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An environmental analysis of FCEV and H_2-ICE vehicles using the Ecoscore methodology

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Abstract

The environmental issues caused by fossil fuels for transportation are numerous: greenhouse gas emissions are enhancing global warming, city smog, ozone and noise are causing major health problems, acid rain impacts our ecosystems, etc. Strong research efforts have therefore been performed towards alternative fuels and drive trains and hydrogen is still one of the most promising – but at the same time controversial – possibilities. The environmental impact of hydrogen – used in a fuel cell (FCEV) or internal combustion engine vehicle (ICEV) - depends strongly on the production pathway for hydrogen and should therefore be evaluated on a well-to-wheel basis.

In this paper, the Ecoscore methodology is used to assess the environmental impact of H_2-ICE and fuel cell vehicles on a well-to-wheel basis. The Ecoscore is an environmental indicator for vehicles taking into account the impact on global warming, air quality depletion (divided into impact on human health and ecosystems) and noise. The Ecoscores of two FCEV and one H_2-ICEV are calculated for different hydrogen production pathways (electrolysis and Steam Methane Reforming (SMR)), as well as for different methods of hydrogen storage (compression and liquefaction) and distribution (pipeline and truck). The highest Ecoscores – and thus best results - are obtained for vehicles using hydrogen from electrolysis produced with 100 % renewable energy, followed by SMR and then electrolysis using the Belgian electricity mix. Compression appears to be better than liquefaction to store hydrogen due to the high energy use for the liquefaction process, and this compressed hydrogen should be transported through pipelines in stead of by trucks to obtain the best environmental performance.

Keywords: hydrogen, fuel cell, ICE (internal combustion engine), environment, energy

1 Introduction

Hydrogen can be used as an energy carrier for vehicles with a fuel cell, thus generating electricity for the electric drive train. The efficiency of a fuel cell electric vehicle (FCEV) is more or less twice as high as the efficiency of a conventional petrol internal combustion engine (ICE) vehicle [1], moreover an FCEV is a so-called ‘zero-(direct)emission vehicle’, only emitting water vapour. Not only can hydrogen be used in vehicles with a fuel cell, it can also be combusted in an ICE. Through limited adjustments, a petrol car can be adapted to the use of hydrogen or hydrogen-natural gas mixtures. Due to the specific characteristics of hydrogen, the efficiency of the engine is higher than with other fuels. The emissions caused by burning hydrogen are very low and are generally due to the combustion of lubricating oil. Nitrogen oxides will also be formed, although they can be catalytically removed [2].

There are many possible pathways to create hydrogen fuel, using various energy sources and resulting in a wide range of total energy consumptions, greenhouse gas emissions and other pollutants. When considering hydrogen as a fuel, it is particularly important to consider and investigate these different production pathways as they represent a dominant part of the total energy use and of the total emissions in case of a well-to-wheel (WTW) analysis.

One of the benefits of hydrogen is that, in theory, it can be produced from virtually any primary energy source. This can generally be done either via a chemical transformation process or through electricity via electrolysis of water. Currently, the most widespread hydrogen production process is steam reforming of natural gas (SMR). Electrolysis uses electricity to split the water molecule into hydrogen and oxygen molecules. The use of electricity as the energy vector to produce hydrogen opens the door to the use of a large variety of primary energy sources including fossil fuels, but also renewable energy (e.g. biomass, wind and solar energy) [3].

As the lightest of all gases, hydrogen has a low volumetric energy density and must therefore be either compressed at very high pressures (up to 700 bar) or liquefied at very low temperatures (-253 °C) to be stored in any significant quantity. Hydrogen can also be stored in a solid state, but no automotive applications are available yet. Hydrogen storage presents major challenges, particularly for transport applications [4].

2 Ecoscore methodology

To compare 'zero-emission vehicles', such as FCEV and battery electric vehicles (BEV), with vehicles using other fuels or drive trains, from an environmental point of view, not only the tailpipe emissions should be taken into account, but the whole WTW emissions. This includes the indirect or well-to-tank (WTT) emissions which are caused by the extraction of the raw materials, production and distribution of the fuel, as well as the direct or tank-to-wheel (TTW) emissions from the use of the vehicle. An environmental rating tool for vehicles, called 'Ecoscore', has been developed by the Vrije Universiteit Brussel in collaboration with VITO and ULB in commission of the Flemish government [5]. It has been developed for light and heavy duty vehicles as well as two-wheelers, but the methodology will be described specifically for passenger vehicles, since they are the subject of this paper. The Ecoscore methodology takes into account the impact of the vehicle's WTW emissions on three damage categories: global warming, air quality depletion (split up into impact on health and ecosystems) and noise (Figure 1). The Ecoscore is a number between 0 and 100, with 100 representing a perfectly clean and totally silent vehicle. It must be noted that the emissions from the vehicle production, maintenance and end-of-life phase are not taken into account in this WTW approach because of less differentiating emission data or data availability issues.

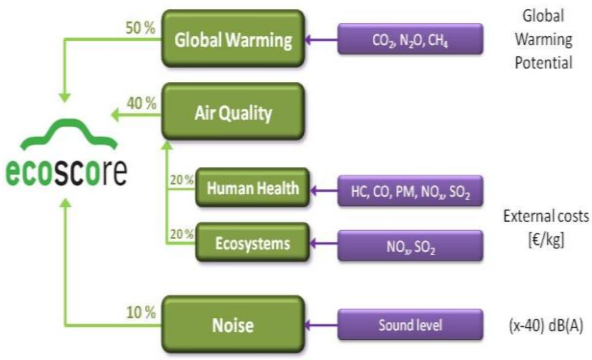

Figure 1: Overview of the different impact categories, their weights, characterisation and corresponding pollutants as used in the Ecoscore methodology.

The environmental evaluation of a vehicle is being done according to a sequence of five steps, similar to those used in a standardised Life Cycle Assessment (LCA): inventarisation, classification, characterisation, normalisation and weighting.

2.1 Inventarisation

In the first step of inventarisation, the direct and indirect emissions associated with the vehicle are collected. Direct emissions and fuel consumption are derived from the vehicles' homologation files, which are available for all road vehicles on the European market. These homologation data differ from real vehicle emissions, but they provide a common evaluation basis for all vehicles to be assessed. Type approval tests give information on the so-called 'regulated' direct emissions, more specifically on CO (carbon monoxide), NO_x (nitrogen oxides), HC (hydrocarbons) and PM_{10}

(particulate matter), expressed in g/km. Besides the regulated emissions, some unregulated emissions are considered as well: CO_2 (carbon dioxide), SO_2 (sulphur dioxide), N_2O (nitrous oxide) and CH_4 (methane). CO_2 and SO_2 are calculated from the fuel consumption and based on the fuel characteristics, the direct emissions of N_2O and CH_4 are mainly dependent of the applied vehicle technology.
The indirect emissions ($E_{j,indirect}$) of passenger vehicles, expressed in g/km, are calculated as follows:

$$E_{j,indirect} = \frac{1}{3{,}6.10^{11}} . F_j . \rho . EC . FC \qquad (1)$$

with F_j the indirect emission factor for pollutant j (in mg/kWh); ρ the fuel density (in g/l); EC the energy content of the fuel (in kJ/kg) and FC the fuel consumption of the vehicle (in l/100km). The factor $1/3{,}6.10^{11}$ is a conversion factor.
In the case of hydrogen vehicles, the formula is adjusted in the following way:

$$E_{j,indirect} = F_j . FC \qquad (2)$$

With F_j the indirect emission factor for pollutant j (in g/kg H_2) and FC the hydrogen consumption (in kg H_2/km).

2.2 Classification

In the second step of the methodology, the emissions collected during the inventory phase are assigned to the impact categories to which they contribute. The impact categories considered in the Ecoscore methodology are global warming, air quality depletion (divided into impact on human health and ecosystems) and noise. The considered pollutants contributing to these categories are indicated in Figure 1.

2.3 Characterisation

Depending on the considered impact category, different impact factors are used for the characterisation of the damage due to both the indirect and direct emissions. Different impact factors are used for direct and indirect emissions damaging human health, since the impact of emissions affects a higher number of people in an urban environment than in rural surroundings, where there are less human receptors. Since fuel production plants are assumed to be located outside cities, indirect emissions are considered to be rural emissions.

The calculation of the partial damage ($D_{i,j}$) of each pollutant j can be represented by the following equation:

$$D_{i,j} = \delta_{i,j,indirect} . E_{j,indirect} + \delta_{i,j,direct} . E_{j,direct} \qquad (3)$$

with $\delta_{i,j}$ the impact factor of pollutant j to the category i and E_j the total contributing emissions of pollutant j to the category i.
The total damage of each impact category i (Q_i) can be obtained by summing up the partial damages for the different categories, as follows:

$$Q_i = \sum_j D_{i,j} \qquad (4)$$

The contributions of the different greenhouse gases to global warming are calculated using global warming potentials (GWP), as defined by the Intergovernmental Panel on Climate Change (IPCC). External costs, expressed in euro/kg and based on the EU ExternE project [6], are used for the inventoried air quality depleting emissions. For the impact on human health, a weighted average of urban and rural external costs is used, using the national split between urban and rural mileage as a weight factor (different for light duty, heavy duty and two-wheelers). The impact factors as used in equation (3), can now be calculated as the weighted average of urban and rural specific external costs (SEC), according to the following equations:

$$\delta_{i,j,indirect} = SEC_{i,j,rural} \qquad (5)$$
$$\delta_{i,j,direct} = \sigma_{urban} . SEC_{i,j,urban} + \sigma_{rural} . SEC_{i,j,rural}$$

with $\sigma_{urban/rural}$ the urban/rural mileage distribution percentage. For light duty vehicles this parameter is 25 % urban and 75 % rural mileage.
For the damage calculation of impacts on ecosystems due to acidification and eutrophication, external costs are used as well. Abatement costs of emission reductions for NO_x and SO_2, as presented by [7], are used.
Noise pollution is expressed in dB(A), a decibel scale with A-weighting to take the sensitivity of human hearing into account. In this methodology, the inventoried noise level is decreased with a base value of 40 dB(A), corresponding to a non-disturbing background sound level, to obtain values proportional to the inconveniences. The calculation of noise related damage is given through equation (6).

$$Q_{noise} = D_{noise} = E_{noise} - 40 \qquad (6)$$

An overview of the urban and rural characterisation factors for the corresponding pollutants and impact categories is given in Table 1.

Table 1: Overview of characterisation factors corresponding with the inventoried pollutants for each impact category [5].

Classification	Inventory	Characterisation rural	Characterisation urban	Unit
Global Warming	CO_2	1	1	GWP
	CH_4	23	23	GWP
	N_2O	296	296	GWP
Air Quality				
Human Health	HC	3	3	€/kg
	CO	0,0008	0,0032	€/kg
	PM_{10}	103,49	418,61	€/kg
	NO_x	1,152	1,483	€/kg
	SO_2	6,267	14,788	€/kg
Ecosystems	NO_x	0,176	0,176	€/kg
	SO_2	0,113	0,113	€/kg
Noise	Sound Level	x-40		dB(A)

2.4 Normalisation

To quantify the relative severity of the evaluated damages of each damage category, a normalisation step based on a specific reference value is performed. The reference point for light duty vehicles is the damage associated with a theoretical passenger vehicle of which the emission levels correspond with the EURO 4 emission target levels for petrol vehicles, a CO_2 emission level of 120 g/km and a noise level of 70 dB(A). The normalised damage on category i (q_i) is calculated as follows:

$$q_i = \frac{Q_i}{Q_{i,ref}} \qquad (7)$$

with Q_i the total damage of the assessed vehicle on category i and $Q_{i,ref}$ the total damage of the reference vehicle on category i.

2.5 Weighting

In a final step, the normalised damages are weighted before they can be added to become the "total environmental impact" (TI).

$$TI = \Sigma_i \, \alpha_i . q_i \quad \text{and} \quad \Sigma_i \, \alpha_i = 1 \qquad (8)$$

with α_i the weighting factor of impact category i. These weighting factors reflect policy priorities and decision makers' opinions.

The reference vehicle itself presents a total impact of 100. A vehicle with higher or lower emission levels when compared to the reference vehicle, will have a total environmental impact higher, respectively lower than 100.

For communication purposes, the total impact is transformed into an Ecoscore, ranging from 0 to 100, with 0 representing an infinitely polluting vehicle an 100 an emission free and silent (40 dB(A)) vehicle. The reference vehicle corresponds to an Ecoscore of 70. The transformation is based on an exponential function, according to equation (9).

$$Ecoscore = 100.e^{-0,00357.TI} \qquad (9)$$

3 Assessment of H_2 as a fuel

In this paper, the environmental impact of different vehicle technologies is compared, with special attention to FCEV and H_2-ICEV, but also different hydrogen 'pathways' are considered. Based on data availability and economic relevance, different scenario's have been created by varying the used energy source/carrier (100 % natural gas, Belgian electricity mix or 100 % renewable electricity), the hydrogen production process (SMR or electrolysis), hydrogen storage process (compression or liquefaction) and finally the hydrogen distribution (pipeline or truck). These different pathways are shown schematically in Figure 2. Each step of the pathway with the different assumptions, information sources and specific data used to calculate the impact are sequentially described in the following paragraphs.

3.1 Hydrogen production and energy sources/carriers

Hydrogen is not an energy source but an energy carrier and as such, it requires an energy source for its manufacture. Hydrogen is already produced in

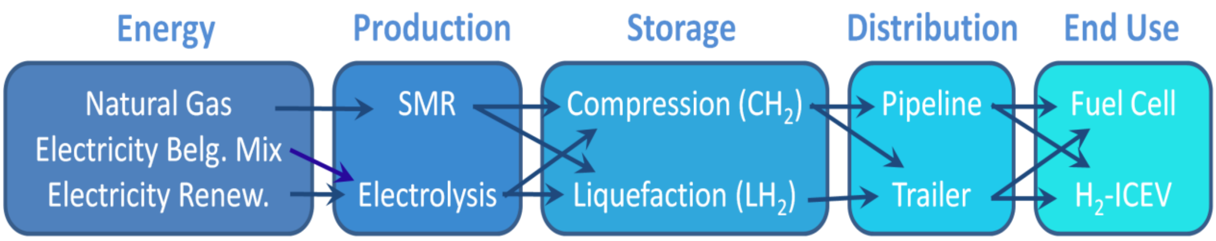

Figure 2: Overview of the different hydrogen 'pathways' considered in this paper.

large quantities for use in the process industries (mainly for ammonia synthesis and in refining of crude oil). It can be produced in many different ways, using a wide range of energy sources and technologies, being steam reforming of hydrocarbons, coal gasification, electrolysis, partial oxidation of hydrocarbons, bioconversion, thermo- and photolysis. Some of these technologies are already being applied on a large scale, others are still in the development phase [8].

3.1.1 Steam Methane Reforming

Steam reforming of natural gas (essentially methane) (SMR) is currently the least expensive production method and makes more than 90 % of the hydrogen production worldwide [2]. The catalysed combination of methane and water at high temperature produces a mixture of CO and H_2, known as 'syngas'. The 'CO-shift' reaction then combines CO with water to form CO_2 and H_2. Steam reforming of heavier hydrocarbons is also possible, but is currently not applied on a large scale [3]. The efficiency of this production process in a centralized plant with extra steam for exportation varies between 80 and 90 %, but it may be less, especially for decentralized plants [9,10].

The emissions caused by hydrogen production through SMR as used in this paper, were found in the study of Spath & Mann [11]. In this study an average centralized SMR plant was considered, with a natural gas and electricity mix corresponding to the mid-continental US. The energy efficiency of the hydrogen plant is 89,3 % on higher heating value (HHV) basis. The airborne emissions used for the Ecoscore calculations take into account the natural gas production and transport, electricity generation and hydrogen plant operations. Emissions due to the construction and decommissioning of the plant and natural gas pipelines are not included in this analysis.

3.1.2 Water electrolysis

The second most applied hydrogen production process is water electrolysis, in which electricity is used to split the water molecule into hydrogen and oxygen. This is a well established technology, both at large and small scale. Electrolysis is more expensive and energy-intensive than SMR, but the use of electricity as the energy vector opens the door to the use of a large variety of energy sources, including fossil and biomass, but also wind and nuclear energy [3]. Also, electrolytic production of hydrogen offers one method of storing electricity from intermittent sources [9]. The efficiency of hydrogen production using electrolysis ranges between 70 and 90 % [9,12]; in our analyses an efficiency of 75 % is assumed.

Two types of electricity used for electrolysis are considered in this paper: the Belgian electricity supply mix based on Ecoinvent data [13] and electricity based on 100 % renewable energy (e.g. wind energy). The composition of the Belgian electricity supply mix according to Ecoinvent is shown in Table 2. The supply mix has been chosen, since this also includes the electricity which is imported to Belgium from France, the Netherlands and Luxemburg.

Table 2: Composition of the Belgian electricity supply mix, based on [13].

Energy source	Share [%]
nuclear	47,2
gas	24,0
coal	9,2
oil	1,7
renewables	2,6
import	15,3

The electricity supplied to the hydrogen plant is considered to be medium voltage; electricity used to power e.g. BEV's is supplied at low voltage. Both types of electricity cause different levels of airborne emissions due to losses during the electricity distribution process. The pollutant emissions due to electrolysis are calculated with the Ecoinvent electricity data (Table 3) and are considering an efficiency of 75 %. Electrolysis using only renewable energy is assumed to cause no airborne emissions.

Table 3: Airborne emissions from the Belgian electricity supply mix at medium voltage, based on [13].

Belgian Electricity Supply Mix Medium Voltage [mg/kWh]	
CO_2	325522,10
N_2O	11,76
CH_4	322,65
CO	156,50
NO_x	561,23
NMHC	60,71
SO_2	610,27
PM_{10}	263,48

3.2 Hydrogen storage

Hydrogen exhibits the highest energy density per mass of all chemical fuels: 120 MJ/kg LHV (lower heating value) or 142 MJ/kg HHV. The volumetric energy density on the other hand is very low, making it hard to store hydrogen in a cost efficient way. Especially for automotive applications, the volumetric and gravimetric density of hydrogen in a storage material is crucial.

At ambient temperature and pressure, hydrogen is a gas, but it can be stored as a gas, liquid or solid. In the case of solid storage, the hydrogen exists as a chemical compound and not as a pure substance. In current hydrogen demonstration vehicles, hydrogen is usually stored as a compressed gas in lightweight composite materials, or in some other cases as a liquid in cryogenic tanks.

3.2.1 Compressed hydrogen

Storage of hydrogen in compressed gas form is the most common storage form today. Standard cylindrical flasks use pressures of 10-20 MPa, and fuel cell vehicle tanks are currently in the range of 25-35 MPa. Tests are ongoing with pressure increased to 70 or even 80 MPa, reaching a volumetric density of 36 kg/m^3, in order to be able to store enough energy to obtain acceptable ranges for passenger cars. While flasks for stationary use are usually made of steel, weight considerations make composite fibre tanks more suitable for vehicle applications. In contrast to liquefaction, the energy required for compression of hydrogen is relatively small [8].

When hydrogen is distributed through pipelines operating at 10 MPa, the hydrogen will be compressed at the filling station from 10 to 40 MPa (for vehicles with a storage tank at 35 MPa). This compression requires 3 % of the energy content on HHV basis, so 4,32 MJ/kg. For a vehicle tank at 70 MPa (compression to 80 MPa), the energy use amounts up to 12 % on HHV basis [9].

When hydrogen is distributed by truck, it may undergo a first compression at the production site to 20 MPa, using 8 % of the HHV energy content. After distribution by truck, the hydrogen is stored at the filling station at 10 MPa and then compressed a second time to 40 MPa, again using 3 % of the energy content [9].

For the assessment of the different hydrogen vehicles in this paper, the energy used for compression, liquefaction and distribution is assumed to be electricity, corresponding with the emissions from Table 3.

3.2.2 Liquid hydrogen

Hydrogen can be stored as a liquid in a cryogenic tank by cooling it to 20 K or -253°C at ambient pressure. The volumetric density of liquid hydrogen is 70,8 kg/m^3 and slightly higher than that of solid hydrogen (70,6 kg/m^3) [14].

This transformation of gas into liquid enables large amounts of hydrogen to be shipped by tanker, truck and rail. The downside is the high energy requirement for liquefaction, more precisely 23 to 40 % of the HHV energy content [8]. An energy use of 15,78 kWh/kg (40 % HHV) is assumed for the calculations. Another part of the energy content is lost by boil-off (3 to 4 % a day). Very special material is required for the tank which has to be very well insulated at very low temperatures and which is very expensive [2]. The challenges of liquid storage are the energy-efficient liquefaction process and the thermal insulation of the cryogenic storage vessel in order to reduce the boil-off of hydrogen [14].

3.2.3 Solid-state storage

Hydrogen can be stored in solid materials, in which hydrogen can be either physically adsorbed (e.g. in activated carbon or carbon nano-tubes) or chemisorbed to the solid in hydrides [15]. No prototype vehicles with solid-state hydrogen storage exist today due to respectively the heavy weight or the huge energy losses to produce the hydrides [9].

3.3 Hydrogen distribution

To tank hydrogen at a filling station, it has to be distributed from the production and conversion plant, either through pipelines for compressed hydrogen or by truck for compressed or liquid hydrogen. Also transport by train or ship is possible, but won't be considered in the context of this paper. Hydrogen can also be produced on-site at the filling station through electrolysis or by SMR. The compression of the hydrogen is then also performed on-site, before filling up the vehicle's hydrogen tank. For this small-scale local hydrogen production, the existing electricity or gas distribution infrastructure can be used. Local hydrogen production reduces distribution costs, but cannot benefit from economies of scale and apply carbon capture and storage (CCS) when using fossil fuels for hydrogen production [2].

3.3.1 Pipeline distribution

In the US a hydrogen pipeline network of more than 700 km exists, in Europe this is even 1500 km long, running partly through Belgium. This pipeline operates at 10 MPa of pressure [17]. The current networks exist only for the limited industrial hydrogen markets, so serious investments would be required to extend it for wider use, e.g. in automotive applications [2]. Pipelines might be the least expensive option for delivery of large quantities of hydrogen [17].
To transport hydrogen gas through a pipeline, a compressor is installed every 150 km, consuming 1,16 % of the local energy flow (per 150 km) [9]. In our analyses, an energy consumption (as electricity) of 0,77 % or 1,09 MJ/kg on HHV basis is assumed for pipeline distribution over 100 km.

3.3.2 Distribution by truck

Liquid hydrogen delivery is used today to deliver moderate quantities of hydrogen over medium to long distances [16]. Even though liquid tanker trucks might be the least expensive delivery option in the near term – and carry ten times the amount of hydrogen transported by trucks carrying compressed hydrogen canisters – this approach is still undesirable for large-scale use due to the very high energy cost. Distribution of compressed hydrogen in trailers is relatively expensive due to the low energy density [17].
A modern 40 ton tube-trailer truck can carry 320 kg hydrogen at a pressure of 20 MPa, but delivering only 288 kg or 90 % of its payload to the customer. In the future, trucks with improved high-pressure canisters will be able to carry 500 kg of hydrogen, of which 400 kg could be delivered to the customer [9]. In our calculations, a truck with a payload of 400 kg compressed hydrogen will be considered at a pressure of 20 MPa, transported for 100 km. This truck consumes 40 kg diesel per 100 km. Since the truck has to return with 39,6 kg weight, 79,6 kg diesel is consumed for a delivery distance of 100 km [9].
While in most cases the transport of fuels is weight-limited, for liquid hydrogen it is limited by volume since a lot of space is needed in the truck for the container, thermal insulation, safety equipment, etc. A 30 ton truck could therefore deliver an amount of 2100 kg liquid hydrogen instead of the 4200 kg without the extra equipment. The truck consumes 57,9 kg diesel for a delivery distance of 100 km [9].
The transfer of liquid hydrogen from the filling station to the hydrogen vehicle requires no additional energy, since it can be drained by the action of gravity [9].
The emissions of the diesel truck are calculated on a WTW basis. The direct emissions of CO, NO_x, NMHC and PM_{10} correspond to the Euro IV emission standard for heavy duty vehicles, the emissions of CO_2, N_2O, SO_2 and CH_4 are calculated from the fuel consumption. The indirect emissions are also calculated based on the fuel consumption and emission factors from MEET [18] (see Equation 1).

3.4 Fuel cell and H_2-ICE vehicles

3.4.1 Assessed fuel cell vehicles

All major OEM car manufacturers have some kind of FCEV development programme going on, but today FCEV's are available only as prototype-demonstrators, most of them using the Proton Exchange Membrane Fuel Cell (PEMFC) type [2].
Based on available data from literature, two FCEV's have been selected for the Ecoscore assessment: the Honda FCX Clarity [19] and the Renault Scénic ZEV H_2 [20] (Table 4). Both vehicles use compressed hydrogen (CH_2) to fuel the fuel cell, stored at a pressure of 345-350 bar. The hydrogen consumption of both vehicles is measured on different test cycles, the American EPA-based cycle for the Clarity and the European NEDC combined cycle for the Scénic ZEV. The sound level of the vehicle is set at 74 dB(A), being the most recent European sound level standard for light duty vehicles (directive 70/157/EEG of 1996), since no specific data were retrieved.

Table 4: Overview of some technical and environmental characteristics of the assessed hydrogen fuel cell and ICE vehicles.

Vehicle	Technology	H_2 storage	Vehicle weight [kg]	Engine power [kW]	Range [km]	Test cycle	Consumption [kg H_2/km]	NO_x [g/km]	CO [g/km]	CO_2 [g/km]	NMHC [g/km]	Noise [dB(A)]
Honda FCX Clarity	PEMFC hybrid (with battery)	4,1 kg CH_2 at 345 bar	1625	100	451	EPA based	0,0023	0	0	0	0	74
Renault Scénic ZEV H_2	FC	3,7 kg CH_2 at 350 bar	1850	90	350	NEDC	0,0106	0	0	0	0	74
Ford P2000 2.0l	H_2-ICEV	1,5 kg CH_2 at 248 bar	n.a.	110	96	EPA-75	0,0044	0,4598	0,0051	0,8699	0,0047	74

3.4.2 Assessed H_2-ICE vehicles

The H_2-ICE technology can be seen as a temporary step to boost the use of hydrogen as a fuel and pave the way for the introduction of the fuel cell, with its higher efficiency, on a longer term. Today, BMW and Ford are the strongest advocates of the H_2-ICE technology, producing some prototype vehicles [2]. For the analyses made in this paper, one H_2-ICE vehicle has been considered: the Ford P2000, a family sedan [21] (Table 4). The P2000 stores compressed hydrogen (CH_2) at 248 bar and has no exhaust after-treatment system. As for the assessed FCEV's, a sound level corresponding to the European standard of 74 dB(A) is assumed due to a lack of more precise data. The vehicle was tested on the American EPA-75 (city and highway) cycle. The traces of carbon based emissions of the H_2-ICEV are generally attributed to the combustion of lubricating oil [21].

4 Results

The environmental performance, expressed as Ecoscore, has been calculated for the different assessed hydrogen vehicles, as described by the chapters 2 and 3. For each vehicle, different scenarios of hydrogen 'pathways', as presented in Figure 2 have been analyzed. The results are presented in Figure 3.

For all three vehicles, the results can be interpreted in the same way. The assessed hydrogen production process with the best environmental performance is water electrolysis using 100 % renewable energy, followed by SMR. Electrolysis using the current Belgian electricity mix provides the worst results for these vehicles amongst the assessed scenarios. Within the same hydrogen production process, the use of compressed or liquefied hydrogen can be mutually compared. Due to the high energy use for liquefaction, this method of hydrogen storage has the highest environmental impact and thus lowest Ecoscore. Since compressed hydrogen can be distributed to the filling station either by pipeline or by truck,

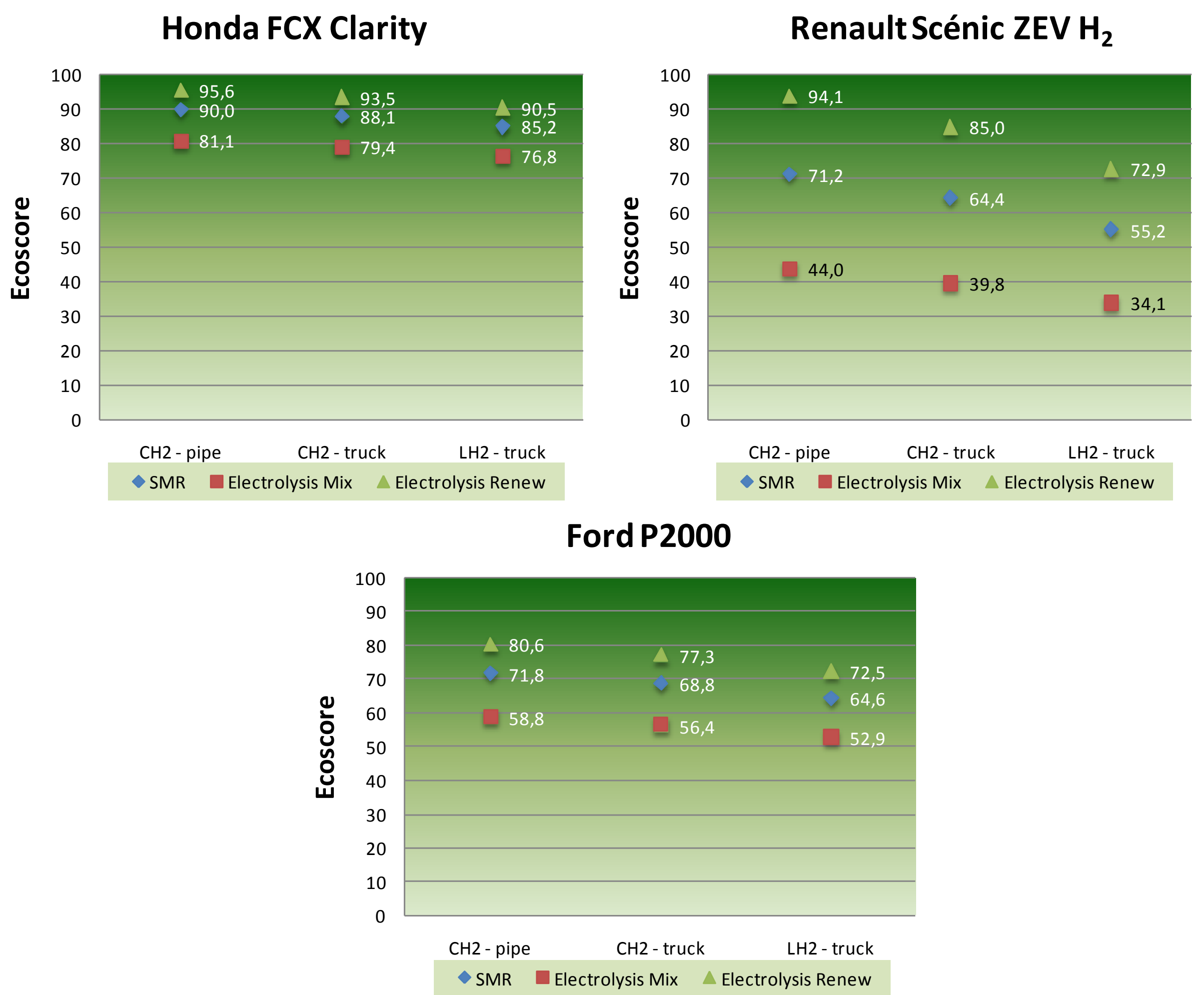

Figure 3: Ecoscores of the different hydrogen pathways for each assessed hydrogen vehicle (top row = FCEV, bottom row = H_2-ICEV).

these distribution methods can be compared as well. For all vehicles, the distribution of compressed hydrogen by pipeline has proven to give the best Ecoscore. Considering all aspects of the hydrogen ‘pathways’, the best results and highest Ecoscore are obtained for vehicles using hydrogen produced by electrolysis from renewable energy, compressing the hydrogen and distributing it by pipeline to the filling station.

Since all assessed vehicles are prototypes only and have been tested on different test cycles, their tailpipe emissions and hydrogen consumption are not perfectly mutually comparable. Due to the higher energy efficiency of FCEV’s and their zero exhaust emissions, their Ecoscores are expected to be higher than for H_2-ICEV, which can be observed from Figure 3. The calculated Ecoscores depend strongly on the hydrogen consumption of each vehicle. Therefore the Renault Scénic ZEV H_2 obtains lower Ecoscores, since its hydrogen consumption is more than twice as high as the P2000 and is even almost five times higher than the FCX Clarity.

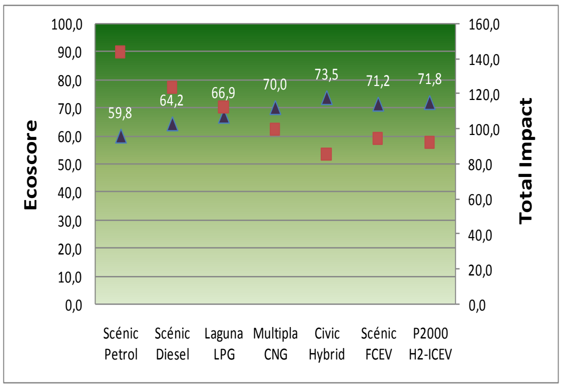

Figure 4: Ecoscore (triangles) and Total Impact (squares) of the assessed vehicles of different fuel technologies or drive trains.

To create an idea of the environmental performance of hydrogen vehicles compared to other fuel technologies, a selection of vehicles of the family car type was made, as described in Table 5. The Ford P2000 represents the H_2-ICEV and the Renault Scénic ZEV H_2 the FCEV since it has been tested on the NEDC cycle. For both vehicles, the scenario with hydrogen produced by SMR, compressed and distributed by pipelines was chosen, since it is assumed to be the most likely scenario in the case of Belgium. The other vehicles (petrol, diesel, LPG, CNG and petrol hybrid) were all tested on the NEDC cycle and were chosen based on their similarity with the assessed hydrogen vehicles (in case of Renault Scénic), their engine power or data availability. For all vehicles, a sound level of 74 dB(A) was considered to use the same noise assumptions as for the hydrogen vehicles.

Figure 4 shows that the hydrogen vehicles have a lower Ecoscore and thus higher environmental impact than the petrol hybrid vehicle (Honda Civic), but a higher Ecoscore than the assessed vehicles using petrol, diesel, LPG or CNG. The results however could change drastically if a different hydrogen scenario was chosen.

5 Conclusions

To compare vehicles using different fuels or drive trains, a well-to-wheel assessment, including both tailpipe and indirect emissions, is necessary. The Ecoscore methodology calculates the environmental impact of a vehicle on a WTW basis, taking into account its impact on greenhouse effect, human health, ecosystems and noise. Vehicles using hydrogen, either in an ICE or FC, are still in the prototype phase and are not commercially available yet. An important argument for their introduction on the market is their alleged environmental benefit compared to conventional ICE vehicles. Hydrogen however, differs with fossil-based fuels, such as diesel and petrol, in the way that it is not an energy source as such, but it has to be produced from primary

Table 5: Overview of some technical and environmental characteristics of the assessed vehicles. Fuel consumption and CO_2-emissions are measured on the NEDC test cycle, except for the Ford P2000, which is tested on the EPA-75 cycle.

Vehicle			Fuel/ Technology	Power [kW]	Weight [kg]	CO_2 [g/km]	Fuel Consumption [l/100km or kg H_2/km]	Total Impact	Ecoscore
Renault	Mégane Scénic	2.0 l	Petrol	102	1290	191	8	144,1	59,8
Renault	Mégane Scénic	1.9DCI130 DPF	Diesel	96	1430	159	6	124,3	64,2
Renault	Laguna Grandtour	1,6 l	LPG	79	1290	168	10,1	112,7	66,9
Fiat	Multipla	1,6 l	CNG	76	1470	161	9	100,1	70,0
Honda	Civic	1.3 l	Petrol Hybrid	70	1293	109	4,6	86,1	73,5
Renault	Mégane Scénic	ZEV H2	FCEV	90	1850	0	0,0106	95,13	71,2
Ford	P2000	2.0 l	H_2-ICEV	110	n.a.	0,8699	0,0044	92,93	71,8

energy sources such as fossil fuels, nuclear or renewable energy. These different production methods, combined with different ways to store and transport hydrogen, resulting in different hydrogen pathways, create a wide range of energy uses and environmental impacts.
The hydrogen pathways assessed in this paper, revealed that the highest Ecoscore for hydrogen vehicles is obtained when hydrogen is produced via electrolysis with 100 % renewable energy, followed by SMR and then electrolysis using the current Belgian electricity mix. The produced hydrogen should be compressed and transported through pipelines instead of being transported by truck or liquefied to reduce the impact as much as possible. The higher efficiency of an FCEV compared to H_2-ICEV results in a better environmental performance and consequently higher Ecoscore. The hydrogen consumption of the car is a crucial parameter in the Ecoscore calculation due to the high amount of indirect emissions and the lack of, or very low, tailpipe emissions for respectively FCEV or H_2-ICEV.
An environmental evaluation of hydrogen vehicles should therefore always take into account all steps of the hydrogen pathway to obtain an objective image of its actual impact in comparison with other vehicle technologies.

Abbreviations

BEV	Battery Electric Vehicle
CCS	Carbon Capture and Storage
CH_2	Compressed Hydrogen
CNG	Compressed Natural Gas
EPA	US Environmental Protection Agency
EU	European Union
FCEV	Fuel Cell Electric Vehicle
FTP	Federal Test Procedure
GWP	Global Warming Potential
HHV	Higher Heating Value
ICE	Internal Combustion Engine
IPCC	International Panel on Climate Change
LCA	Life Cycle Assessment
LH_2	Liquid Hydrogen
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
NEDC	New European Driving Cycle
OEM	Original Equipment Manufacturer
PEMFC	Proton Exchange Membrane Fuel Cell
SMR	Steam Methane Reforming
TTW	Tank-to-Wheel
US	United States of America
WTT	Well-to-Tank
WTW	Well-to-Wheel

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