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LIFE CYCLE ASSESSMENT OF HYDROGEN USE IN PASSENGER VEHICLES

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Abstract

This life cycle assessment (LCA) presents initial findings of potential environmental and human health impacts from fuel cell hybrid electric vehicles (FCHEV). The LCA is significant because it is based on the ecoinvent database of emissions and background processes, and it assesses a broad range of emission pathways. Although the paper highlights key areas in the life cycle of FCHEV, including the production of hydrogen (H_2), it also highlights the need for additional and more accurate data on FCHEV production. Results are compared to internal combustion engine vehicles (ICEV).

Introduction

The environmental burdens associated with conventional road transportation extend much further than the combustion gases produced whilst driving; there are significant contributions from all other steps in the life cycle of the vehicle i.e. fuel supply, road infrastructures, as well as non-exhaust emissions from the vehicle (mainly from the tyres and brakes). Using hydrogen in fuel cell vehicles is seen as a possible solution to increase the security of transport-related fuel supply whilst offering the potential to reduce greenhouse gas (GHG) emissions[1-3]. But hydrogen is an energy carrier which must be produced from other primary energy resources and means that the specific primary energy resource used and the method of conversion are highly influential on the overall environmental balance as has been shown in previous research[4-8]. These studies have either focused on North American fuel chains and vehicle use or assess only specific greenhouse gas emissions (GHG) and energy demand. They may also be conducted within restrictive system boundaries which do not account for background processes and the demand for capital goods (e.g. production and transport infrastructures). An objective assessment of the environmental performances of conventional with alternative options of passenger transport therefore requires the inclusion of all direct and indirect processes and to compare them on the basis of a range of cumulative burdens on the environment and human health.

Under the objectives of the THELMA project[a] on electric mobility in Switzerland, the research presented in this paper is the life cycle assessment (LCA) of a fuel cell hybrid electric vehicle (FCHEV) running on gaseous hydrogen (H_2) from different production pathways. The use of this passenger vehicle is compared with that of a gasoline internal combustion engine vehicle (ICEV). As a basis for comparison, all of the results refer to the functional unit of 1vkm (vehicle km). Inventory datasets for the FCHEV and H_2 production pathways were modelled using the ecoinvent life cycle database of background processes[9]. For the FCHEV H_2 is produced by decentralised processes located at the fuelling station and representative of current (2010) technologies. The H_2 is pressurised to 700 bar [10]. The fuel cell technology is that of a polymer electrolyte membrane (PEM), also sometimes referred to as a proton exchange membrane. The results are shown in an impact assessment which considers GHG, non-renewable resource depletion (abiotic resources), acidification and eutrophication, ecotoxicity and respiratory inorganics - the latter being related to human health. In comparison with the ICEV, the integration of fuel cells and other necessary drivetrain components in vehicles is a relatively new venture and still very much under development towards large-scale production volumes; a development which could still take at least another 10 to 15 years[11, 12, 13]. Also due to the lack of "real-life experience" regarding daily use, the performance parameters of the fuel cell as assumed in this study (e.g., system efficiency and lifetime) are therefore associated with relatively high uncertainties. A sensitivity analysis determines the influence of these factors on the LCA results.

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[a] Technology-centered Electric Mobility Assessment (THELMA). An inter-disciplinary project examining road transport technologies in the context of climate friendly policies. A collaboration between six laboratories of the PSI and ETH Zürich: www.thelma-emobility.net

Materials and Methods

The ICEV acts as the benchmark technology in the comparison and is based on a mid-sized European passenger car (engine displacement 1.4-2.0 litres) using a modern gasoline EURO 5 standard engine for the calculation of exhaust emissions. Its fuel consumption is 7.5 litres/100km, which corresponds to the average of the current European gasoline vehicle fleet[14]. The Swiss supply and refining chain is used for the gasoline fuel. The fuel cell drivetrain allows a reduction of fuel requirement of almost 55%, resulting in a consumption of 3.47 litres gasoline equivalents/100 km[15,16]. The passenger vehicle used is the same model for both the FCHEV and the ICEV but with a replacement of the power unit and associated components of the drivetrain. As well as including the manufacture, maintenance and disposal of the vehicle, the transport function also includes emissions from brake and tyre wear, as well as the demand for road infrastructure. The basic characteristics of the two vehicles according to the current status of technology as assumed in this study are shown in Table 1.

Passenger car technology	Gasoline ICEV	Hydrogen FCHEV
Standard	EURO 5 (2011)	2010-2015
Net engine/fuel cell power (kW)	80	80
Total transport (km/lifetime)	150 000	150 000
Weight (kg)	1060	1434
Range (km/fuelling)	730	500
Fuel cons. (l gasoline eq./100 km)	7.5	3.47
Fuel cons. in 2010 (MJ/vkm)	2.4	1.1

Table 1. Characteristics of the ICEV and FCHEV for current technology status.

Specifically regarding the FCHEV, the characteristics of the fuel cell and hybrid system are shown in Table 2. For the fuel cell stack we use a power density of 1.5kW/kg[15]. Efficiency losses within the fuel cell system (fuel cell stack and balance of plant so not including fuel tank, motor, battery etc.) mean that it is necessary for the fuel cell stack to have a power of 100kW. Overall, the fuel cell system is modelled with a weight of 197kg. Advances in fuel cell durability mean that for a period of 10 years use in a vehicle, a fuel cell systems' capacity is expected to deteriorate by no more than 15%, and this in a fuel cell produced in 2010 [10]**.** Replacement of the fuel cell over the lifetime of the vehicle is therefore no longer expected to be necessary**.** For other important aspects of the fuel cell system a sensitivity analysis (SA) was necessary to reflect the main uncertainties in the current modelling of fuel cell performance and inventory as well as expected technological developments and to determine the relative influence of these on the assessment results. In the SA, fuel cell stack power is reduced to 55kW to reflect lower internal losses in the fuel cell system and an optimised system management between fuel cell and battery, including a higher proportion of peak load taken from the battery. The power loss in the fuel cell system of 20% in 2010 reduces to around 10% in the SA, giving a net power from the fuel cell system of 50kW. It is expected that battery technology will develop in parallel in order to achieve this. The drivetrain itself is modelled as operating with an increase in efficiency to 65%, also accounting for a higher degree of recaptured braking energy. The cumulative effect of these changes to the fuel cell and drivetrain is a 22% reduction in H_2 demand from 9g/vkm to 7g/vkm. In the fuel cell stack we reduced the platinum consumption from 0.6g/kW to 0.3g/kW and the energy demand for production of the stack itself is reduced from 17kWh/kW to 8.5kWh/kW. Results of the SA are given at the end of the paper.

Hydrogen FCHEV	**2010**	**Sensitivity analysis**
Fuel cell	Proton Exchange Membrane	Proton Exchange Membrane
Fuel cell stack power (kW)	100	55
Net fuel cell power (kW)	80	50
Drivetrain efficiency	45%	65%
H_2 consumption (g/vkm)	9	7
Platinum in fuel cell stack	60g (0.6g/kW)	16.5g (0.3g/kW)
Recovered braking energy	57% [15]	>57%
Battery	2kWh Li-Ion	2kWh Li-Ion

Table 2. Specific characteristics of the FCHEV in 2010 and in a sensitivity analysis on key parameters.

The life cycle inventories of the fuel cell system, comprising of a fuel cell stack and other necessary components (balance of plant) are shown in Table 3. Data was taken from Gerboni et al. 2008[17] and adjusted to suit the final weight of the fuel cell unit.

Life cycle inventories for H_2 production were compiled using published data, stoichiometric calculations and existing datasets within the ecoinvent database[9,18]. Where necessary, updates and adjustments to relevant datasets were conducted. Production is assumed to be at the site of the vehicle fuelling station and therefore does not require a transport of the H_2 in pipelines or pressurised tanks. The fuelling station inventory including storage facilities is taken from Maack (2008)[19]. The currently used feedstocks for H_2 production are shown in Figure 1.

Process	Unit	Fuel cell stack	Balance of plant
Chromium steel 18/8, at plant	kg/kW	0.01	0.33
Aluminium, production mix, at plant	kg/kW	0.05	0.22
Steel, low-alloyed, at plant	kg/kW		1.1
Platinum, at regional storage	kg/kW	0.0006	
Glass fibre, at plant	kg/kW	0.01	
Carbon black, at plant	kg/kW	0.0001	
Graphite, at plant	kg/kW	0.431	
Polyvinylidene chloride, granulate, at plant	kg/kW	0.16	
Tetrafluoroethylene, at plant	kg/kW	0.01	
Polypropylene, granulate, at plant	kg/kW		0.07
Polyethylene, HDPE, granulate, at plant	kg/kW		0.44
Electricity, low voltage, production UCTE, at grid	kWh/kW	17	5
Transport, freight, rail, average Europe	tkm/kW	0.088	0.48
Transport, lorry, 16-32t, EURO V	tkm/kW	0.044	0.24

Table 3. Production inventories of the PEM fuel cell system.

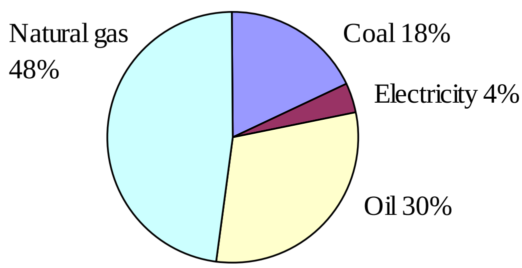

Figure 1 Shares of direct feedstocks to hydrogen production[19, 21].

For the purposes of the research conducted for this paper, on-site production at the fuelling station was assumed to be done by using either natural gas via steam methane reforming (SMR Nat gas), electricity in an electrolyser using either the average European low-voltage electricity mix (Electrolysis UCTE) or the Swiss supply mix (Electrolysis CH), or biomass in a steam methane reforming process of gasified wood (SMR syngas). The following paragraphs provide an overview of these H_2 production pathways, after Simons & Bauer (2011)[18], and some important specifications are given in Figure 2 and Table 4.

SMR Nat gas: SMR is currently the main method employed for the production of H_2 and can be small-scale for on-site H_2 production. Consisting primarily of methane, natural gas can be reacted with steam to form a carbon monoxide and hydrogen rich synthesis gas (syngas). This hot syngas is then fed through high and low temperature shift reactions to further convert the carbon monoxide and additional steam H_2 and CO_2. In a final stage, the H_2 is separated from the CO_2 using chemical adsorption and the H_2 stream is purified in a pressure swing adsorption (PSA) unit. The tail gas (offgas) from the PSA unit is used to preheat the natural gas feedstock. Natural gas, which also powers the catalytic steam reforming unit, is delivered to the SMR plant as a supply mix consisting of long-distance pipeline transport from diverse international gas fields, as shown in Figure 2.

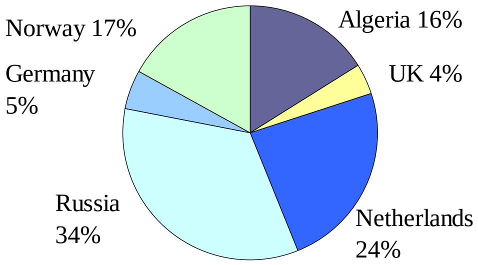

Figure 2 The European natural gas supply mix[22].

The overall conversion efficiency of the SMR of NG process is 67% based on the lower heating value (LHV). The output pressure is 30bar.

SMR Syngas: The gasification of biomass with product gas reforming has a high potential to become commercially viable due to synergies of the technology with those described above for SMR of natural gas, as well as coal gasification. The biomass feedstock modelled is mixed wood chips sourced as a waste material from industry. For the production of H_2 the biomass gasifier produces a high temperature (800-900℃) syngas with a pressure of 2 0-30bar. Waste heat from the gasification is used to dry the biomass to around 15% humidity. Following gasification the syngas is scrubbed of tars and other particles prior to undergoing reforming and purification processes similar to that in the SMR of natural gas (where natural gas is used to generate steam), producing a purified H_2 stream at 30bar pressure. The overall LHV efficiency is 56%.

Electrolysis UCTE: Electrolysis is the splitting of water molecules into hydrogen and oxygen by passing direct electric current between two electrodes separated by an ion exchange membrane. Oxygen is produced at the anode and hydrogen at the cathode, both in very pure form. However, electrolysis represents the conversion of one energy carrier (electricity) into another (H_2) and therefore carries with it the efficiency penalties of the preceding conversion stages. In this research, H_2 is produced using a low temperature bipolar alkaline electrolyser. Here, potassium hydroxide is added to the water to about 30wt% in order to improve its conductivity as an electrolyte. Although this is the least efficient form of electrolyser it is the most developed. The electrolyser requires almost 47kWh electricity per kg H_2 although with auxiliary services and compression to 700 bar this increases to 57.2kWh. This represents a conversion efficiency of 58%. The electricity sources of the UCTE mix are shown in Table 4.

Electrolysis CH: For this scenario the same electrolysis system is used but with electricity from the Swiss low-voltage supply mix which takes average yearly imports and exports into account[23]. The proportions of electricity sources are also detailed in Table 4.

	Nuclear	**Fossil**	**Hydro**	**Others**	**GHG intensity**
CH (based on 2005)	49.3%	8.1%	35.4%	7.2%	140 g(CO_2 eq.)/kWh
UCTE (based on 2005)	31.6%	51.2%	11.4%	5.8%	590 g(CO_2 eq.)/kWh

Table 4. Electricity mixes of the UCTE and Swiss low-voltage electricity supplies[23].

Following the Life Cycle Impact Assessment (LCIA) approach, the assessment of the environmental performance of the different vehicles used selected indicators to represent transport related impacts at both the global and regional levels, the individual characteristics of which are shown in Table 5. At the global level the contributions to climate change (largely due to the combustion of fossil fuels) and the depletion of non-renewable resources (not including fossil fuels) are reflected. On the regional level an assessment of the potential impacts on ecosystem quality using generalised LCIA pathways for pollutants to air, water and soil, and on human health using average exposure to airborne substances is made. Due to limitations in the LCIA methodology, the specific locations of the emissions throughout the complete process chains are not taken into account in the estimation of potential impacts.

	Indicator	**Units**	**Description**	**Main substances**
Global level	Greenhouse gas (GHG) emissions	g (CO_2 eq.)	The global warming potentials (GWP) of GHG are calculated using the CO_2 equivalent GWP factors determined by the IPCC[24].	Carbon dioxide, methane, dinitrogen monoxide, Fluoro-chlorohydrocarbons
	Abiotic resource depletion	g (Sb eq.)	The indicator quantifies the extraction of metal ores where all single metals are expressed in mass of antimony (Sb)-equivalents, thus reflecting the scarcity of the different ores relative to the reference ore (antimony).	Metal ores, e.g. copper, iron, platinum, etc.
Local and regional level	Acidification & Eutrophication	PDF*m^2*yr	Reflecting potential impacts on biodiversity due to human activities, the indicator measures the potentially disappeared fraction (PDF) of flora and fauna species per unit area and time due to precipitated emissions which alter natural pH and nutrient levels.	Ammonia, nitrous oxides and sulphur oxides.
	Ecotoxicity	PAF*m^2*yr	Also reflecting potential impacts on biodiversity, the indicator measures the potentially affected fraction (PAF) of flora and fauna species per unit area and time due to toxic emissions to the air, earth and water.	Heavy metals, dioxins and hydrocarbons.
	Respiratory inorganics	DALY	The potential direct and indirect impacts to the health of the global population is assessed using the Disability Adjusted Life Year (DALY) which combines premature mortality and years of life lost due to the suffering of disabilities caused by airborne pollutants.	Particulate matter, ammonia, nitrous oxides and sulphur oxides.

Table 5. The impact indicators used in the comparative assessment.

Results and Discussion

Figures 3 to 7 present the results according to the indicators used. Contributions from different life cycle stages to overall emissions/impacts per vehicle kilometre are shown separately where “road” indicates contributions mostly from road construction and maintenance (with the same demand factor for all vehicles); “vehicle manufacture” summarises contributions from the construction of the car body and the drivetrain; “vehicle maintenance” represents contributions due to replacement of vehicle components; “vehicle disposal” indicates the burdens due to end-of-life disposal of the car, and "driving" contains all contributions from fuel production and combustion as well as particle emissions from break and tire wear.

In Figure 3, emissions of GHG are mostly associated with the driving of the vehicles. For the ICEV around 80% of the emissions associated with driving are from the fuel combustion and only 20% originate in the fuel production chain, whereas for the FCHEV all driving related GHG emissions are caused in the production of the H_2. The manufacture of the fuel cell and hybrid drivetrain (contributing 60% of GHG emissions from vehicle production) requires energy intensive processes which lead to GHG emissions from the primary energy mixes of the electricity used. A break-down of the most significant processes in terms of GHG in the production of the fuel cell stack is shown in Figure 4.

Currently, most H_2 is produced from natural gas via steam methane reforming and in comparison to a modern ICEV this would lead to only marginal reductions in overall GHG. The GHG emissions from this H_2 production process are associated with both the conversion of the natural gas used as a H_2 source as well as the natural gas combusted to provide process heat. Even though CO_2 from biogenic sources is not included in the quantification of GHG, producing H_2 from the gasification of wood (SMR syngas) still leads to significant emissions due to three main factors; one being the consumption of energy intensively produced gasifier bed materials (21% of overall total); another being the use of fossil fuels for process heat and electricity generation (14.4%), and the third being the transportation from origin to gasification plant of the wood feedstock (7.6%). These three processes amount to 43% of overall emissions and account for approximately 75% of the emissions associated with driving.

The ICEV performance under this indicator would equate to the use of a FCHEV where the H_2 is produced by electrolysis using an electricity mix of around 374g(CO_2 eq.)/kWh. With GHG emissions of approximately 140g(CO_2 eq.)/kWh (compared with 590g(CO_2 eq.)/kWh for the UCTE mix), electricity from the Swiss electricity supply mix in an electrolyser produces H_2 with the significantly lower emissions and enables an overall reduction in GHG emissions of 45% compared with the ICEV. The main sources of emissions in the low voltage Swiss electricity mix are German and French imports, accounting for around 57% and 20% respectively. Electrolysis with the UCTE mix would lead to a significant increase in GHG emissions per vkm due to the more than 50% share of electricity from fossil fuel sources. The results of this first indicator therefore show that the production of H_2 is a critical variable in influencing the total GHG emissions but where it is not necessarily the method of H_2 production (i.e. SMR or electrolysis) which is the most influential factor as electrolysis leads to both the best and the worst results. The more influential factor is the actual primary energy sources used.

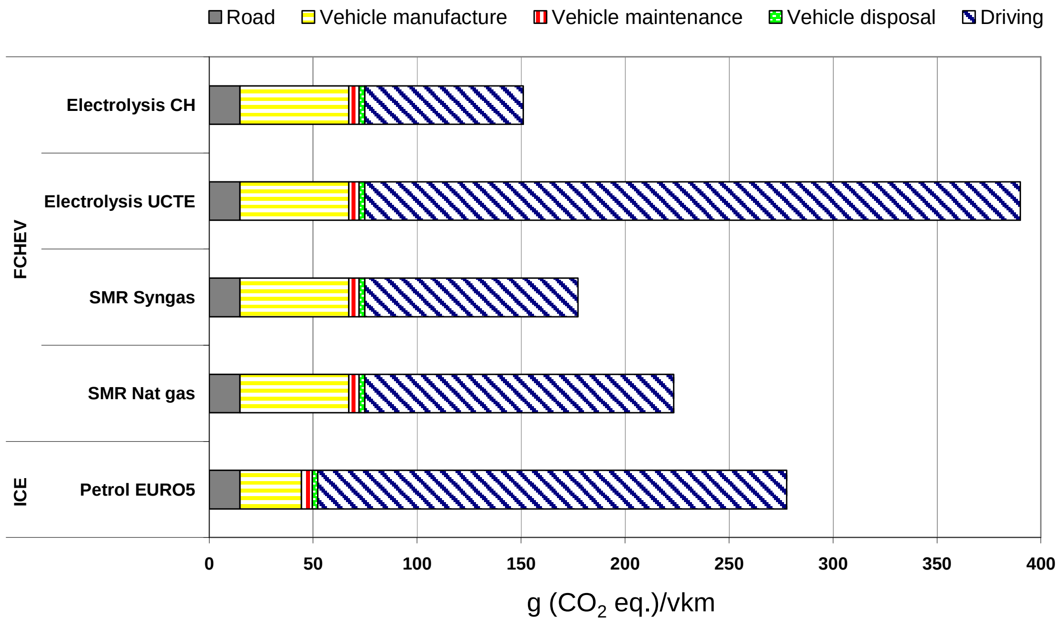

Figure 3. GHG emissions per vehicle km.

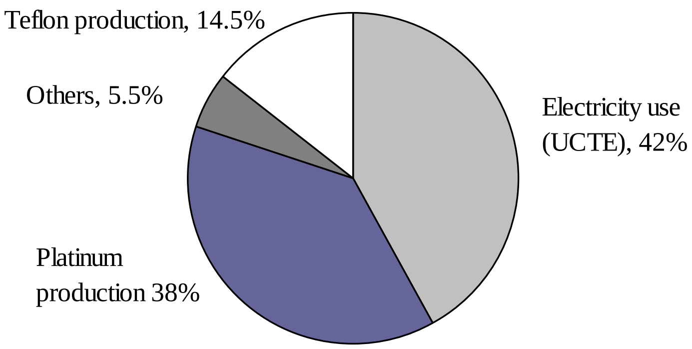

Figure 4. GHG emissions from the production of a 100kW PEM fuel cell stack.

As vehicle technologies change, so also do the requirements for particular metals due to the differences in their specific qualities. When considering the number of vehicles produced and used around the world then a reliance on more scarce elements can be restrictive to the market expansion of a vehicle technology. Figure 5 shows that, on an individual basis, an FCHEV leads to an 80% higher depletion of scarce and non-renewable resources (metals) than the ICEV. Here, the higher degree of electronic components used for management of the fuel cell system and the regulation of energy flows within the FCHEV drivetrain form the main contribution (49%), caused particularly by the use of precious metals in circuit boards. The use of platinum as a catalyst in the electrodes of the fuel cell contributes around 21% to the resource depletion during the vehicle manufacturing stage.

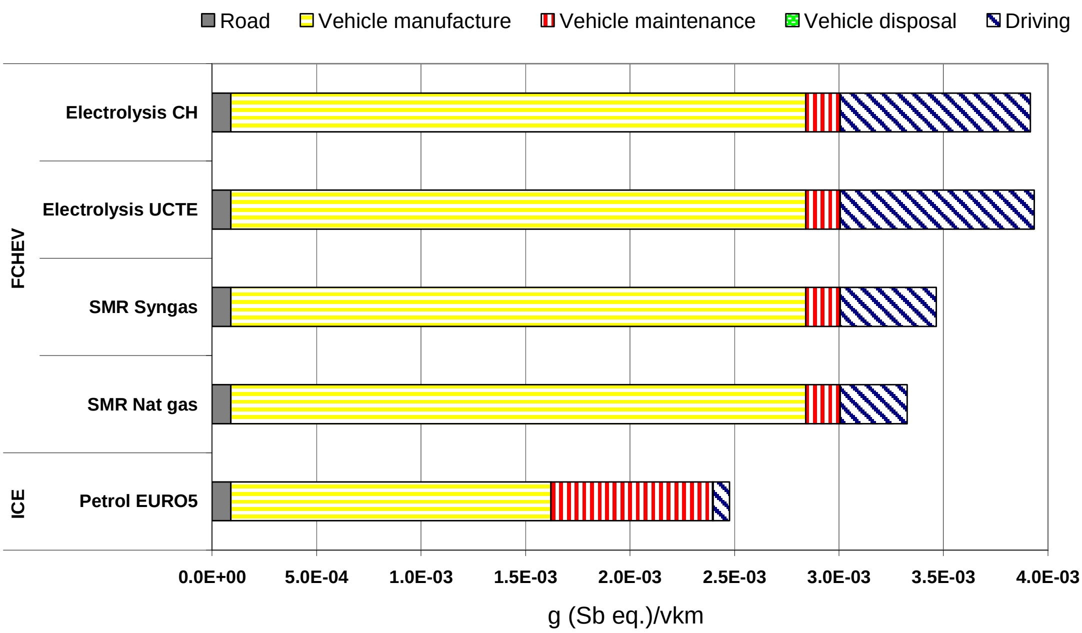

Figure 5. Abiotic resource depletion per vehicle km

Ecoinvent methodology accounts for the recycling of already separated material in the recycled content of a supplied metal according to market shares. In the case of platinum, 95% is from primary sources (mining) and only 5% from secondary sources according to the market share in 2002[25]. Should the FCHEV achieve sufficient market share then it is to be expected that developing processes to extract platinum from used fuel cell stacks in order to make it available as a secondary source will be an essential aspect of vehicle end-of-life (EOL) reprocessing, together with the development of an alternative electrode catalyst. In this LCA no such EOL extraction processes where considered. This is also the case for the sensitivity analysis (SA) below.

Maintenance of the ICEV is shown to be significantly more demanding than the maintenance of the FCHEV, largely due to the replacement of the lead-acid battery and therefore due to the use of lead.The high level of electrification in the FCHEV drivetrain increases the quantity of electronics and thus also the demand for relatively scarce metals. The amount of electronics and the materials in them are an aspect of uncertainty for both ICEV and FCHEV and where the dataset currently available for ICEV production is representative of vehicle manufacture around the turn of the millennium. With the increasing integration of electronics and increasing average vehicle weight it is likely that a modern ICEV will cause a higher depletion of these resources. However, specific data on the amount of electronic components built into a FCHEV was also not found during research for this paper and it is quite likely that the 10kg used is a very low representation. For the results therefore, the gap between ICEV and FCHEV would not necessarily close as a result of further data. Around 20% of the overall depletion of abiotic resources for both of the electrolysis scenarios is due to vehicle driving, where approximately 85% of this (17% of total) is from the use of copper and lead in the electricity supply and distribution networks. For the SMR syngas production pathway higher resource use in comparison with the SMR Nat gas scenario are shown, due largely to the use of lorries for transporting the feedstock as well as the use of zinc oxide to absorb sulphur in the clean up of the syngas.

Acidification and eutrophication (Figure 6) occurs when airborne substances containing sulphur and nitrogen enter water and soil courses via precipitation. The combustion of fossil fuels to generate electricity is a major cause of such emissions and, as well as being visible in the electrolysis processes, their use can be seen in the background processes of extracting minerals and for vehicle production and maintenance, as well as in the provision of road infrastructures. Significant emissions from the H_2 via SMR syngas process are caused by the combustion of gasification products to provide heat for the process (13% of total), as well as from feedstock transport in diesel fuelled lorries (9.6% of total) and the use of electricity in both the gasification and steam reforming processes (8% of total). Combusting natural gas (for process heat in H_2 from SMR Nat gas) causes relatively low nitrous emissions and also does not cause sulphurous emissions. Most of the nitrous emissions occur during natural gas refining (sweetening). Compression of H_2 up to the required pressure uses electricity from the mix available, for both of the SMR processes this is the UCTE mix.

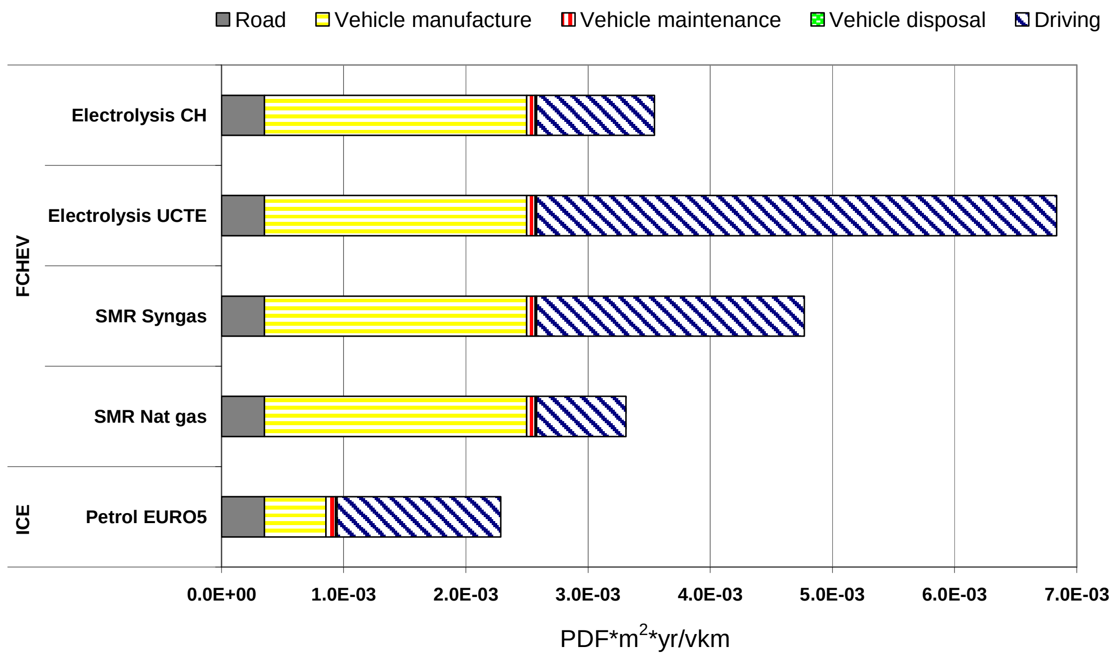

Figure 6. Potential impacts on biodiversity due to emissions leading to acidification & eutrophication.

For the ICEV more than 90% of the contributions from driving occur in the production of the fuels due to the difference between the quality of the finished gasoline fuel and those used in its extraction and upgrading processes, but also due to the stringent emissions regulations of the EURO 5 standard engine. If increased regulation were imposed on hydrocarbon producers then nitrogen and sulphur emissions per vehicle km could be reduced to such extent that vehicle driving would no longer be the dominant stage in the complete life cycle under this indicator.

Concerning ecotoxicity (Figure 7), the potential impacts from the FCHEV's production, maintenance and disposal phases are approximately equal to the total ecotoxicity impacts associated with the ICEV, and can be traced back to the emissions in background processes; primarily from mining and metals extraction. Around 0.025 PAF*m^2*yr/vkm of potential impacts from the driving phase of both vehicles are caused by heavy metal emissions from tyre and brake wear. In the case of the ICEV this accounts for the majority of impacts from this stage of the complete life cycle. For the production of H_2 using electrolysis, much of the potential impacts are due to emissions from the electricity distribution networks. These are either in the form of direct leakages to the ground of heavy metals from electricity cable pilons and substations, or from heavy metal emissions during the mining and processing of copper for cabling requirements. This explains why the potential impacts from both electrolysis scenarios are relatively high and almost regardless of the electricity generation sources. For the SMR processes these are also from the mining and production of metals used in infrastructures – the scarcity of the metals here not being as influential as the quantities used.

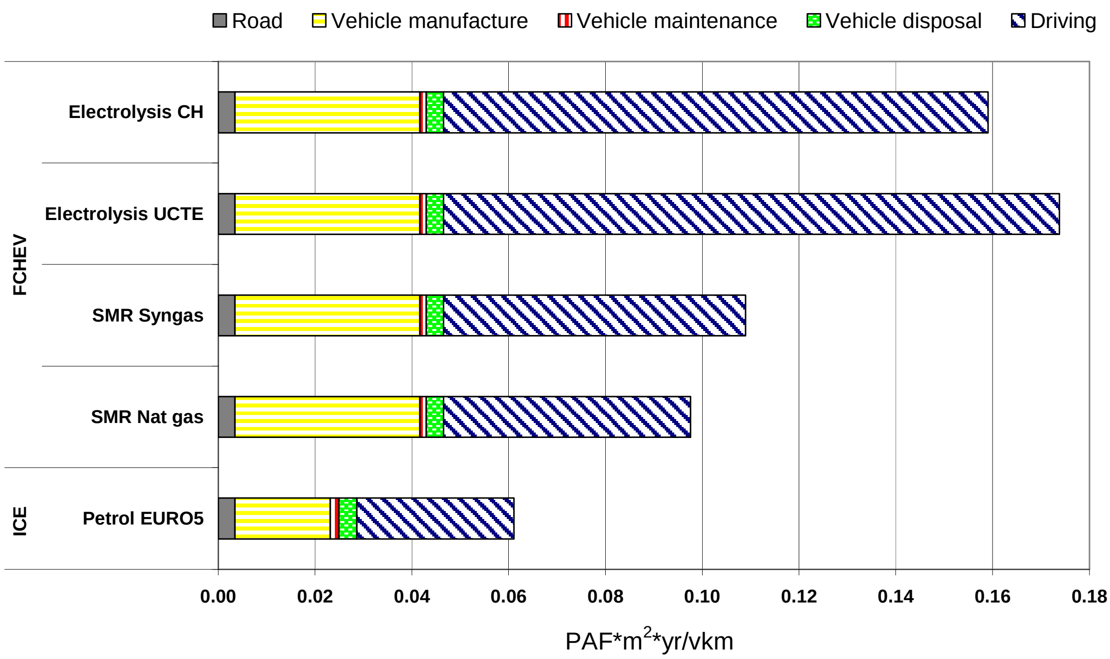

Figure 7. Potential impacts on biodiversity due to ecotoxic emissions

Potential impacts on human health (Figure 8) due to the inhalation of particles and toxic emissions are also largely attributable to the combustion of fossil fuels, particularly solid fuels such as coal and lignite. 45% of the potential impacts due to emissions occurring in the manufacturing and maintenance processes of the FCHEV are attributable to the refining of platinum, with the remaining due to the processing of other metals and emissions from energy supply. Potential impacts on human health from the combustion of fossil fuels are therefore also the main contributing factor to H_2 produced via electrolysis using the UCTE mix. Wood gasification causes significant particle emissions, specifically between the sizes of 2.5 and 10 micrometers (µm). As seen in previous impact indicators, also the transport of the feedstock and other indirect processes using fossil fuels cause the SMR Syngas scenario to have relatively high potential impacts.

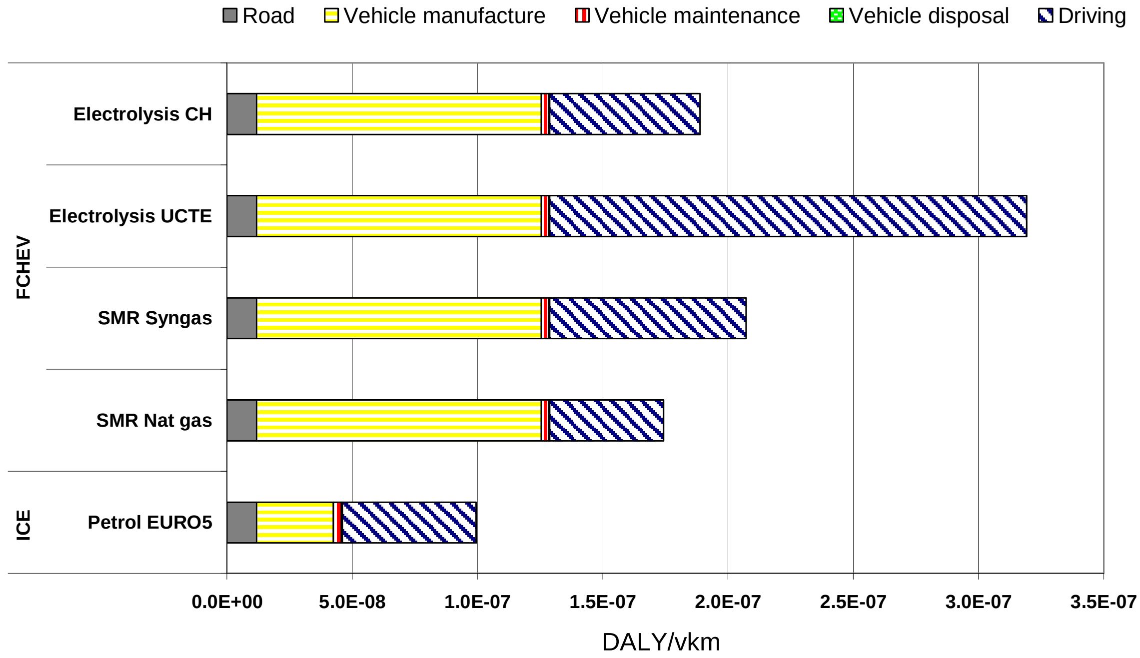

Figure 8. Potential impacts on human health due to air pollutants.

Sensitivity analysis (SA): By applying the alterations to the FCHEV detailed in Table 2, the scenario of the SA is compared with an unaltered scenario for the ICEV (Figure 9). SMR Nat gas is used in the SA scenario as it currently represents the most widely used method of producing H_2 although the SA did not include any potential technology developments in either the SMR process or its associated background processes. To enable a comparison the SA shows the results for the unchanged SMR Nat gas scenario as well as those of the ICEV (also unchanged). Under each indicator, the results are made relative to the worst performing 2010 scenario.

On the global level, the changes made in the SA result in a reduction of GHG emissions by 18% between the SMR Nat Gas and the SMR NG (SA) scenarios, due largely to the higher efficiency of the fuel cell. Specific GHG emissions for the latter become around 72g(CO_2 eq.)/vkm for the driving phase and 110g (CO_2 eq.)/vkm overall. Although the use of electronic control units remains an unchanged factor in the SA, the reduction in platinum use per kW and a reduction in fuel cell system capacity reduces the demand for scarce and non-renewable resources (fossil fuels not included) by 19% to be only 10% higher than the ICEV. As was applied to the SMR Nat gas scenario, currently undeveloped processes to extract platinum from fuel cell stacks at EOL were also not considered in the scenario used in the SA.

Potential local and regional impacts on the environment and human health show a mixed response to the SA scenario. For acidification and eutrophication the potential impacts are reduced such that the overall level is below that of the ICEV; a fall of 36%. For ecotoxicity the effect is less pronounced, with the reduction being less than half of the original difference between SMR Nat gas and ICEV and, at around 17%, the lowest reduction for all indicators. The mining and beneficiation of platinum releases several substances toxic to the health. A reduced demand for this metal therefore has a significant effect on this indicator, also showing around a 36% decrease but which is here not enough to result in a lower overall impact than that of the ICEV.

Figure 9 also compares the relative contributions of each life cycle stage to the cumulative totals in a form of overview. For instance, it can be seen that the demand for road infrastructure and the maintenance and disposal of the FCHEV all have relatively insignificant contributions.

Without considering how the hydrogen is produced, the sensitivity analysis shows that the environmental burdens from the production of the FCHEV will remain more intensive than for the production of the ICEV.

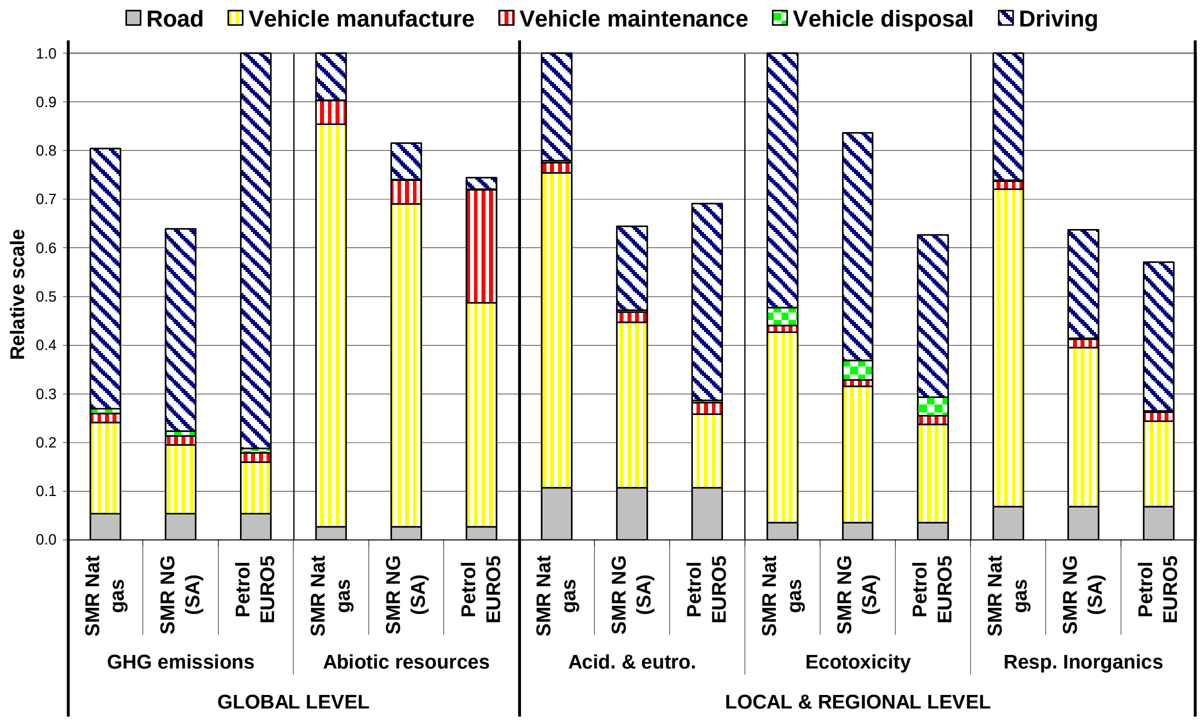

Figure 9. Results of the FCHEV sensitivity analysis (SA)

Conclusions

The results of this comparative LCA show that according to the current state of technology a transition to hydrogen fuel cell drivetrains in passenger vehicles is not automatically a more environmentally benign solution to using conventional fossil-fuelled internal combustion engine vehicles; pronounced reductions are not seen across a wide range emissions and potential impacts. However, due to the globally significant influence of individual mobility and transport on the world climate it is of critical importance that FCHEV demonstrate the ability to reduce life cycle GHG emissions. Here, the production of H_2 is the deciding factor, and it was found that SMR from both natural gas and syngas from wood could achieve this, as could electrolysis using a power mix with a rather low GHG intensity. In this particular case electrolysis using the Swiss electricity supply mix (Table 4) was shown to reduce GHG emissions the most. With only 8% of electricity from fossil fuelled power plants in the Swiss mix, significant further reductions via the electrolysis method may only be achievable via an increase in electrolyser efficiency, or use of 100% renewable or nuclear power sources with very low GHG intensities.

The mining and processing of ever-scarcer non-renewable resources will only be heightened by the rapidly increasing demand for motorised personal mobility. In this assessment it has been shown that a current FCHEV significantly increases this demand beyond that of an ICEV although a closer analysis of the components of particular relevance to this aspect is necessary.

Potential regional impacts on the environment and human health are also not seen to be lower than for the ICEV. Here the mining and processing of metals used in the production of the FCHEV is also the most dominant contributing factor, particularly to acidification and eutrophication as well as human health. Results for ecotoxicity are influenced more strongly by the leaching of heavy metals into ground and water systems and for this the scenarios depending heavily on electricity are shown to cause the most impacts.

The sensitivity analysis (SA) showed that global level impacts due to GHG emissions and non-renewable resource depletion could reduce by almost 20% according to the alteration of the specific FCHEV parameters. Regional level potential impacts on the environment and human health would reduce by more than 35%. Whilst climate change would be partly mitigated by FCHEV operating under these conditions, it would tend to place greater burden on the competition for scarce resources whilst not leading to discernable improvements in the regional environment. It will therefore be necessary for the resource intensity of the fuel cell to be improved before the potential impacts on the regional environment achieve lower levels to that of conventional vehicles, even more so as the development and fuel efficiencies of these will not remain stagnant at the level representative of today's average..

The manufacturing stage of the FCHEV's life cycle is currently associated with high uncertainties due to lack of "real-life" experience in their production and performance. The availability of representative data is therefore vital in the compilation of accurate input/output inventories of these stages and thus to a concise and unbiased comparison using LCA.

Of significant influence on the environmental performance of fuel cell vehicles are the various H_2 production methods so that an analysis of a broader range of options and their possible developments is important in order to be able to determine the most suitable, either currently in operation or under development towards commercialisation.

Research for this paper compiled life cycle inventories of FCHEV and incorporated previous work on H_2 production. Although the results reflect the inclusion of comprehensive background processes and have not been limited to GHG emissions, the authors recommend broadening the scope of the assessment to include other burdens and impacts on the environment as well as a more exposure-orientated assessment of the potential impacts on human health, including site-specific aspects of emissions and impacts which are not covered due to the limitations of the LCIA methods in this respect. This would particularly look at changes in the location and exposures to direct emissions from driving, often occurring in urban environments. A future LCA could also look at the consumption of specific resources such as water. When assessing future transport options, taking into account potential progress in fuel cell technologies as well as a comparison with other alternatives under development, such as battery electric vehicles and alternatively fuelled ICEV's, would also further increase a work's relevance.

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