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Life Cycle Assessment of Fuel Cells and Relevant Fuel Chains

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Abstract

The assessment of fuel cells as environmentally friendly energy conversion systems in mobile and stationary applications must consider the production, operation and disposal/recycling of the systems compared to conventional competitors. The results of a life cycle assessment (LCA) of fuel cells show that they can contribute significantly to a global reduction in environmental impacts, as exemplified in this paper by the global warming potential and the acidification. Particularly attractive is the use of fuel cells in combined heat and power production (CHP).

However, as the conventional technologies – internal combustion engines, gas turbines, combined cycle plants - are continously improving, each potential application of fuel cells should be optimised carefully with respect to environmental characteristics. In stationary applications, for instance, an optimisation of the total efficiency (including heat output) is recommended, especially for low temperature fuel cells. In passenger cars, the question of the best fuel is essential for the result of the LCA. Fuel cells with hydrogen are clearly superior to methanol fuel cell cars. In addition, the production of the fuel cell system is of relevance. Here, recycling of the catalyst materials plays a key role in the overall assessment.

1. Fuel Cells for various applications

In the energy sector, there are various applications of fuel cells where different types (low, medium, high temperature) are suited (***figure 1***):

- **the electricity production (including heat production when used in combined heat and power production CHP)**: Properties like modularity, flexible operation in partial load, good emission and efficiency characteristics and a low noise level favor the application of fuel cells in combined heat and power applications from 1 kW_{el} to some MW_{el}. In the long term, the use of fuel cells for more centralised electricity production is of interest, particularly in combination with a gas (and steam) turbine.
- **mobile applications**: Because of the properties mentioned above, particularly because of the zero (hydrogen) or extremely low (methanol, gasoline) emission levels, fuel cells are attractive energy sources for powering electric drive trains in passenger cars, busses, heavy duty vehicles, ships, trains or airplanes.
- Another market is the use of fuel cells in **portable applications** where the cost pressure is much lower and other environmental benefits can be achieved (e. g. the elimination of heavy-metal containing batteries or diesel electricity generators).

Sector	Application	Challenges
portable 	•Communication •Camping and milit. •Stand-alone •and others	•Mass specific power (storage!) •recharging/H_2 distribution •Reliability, safety
mobile 	•Passenger car •Busses/heavy duty •Rail •Ships, airplanes	•**6 C**: Costs, cold-start, „cilogramm“, energy **c**arrier (fuel and efficiency), cooling, customer
stationary 	•domestic CHP •decentralised CHP •industrial CHP •central electricity	•Cost (liberalised electricity market) •Lifetime

Figure 1 Applications and challenges of fuel cells

2. Life Cycle Assessment of Fuel Cells

The appropriate instrument to investigate environmental impacts of new products and services is the life-cycle assessment (LCA). The two key elements of LCA are

- the assessment of the total life-cycle ("cradle-to-grave approach"), involving the exploration of materials and fuels, the production and operation of the investigated objects and their disposal/recycling; and
- the assessment of different environmental impacts to resources, human health and ecosystems.

According to international standards [1], the LCA consists of four steps (***figure 2***): the *Goal and Scope Definition* in which the investigated product, the data sources and system boundaries are described and the functional unit - i.e. the reference of all related in- and outputs - is defined. The *Inventory Analysis* "involves data collection and calculation procedure to quantify relevant inputs and outputs" [1]. The potential impacts of the in- and outputs of the Inventory Analysis are then determined by the *Impact Assessment* which categorises and aggregates the in- and outputs from or to the biosphere. For that purpose, impact categories, such as the global warming, are defined and characterisation factors calculated which determine the contribution of different substances to that particular impact category (e g. CO_2, CH_4 or N_2O to global warming). In the fourth step, the *Interpretation*, the findings from the inventory analysis and the impact assessment are combined to give recommendations or draw conclusions.

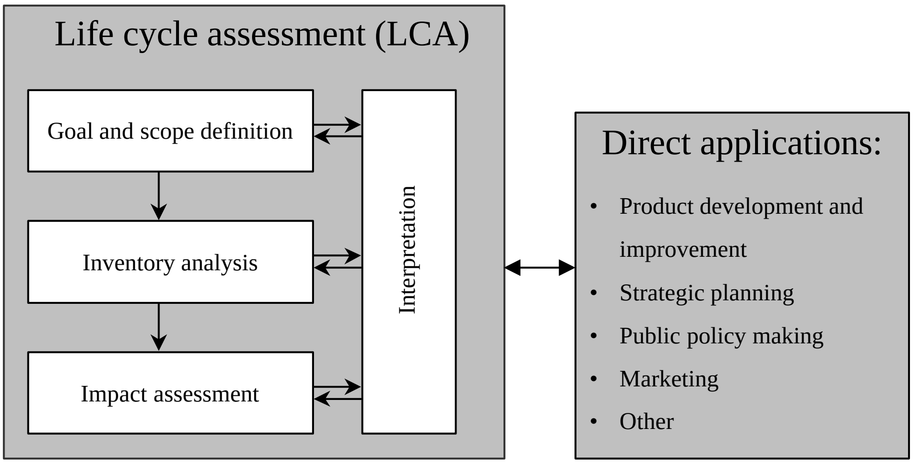


Figure 2 Life-Cycle Assessment according to [1]

In this paper, results from detailed LCAs of the stationary and mobile application of fuel cells, to be published in [2], are reported. For this article, two examples are chosen from a number of investigated systems and impact categories: a passenger vehicle where the service "1 km transportation" is evaluated, and systems for stationary power generation where the functional unit is 1 kWh_{el}.

To achieve a transparent presentation, only global warming potentials and acidification are reported here. The global warming potential (GWP) is calculated for CO_2, CH_4 (21 kg CO_2-eq./kg CH_4) and N_2O (310 kg CO_2 eq./kg N_2O) using a reference time of 100 years. The acidification potential (AP) assesses the increase in acidity through emission of acids and compounds which can be converted to acids. The factors used are taken from [3]. Main contributors are the reference substance SO_2 and NO_x (factor 0,7 kg SO_2 eq./kg NO_x). To consider the fact that in regions such as deserts and oceans, emissions with local or regional effects (such as acidifying emissions) usually have less impact the concept of "geographical regions" as described in [4] is applied in the impact assessment which weighs local emissions (not the global emissions such as CO_2!) according to the place of emission. Note that on an inventory level, all emissions are treated equally. In the case of fuel cells, this is only relevant for emissions from off-shore natural gas extraction, the tanker transport and the emissions from solar thermal power plants in the desert.

For further details and additional LCAs the reader is referred to [2]. In this reference, mobile (hydrogen and methanol fuel cell vehicles, gasoline, diesel and methanol internal combustion engines ICE) and stationary (SOFC, PEFC, natural gas engine, gas turbine, combined cycle power plant) systems with fossil and regenerative fuels are investigated. Time frame for all investigations was 2010. This implies that also for the "conventional" systems, an improvement potential is assumed. LCAs were carried out for German conditions.

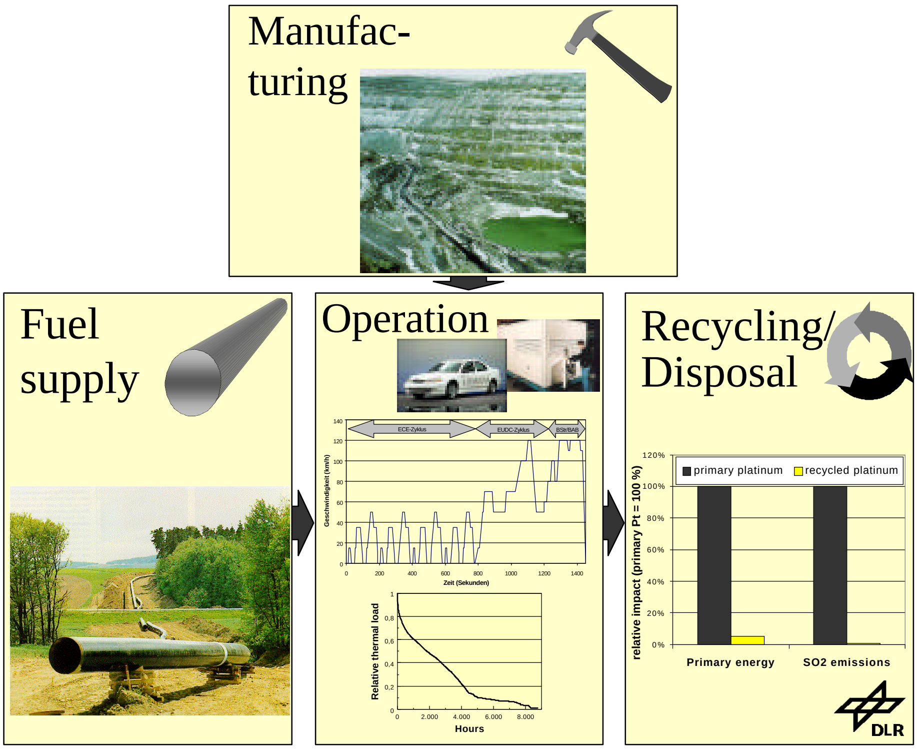


Figure 3 Life-cycle of fuel cell energy production

Example 1: SOFC in industrial cogeneration and centralised electricity production

One attractive option for the use of fuel cells is the industrial cogeneration where in many cases, a simultaneous demand for electricity and process heat on a high temperature level occurs and other attractive conditions for the use of fuel cells coincide [5]. In these cases, natural gas is the fuel of choice.

Fuel supply. The life-cycle of natural gas comprises the exploration and extraction, the processing and transport to Germany. In this study, an adaption of [6] (future import mix, reduced methane leakage according to [7]) was used.

Manufacturing and recycling. Manufacturing SOFCs involves a number of "exotic" materials such as ZrO_2, Ni, rare earth compounds and, depending on the concept used, further materials such as chromium for bipolar plates (in the case of the planar concept). For these materials, LCAs were carried out based on detailed information from mining companies and manufacturers, including extraction and processing of the materials and the production of components. In ***figure 4,*** the primary energy demand, the global warming potential and the acidification per kg of material produced are shown. It can be seen that the materials exhibit rather different environmental profiles, especially due to differing demands for processing energy (calcination, etc.) and due to allocation procedures [2]. In addition, process specific direct emissions, such as the SO_2 emissions from processing of sulfidic ores during nickel production, have to be considered and lead to unproportionally high acidification in that particular case (see also platinum group metals for PEFCs below).

Operation. The operation of SOFCs leads to minimal direct emissions due to relatively low (compared to combustion engines or turbines) operating temperatures (for thermal NO_x emissions) and gas cleanup requirements (e. g. the required SO_2 removal). The emissions were deduced from average emissions from reformer burners. Essential for the LCA of the systems are the assumed electrical and thermal efficiencies. For all systems, careful estimations for future developments of efficiencies and emissions were made based on literature data, expert interviews and measured data from existing, modern plants. The simultaneously produced heat in combined heat and power systems was credited with heat from a modern natural gas burner so that the environmental impacts refer to 1 kWh electricity output.

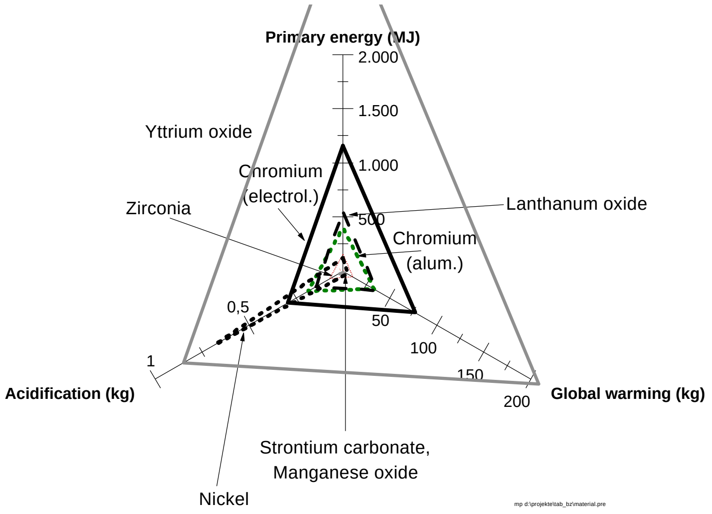


Figure 4 Selected environmental impacts associated with the production of 1 kg of different SOFC relevant materials

Total life-cycle results. In ***figure 5****(above)*, the GWP and acidification of cogeneration and central (i. e. only electricity generating) systems and the contribution of manufacturing and fuel supply to the total life cycle emissions are shown.

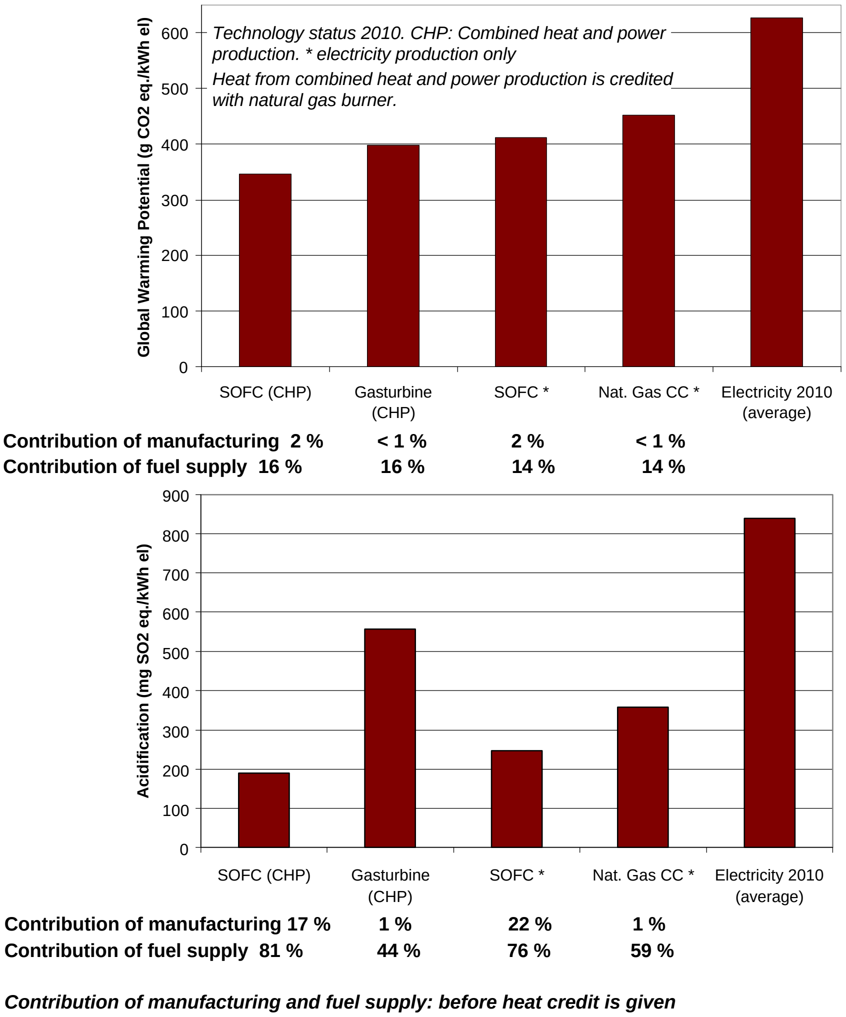


Figure 5 Global warming potential (above) and acidification (below) of various electricity generating systems. Average electrical efficiencies over lifetime: SOFC/GT (cogen.): 57 %, gas turbine: 39 %, SOFC/GT (central): 65 %, Natural gas CC: 58 %, electricity mix: 36 %.

It is obvious that high-temperature fuel cells in this application offer significant advantages compared to the competing technologies. Considering the global warming potential, a SOFC in cogeneration is 12 % more efficient than a future gas turbine and even 47 % more efficient than a future German electricity mix. The competition for high efficiencies is, however, becoming stronger. The advanced turbine programme, for instance has lead to gas turbines with electrical efficiencies as high as 40 % in the MW range. Natural gas combined cycle (CC) power plants can have efficiencies of 60 % at the beginning of their life-time.

The advantages of fuel cells are even more obvious in the case of local emissions and related impact categories (e. g. acidification). On a life-cycle basis, the SOFC produces 70 % less acidification than a low-NO_x gas turbine and 30 % less than a modern natural gas CC. The acidifying emissions in the case of SOFCs stem almost exclusively from the energy chain and the production of the system. For gas turbines, in contrast, the direct NO_x emissions account for more than 50 % of total acidification.

At the same time, a gas turbine in the 5 MW_{el} power range produces less greenhouse gases than a SOFC without cogeneration. Combined heat and power production should therefore generally be promoted. In addition, not only the electrical, but the total efficiency needs to be optimised. This is even more important for PEFCs in the 100 kW_{el} range where engine-CHPs show total effiencies of up to 100 % (LHV) because the upper heating value, i. e. the heat of condensation, is used. However, the development of high-efficiency centralised electricity production based on fuel cells decreases the gap between cogeneration and non-cogeneration plants.

As fuel cell plants are in certain limits modular, and thus the specific costs are not so much dependent on the size of the plant, the optimal size of such plants will be at lower power. The introduction of fuel cells means the continuation of the process of decentralisation of power production which started with high-efficiency gas turbines, CC plants and CHP engines.

The infrastructure, i. e. the production of the SOFC system, is of almost no significance for the GWP and contributes less than 20 % to the life-cycle acidification. There, the share is higher because of the low absolute emissions contributing to acidification. In addition, these emissions depend on the system design chosen. In this particular case, the emissions are caused by the electricity for production (e. g. sintering the membrane-electrode assembly and electro-chemical etching of the interconnects) and the chromium for the planar interconnects. For tubular SOFCs, the environmental impacts from production are different.

Example 2: PEFC in a passenger car

Fuel options. The question of the right fuel is of higher importance in the case of mobile fuel cells. Not only the questions of storage systems, costs for fuel production or infrastructure considerations have to be answered – this is beyond the scope of this paper – but also the environmental impacts for the different fuels is of importance. For this purpose, various fuel supply chains, two examples of which are shown in ***figure 6***, were investigated in detail. Selected results are shown in ***figure 7*** [2, 12].

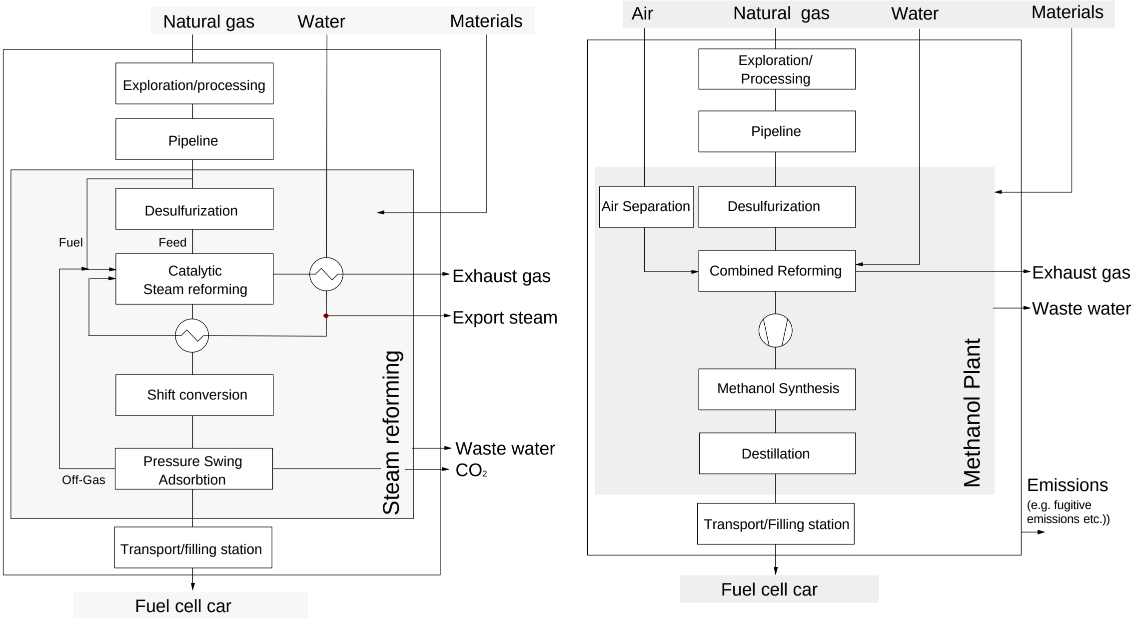
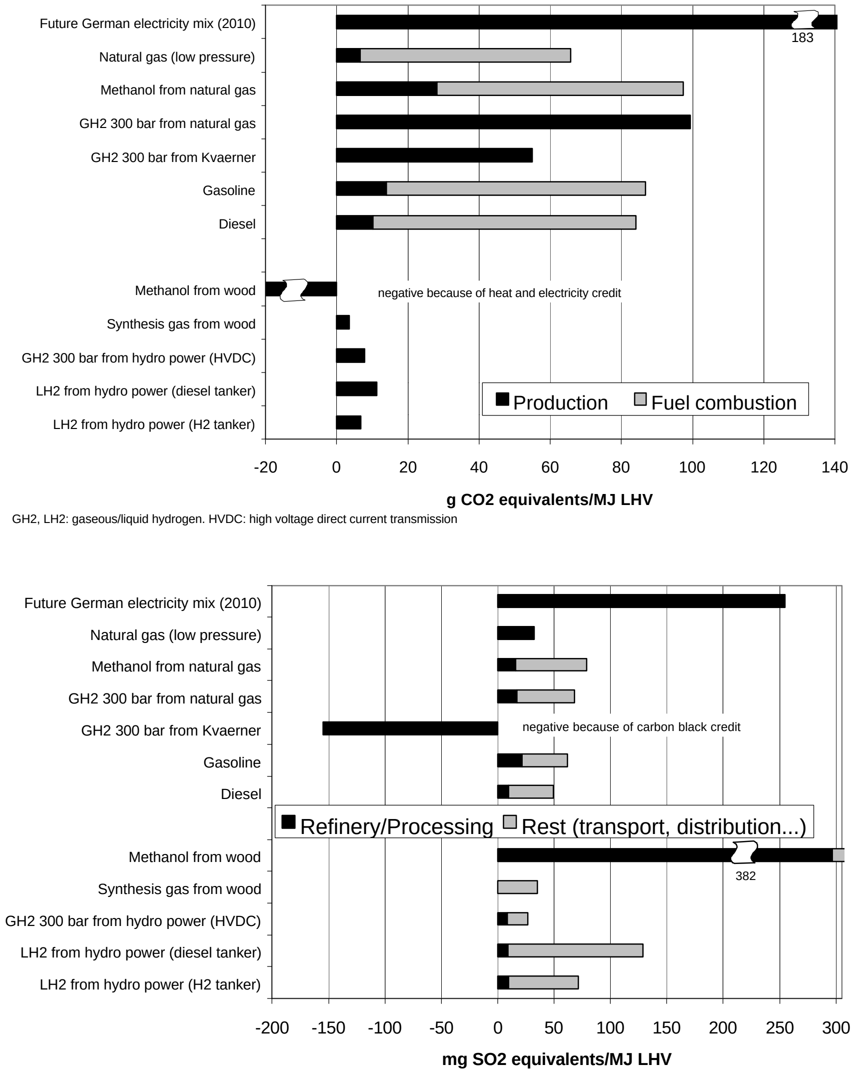


Figure 6 Hydrogen (left) and methanol (right) production from natural gas



GH2, LH2: gaseous/liquid hydrogen. HVDC: high voltage direct current transmission

Figure 7 Global warming potential (above) and acidification (below) of various fuel supply chains

Four factors are of importance for the LCA of fuels:

- the energy requirements for processing (which are higher for fossil hydrogen and methanol than for diesel and gasoline). In this context, it is important to distinguish between mixes – i.e. the production of gasoline in average refineries – and marginal plants, i. e. new plants which are built to meet an increasing demand. For methanol, for instance, efficiencies of average plants are well below 65 % (***figure 8***) leading to CO_2 emissions in the order of 30 to 40 g CO_2/MJ LHV methanol.

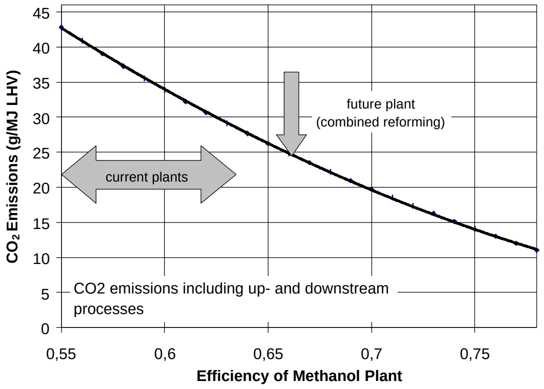


Figure 8 CO_2 emissions of methanol production as a function of the efficiency of the plant (including up- and downstream processes (natural gas supply, transport from Norway to Germany))

Nowadays, methanol is mainly used as a chemical commodity. To produce methanol as a fuel, the global production capacity would need to be drastically increased. For the future methanol production, therefore, modern combined reforming plants (η = 66 % averaged over the life time) are assumed.

- the primary energy carrier (e. g. natural gas has a lower CO_2 emission factor per energy unit than crude oil, biomass is – except for fossil energy use for transportation and processing – greenhouse neutral);
- the upstream and downstream processes, e. g. different requirements for transportation or distribution; and
- the possible use of joint products (e. g. carbon black as a joint product of hydrogen production in the Kvaerner process, steam from H_2 steam reforming).

Beyond the general comparison of fuels, detailed suggestions for improvements can be made based on LCAs. As an example, ***figure 9*** compares different transport scenarios [2]. It is interesting to see that in this configuration, liquid H_2 (LH_2) (transported in a tanker with H_2 as fuel) has a better GWP balance than gaseous H_2 (GH_2), primarily because the liquefication takes place at the production facility with renewable electricity and no conventional electricity is needed as for compressing the GH_2 at the filling station. The acidification, however, is significantly higher due to the NO_x (and for heavy oil: SO_2) emissions.
See also reference [8] for further hydrogen LCAs.

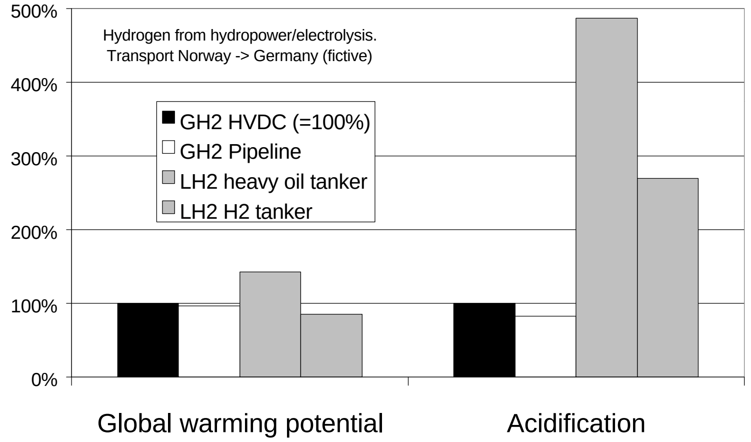


Figure 9 Comparison of global warming potential and acidification for different transport scenarios of renewable hydrogen (normalized to GH_2 with high voltage direct current (HVDC) transmission)

Manufacturing can contribute a significant percentage to life-cycle impacts. In conventional cars, for instance, the production of the car body, the engine, etc. is responsible for 10 to 25 % of total global warming emissions. In fuel cell vehicles, this relative contribution will be higher because (1) the absolute impacts are lower and thus the relative significance of production is higher and (2) the production of fuel cell vehicles leads to higher environmental impacts due to the higher weight and the use of catalyst materials (platinum group metals PGM). The LCA of fuel cell stack production was assessed using industry data for materials (PGM from south africa, natural and synthetic graphite, membrane, PTFE and others) and for the stack production (next generation Ballard stacks with reduced PGM loading) [9]. In [9], the methodological problems associated with LCAs of PGMs are discussed. Due to the early stage of development, the balance-of-plant materials could only be estimated. Of particular importance are the PGM for catalyst materials in the stack, the reformer and an eventual Pd/Ag membrane for gas cleanup (with methanol as a fuel). Even assuming a PGM recycling rate of 75 %, the contribution of the production to, e.g., life-cycle acidification amounts to 70 % (fuel: H_2). It has to be mentioned that the "recycling rate" not only considers the technically feasible platinum recovery, but also depends on a number of additional factors, such as the economic incentive (depending on the PGM price), the availability of recycling infrastructure, the export quota in countries without such infrastructure (e. g. about one third of the German decommissioned vehicles is exported to Eastern European countries) and the distribution of PGM in the fuel cell. So far, 52 % of the car catalysts in Germany are recycled [10]. It is likely, however, that due to the much higher PGM use in fuel cell cars, recycling will be mandatory. This could be reinforced by measures such as leasing of the stacks to the car owners or deposits which ensure a high return rate. Thus, higher recycling quotas than for car catalysts should be assumed. In addition, strong alliances between fuel cell manufacturers and mining companies should secure the supply and environmental standard of the metals.
The production of the car body and the conventional vehicle is taken from [11].

Operation. Of primary importance is the efficiency of the power train and the fuel economy. The fuel cell car (750 kg base weight) is defined in detail in [2]. In short, the driving cycle consists of urban, extra-urban and highway parts (figure 3, box "operation"). Assuming an optimistic, but realizable system efficiency curve and considering the higher mass of the fuel cell vehicle, a hydrogen consumption of 1,03 MJ/km (in the case of hydrogen as fuel) and a methanol consumption of 1,26 MJ/km for methanol fuel cell cars are calculated, significantly lower than for conventional internal combustion vehicles (1,6 MJ/km) despite of the higher mass of the vehicle. For ICE, 1,6 MJ gasoline/km and emissions conforming to the Euro 4 emission standards (which will be mandatory from 2005 on) are assumed.

Data quality. The data quality for the fuels and the production of the car body, the combustion engine and the stacks is high. The periphery (reformer, gas cleanup,...), however, could only be estimated due to the early stage of development for series production of these systems. The fuel consumption is based on model calculations. Therefore, a complete LCA should be repeated once the first series products and measured data for fuel consumption are available.

Total life-cycle results *(figure 10)*. The global warming potential for hydrogen fuel cell cars is below future gasoline or diesel cars. If the production of the vehicle is not considered, H_2 fuel cell cars are about 30 % more greenhouse friendly based on the average driving cycle chosen for analysis. However, the higher production impacts (assuming 75 % PGM recycling) reduce that advantage to 12 % compared to future improved gasoline vehicles.
The fuel cell car shows clear GWP advantages for innovative H_2 production paths, such as the Kvaerner CB&H process or electrolysis with electricity from renewable primary energy carriers. It has to be mentioned that in principal, H_2 can also be used in internal combustion engines. However, in these engines the H_2 consumption is higher and direct emissions, such as NO_x, occur.
Fuel cells with fossil methanol show no GWP advantage. Figure 10 shows that the direct emissions are lower due to a better power train efficiency. Unfortunately, methanol production, with an efficiency of 65 to 70 % for modern combined reforming plants, is less efficient than todays gasoline and diesel production. Therefore, the share of „fuel supply“ in figure 10 is higher. In addition, the production of the methanol fuel cell vehicle leads to higher impacts (higher than for H_2 because of additional components, particularly the platinum group metals for the catalytic refomer burner and an eventual membrane gas cleanup). Methanol produced from wood avoids the increase in GWP. It should be mentioned that methanol can also be used in the internal combustion engine.
Regarding acidification (and other impact categories dominated by NO_x emissions), fuel cells are zero (H_2) or almost zero (methanol) emission cars. For H_2, the acidification from the energy chain and production is well below the combustion engine with the exception of the LH_2 transported with a heavy oil tanker (see also figure 7). For methanol, there is no clear advantage. The acidification of production of fuel cell cars stems mainly from SO_2 from PGM production. For other impact categories, where SO_2 is insignificant (e. g. nutrification and carcinogenity) the advantages of fuel cell cars are more pronounced.
On the other hand, fuel cells offer the advantages of electric vehicles, including the possibility of brake energy recovery with an adequate storage device.

Recommendations. All systems, including the gasoline and diesel vehicles, possess significant improvement potentials. Once mass reduction and reduction of rolling and air resistance have been realised, fuel cells, particularly with hydrogen as a fuel, will become more competitive, not only because of reduced weight, volume and cost problems. The required storage for H_2 would be much lower. In addition, an optimised combination of battery and fuel cell hybrids is recommended. A battery/fuel cell hybrid would not need to operate at full load during accelleration; in an urban driving situation, operation at < 20 % partial load is avoided. This is important because the fuel cell system has an optimum efficiency at partial load > 20 %. Employing a battery also allows brake energy recovery and reduces the amount of catalyst material needed.

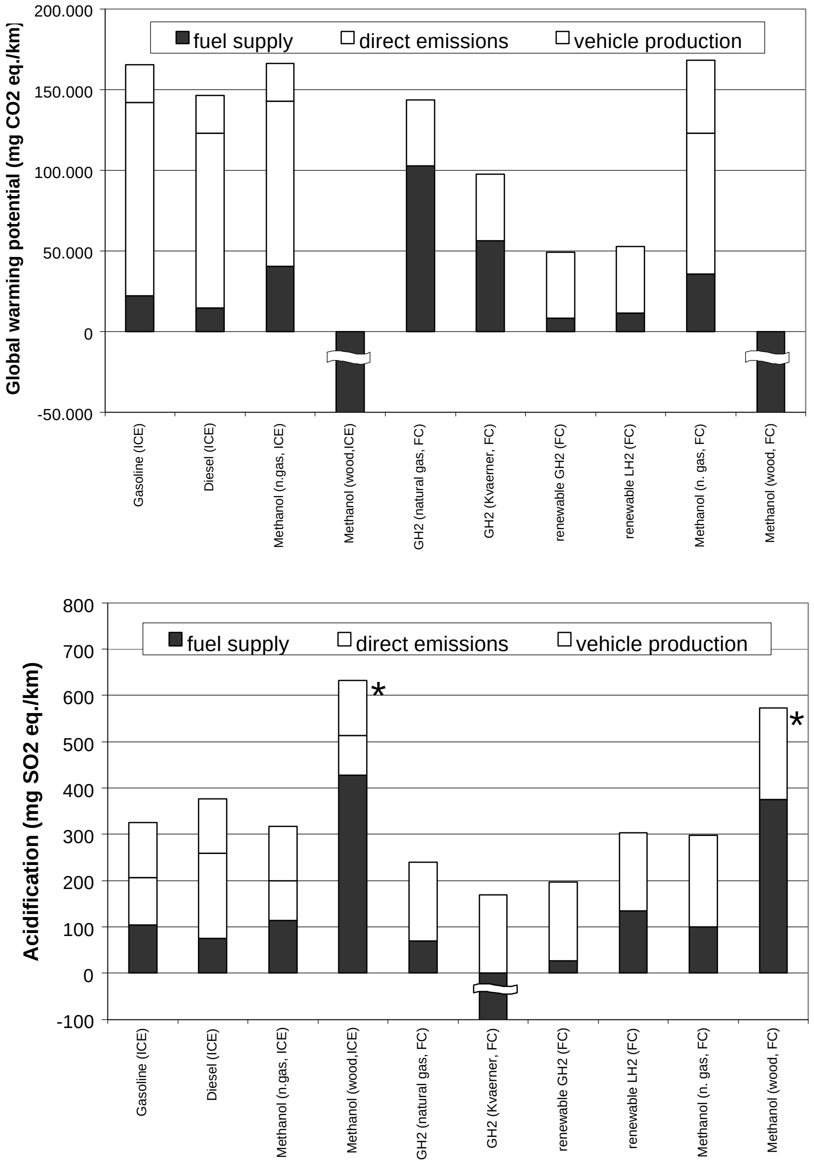


Figure 10 Global warming potential (above) and acidification (below) of passenger cars with different drive-trains and fuels (ICE: internal combustion engine; FC: fuel cell assuming 75 % Pt recycling). Technologies status 2010. * High acidification is caused by purge gas that is burnt in an engine CHP; these emissions can be avoided by different process options [2].

Conclusions

Fuel cells are promising future energy converters with a high potential for clean and efficient electricity, and thus mobility, and heat production. However, to get the full picture, fuel cells must be analysed on a life-cycle basis to determine the environmental competitiveness. Carrying out LCAs shows that fuel cells are environmentally attractive but that fuel cells do not eliminate the need to carefully optimise the energy system e. g. by increasing the share of renewable primary energy carriers (stationary) and reducing the overall energy need. In addition, conventional energy systems such as gas turbines, combined cycle power plants, engine CHPs and conventional drive trains such as gasoline and diesel internal combustion engines are continously optimised in terms of energy efficiency and environmental performance, increasing the pressure on the development of fuel cells (***table 1***).

Fuel cells should, therefore, be embedded in a strategy of „energetic creativity“, involving, for instance, the reduction of the mechanical energy demand of vehicles (e. g. light-weight), the optimisation of fuel cell/battery hybrid systems and of recycling strategies, an increase in the thermal efficiency in CHP applications, and also more unconventional ideas such as hybrid power plant/car systems (to increase the load factor), using fuel cells as chemical production plants in industrial CHP (synthesis gas, hydrogen), etc.

		Primary energy [1]	Global warming	Acidification	Nutrification	S-Smog/ NMHC	Carcinogenity	Competitor
PEFC mobile (passenger car)	H_2 fossil	+	+	++	++	++	++	ICE (Gasoline, Euro 4)
	H_2 reg.	++	++	+/++[2]	++	++	++	
	MeOH fossil	-	o	+	++	++	++	
	MeOH reg.	++	++	-- [3]	-- [3]	o	-- [3]	
	MeOH fossil	+	+	++	++	+	++	Methanol DI fossil
	MeOH reg.			+	+	+	+	Methanol DI reg.
PEFC stat.	Nat. gas	-	o	++	++	+	++	Nat. gas engine CHP
SOFC	CHP, nat. gas	+	+	++	++	+	+	GT (nat. gas)
	CHP, biomass	o	o	++	++	+	+	GT (biomass)
	central, nat. gas	+	+	+	++	+	+	Nat. gas CC

++ great advantage, + advantage, o neutral or not significant, - disadvantage, -- great disadvantage
GT gasturbine, ICE internal combustion engine, Euro 4 advanced european emission standard (2005). DI direct injection, CC combined cycle [1] only non-renewable. [2] ++ for CH_2
[3] strongly depending on process and competing system. Large improvement potential

▨ lower data quality

Table 1 Comparison of fuel cells with their competitors

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