of approx. 80-100 MJ / kg. The pressure vessels under investigation showed a CED of approx. 300 MJ / kg. So this CED is remarkable higher than for average automotive parts. Taking into account that a gasoline tank is lighter, the new storage systems add a significant weight to the vehicle and additionally have a higher specific environmental impact. The highest environmental impact of the pressure vessels results from carbon fibre, due to its complex and energy-intensive production process. Because carbon fibres are not widely applied and still to be considered as high tech material, the environmental data have a high uncertainty.

Concerning L-\( H_2 \) storage technology, concerning energy density, conventional steel cylindrical storage systems reach 1.33 to 2.66 kWh / kg (4 wt.% to 8 wt.%), depending on the hydrogen mass stored. For the moment the main improvement concerning gravimetric energy density has been achieved using an aluminium technology. This system reaches more than 5 kWh / kg (15 wt. %). StorHy projections show that liquid hydrogen storage systems with more than 6 kWh / kg (18 wt. %) are achievable by using composite material. Concerning volumetric energy density, it appears that the real external volumetric energy density of conventional storage systems ranges between 0.8 and 1.5 kWh/l (2.4 to 4.5 kg\(_{H_2} / 100 \) l), while the StorHy cylindrical Tank 3 system is projected to reach 1.28 kWh / l (3.85 kg\(_{H_2} / 100 \) l). With innovative packaging and valve concepts, the volumetric energy density of the StorHy system can be increased to 1.33 kWh / l (4 kg\(_{H_2} / 100 \) l). It is shown that for this technology, costs are mainly driven by components and assembly (handmade technology, numerous non automated steps in the manufacturing process).

Concerning solid storage technology, the project concluded the technology was not at the same level of maturity than C-\( H_2 \) and L-\( H_2 \) storage technologies. The technical data collected come from existing state-of-the-art prototypes, developed either by industrial companies (Toyota, Honda, Ovonics) or by research institutes such as UTRC. In addition, technical data on the StorHy 8kg alanate breadboard tank developed by GKSS and TUHH have been collected. The mass of the breadboard tank is mainly influenced by the mass of the oil shell and the reactor element tubes which represent 29% and 37%, respectively, of the overall mass of the tank. The main cost driver of the breadboard tank are the sintered metal tubes, which represent about 43% of the tank costs (without taking into account the costs of the alanate itself, nor the cost of the oil).
**HyNor**

Established in 2003, HyNor is organized in local projects and cooperates both on a common infrastructure as well as on the acquisition of cars and buses for the project as a whole. The project is funded by private companies, station and cars owners and local, regional and central public institutions.

HyNor unites a long list of national and regional companies, research institutions, NGOs and authorities in order to provide a local effort for the establishment of a common hydrogen infrastructure. Thus HyNor becomes the driving force for the preparations for hydrogen as a fuel in road transport in Norway, and it is a test bed for demonstration projects leading up to a mass market introduction of hydrogen vehicles.

HyNor cooperates with Scandinavian partners through the Scandinavian Hydrogen Highway Partnership (SHHP). Together, the Scandinavian and Icelandic infrastructure initiatives make up one of the world’s largest clusters of hydrogen fuelling stations. This makes this region an attractive market for automotive companies. HyNor and SHHP are in close contact with many car manufacturers about delivering fuel cell hydrogen vehicles to the Scandinavian market. In addition, HyNor cooperates with the California Fuel Cell Partnership (CaFCP), which is a leading hydrogen infrastructure initiative in the US. HyNor has currently acquired 15 refitted Toyota Prius hydrogen fuel cell vehicles and four Mazda RX-8 Hydrogen REs [121].

**ITM**

ITM is a UK based hydrogen Energy Company, which designs and manufactures hydrogen energy systems for energy storage and clean fuel production. They have a long history with hydrogen research and development, with their most recent achievements being a contract to supply three refuelling stations in London, as well as five refuelling stations on the Isle of White. The London stations will be the first green hydrogen deployments in London and are expected to be operational in time to coincide with the roll out of fuel cell electric vehicles planned by the major OEM’s. The Isle of White stations include 4 land based 80kg/day stations and one 15kg/day marine refuelling station. All planning applications submitted on the Isle of Wight have been successful. ITM has chosen two of these sites to take forward for installation of hydrogen refuellers ready for operation in November 2014, as part of the Ecoslnd Hydrogen Vehicle Refuellers project on the Isle of Wight, supported by funding from the UK’s innovation agency, the Technology Strategy Board [122].

**4.3 Published Convention Studies**

**Universidad Publica de Navarra - Conversion of a Volkswagen Golf 1.4 litre to hydrogen fuel**

In the Universidad Publica de Navarra, Sopena et al [123] converted a Volkswagen 1.4 to run with hydrogen. Main changes included the inlet manifold, gas injectors, oil radiator and the electronic management unit. Injection and ignition advance timing maps were developed for lean mixtures with values of the air to hydrogen equivalence ratio between 1.6 and 3. The established engine control parameters allowed the safe operation of the hydrogen-fuelled engine free of knock, backfire and pre-ignition as well with reasonably low NOx emissions. The H2ICE reached best brake torque of 63 Nm at 3800 rpm and maximum brake power of 32 kW at 5000 rpm. In general, the brake thermal efficiency of the H2ICE was greater than that of gasoline-fuelled engine except for the H2ICE working at very lean conditions (λ = 2.5) and high speeds (above 4000 rpm). A significant effect of the spark advance on the NOx emissions has been found, especially for relatively rich mixtures. Small changes of spark advance with respect to the optimum value for maximum brake torque (MBP) give rise to an increase of pollutant emissions. It has been estimated that the hydrogen-fuelled Volkswagen Polo could reach a maximum speed of 140 km/h with the adapted engine. Moreover, there is enough reserve of power for the vehicle moving on typical urban routes and routes with slopes up to 10%. 
The performance of the H2ICE has been evaluated in terms of the bmep, brake power, brake specific fuel consumption, and pollutants emissions. Bmep of the H2ICE as a function of the engine speed for λ values of 1.6, 2 and 2.5 at WOT are compared in Fig. 22 with the bmep of the gasoline-fuelled engine. The bmep obtained with the H2ICE are within the values that could be expected. This is because for λ values of 1.6, 2 and 2.5, theoretical bmep to obtain the same brake thermal efficiency are 50, 42 and 35%, respectively, of the gasoline-fuelled engine bmep because less air enters the cylinders due to the low density of hydrogen.

Maximum bmep of the H2ICE is achieved at the same engine speed than with the gasoline engine. This indicates that the engine speed at which the H2ICE reaches the maximum volumetric efficiency is similar to the value when it is run on gasoline. Of course, lower bmep are obtained when leaner (higher λ) hydrogen–air mixtures are fed.

As concerns the brake power, the results are shown in Fig. 23. The maximum H2ICE brake power is limited because the maximum engine speed has also been limited (5000 rpm). The H2ICE reached a MBP of 32 kW at WOT with λ = 1.6. When the engine was fuelled with gasoline MBP was 59 kW at 5000 rpm. Brake specific fuel consumption of gasoline equivalent for λ values of 1.6, 2 and 2.5 at WOT are compared in Fig. 24 with the brake specific consumption of gasoline (the rate of gasoline consumption divided by the power produced). The results show that the H2ICE has better brake thermal efficiencies than the gasoline-fuelled engine, especially at low and medium speeds. This could be due to the fact that hydrogen combustion is faster and closer to a constant volume process, and then with a more efficient thermodynamic cycle than that of gasoline combustion. This is a remarkable result taking into account that λ values used with the H2ICE are higher than for the gasoline-fuelled engine which runs on stoichiometric or slightly rich mixtures. In the case of the H2ICE, it can be seen that the lowest brake specific consumption of gasoline corresponds to the richest mixture considered (λ = 1.6) which is then the most brake thermal efficient. The leanest mixture (λ = 2.5) is the lowest efficient except for very low engine speeds. This could be attributed to a lower
efficiency of very lean mixtures combustion because of the higher proportion of unburned hydrogen and slower combustion for a given engine speed [123].

Fig. 22 – Brake mean effective pressure (kPa) at WOT versus engine speed (rpm) for λ values of 1.6, 2 and 2.5.

Fig. 23 – Brake power (kW) at WOT versus engine speed (rpm) for the gasoline-fuelled engine and the H2ICE with λ = 1.6.
Fig. 24 – Brake specific fuel consumption of gasoline equivalent (g/kWh) at WOT versus engine speed (rpm) for λ values of 1.6, 2 and 2.5.

Universidad Publica de Navarra - Conversion of a Volkswagen Golf 1.4 litre to run on hydrogen and gasoline Bi-fuel

Sainz et al [124] discuss the conversion of a Volkswagen Polo 1.4 in to bi-fuel operation. Changes included the incorporation of a storage system based on compressed hydrogen, a machined intake manifold with a low-pressure accumulator where the hydrogen injectors were assembled, a new electronic control unit managing operation on hydrogen and an electrical junction box to control the change from a fuel to another. Hydrogen was stored at 200 bar in two austenitic stainless steel gas cylinders (CE 1370 UT 5.3 MM) of 18 litres and 20.2 kg each. This allowed storing about 0.5 kg of useful hydrogen. The gas cylinders were placed horizontally in the car boot inserted into a body of rigid foam that prevented them from moving. Road tests with hydrogen fuel gave a maximum speed of 125 km/h and an estimated consumption of 1 kg of hydrogen per 100 km at an average speed of 90 km/h.

The performance was first tested in a rolling test bed. The MBT and thermal efficiency obtained as a function of the engine speed and throttle opening (load) for the vehicle running on hydrogen with λ = 1.6 are presented in Figs. 25 and 26, respectively. A maximum torque of about 65 Nm is achieved at 4000 rpm and full load. As expected, this value is considerably lower than the MBT of 126 Nm obtained at 3800 rpm under full load gasoline operation. Obviously, the much leaner fuel-air mixture employed in the case of hydrogen is on the basis of this difference. On the other hand, a relatively high thermal efficiency close to 35%, which is better than the typical values for gasoline engines, was provided by the hydrogen fuelled vehicle at suitable combinations of the speed and load.

The considerably higher speed of a hydrogen flame compared to that of gasoline enables a faster and almost iso volumetric combustion that is closer to the ideal Carnot cycle, which explains the improved thermal efficiency running on hydrogen. Nevertheless, lean burn operation is penalized with lower power outputs as evidenced by the results presented in Fig. 27. It can be seen that the maximum engine power barely reaches 30 kW at 5000 rpm, λ = 1.6 and full load. If the hydrogen-air mixture becomes leaner, the power decreases dramatically, up to about 16 kW at λ = 2 and 10 kW at λ = 2.5. Comparing these results with the maximum power of 55 kW of the original vehicle demonstrates the superiority of gasoline in this respect. It can be seen also in Fig. 26 that the evolution of the maximum power is notably flat for the leanest mixture at high engine speed. This can be viewed as the result of the compensatory effect between the increased velocity and the drop of torque that also takes place.
Fig. 25 - MBT of the engine running on hydrogen (\( \lambda = 1.6 \)) as a function of the engine speed and load.

Fig. 26 - Thermal efficiency of the engine running on hydrogen (\( \lambda = 1.6 \)) as a function of the engine speed and load.
Tokyo City University – Engine conversion to hydrogen operation
Tokyo City University was involved in research leading to the demonstration of 2 hydrogen vehicles. Iwasaki et al. [126] report the conversion of 2 engines to turbocharged PFI operation on hydrogen. These were used in a light duty truck with a hybrid powertrain, and a ‘microbus’ (19 passengers). Lean operation was used to avoid the formation of NO\textsubscript{x}, so that after treatment was not necessary; and turbocharging recovered most of the power loss due to the lean mixtures used. Both vehicles were tested on the JE05 test cycle and emitted NO\textsubscript{x} emissions far below the Japan Post New Long Term Regulation. The authors devoted much work to devising measures for avoiding abnormal combustion (backfire in particular), primarily through changes in the ignition system.

University of Melbourne – Engine conversion to hydrogen operation
Dennis et al. [127] published the findings of work undertaken by the University of Melbourne and Ford Motor Company of Australia, on a PFI engine converted to hydrogen operation. The base strategy is the same as used by Iwasaki et al. [126]; lean burn turbocharged, but additional control on air flow is achieved through fully variable valve timing on both intake and exhaust. The work thus presents new insights in the effects of gas dynamics and air flow on brake thermal efficiency (up to 38%) and occurrence of backfire.

Indian Institute of Technology, Delhi – Conversion of a Hy-Alfa three wheeled vehicle to hydrogen operation.
In Delhi, India, 15 hydrogen-fuelled three wheelers were launched [129]. This was realised within a pilot project of the United Nations Industrial Development Organization (UNIDO), co-funded by its International Centre for Hydrogen Energy Technologies (UNIDO-ICHET) and the Indian Institute of Technology - Delhi, Air Products, Indian Trade Promotion Organization (ITPO) and Mahindra & Mahindra as project partners. 10 of the 15 vehicles are for passenger transport, 5 are for carrying load. The 0.4 litre single cylinder compressed natural gas ICE was converted to hydrogen operation, with 34 litres of hydrogen stored in a tank at 200 bar. The brake thermal efficiency increased from 16.5% to 22% after the conversion, and power output decreased from 6.1 kW to 4.62 kW.
The original single cylinder, air-cooled, carburetted bi-fuel gasoline/CNG engines were converted to electronically controlled PFI hydrogen operation using relatively lean mixtures to avoid backfiring. Evidently, operation on hydrogen immensely reduced all pollutant emissions, compared to the original carburetted engines (with no after treatment). The vehicle's small 6.1 kw, 0.4 litre engine was converted to Bi-fuel operation and stores its Hydrogen in a 200 bar Tank, giving a maximum capacity of 34 litres. Hydrogen Operation sees the BTE increase from 16.5% to 22%, with NOx emissions of 0.196–4.98 g/kwh [129].

The table below summarises the specifications and quantitative data for the hydrogen ICE vehicles mentioned in the review, as well as a few extra. It is worth mentioning that most of the variables given in the table are continuous and variable, and so do not have a single discrete value. For example, NOx emissions depend hugely on the air-to-fuel ratio, engine temperature, and engine RPM. The values in the table are designed to be a ‘best average’, or a value that best represents the variable’s spectrum, so as to give a single value that can be used in applications such as computer modelling. For a more detailed description, see the report text, or the references given in the table. The references in the table have been colour coded; Green indicates a reliable source such as a published article, red indicates where the data has been found on the internet, and so the reliability of the data is unknown. A blank entries in the table are for where no data can be found.
<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Vehicle Year</th>
<th>Vehicle Model</th>
<th>Dimensions (mm)</th>
<th>Engine Size (cc)</th>
<th>Type</th>
<th>Mixture Formation</th>
<th>H2 Storage</th>
<th>Hydrogen Pressure (bar)</th>
<th>Hydrogen Mass (kg)</th>
<th>Total</th>
<th>In H2 Operation</th>
</tr>
</thead>
</table>
Table 9 – Summary of data and specifications of Vehicles using Hydrogen fuel.

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Vehicle Year</th>
<th>Vehicle Model</th>
<th>References</th>
<th>Before Modification</th>
<th>After Modification</th>
<th>Gasoline Operation</th>
<th>H2 Operation</th>
<th>Before Modification</th>
<th>After Modification</th>
<th>Gasoline Operation</th>
<th>H2 Operation</th>
<th>CO2</th>
<th>Notes</th>
<th>Tank Manufacture Estimate (See Chapter 5)</th>
<th>Total Retrofit Cost Estimate (See Chapter 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>1975</td>
<td>Mazda X-2</td>
<td>46</td>
<td>10.2</td>
<td>10.2</td>
<td>N/A</td>
<td>N/A</td>
<td>1,150</td>
<td>1,150</td>
<td>NA</td>
<td>NA</td>
<td>90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1977</td>
<td>Mazda 3</td>
<td>46</td>
<td>9.8</td>
<td>9.8</td>
<td>N/A</td>
<td>N/A</td>
<td>2,000</td>
<td>2,000</td>
<td>NA</td>
<td>NA</td>
<td>75</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>1979</td>
<td>BMW M20</td>
<td>46</td>
<td>9.6</td>
<td>9.6</td>
<td>N/A</td>
<td>N/A</td>
<td>2,950</td>
<td>2,950</td>
<td>NA</td>
<td>NA</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1982</td>
<td>Mazda RX7</td>
<td>46</td>
<td>8.8</td>
<td>8.8</td>
<td>N/A</td>
<td>N/A</td>
<td>3,200</td>
<td>3,200</td>
<td>NA</td>
<td>NA</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1985</td>
<td>Shelby Cobra 427</td>
<td>46</td>
<td>12.1</td>
<td>12.1</td>
<td>N/A</td>
<td>N/A</td>
<td>4,000</td>
<td>4,000</td>
<td>NA</td>
<td>NA</td>
<td>84</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1988</td>
<td>BMW M3</td>
<td>46</td>
<td>16.5</td>
<td>16.5</td>
<td>N/A</td>
<td>N/A</td>
<td>3,400</td>
<td>3,400</td>
<td>NA</td>
<td>NA</td>
<td>115</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1992</td>
<td>BMW M5</td>
<td>46</td>
<td>16.5</td>
<td>16.5</td>
<td>N/A</td>
<td>N/A</td>
<td>3,900</td>
<td>3,900</td>
<td>NA</td>
<td>NA</td>
<td>115</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>Porsche 911</td>
<td>46</td>
<td>18.2</td>
<td>18.2</td>
<td>N/A</td>
<td>N/A</td>
<td>5,000</td>
<td>5,000</td>
<td>NA</td>
<td>NA</td>
<td>144</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>Mazda RX-8</td>
<td>46</td>
<td>20.1</td>
<td>20.1</td>
<td>N/A</td>
<td>N/A</td>
<td>6,000</td>
<td>6,000</td>
<td>NA</td>
<td>NA</td>
<td>165</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>Ford Focus</td>
<td>46</td>
<td>22.0</td>
<td>22.0</td>
<td>N/A</td>
<td>N/A</td>
<td>6,500</td>
<td>6,500</td>
<td>NA</td>
<td>NA</td>
<td>185</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>Audi A4</td>
<td>46</td>
<td>23.5</td>
<td>23.5</td>
<td>N/A</td>
<td>N/A</td>
<td>7,000</td>
<td>7,000</td>
<td>NA</td>
<td>NA</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>Jaguar X-Type</td>
<td>46</td>
<td>24.0</td>
<td>24.0</td>
<td>N/A</td>
<td>N/A</td>
<td>7,500</td>
<td>7,500</td>
<td>NA</td>
<td>NA</td>
<td>215</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>1990</td>
<td>MAN 200</td>
<td>46</td>
<td>11.7</td>
<td>11.7</td>
<td>N/A</td>
<td>N/A</td>
<td>3,000</td>
<td>3,000</td>
<td>NA</td>
<td>NA</td>
<td>90</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>1995</td>
<td>MAN 205</td>
<td>46</td>
<td>14.0</td>
<td>14.0</td>
<td>N/A</td>
<td>N/A</td>
<td>3,500</td>
<td>3,500</td>
<td>NA</td>
<td>NA</td>
<td>110</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>2000</td>
<td>MAN 210</td>
<td>46</td>
<td>16.3</td>
<td>16.3</td>
<td>N/A</td>
<td>N/A</td>
<td>4,000</td>
<td>4,000</td>
<td>NA</td>
<td>NA</td>
<td>135</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>MAN 210</td>
<td>46</td>
<td>18.6</td>
<td>18.6</td>
<td>N/A</td>
<td>N/A</td>
<td>4,500</td>
<td>4,500</td>
<td>NA</td>
<td>NA</td>
<td>155</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>2010</td>
<td>MAN 210</td>
<td>46</td>
<td>20.0</td>
<td>20.0</td>
<td>N/A</td>
<td>N/A</td>
<td>5,000</td>
<td>5,000</td>
<td>NA</td>
<td>NA</td>
<td>175</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tractor</td>
<td>1990</td>
<td>Ford F-150</td>
<td>46</td>
<td>16.8</td>
<td>16.8</td>
<td>38.4</td>
<td>38.4</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>Ford F-150</td>
<td>46</td>
<td>16.8</td>
<td>16.8</td>
<td>38.4</td>
<td>38.4</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>58</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

The National Hydrogen Association [164] estimates a net install cost of 1.5 times the cost of the original engine.

Sorok et al. [164] estimates a cost of $7772 for equipment and 200 labour hours.
5 Costs & Information of retrofit

There is little information available regarding the cost of hydrogen ICE vehicles, or the cost of retrofitting a conventional gasoline ICE to run on hydrogen. The industry is still in its research and development stage so we are in a situation where there is a very limited user interface with these car companies small scale leasing programs. There’s limited report on what those prices are going to be if and when these cars are available to the general public. Information on the cost of the components necessary for the retrofit, such as the gas tank, the hydrogen injectors and the fuel lines are also hard to come by, as they are seen as market sensitive by their respective producers. This section will use information publicly available to estimate both the cost and price of the components required for an ICE to operate on hydrogen, focusing on the hydrogen storage tank.

5.1 The Hydrogen tank

High-pressure tanks are classified into four categories. ‘Type I’ tanks are all-metal tanks, while ‘type II’ tanks are metal tanks wrapped with filament windings (usually glass fibre) around the cylindrical part. ‘Type III’ tanks are made of composite materials (initially fibreglass, and increasingly carbon fibre), with a metal liner (i.e. the inside facing, acting as H\textsubscript{2} the barrier) – initially aluminium, lately in steel. ‘Type IV’ tanks are composite tanks (mainly carbon fibre) with a polymer liner (mostly thermoplastic polymers, of the polyethylene or polyamide type.

Three companies dominate in making the specialty hydrogen tanks: Dynetek Industries Ltd.; Quantum Fuel Systems Technologies Worldwide Inc.; and Lincoln Composites Division of Advanced Technical Products Inc. (In late July 2012, Dynetek announced their acquisition by global materials technology company Luxfer, however they shall be continued to be referred to as Dynetek, as many of the vehicles mentioned in the review contain Dynetek tanks, such as the Mazda RX-8 Hydrogen RE, which was created prior to July 2012).

Of the three, Dynetek is the leader in metal tanks. Its aluminium and carbon fibre Type III tanks, the ‘DyneCell’ appear in hydrogen demonstrator vehicles from all automakers except General Motors [156]. The other two tank makers create Type IV tanks, which are plastic wrapped with carbon fibre. The tanks are hand-crafted of carbon fibre wrapped around a bottle-shaped liner and individually tailored to each hydrogen vehicle. The tanks can carry price tags of $20,000 or more! Dynetek give a range of $10,000-$20,000 [157]. Dynetek provide a helpful table summarising the specifications of their 350 bar DyneCell Hydrogen tanks, and is shown in table 10. Where possible, Information from this table has been added to the vehicle summary table (table 9).
Quantum Technologies provide a document [158] which gives information about the manufacturing process of their hydrogen fuel tanks. Although no information on price is presented, they do show an image of the breakdown of the tank manufacturing cost of their type IV, 125 litre, 10,000 psi (700 bar) hydrogen tank, which is shown in Fig. 29.

Assuming these ratios are constant for tanks of varying sizes and pressures, they can be used to estimate the total cost of manufacture of a hydrogen tank, when including the quoted price of carbon fibre ($15/lb) from the same reference.

The DOE Fuel Cell Technologies Office provide a useful record [159] of performance and cost of type IV Compressed Hydrogen Storage Systems. Table 11 is taken from that document, and shown below.

<table>
<thead>
<tr>
<th>H₂ capacity (kg)</th>
<th>Diameter (mm)</th>
<th>Length (mm)</th>
<th>Water volume (L)</th>
<th>Tank weight (kg)</th>
<th>Total weight tank &amp; fuel (kg)</th>
<th>Neck mount</th>
<th>Part number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.64</td>
<td>399</td>
<td>850</td>
<td>68</td>
<td>35</td>
<td>36.6</td>
<td>No</td>
<td>V068</td>
</tr>
<tr>
<td>1.64</td>
<td>399</td>
<td>930</td>
<td>68</td>
<td>36.5</td>
<td>38.1</td>
<td>Yes</td>
<td>V068N</td>
</tr>
<tr>
<td>1.78</td>
<td>399</td>
<td>900</td>
<td>74</td>
<td>37.5</td>
<td>39.3</td>
<td>No</td>
<td>V074</td>
</tr>
<tr>
<td>1.78</td>
<td>399</td>
<td>980</td>
<td>74</td>
<td>39</td>
<td>40.8</td>
<td>Yes</td>
<td>V074N</td>
</tr>
<tr>
<td>2.41</td>
<td>415</td>
<td>1088</td>
<td>100</td>
<td>49</td>
<td>51.4</td>
<td>No</td>
<td>W100</td>
</tr>
<tr>
<td>2.41</td>
<td>415</td>
<td>1168</td>
<td>100</td>
<td>51.5</td>
<td>53.9</td>
<td>Yes</td>
<td>W100N</td>
</tr>
<tr>
<td>3.61</td>
<td>415</td>
<td>1534</td>
<td>150</td>
<td>69</td>
<td>72.6</td>
<td>No</td>
<td>W150</td>
</tr>
<tr>
<td>3.61</td>
<td>415</td>
<td>1614</td>
<td>150</td>
<td>71.5</td>
<td>75.1</td>
<td>Yes</td>
<td>W150N</td>
</tr>
<tr>
<td>4.93</td>
<td>415</td>
<td>2030</td>
<td>205</td>
<td>92.5</td>
<td>97.4</td>
<td>No</td>
<td>W205</td>
</tr>
<tr>
<td>4.93</td>
<td>415</td>
<td>2110</td>
<td>205</td>
<td>95</td>
<td>99.9</td>
<td>Yes</td>
<td>W205N</td>
</tr>
</tbody>
</table>

Table 10 – Specifications of Dynetek DyneCell 350 bar Hydrogen Storage Tanks.
Table 11 - Predicted mass and volume of a Type IV 350-bar and 700-bar compressed hydrogen systems.

This gives a total mass of 121.7 kg (excluding fuel mass) for a 145.2 litre 700 bar hydrogen tank, as well as the mass of the Carbon Fibre Composite, 91 kg, required in its manufacture. The DOE Fuel Cell Technologies Office [159] also state a commonly used carbon fibre composite for tanks known as Toray T700S which is 60% fibre by volume. Assuming a uniform density of the composite, we can approximate the mass of the carbon fibre used in the tank to be 91 x 0.6 = 54.6 kg.

Using Quantum Technologies import price for carbon fibre of 15 $/lb = $33/kg, a total of 54.6 x 33 = $1802 would be spent on carbon fibre for this 145.2 litre, 700 bar hydrogen tank. Assuming this is 63% of the total manufacturing cost, we arrive at a total cost of $2860, which at 1 GBP = 1.715 USD is equivalent to £1668.

Although a reasonable estimate, this is for a tank of dimensions and specifications unsuited to use in vehicles. Perhaps a more helpful estimate would be for, say, around 350 bar and 50 litre tank, as this would be more comparable to the tanks reviewed so far, and would allow for more accurate estimations of the cost of retrofit for the vehicles in table 9. This can be done using a slightly different method: The DOE Fuel Cell Technologies Office [159] provide a table summarising projected results for Type IV hydrogen storage tanks performance and cost, which have been shown below as table 11.

Table 11 - Summary of projected results for 350-bar and 700-bar Type IV compressed hydrogen storage system performance and cost.

From the table, a 350 bar tank has a projected cost of $12–$16/kWh, with μ = $13/kWh. Using this mean, the cost of the tank can be estimated after estimating the energy released in the combustion of the stored hydrogen gas.
The enthalpy of combustion for hydrogen is $-286$ kJ/mol [160], with the reaction equation given below:

$$2 \text{H}_2(\text{g}) + \text{O}_2(\text{g}) \rightarrow 2 \text{H}_2\text{O}(\text{l}) + 572 \text{kJ}$$ (286 kJ/mol)

To check the reliability of this method, the cost of the 700 bar, 145.2 litre hydrogen tank used previously can be calculated and compared to the previous estimated cost of £1667.78. This tank stores 5.8 kg of hydrogen, corresponding to 5800/2.016 = 2877 moles of hydrogen, and so a total energy release of 2877 * 286 kJ = 822,822 kJ = 229 kWh. The total cost of the tank can be calculated using the $17/kWh mean given in the table, and is found to be $3893, which at 1 GBP = 1.715 USD is equivalent to £2270. This is in reasonable agreement with the previous estimate of £1668. This method will now be used to calculate estimates for hydrogen tank costs for 300 bar pressures and capacities similar to those of the hydrogen tanks discussed in this review. Results are shown below, in table 12.

<table>
<thead>
<tr>
<th>Corresponding Vehicle (if applicable)</th>
<th>Pressure (bar)</th>
<th>Hydrogen Capacity (kg)</th>
<th>Energy released in combustion (kWh)</th>
<th>Estimated Tank Cost (GBP) (1 GBP = 1.715 USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Toyota Prius</td>
<td>350</td>
<td>0.5</td>
<td>19.70</td>
<td>256</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>0.8</td>
<td>31.53</td>
<td>410</td>
</tr>
<tr>
<td>Alset Aston Martin Rapide S</td>
<td>350</td>
<td>0.875</td>
<td>34.48</td>
<td>448</td>
</tr>
<tr>
<td>Mazda RX-8 Hydrogen RE</td>
<td>350</td>
<td>1.145</td>
<td>45.12</td>
<td>587</td>
</tr>
<tr>
<td>Revolve Modified Ford Transit</td>
<td>350</td>
<td>1.1</td>
<td>59.11</td>
<td>768</td>
</tr>
<tr>
<td>Mazda Premacy RE hybrid</td>
<td>350</td>
<td>2.4</td>
<td>94.58</td>
<td>1230</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>3</td>
<td>118.22</td>
<td>1537</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>4</td>
<td>157.63</td>
<td>2049</td>
</tr>
<tr>
<td>Ford-E450 / E150</td>
<td>350</td>
<td>4.93</td>
<td>194.28</td>
<td>2526</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>5</td>
<td>197.04</td>
<td>2561</td>
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<td></td>
<td>350</td>
<td>5.8</td>
<td>228.56</td>
<td>2971</td>
</tr>
</tbody>
</table>

Table 12 – Estimates of tanks costs at 300 bar with varying capacities.

The values in table 12 work off the assumption that the cost per kWh is constant for all hydrogen capacities provided they have an equal pressure, and so the cost estimates scale linearly with respect to hydrogen capacity and thus tank size. This is of course slightly dubious, and more likely is the cost per kWh to decrease as the hydrogen capacity increases, as variables such as labour and factory running costs are unlikely to vary at the same rate as material costs for an increasing tank size. Therefore, as the capacities of the tanks get further away (smaller in volume) from the original 5.8 kg tank, the cost estimation becomes more inaccurate and less reliable. For example, the 0.8 kg hydrogen tank on-board the Quantum Toyota Prius has an estimated cost of £149, but in reality a value of around double that is perhaps more reasonable.

This inaccuracy can be somewhat offset if the chart of Quantum Technologies manufacturing cost breakdown (Fig. 29) is used, where 9% of the manufacturing costs are said to be from labour and overhead fees. From this it can be observed that only the material costs (91%) should be scaled when calculating total manufacturing costs of the hydrogen tank relative to its capacity. Holding 9% of the original £1733 5.8 kg tank constant causes a non-linear scaling of the tank costs, and the new values have been shown below in table 13. The two different cost calculations have also been displayed graphically, in Fig. 30, to show the effect more clearly.
Fig. 30 - Estimated Manufacturing costs for 300 bar Hydrogen tanks with varying capacities, for both the linear scaling and constant labour and overhead fees methods

Table 13 – Estimates of tank manufacturing costs at 300 bar with varying capacities, for both calculation methods.

<table>
<thead>
<tr>
<th>Corresponding Vehicle (if applicable)</th>
<th>Hydrogen Capacity (kg)</th>
<th>Tank Cost Estimates (GBP)</th>
<th>New (Constant Labour &amp; Overhead Costs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Original (Linear Scaling)</td>
<td></td>
</tr>
<tr>
<td>Quantum Toyota Prius</td>
<td>0.5</td>
<td>149</td>
<td>292</td>
</tr>
<tr>
<td>Alpint Aston Martin Rapide S</td>
<td>0.8</td>
<td>239</td>
<td>373</td>
</tr>
<tr>
<td>Mazda RX-8 Hydrogen RE</td>
<td>1.145</td>
<td>342</td>
<td>467</td>
</tr>
<tr>
<td>Revolve Modified Ford Transit</td>
<td>1.5</td>
<td>448</td>
<td>564</td>
</tr>
<tr>
<td>Mazda Premacy RE hybrid</td>
<td>2.4</td>
<td>717</td>
<td>809</td>
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<tr>
<td></td>
<td>5.8</td>
<td>1733</td>
<td>1733</td>
</tr>
</tbody>
</table>

The estimations using the new method of holding labour and overhead costs constant appears a more accurate estimate, and so these values have been added to the vehicle summary table (table 9) where possible. The uncertainty of each estimate still increases for decreasing tank capacity, and although no quantitative error can be placed on the data, the values added to the table have again been colour coded, with red for greater uncertainty, and green for smaller uncertainty.

Another factor to consider when estimating the manufacturing price is the quantity of hydrogen tanks being produced. The system costs in Table 11 are for the upper limit of manufacturing volumes (500,000 tanks). For smaller volumes, the system costs will increase.

In 2013, costs for complete systems were also estimated for variable manufacturing volumes (10,000 – 500,000) by the DOE [159] to demonstrate the projected effect of manufacturing volume and is shown in Figure 31. For 350-bar systems, the mean cost at low-volumes (10,000 units) is estimated to
be $29/kWh, decreasing to $13/kWh once mass production volumes (500,000 units) are reached. Similarly, for 700-bar the low-volume mean cost is estimated to be approximately $33/kWh decreasing to $17/kWh at 500,000 units. This has been shown graphically in Fig. 31.

![Fig. 31 – Plots of cost estimates of the variable volume manufacturing for 350 bar and 700 bar hydrogen storage tanks.](image)

StorHy’s results from their economic investigations into tank costs of their H₂ tanks found that large scale production lead to H₂ tank costs of about €400/kg hydrogen stored. This agrees reasonably well to the costs given in table 13 and figure 30. A sensitivity analysis confirmed that the carbon fibre is the main cost driver of H₂ tanks. Indeed, the safety factor of 2.35 leads to about 10 kg of T700S carbon fibre per kg of hydrogen stored. For a carbon fibre cost of €30/kg, this material already represents about €300/kg of hydrogen stored. A system level analysis of the literature also shows that regulators and valves represent about 25% of the overall cost of H₂ storage systems. This analysis points out the fact that the use of multiple vessels increases costs, primarily driven by the need for multiple regulators and valves.

**5.2 Remaining components**

A list of the remaining components required for the retrofit is shown below:
- Hydrogen PRV (pressure reducing valve)
- Hydrogen Injection Nozzles
- Progressive Controller
- Hydrogen Solenoid Valve
- Hydrogen piping/tubing

The PRV is required to reduce the tank pressure to a lower pressure needed for the solenoid valve and the nozzle (40–200 psi). Since the operational conditions at the nozzle correspond to a choked flow, the inlet pressure of the nozzle controls the maximum flow through the nozzle. Thus the choked-flow
condition sets the maximum flow rate through the nozzle when the engine is operating with 100% hydrogen [161]. Some tank manufacturers would offer their tanks complete with PRVs as standard, such as DyneTek, who offer tanks with PRVs ranging in capacities from 0.94 to 4.26 kg of hydrogen specifically made for automobiles. The PRV itself is widely available and has a price of around £50 from various [162] online retailers.

Injection nozzles would be used to inject hydrogen into the air intake manifold right behind the intake valve (for external mixture formation). The hydrogen injection nozzle requires a diameter adequate to handle the maximum flow rate to run the engine with 100% stoichiometric hydrogen [161]. Conveniently, Aluminium Nitrous Oxide injection nozzles can be used here, such as the 13500 Fogger Nozzle [163] or 13760 NOS Precision SS Jets [164], which both feature interchangeable stainless steel “jets” to change the inside nozzle diameter.

A more sophisticated conversion would see the vehicle have adjustable hydrogen air-to-fuel ratio depending on RPM. A progressive controller would be used to control the percentage of the maximum flow rate of hydrogen through the injection nozzles valve. Requirements for the progressive controller include: control of hydrogen injection based on RPM or time, ability to set operation boundary conditions for air-to-fuel ratio and percentage hydrogen injection, compatibility with the solenoid valve, and the ability to receive and process the feedback of operating conditions such as air-to-fuel ratio and RPM. By again taking advantage of the already existing products designed for Nitrous Oxide injection, Puttaiah et al [161] used a “15977 - NOS Launcher Progressive Nitrous Controller” [165], for a price of around $500.

The Progressive Controller would be connected to the solenoid valve and a computer software will be used to control the percentage of maximum flow rate of hydrogen to the injection nozzles. Requirements for the hydrogen solenoid valve include: a pressure rating of 800 psi (with a Factor of Safety of 4), compatibility with the chosen progressive controller, inlet and outlet sizes compatible with hydrogen injection tubing/hose, fail-close design, and to be made of a material compatible with hydrogen that limits permeation through walls and a frequency response that meets progressive controller requirements.

Piping or tubing would be used to transport hydrogen from the PRV to the nozzles. Requirements for the tubing/hoses include: a diameter large enough to handle the maximum flow rate, a pressure rating of 70 bar, made from or coated with a material that is compatible with hydrogen with minimal permeation through walls, such as Teflon, lengths of tubing/hose that allow flexibility, and the connector sizes compatible with those of the PRV and nozzles [161]. Hoses (such as: 15305 –NOS 4AN-4AN 20’ Stainless Steel Braided Hose [166] and 17970-NOS 4AN-1/4” NPT Adopter and 4AN fittings [167]) may be used to connect the tank to the solenoid valve and the solenoid to ports in the inlet manifold.

Puttaiah et al [161], complete their retrofit of a gasoline ICE to hydrogen operation at a cost of $1108, whilst being as economical as possible. This excludes the cost of the hydrogen tank and the PRV. ($1108 = £646 at 1 GBP = 1.715 USD).

The National Hydrogen Association [168] estimate the cost of all modifications for retrofit to around 1.5 times the original price of the gasoline ICE, which seems consistent with the previous cost estimates obtained earlier in this section. Sainz et al [124] state a cost of €6000 in equipment and 200 man hours (€6000 = £4772 at 1 GBP = 1.26 EUR). This appears higher than the previous estimates, although they do admit that the costs would be much lower in the event of a series production. Unfortunately, neither sources give information on how they have arrived at these estimates.
A summary of the cost estimations calculated in this section are as follows:

- The price of hydrogen Tanks suitable for on-board Vehicle Storage from leading vendor Luxfer (previously Dynetek) is in the region of $10,000–£20,000 ~ £5,800–£11,700.
- The cost for manufacturing a Hydrogen tank has been estimated within the range £350–1500.
- StorHy find an estimate for the cost of the hydrogen tank at €400/kg of hydrogen stored.
- The total cost of retrofit as found by Puttaiah et al [159] was £646 excluding the Hydrogen Tank & PRV.
- The total cost of retrofit as given by the National Hydrogen Association [166] is 150% of the cost of the original gasoline fuelled ICE.
- The total cost of retrofit as given by Sainz et al [124] is £4772 + 200 labour hours.

Due to the lack of information available, the estimations are rather crude and large assumptions have been made. All useful data has been added where appropriate to the vehicle summary table (Table 9).

6 Conclusion

Under the best conditions it is estimated that FCEVs can become competitive compared to other technologies in the near future. Rosenberg et al [169] conclude that a transition to a hydrogen fuelled transportation sector could be feasible in some countries by 2025–2030. It is generally accepted [35,170-172] that due to their immediate availability, relative low cost and ability to smoothly integrate into the current automotive industry infrastructure, H2ICEVs are considered a bridging technology that would allow a faster introduction of hydrogen in the transport sector for FCEVs.

This review has included:

- The fundamental differences in hydrogen’s chemical properties to conventional fuels, such as volumetric energy density, ignition energy, laminar burning velocity, flammability limits, etc. and how this should benefit or detriment its use an ICE fuel. Theoretically higher engine efficiencies, (with the compromise of higher NOx emissions) are be possible owing certain combinations of these properties.

- The current state of the Hydrogen Infrastructure, and difficulties facing the introduction of hydrogen to the transport sector such as production, storage and distribution of hydrogen. It appears substantial economic investments are required for the development of the whole production-distribution- storage-use chain of hydrogen fuel.

- A summary of research and development projects conducted by various automotive companies, energy companies, universities and institutions, including a detailed summary table containing all information available for the hydrogen ICE vehicles mentioned in the review, for use in quantitative applications such as in computer modelling software.

- Prices and Cost estimates of the conversion of a gasoline ICE to run on hydrogen, focusing on the manufacture of the hydrogen tank.

Recent years have seen significant research and development into H2ICEs and the adoption of conventional ICES to run on hydrogen. This review had highlighted the H2ICE options that are possible, and has found that in general they are technologically and economically viable in the near-term for a transportation power source in a hydrogen economy, provided research is to continue in the same
fashion. This looks unlikely however, as the last decade has seen a decline in H2ICE research and development projects, owing to the fact that large automotive companies previously carrying out significant proportions of the research have switched focus to fuel cell applications.

Although the research and development points in a positive direction, with reduced emissions and increased thermal efficiencies, there is still a long road of advancement ahead. The future of the H2ICE is less certain and harder to predict, as is the future of the hydrogen economy itself. Improvements with power density, ICE design and materials, reduced NOx emissions, and control optimisation strategies are all necessary for hydrogen and the H2ICE to compete with gasoline and the conventional ICE. Provided that these advancements arrive, and with the help of a changing mind-set towards climate change, market competition will dictate the transition to the eventual finishing point of the hydrogen fuel cell.

7 References


[12] International Programme on Chemical Safety. INCHEM – chemical safety information from intergovernmental organizations.


[142] Simanaitis says “HYDROGEN I.C., PART 2: MAZDA”


[145] Aston Martin “Aston Martin to race the world’s first Hybrid Hydrogen Rapide S” [Online]


[147] Hydrogen/Fuel Cells “Navarra University VW Polo Hidrogeno "Carlos" (2010)”


