Energy Technology Network
ETSAP
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Automotive Hydrogen Technology

HIGHLIGHTS

- **PROCESS AND TECHNOLOGY STATUS –** Hydrogen (H_2) can be used as a transport fuel in both internal combustion engines (ICEs) and fuel cells vehicles (FCVs). It can be produced directly from fossil fuels and renewable energy sources, or indirectly from electricity via water electrolysis. The cheapest way to produce hydrogen is natural gas reforming or coal gasification at a central plant. These processes however produce significant amounts of CO2 emissions. Large-scale hydrogen production from natural gas and coal are then environmentally affordable only if combined with carbon capture and storage (CCS, ETSAP TB E14) technologies. Because internal combustion engines are a mature technology H_2-based ICEs can be relatively simple to produce now. However, as hydrogen has a very low density, there are technical problems to overcome for storing enough amount of hydrogen in the vehicle tank in order to achieve a sufficient range of operation. H_2 storage in fuel cell vehicles (FCVs) could be of less concern (although still significant) due to the significantly higher efficiency of the fuel cell engine. However, FCVs still have overall cost and durability issues that need to be addressed before commercialization. The driving range of FCVs is anticipated to be similar to conventional ICE vehicles in the future.

- **PERFORMANCE AND COSTS –** H_2-based ICE vehicles could be produced today with up to 25% improvement in efficiency over conventional spark-ignition vehicles. In comparison, future H_2 FCVs are anticipated to be 2-3 times more efficient than conventional vehicles. While H_2-fuelled ICE vehicles are not too dissimilar in cost to a conventional car, the more efficient and virtually zero-emissions FCVs requires expensive materials (e.g. platinum) and components, and it is unlikely that they will become competitive in the coming decade. Moreover, because of the low density and low boiling point, hydrogen on-board storage in gaseous or liquid form is also costly and energy-intensive. Production of hydrogen from renewable energy sources (either directly or indirectly via electrolysis) could make a significant contribution to reducing carbon emissions in transport because hydrogen combustion in air produces no direct CO_2 emissions and few amount of other pollutants. However, whatever the primary energy source, hydrogen production is based on costly and energy-intensive processes. Hydrogen use is therefore economically and environmentally affordable only if the end-use technologies are cheap and highly efficient. In addition, because of the low energy density by volume, hydrogen transportation and distribution (e.g. by pipelines) is also costly and more energy-intensive in comparison with natural gas. Hydrogen production from on-site water electrolysis at re-fuelling stations or bus depots is a relatively more common place because it makes distribution network unnecessary. To overcome all these issues and make hydrogen an affordable fuel for the automotive market, research efforts focus on lowering costs and improving efficiency of the hydrogen production processes, reducing the cost of fuel cells and developing technologies for hydrogen storage in solid materials.

- **POTENTIAL AND BARRIERS –** The technology of H_2-fuelled ICEs is rather well known and the main barriers for this kind of engines are supply and cost of hydrogen and adequate hydrogen storage. As far as FCVs, it is unlikely that the technology learning rate will be sufficient to get competitive costs over the next 10-15 years. A primary component of the fuel cell cost is the catalyst, which is made of platinum or other scarce materials, but cost reductions and optimisation are also needed for other components of the fuel cell engine and vehicle. In addition to this, FCVs development is also jeopardised by the difficulties in hydrogen production and distribution.

TECHNOLOGY STATUS AND PERFORMANCE -

■ **Hydrogen** (H_2) is an energy carrier that can be obtained from all primary energy sources (ETSAP TB S06) including fossil fuels (via natural gas reforming and coal gasification), renewable and nuclear energy (via biomass-based physical and thermo-chemical processes, solar photo-electrolysis, biological processes, and high-temperature water splitting based on solar or nuclear heat). Hydrogen can also be obtained from water electrolysis. If hydrogen is produced from renewable and nuclear energy, or from natural gas- and coal-based processes using CO_2 capture and storage (CCS), then it is largely carbon-free and may help reduce CO_2 emissions and diversify energy supply. If hydrogen is produced by water electrolysis, the associated emissions are those generated by the upstream electricity generation. At present, hydrogen is produced mostly in chemical and refinery industry from fossil fuels, notably from natural gas and refinery/chemical off-gases reforming, and from coal gasification. If hydrogen is to be used as a transport fuel, decentralised hydrogen production is the best choice for market uptake as it minimises the needs for distribution infrastructure. However, decentralised production is less efficient than large-scale, centralised production. In addition, for economy reasons, small-scale decentralized production processes do not allow the use of CCS technologies to mitigate the CO2 emissions when fossil fuels are used as the primary feedstock.

■ **Hydrogen Internal Combustion Engines (H_2ICEs)** - Having been developed and improved for over a century, internal combustion engines (ICEs) are now a mature and cheap technology. A hydrogen-powered ICE can run on pure hydrogen (H_2) or a blend of H_2 and compressed natural gas (CNG). This fuel flexibility

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would allow H_2ICEs to be used even without a full developed hydrogen refuelling infrastructure, which will remain to the medium term. H_2ICEs perform well under all weather conditions, require no warm-up, have no cold-start issues (even at subzero temperatures), and are highly efficient. They can perform with around 42% maximum efficiency [2], and up to 25% better efficiency than conventional spark-ignition engines [3], with potential for further gains using waste heat. While consumers and public perception are rather familiar with conventional internal combustion engines, H_2ICEs may still have to overcome the unsafe perception originated from the Hindenburg disaster in 1937 [16], regardless of whether the cause of that accident was hydrogen or not. Because the H_2ICE is seen as a bridging technology to fuel cells, only a few investors and car makers undertake R&D efforts in this field. BMW and Mazda appear to be the leading companies pursuing H_2ICEs for relatively mainstream car models. Ford and Ronn Motor Company produce more exclusive hydrogen-compatible vehicles. The BMW Hydrogen 7 series is the world's first production-ready H2ICE vehicle, which can also run on regular gasoline. The BMW reaches an efficiency of 42%, and some 100 cars have been loaned to celebrities to raise the profile of the technology and demonstrate its commercial feasibility [11]. Mazda have been working on H_2ICE technology since 1991 and has been leasing its latest model, Mazda Premacy, to government fleets in March 2009 [6]. The Premacy uses a dual fuel rotary ICE running either on gasoline or hydrogen. Its range on hydrogen only is some 200km. Ford have developed the Super Chief, a pick-up truck capable of 12% higher efficiency than the conventional version, with 99% less CO_2 emissions when using hydrogen from renewables. The vehicle is also capable of running on gasoline and E85 [4]. Ronn Motor Company is the only firm that demonstrates the production of hydrogen by electrolysis on-board, albeit at considerably high extra-cost. The benefit though is the avoidance of the concerns associated with hydrogen on-board storage. The Scorpion sports car is capable of 40mpg, 200mph, 0-60mph acceleration in 3.5 seconds and near zero CO_2 emissions when using hydrogen generated from renewable sources [4].

■ **Fuel Cells (FCs) and FC Vehicles (FCVs) -** Fuel cells are electrochemical device that generates electricity and heat using hydrogen as a fuel (or a H_2-rich fuel) along with oxygen (O_2) from air. Fuel cells consist of an electrolyte sandwiched between two electrodes – an anode and a cathode (FC stack, Figure 1). Activated by a catalyst on the anode side, the H_2 atoms split into electrons and ions. Electrons migrate to the cathode through an external circuit and generate electricity, while ions migrate through the electrolyte and reunite with electrons and O_2 on the cathode side, producing heat and water. There are variants of this basic process, depending on FC types and fuels. H_2-powered fuel cells maximise the efficiency and the emission reduction benefits of using hydrogen as an energy carrier.

The most suitable fuel cells for hydrogen transport applications are the proton exchange membrane fuel cells (or polymer electrolyte membrane fuel cells, PEMFC). This is because they have a relatively low operating temperatures of around 80^oC, which enables quick start up [1]. They use a solid polymer membrane electrolyte and carbon electrodes, with platinum as a catalyst.

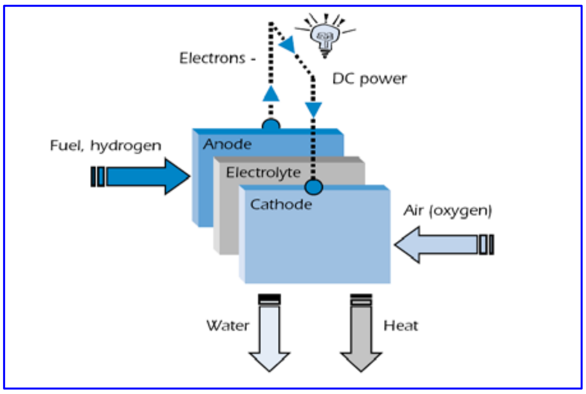

Fig. 1 - Fuel Cell Concept

Their operational efficiency (over 50%) is currently well below the theoretical value of 60%-65% [9], but it is still more than twice that of typical ICEs (20-25%), though with high sensitivity to operating conditions. PEMFCs also offer good power density, with practical value around to 2-3 kW/m^2. Higher power density (4-6 kW/m^2) could be obtained if new membranes and more active cathodes become commercially available. High power density reduces the fuel cell cost, but also increases energy losses and reduces efficiency. Thus, an optimum power density exists that minimises the cost of the energy output, depending on H_2 and FC costs. Current PEMFCs are less durable than combustion engines. Membranes are sensitive to humidification and anode catalysts are sensitive to poisoning by carbon monoxide (CO) and sulphur (S). They need almost pure electrolytic hydrogen. If hydrogen is produced from gas reforming, extensive clean-up is needed. Current PEMFCs also need cooling to avoid overheating. Current research focuses on high-temperature membranes and new catalysts to improve performance and reduce costs. It is expected that durability of the fuel cells will become equal to that of the vehicle over the next years. PEMFCs can also be used for stationary power generation. Synergies between automotive and stationary applications (e.g. PEM electrolysers for hydrogen production and PEMFCs for hydrogen use) could make the PEM technology even more attractive.

Fuel cell vehicles (FCVs) have gained more momentum than the H_2ICEs over the past five years. This is exemplified by the 2009 Hydrogen Road Tour, a 1,700 mile journey on the west coast of America which demonstrated FCVs and buses as well as fuelling stations and other hydrogen facilities. The Honda FCX Clarity claims a range of 430km [8], which is much closer to that of a conventional vehicle and much higher than that of a battery electric vehicle. The Toyota FCHV-adv, a SUV being leased to consumers in Japan, can easily accommodate large H_2 storage tanks and offers even a greater range of 825 km [10]. In the current FCVs, hydrogen is typically stored on board the vehicle in pressurised tanks. While H_2 has a very high mass energy density (120 or 144 MJ/kg for low or high heating values, respectively), its energy density by volume is significantly lower than any other fuels [27]. This low density and the low boiling point mean that hydrogen transportation and storage in gaseous or liquid form are rather costly and energy-intensive. In the current demonstration vehicles, hydrogen can be stored under a higher pressure (700bar tanks), which reduces the size of the tank but also increases the cost. Therefore, intensive research efforts aim to develop technologies for compact hydrogen storage in solid materials.

Prototypes such as the Honda FCX Clarity and the Toyota FCHV-adv are still a long way from being commercially viable. More viable in the short to medium term are the fuel cell buses. Unlike fuel cell cars, they are not as bound by a widespread hydrogen refuelling stations, as refuelling can be made available at the bus depot. Furthermore, they have a very high annual mileage, meaning that the investment costs can be recouped much quicker than for cars. In July 2009, there were 35 fuel cell buses in operation primarily under the European CUTE programme (Clean Urban Transport for Europe), and a cumulative production of 115 buses [12]. The typical range of a fuel cell bus is over 200km using the roof to store up to 44kg of compressed hydrogen at 350 bar. The capacity is around 70 people and top speed is 80km/h. Reliability is not a problem right now either, and will only get better with time and technology learning. In the CUTE programme, buses were available for use 90-95% of the time [13]. Their commercialisation is “in sight” [23]. Similar demonstrations are under way in Japan, Singapore and California. Early application opportunities are also offered by delivery van fleets which have high annual mileages and frequent returns to depots. In the United States, the UPS delivery company have been using the Daimler-Chrysler “Sprinter” since 2004, and has plans for broader implementation. The Sprinter has a range of 150km and top speed of 120km/h. FedEX in Japan have similar plans using the General Motors HydroGen 3 fuel cell van [9]. Less practical in the short term is the fuel cell motorbike. Intelligent Energy and Suzuki have nonetheless produced the Crosscage fuel cell motorbike, capable of 20-30% CO_2 reduction if hydrogen is produced from natural gas, and even better performance with electrolytic hydrogen. Intelligent Energy have also produced an emission-neutral fuel cell bike, which is anticipated to be ready for fleet orders in 2010. The range of the vehicles is over 160km, with speed around 80km/h [19].

While in the medium to long term fuel cells may offer high efficiency and CO_2 savings, the high cost rules them out for now and are expected to continue to do so in the near future. In addition, refuelling infrastructure and hydrogen storage are key issues for fuel cell vehicles uptake [20]. In the short term, fuel cells will more likely be used for auxiliary power units, air conditioning, battery charging and engine heating to reduce idling emissions [21].

As far as CO_2 emissions are concerned, hydrogen FCVs come out as the greenest options among official demonstration limousines that were selected by the Danish Foreign Ministry for the 2009 COP15 Climate Conference in Copenhagen. In California, AC Transit’s fuel cell buses using hydrogen from natural gas reforming have achieved a 50% CO_2 saving over conventional diesel engines. During tests, the fuel economy for AC Transit’s vehicles was up to 70% better than a control group of diesel buses. UTC Power who supply the AC Transit’s buses predicts that fuel cells will soon become the more profitable option for buses [14].

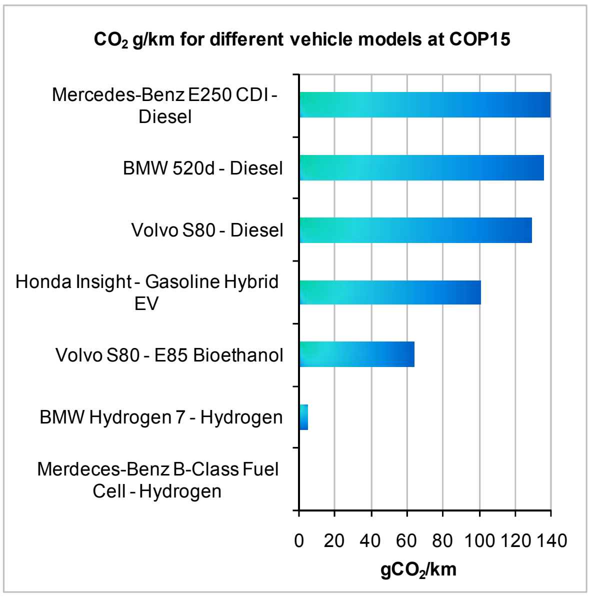

Fig. 2 – CO_2 emissions by different vehicles (Data source: COP15 [17])

■ **Hydrogen Storage –** Hydrogen on-board storage for vehicles is a challenging issue and may have significant impact on hydrogen technology deployment. The target is to store 4-5 kgH_2 for a drive range of some 450 km, while minimising volume, weight (gravimetric density >5-6 %wt.), storage energy, refuelling time, costs, and H_2 release time on demand. To compensate for the low energy density per unit of volume, H_2 storage requires energy-intensive compression between 350 and 700 bar or liquefaction at -253°C. Current commercial options do not fully meet compactness and cost requirements. Both gaseous and liquid storage of H_2 need more space than energy-equivalent gasoline, and more costly tanks. On-board reformers to produce H_2 from fossil fuels also proved to be a very challenging and expensive option. Storage in solid materials may offer decisive advantages (smaller volume, low pressure and energy input) but development is still underway, with a number of materials under investigation.

Gaseous storage in carbon-fibre composite (CFC) tanks at 350 bar is commercially available, but 700-bar tanks require new standards and certifications in most countries. Main issues include cyclic loading, lifetime, cost and user's safety perception. Electricity for compression claims roughly 12% of the H_2 energy content (LHV). Tank costs may reach €2,000-€2,500/kgH_2. Large production promises costs below €400-€500/kg [9]. The basic material (CFC) has a major impact on costs.

Liquid storage at -253°C permits high gravimetric density. Target values are 20 %wt., including tank weight, insulation materials and systems to recover boil-off losses. Today's practical values are around 5 %wt. Electrical energy for liquefaction is around 30%-35% of H_2 energy content.

Solid Storage - The most developed materials for solid storage are metal hydrides with storage potential exceeding 8 %wt. [9]. New materials such as complex hydrides and alanates could gain appeal in the future. Carbon nano-tubes and graphite nanofibres attracted much attention some years ago but their expected storage performance of 30-60 %wt. has not been confirmed. High-surface materials such as zeolites, metal organic frameworks (MOF) and clathrate hydrates are in early stage of development. The question is whether they can be engineered to store significant amounts of H_2 at suitable temperatures. Rechargeable hydrides have been investigated in depth and their potential is well known. Elemental hydrides are too stable (or too unstable) at operating temperatures. Alloys and intermetallic compounds have low gravimetric density (< 2.5 %wt.). Nano-crystalline and amorphous hydrides suffer from unsuitable storage capacities and release temperatures. Complex hydrides (alanates and borohydrides) are promising options requiring further development. For example, NaAlH4 alanate offers favourable kinetics with reversible storage at around 4-5%wt. R&D focuses on catalysts to improve performance. Borohydrides (LiBH4) have higher capacity than alanates, but H_2 release reversibility is more difficult. Water-reactive chemical hydrides can be handled safely in the form of mineral-oil slurry. They release H_2 through water injection into slurry without heat input. Theoretical storage is around 5-8%wt. MgH_2 is likely to offer the best performance/cost combination. The key issue is the cost of re-converting the spent hydroxide back into the hydride. Thermo-chemical hydrides such as ammonia borane are potentially suitable for H_2 storage, but the reaction is not reversible (off-board regeneration).

This synthetic overview of solid storage technologies show that a number of options exist but substantial further R&D is needed. The ongoing impressive advances in solid-state physics and materials science may lead to unexpected advances in hydrogen solid storage.

CURRENT COSTS AND COST PROJECTIONS –

While the current investment cost of the H_2ICE vehicles does not significantly differ from the cost of the conventional ICE vehicles, the cost of the FCVs is much higher and strongly influenced by the cost of the FC engine. For both vehicles, the fuel cost per mile also depends significantly on the cost of hydrogen.

Hydrogen costs are discussed more extensively in ETSAP TB S06. In the IEA Technology Essential brief on Hydrogen Production and Distribution (IEA, 2007) the production cost of electrolytic hydrogen in decentralised facilities has been estimated at €43 per JG-H_2 (inflated to 2010 prices). Centralised, fossil fuel-based production with CCS is projected to fall to around €11 per JG in the coming decades. More recent estimates (2009) for delivered hydrogen obtained from state-of-the-art electrolysis in forecourt refuelling stations provide cost of €39/GJ dispensed at the pump (inflated to 2010 prices). This is a decentralised production and includes an electrolysis production cost of €25/GJ, compression, storage and dispensing costs of €14/GJ-H_2. These costs are evaluated using EIA Annual Energy Outlook (EIA-AEO, 2005) High A Case industrial electricity average costs of €0.043/kWh [28]. The current (2009) state-of-the-art plant gate cost for hydrogen from a central electrolysis operation has a base-case estimate of €28/GJ. These costs are evaluated at an assumed renewable-based electricity cost of €0.037/kWh. No account is taken for distribution costs in this estimate, which may outweigh the benefits of centralised production depending on location.

By 2020, H_2 is projected to cost anything from comparable to regular gasoline prices to 7 times that price. This depends on the methods used for its production, distribution and storage. The cheapest option is centralised reforming of natural gas with pipeline distribution. In a low price scenario this would compete with regular gasoline prices. The most expensive option would be localised electrolysis, using electricity from least cost renewable energy or future nuclear power. In a high price scenario this would cost around seven times the cost of regular gasoline in 2020 [9].

Crucial to reducing H_2 costs in the long term is the coal-based cogeneration of H_2 in the integrated gasification combined cycles (IGCC) and the carbon capture and storage (CCS) technologies. Development of nuclear and renewable energy may in fact favour the hydrogen and FC market, but they also deliver cheap CO_2-free energy and biofuels which compete with hydrogen as an energy carrier. Cost reductions are also needed for the hydrogen transmission and distribution infrastructure [9].

Today's **cost of FCVs** is unknown because developers are keen to protect their commercial interests. Prototypes such as the Honda FCX Clarity and the Toyota FCHV-adv are still a long way from being commercially viable. This is likely to continue into the medium, and perhaps long term. Over the next 2 years, Honda will lease 200 of its FCX Clarity FCV in the US and Japan for €400 per month, which most commentators believe includes a heavy subsidy even at that price. Based on current technology, the cost of manufacture is thought to be over €540,000 [7]. Because of these high costs, widespread CO_2 abatement in transport from hydrogen introduction is unlikely to occur in the short to medium term, but experts say fast technology learning offers the potential to reduce this cost by a factor of ten [9]. The assumptions in the UK MARKAL model include capital costs for FCVs that are not competitive with ICEs until after 2050, although overall annualised costs for niche applications such as fuel cell buses and 2-wheelers may become viable much sooner. Because high efficiency compensates for higher vehicle cost (by reducing fuel costs), vehicles with high annual mileage such as buses and delivery vans represent niche markets where the fuel cell technology can more easily compete with ICEs. This helps explain the development of the Suzuki/Intelligent Energy bikes and the CUTE programme.

In general, the cost reduction for PEMFC depends on the improvement of the basic components. Polymer membranes (e.g., nafion) working at some 80ºC need a platinum catalyst, which is expensive and sensitive to poisoning. New materials (sulphonated plastic, ormosil) working at higher temperature, with less sensitivity to poisoning, promise technical breakthroughs and cost reduction by a factor of more than ten. The same level of cost reduction is expected for the electrodes and bipolar plates that currently dominate the FC cost prototype because of the almost manual manufacturing. Electrode costs may be reduced through industrial production technologies that require less platinum. Current systems require 0.6-0.8 mg platinum/cm^2, (about 1g/kW) while gas diffusion layer (GDL) technologies may result in better catalyst distribution and reduced amount (up to 0.2 mg/kW). This is important not only for the fuel cell cost but also to guarantee that the global availability of platinum would be enough to supply catalyst for a widespread use of PEMFCs. Bipolar plates are currently made from mouldable graphite-polymer composites or coated stainless steel. The use of industrial injection-moulded plastics (carbon polymers) and low-cost steel alloys could also dramatically reduce the current costs. All these combined improvements are needed to reduce the cost of the fuel cell stack at the level of some €80/kW, but cost reductions are also needed for the other components of the FCVs. The cost of the **electric motors** and of the **balance of plant** (including inverter, control electronics, humidification, H_2 and air pressurisation, and cooling systems) should also drop significantly. Expensive single components are also the **converter** and the **battery**[1] to capture re-generative braking energy and to cope with large variations in the DC-input voltage, and the hydrogen **storage system**. If all these cost reductions are achieved, it is estimated that beyond 2030 the incremental cost of a FCV over a conventional vehicle could range between €2,000 and €6,225 [9]. This assumes a technology learning rate between 0.78 and 0.85, equivalent to cost reductions of 22% and 15% with each doubling of production. These values are within the range assumed for other new technologies.

POTENTIAL & BARRIERS – According to the IEA projections (IEA 2005, IEA 2008, [29]), H_2-powered FCVs could gain significant market share over the coming decades, if hydrogen and fuel cell costs will be reduced significantly and if effective policies will be implemented for reducing CO_2 emissions. Hydrogen production costs should be reduced by a factor of 3 to 10, depending on feedstock and process, and PEMFC cost by at least a factor of 10. Under these conditions, FCVs could take a significant share of the passenger car market by 2050. Under less optimistic assumptions, FCVs are unlikely to gain significant market share because competing technologies and fuel options such as natural gas, biofuels, hybrids or electric-battery vehicles could offer more advantages. FCVs require a network of refuelling stations to be built from scratch and a hydrogen transportation infrastructure would imply investment in the order of trillion dollars worldwide [9], a key disadvantage compared to other options.

Conversely, without a major breakthrough in battery technology, FCVs are likely to maintain their advantage in terms of overall range compared to pure electric vehicles. Hydrogen could be produced at the refuelling stations, or produced centrally before being distributed by tankers or pipelines (with additional penalties in terms of energy balance and costs). In the long term, large H_2 production could also come from electrolysis using renewable electricity, and from biomass or coal gasification with CCS. The limitations here are the availability of large amount of renewable energy, the need of cost-effective CCS technologies, the cost and the energy intensity of electrolysis. In the long term,

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[1] Same as for hybrid electrical vehicles (HEVs), FCVs use batteries to store regenerative braking and surplus power produced by the FCs [18]. The power in the batteries is then used to complement FC power during peak power demand (acceleration).

hydrogen could be produced by water splitting using nuclear and solar heat, by photo-electrolysis, by biological processes based on sunlight and micro-algae to produce biomass, or on the use of waste and bacteria. All these technologies are in early stage of development and have low efficiency and/or high costs. Their prospects are currently unclear [15].

In conclusion, H_2ICE-powered vehicles are relatively cheap, efficient and mature for commercialisation, but they are affected by the hydrogen storage and not particularly competitive with conventional vehicles. FCVs are significantly more efficient, but still much more expensive and less reliable than conventional vehicles. Moreover, they are also affected by hydrogen storage issues, though to a lesser extent than H_2ICE-powered vehicles as a result of the better efficiency. In comparison with the past years, Government's and the technical-scientific community worldwide are diminishing their support to hydrogen and fuel cell technologies. Steven Chu, Nobel Laureate and US Secretary for Energy, clearly questioned the ability of hydrogen to make a contribution in the medium term to energy supply and emissions reduction in transport.

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Table 1 – Summary Table: Key Data and Figures for Hydrogen ICE and Fuel Cell Vehicles [22, 24, 30, 31]

Hydrogen ICE Vehicles [22, 24, 30, 31]			
Technical Performance	**Small Cars**	**Medium Cars**	**Large Cars**
Energy Input	Hydrogen		
Base Energy Consumption (kg/km)	N/A	0.0175	0.0268
Base Energy Consumption (MJ/km)	N/A	2.10	3.22
Technical Lifetime, yrs	N/A	12	12
Environmental Impact			
CO_2 and other GHG emissions, g/km (a)	N/A	221.2	338.4
CO_2 and other GHG emissions, g/km (b)	N/A	31.0	47.5
CO_2 and other GHG emissions, g/km (c)	N/A	498.4	762.6
CO_2 and other GHG emissions, g/km (d)	N/A	19.2	29.4
Costs			
Capital Cost, overnight, Euro/unit	N/A	23,213	35,575
O&M cost (fixed and variable), Euro/km	N/A	0.064	0.078
Economic Lifetime, yrs	N/A	12	12
Fuel Cell Vehicles [22, 24, 30, 31]			
Technical Performance	**Small Cars**	**Medium Cars**	**Large Cars**
Energy Input	Hydrogen		
Base Energy Consumption (kg/km)	N/A	0.0091	0.0139
Base Energy Consumption (MJ/km)	N/A	1.09	1.67
Technical Lifetime, yrs	N/A	12	12
Environmental Impact			
CO_2 and other GHG emissions, g/km (a)	N/A	114.9	175.9
CO_2 and other GHG emissions, g/km (b)	N/A	16.1	24.7
CO_2 and other GHG emissions, g/km (c)	N/A	259.1	396.3
CO_2 and other GHG emissions, g/km (d)	N/A	10.0	15.3
Costs			
Capital Cost, overnight, Euro/unit	N/A	580,000	890,000
O&M cost (fixed and variable), Euro/km	N/A	0.290	0.354
Economic Lifetime, yrs	N/A	12	12
Baseline Gasoline Vehicles [30, 31]			
Technical Performance	**Small Cars**	**Medium Cars**	**Large Cars**
Energy Input	Gasoline		
Base Energy Consumption (l/km)	0.062	0.072	0.111
Base Energy Consumption (MJ/km)	2.05	2.38	3.64
Technical Lifetime, yrs	12	12	12
Environmental Impact			
CO_2 and other GHG emissions, g/km (WTT)	143.5	166.7	255.0
CO_2 and other GHG emissions, g/km (WTW)	169.1	196.4	300.5
Costs			
Capital Cost, overnight, Euro/unit	10,279	16,643	25,505
O&M cost (fixed and variable), Euro/km	0.03	0.04	0.05
Economic Lifetime, yrs	12	12	12

Notes: Based on WTW emissions from JEC (2008) for (a) H_2 produced centrally from natural gas, (b) H_2 produced centrally from biomass, (c) H_2 produced centrally from EU average electricity mix, (d) H_2 produced centrally from renewable electricity (offshore wind). Capital cost medium FCV based on [8], converted using 1.16 Euro:£. Dataset is for current (2010) performance and costs.

Table 2 – Hydrogen Production Costs [28]

Costs	**Production**	**Compression, storage and dispensing**	**Total**
Centralized Production	€25/GJ-H_2	€14/GJ-H_2	€39/GJ-H_2
Decentralized production	€28/GJ-H_2		€28/GJ-H_2

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