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Life-cycle analysis of fuel cell system components

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Chapter 94
Life-cycle analysis of fuel cell system components

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1 INTRODUCTION: THE LIFE-CYCLE OF FUEL CELLS

Fuel cells are a future energy system with a high potential for environmentally-friendly energy conversion. They can be used in stationary and mobile applications. Depending on the type of fuel cells, stationary applications include small residential, medium-sized cogeneration or large power plant applications. In the mobile sector, fuel cells, particularly low-temperature fuel cells, can be used for heavy-duty and passenger vehicles, for trains, boats or auxiliary power units for air planes. Mobile applications also include portable low power systems for various uses.

The high efficiency can lead to a significant reduction of fossil fuel use and of greenhouse gas (GHG) emissions. In addition, the electrochemical nature of the reaction, the low temperature in the reforming steps and the necessity to remove impurities in the fuel, such as sulfur, result in extremely low local emissions – an important feature especially in highly populated areas. In vehicle applications, particularly at low speed, reductions in noise emissions are to be expected. Other context specific advantages include the elimination of gear shifts, the higher potential reliability, the compatibility with other electric or electronic devices and new options with respect to the safety design of vehicles.

Thus, clear environmental advantages can be expected in the various application areas of fuel cells. For an environmental evaluation of the different service supply options, an investigation of the complete life-cycle of these options is necessary to ensure that no environmental aspect is neglected. The appropriate instrument for this task is life-cycle assessment (LCA).

In the typical "cradle-to-grave approach" of LCAs, the investigated life-cycle stages involve the exploration of materials and fuels, the production and operation of the investigated objects and their disposal/recycling (Figure 1).

With increasing environmental operation standards of modern energy conversion systems, the up and downstream processes, e.g., fuel supply or system production, are becoming increasingly relevant. While, for instance, in conventional road vehicles, the production of the vehicle only contributes 10% to the life-cycle GHG emissions, this share can increase to 30% in modern fuel saving vehicles. More important than the relative contribution of the production is the absolute impact of production. Very often, technologies exhibiting good characteristics in the use phase lead to higher absolute environmental impacts in the production phase because of the use of more "sophisticated" materials and components. For fuel cells, this implies that the LCA of producing the systems will be of higher importance.

1.1 Brief introduction to LCA

Over the past 10 years, the use of LCA has grown rapidly. Parallel to this development, an international standardization process was started with ISO standards structuring this instrument and giving guidelines for the practitioner. The two key elements of an LCA are

- the assessment of the entire life-cycle of the investigated system, and
- the assessment of a variety of environmental impacts.

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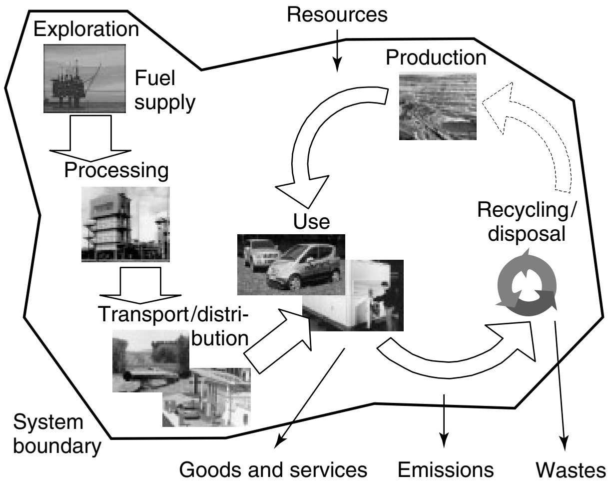


Figure 1. The life-cycle of fuel cells.

According to the International Organization for Standardization (ISO), the LCA basically consists of four steps (Figure 2).

The first step is the goal and scope definition, in which the investigated product system, the intended application of the study, the data sources and system boundaries are described and the functional unit, i.e., the reference of all related inputs and outputs, is defined. The criteria for selecting input and output flows or processes have to be specified. In this step, the data quality requirements, for instance time-related and geographical coverage, the consistency, representativity and uncertainty of the data and the critical review procedure have to be described. A crucial step is the determination of the investigated impact categories (see later).

The inventory analysis (LCI) "involves data collection and calculation procedure to quantify relevant inputs and outputs."[1] These input and output flows involve consumed or produced goods as well as emissions, waste streams, etc. It is essential to consider all life-cycle stages, i.e., system production, operation and disposal/recycling. Principally, there will be iterative steps leading to additional data requirements. The data collection usually follows the process chain, i.e., extraction, conversion, transport, production, use and disposal or recycling, respectively. The phases might as well be divided into smaller phases, the so-called "unit processes". Every unit process of the chain has several incoming and outgoing material and energy flows that are carefully recorded. The main product or the co-products, energy carriers, wastes and emissions into air, water or soil are outputs leaving the system boundaries.

The potential impacts of the inputs and outputs of the LCI are then determined by the impact assessment, which categorises and aggregates the input and output flows to the biosphere to so-called impact categories, such as the global warming potential (GWP), by multiplication with characterization factors.

The development of impact categories with relevant characterization factors has been discussed intensively in Ref. [2] with more recent developments published in the "International Journal of Life-cycle Assessment" and other publications. Impact categories include:

- Depletion of abiotic resources, for instance fossil energy carriers and uranium, metals or other materials.
- Depletion of biotic resources as a measure of overexploitation.
- GWP, as the emission of GHGs influences the stability of solar irradiation and adsorption/reflexion at the surface. These gases, e.g., carbon dioxide, methane, ozone and nitrous oxide, absorb the infrared radiation emitted by the earth and, thus, increase the average temperature. A GWP can be attributed to these anthropogenic climate gases, which evaluate the effectivity in increasing

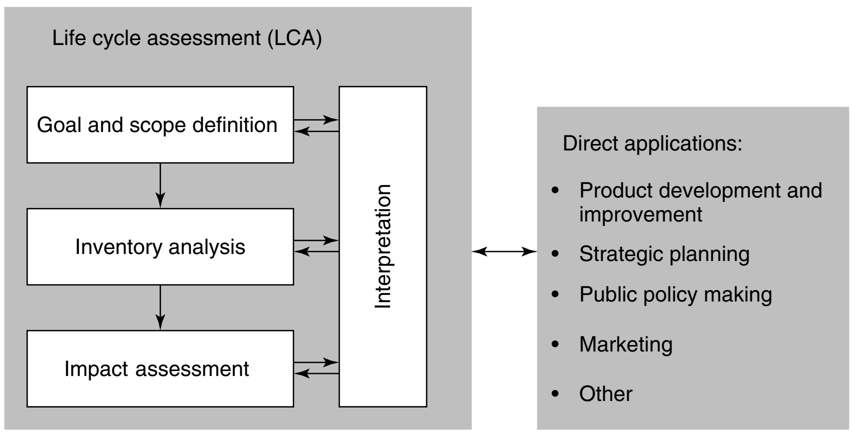


Figure 2. LCA according to Ref. [1].

the temperature relative to carbon dioxide for a given reference time. Most recent GWPs are published by the Intergovernmental Panel on Climate Change.

- Depletion of stratospheric ozone particularly by chlorinated and brominated compounds, nitrous oxide and indirectly by the greenhouse effect. The ozone depletion is usually quantified using the ozone depletion potential with CFC-11 as a reference substance.
- Acidification. Several substances, particularly sulfur dioxide, nitrogen oxide and, indirectly, ammonia, act as proton sources and acidify soil and water. The impact category can be operationalized using the acidification potential, which is the ratio of the number of potential proton equivalents per mass unit of a substance to the number of potential proton equivalents per mass unit of sulfur dioxide as a reference.[2]
- Eutrophication, i.e., the addition of mineral nutrients to soil and water, which results in shifts in increased algal growth, a reduction in ecological diversity and, in some instances, in a lack of oxygen. Mainly nitrogen and phosphorus components contribute to nutrification. Nutrification can be quantified as the ratio between the potential biomass per emitted substance and the potential biomass per reference substance, commonly PO_4^{3-}.[2]
- Emission of ecotoxic and human toxic substances, e.g., pesticides, heavy metals and carcinogenic substances. For these complex impact categories, a number of different quantifications have been tried.[3]
- Emission of radioactive substances.[4, 5]
- Other impact categories, such as land use, noise, waste and odor.

The next, and according to Ref. [6], optional elements of the impact assessment include:

- A normalization, i.e., the division of the environmental impacts per functional unit by reference environmental impacts (e.g., the daily impacts per capita) to gain further understanding of the magnitude of an environmental problem.
- A grouping, for instance sorting the impact categories on nominal or ordinal scales based on value choices.
- a weighting, i.e., "converting indicator results by using numerical factors."[6] It is unavoidable that these aggregation steps are based on assumptions on the value-sphere, i.e., the perceived seriousness of ecological damage.

The last, fourth step is the interpretation, which analyzes the results, reaches conclusions and recommendations while explaining the limitations of the study.

1.2 Goal and scope of this chapter

The goal of this chapter is to present different LCAs in the field of fuel cells, discuss parameters used in the studies, show some respective results and conclusions and also identify knowledge deficits that require further research or practical experience with power plants or vehicles.

2 MOBILE APPLICATIONS

2.1 Overview

Principally, there is a range of potential applications of fuel cells in the mobile sector. However, due to the high market expectations, many of the past efforts have focused on applications in passenger vehicles. The following chapter therefore focuses on this application. A few remarks, however, shall be made regarding other possible applications. In Sections 2.2–2.6, results of different LCAs of passenger vehicles are reviewed following the life cycle phases.

2.1.1 Buses

The use of fuel cells in buses is generally considered as the ideal application for the market introduction of fuel cells. The integration of hydrogen storage systems as well as potential range limitations are of no significance. In addition, low noise and air pollutant emission levels are of higher importance in highly populated urban areas. Due to the typical driving cycle requirements, higher fuel reductions compared to diesel buses can be expected than for passenger vehicles. However, in bus applications hybrid diesel buses are already state-of-the-art. If they are equipped with brake energy recovery, which is particularly attractive in the stop and go city-driving pattern, the achievable reduction potential of fuel cell buses is lower.

2.1.2 Railways

The use of fuel cells in railways is considered particularly for non-electrified railway lines. In electric trains, the use of fuel cells is generally less attractive than in buses because the power requirements differ completely. The shape of the power demanded as a function of time is more rectangular than the driving cycle of city buses: full load and zero load – which are in regions of lower fuel cell system efficiency – occur more frequently. Therefore, the achievable fuel reduction is considered to be less than 10% in certain railway applications.

A range of applications is, however, possible in which fuel cells are competitive not only because of increased power train efficiency, but because of the low pollutant emissions. Examples are boats in natural protection areas or locomotives for mining applications.

2.2 Production of the fuel

2.2.1 General aspects

The question of the "right" fuel is of high importance for the overall assessment of mobile fuel cells. Not only do the questions of storage systems and costs for fuel production or infrastructure considerations have to be answered – this is beyond the scope of this chapter – but also the environmental impacts for the different fuels are of importance. Fuel chains have been assessed in a number of different studies focussing on different environmental impacts, countries and applications.[7–20]

Generally, four factors are of relevance for the LCA of fuels:

The primary energy carrier has an especially high impact on the impact categories global warming and use of abiotic resources. The change from crude oil to natural gas, for instance, is associated with a decrease in CO_2 intensity due to the higher hydrogen to carbon ratio of natural gas. Switching to renewable primary energy carriers clearly reduces these impacts to low inputs of fossil energy along the production chain.

The efficiencies and impacts of processing are also of importance. Today's crude oil-based fuels exhibit an extremely high energetic efficiency of more than 90%. In contrast, steam or combined reforming of natural gas for hydrogen and methanol production, respectively, have comparatively lower efficiencies. In this context, it is important to distinguish between the production of gasoline in average refineries – the so-called technology mix – and marginal plants, i.e., new, single plants built to meet an increasing demand of a specific product and which, thus, exhibit significantly improved performance.

The upstream and downstream processes, e.g., different requirements for transportation or distribution, are the third important factor for the assessment of the fuel supply. The possible use of joint products (e.g., carbon black as a joint product of hydrogen production in the Kværner process or steam from H_2 steam reforming) can reduce environmental impacts if there is a market for the byproduct.

For fuel cell applications, mainly three fuels are of interest for mobile applications: hydrogen, methanol and gasoline. Specific aspects of their life-cycles are discussed in the subsequent sections.

2.2.2 Hydrogen

Roughly 48% of the world wide hydrogen production is accomplished by steam reforming of natural gas, 30% by processing crude oil products, 18% by processing coal and 3% as a byproduct of the chlor-alkali process. However, a number of more innovative production paths exists, such as the carbon black and hydrogen process developed by Kværner with parallel carbon black production, electrolysis from various electricity sources or gasification of biomass. In addition, CO_2 sequestration or the commercial use of CO_2 have been mentioned as ways to lower GHG emissions from the hydrogen supply.

The various hydrogen supply paths differ in terms of the distribution paths, e.g., pipeline transport of natural gas with onsite reforming, pipeline transport of gaseous hydrogen (GH_2), transport of liquid hydrogen (LH_2) by bargen carriers and road trailers and high voltage direct current (HVDC) transportation of electricity with hydrogen conversion close to the end user.

Figure 3 shows a number of supply chains as assessed in Ref. [21] using LCA.

Natural gas steam reforming is one of the most common processes. The efficiency of that conversion depends on the use of the steam produced as a by-product. As the base case, Ref. [22] assumes an extremely optimistic 89% (higher heating value; steam exported), whereas Ref. [19] assumes 70%. In Ref. [15] an efficiency of 81% is used if the coproduct steam is required in further processes.

Gasification of biomass and water electrolysis using renewable electricity are attractive options for producing hydrogen with renewable primary energy carriers. However, the potentials of renewable energies have to be taken into account because they can be used alternatively in stationary heat and power generation. Therefore, each option of using renewable energy should be checked considering cost, "ecoefficiency" and storage requirements. For instance, 1 kWh of wind electricity, fed into the German electricity grid, presently prevents 700 g of CO_2 equivalents by substituting conventionally produced electricity which is, to a large degree, produced in rather inefficient coal power plants. Substituting gasoline by hydrogen produced from the same kWh wind power via electrolysis only prevents 320 g. In future decades, with electricity becoming less CO_2 intensive and oil extraction becoming increasingly difficult, this situation will eventually change.

In any case, hydrogen should not be regarded as a zero-emission fuel. Instead, the supply of hydrogen has also to be considered to determine its related emissions and effects to the environment. As an example, Figure 4 compares the different transport scenarios of hydrogen produced in Norway from renewable electricity and subsequently transported to Germany.[15] It is interesting to see that in

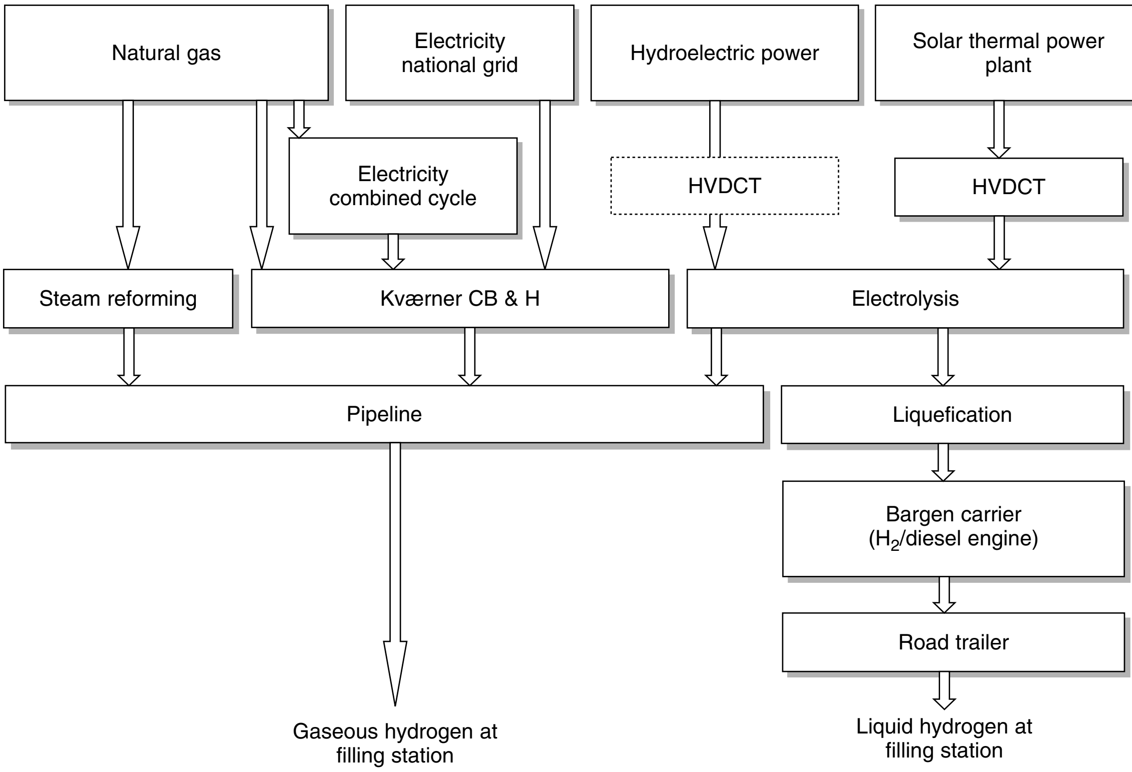


Figure 3. Selected hydrogen production and supply paths.[21]

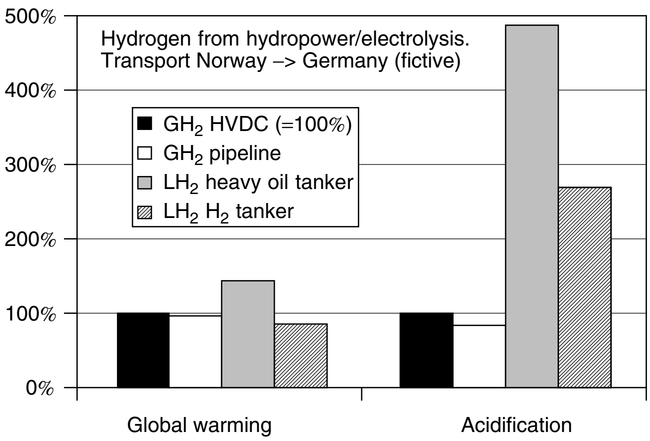


Figure 4. Comparison of GHG emissions and acidification for different transport scenarios of renewable hydrogen (normalized to GH_2 with HVDC transmission).

this configuration, LH_2 (transported in a tanker with H_2 as the fuel) has a better GHG balance than 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. Acidification, however, is significantly higher due to NO_x emissions of the LH_2 tanker and, if heavy oil is used as fuel for the tankers, SO_2 emissions.

2.2.3 *Methanol*

Methanol is under consideration as a "liquid hydrogen storage". If produced from natural gas, the efficiency of the methanol conversion plant is of great importance for the overall impact, especially for the primary energy demand and GHG emissions. Efficiencies of average plants (lower heating value (LHV) methanol/LHV natural gas) are well below 65% leading to CO_2 emissions in the order of 30–40 g CO_2 MJ^{-1} LHV methanol, whereas modern plants will achieve efficiencies higher than 65% depending on the process layout (e.g., use of oxygen) and consequently, the investment costs.

Most studies assume efficiencies in the range between 67 and 68%,[15, 20, 23] which is consistent with the 66% of the newly built combined reforming Statoil plant in Norway as well as planned future plants, whereas some studies assume unrealistically high efficiencies of up to 75%.[24] What is of interest in LCAs is not the efficiency at the optimum operating point, but the efficiency averaged over the lifetime, including degradation effects, start-ups after maintenance, etc. In addition, the marginal efficiency improvements lead to over-proportionally high incremental costs, thus, making efficiently produced methanol clearly more expensive.

Methanol can also be produced using biogen synthesis gases, such as from the gasification of wood or biowaste, anaerobic digestion or CO_2 absorption from air (with additional H_2 input). Technical data of these supply paths is scarce: efficiency numbers are often in the range of 40% for biomass gasification.[9] In these cases, GHG emissions as well as the primary energy demand are very low. Some attention, however, has to be paid to other environmental impacts, such as carcinogenic emissions from the wood supply (chain saws in the forest, etc.) or other process specific emissions, such as the combustion of purge gases from hydrogen enrichment of the synthesis gas.[15]

2.2.4 Gasoline and diesel

The life-cycle of gasoline and diesel production is well documented in each country. In addition to impacts from oil recovery, crude transportation and storage as well as product distribution, refining is of special relevance. Modern refineries have, however, very high efficiencies with low emission levels and are energetically optimized with respect to possible co-product use. Typical German refineries, for instance, consume 5.5% of the product energy content for process heat and 0.5% for electricity supply.[8]

2.3 Production of the vehicle

Manufacturing of future car generations 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 10–25% of total global warming emissions. In fuel cell vehicles, this relative contribution will be higher because (1) the absolute total 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.

However, only limited information is available on the production of vehicles. This life-cycle stage is often assessed by using an average incremental factor or by using material profiles of typical cars for determining the impacts of this phase.

In Refs. [15, 25] an effort has been made to calculate the impacts from fuel cell vehicle production in as much detail as possible. The LCA of fuel cell stack production in Refs. [15, 25] was carried out using industry data for materials (platinum group metals (PGMs) from South Africa, natural and synthetic graphite, membrane, PTFE and others) and for the stack production (next generation Ballard stacks with reduced PGM loading) (Figure 5).

Due to the early stage of development, the balance-of-plant materials could only be roughly estimated. Of particular importance are the PGMS for catalyst materials in the stack, the reformer and an eventual Pd/Ag membrane for the gas clean-up (with methanol as a fuel). The production of the car body and the conventional vehicle in Ref. [25] is taken from Ref. [26].

Figure 6 shows the contribution of different components of the vehicle to the total impacts of producing one vehicle assuming that 75% of the catalyst materials are recycled. It is obvious that the car chassis, tires, etc. contribute similar environmental impacts as the production of the stack. The

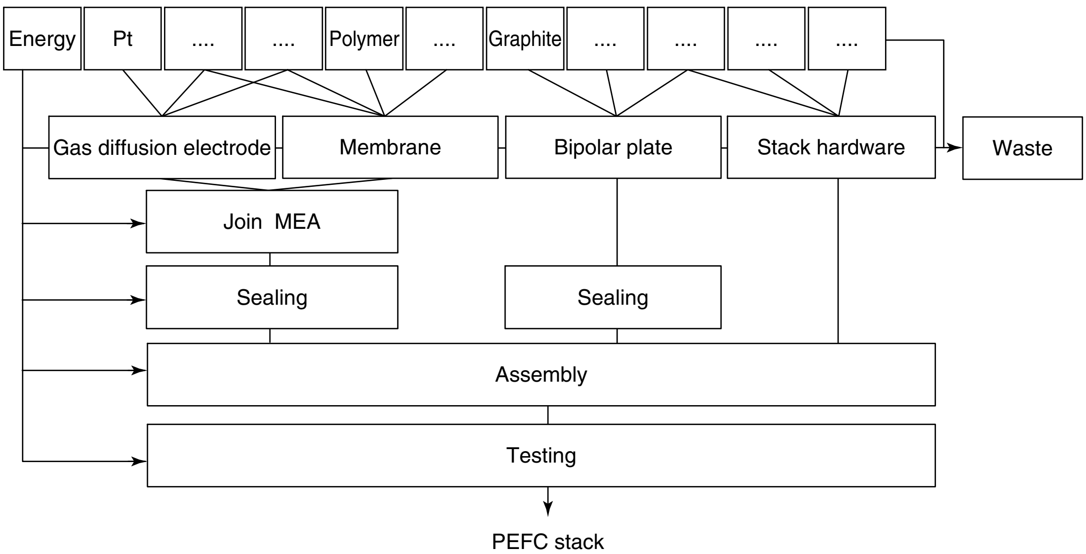


Figure 5. Production process of typical fuel cell stacks at Ballard.

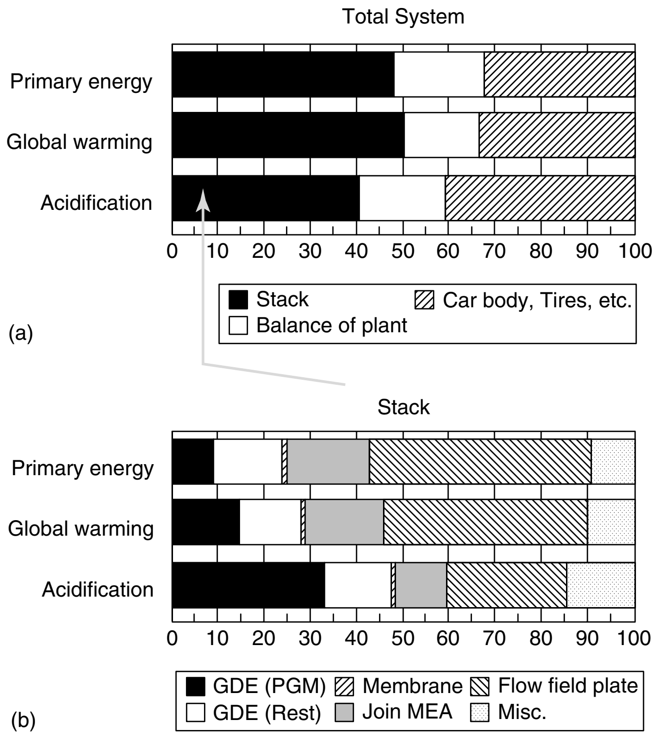


Figure 6. Production of a fuel cell vehicle based on methanol. Contribution of components to primary energy, global warming and acidification. Assumption: 75% PGM recycling.

balance of plant is of less importance. However, this is partly due to the fact that only a streamlined LCA of the balance-of-plant could be carried out.

Analyzing the contribution of the stack production further, two components turn out to be of special relevance. The gas diffusion electrode (GDE) is responsible for a large share of the total acidification and the global warming gas emissions. The crucial material causing the high acidification are the PGMs used as catalysts. PGMs are produced mainly in South Africa (68% of the world platinum supply and 75% of the world rhodium supply[27]) and as a by-product of nickel mining in Russia. Even in the modern African mines, mining of PGMs results in significant environmental interventions, particularly because of SO_2 emissions along the production chain. Part of the SO_2 is emitted during the pyrometallurgical treatment of the material. The tailings of the mining also act as potential sulfur sources even though in arid regions, such as South Africa, the tailings are less relevant with respect to SO_2 emissions. Methodological questions associated with the LCA of PGMs are discussed in Refs. [25, 28].

The flow field plate is the second important component particularly because of the electricity input for resin impregnation of the plate. Higher throughputs for series production have been assumed in this LCA. Even higher production volumes could halve the specific energy consumption. It is interesting that the graphitic plates, commonly considered as a main ecological factor, contribute 13% to the GHG emissions, compared to 17% of the electricity consumption. This is also a result of efforts to reduce the weight of the flow plates. This 13% is partly caused by the graphite production itself and partly by the use of a resin impregnant.

Improvement potentials as identified in Ref. [25] include:

- The reduction of PGM loading. Compared to earlier stack generations, PGM loading has already been reduced substantially from 8 to $1\,\mathrm{mg\,cm^{-2}}$ and $0.3\,\mathrm{mg\,cm^{-2}}$ for future stack generations. The lower limit of the loading is determined by the feasibility of recycling and the loss in performance. Note that as soon as rapid global introduction of fuel cells takes place, recycling becomes a main issue also because of the resource situation (for further information on PGM resources refer to Ref. [29]).
- Maximizing PGM yield during production. The yield of PGMs in the production process is very high already. Selective deposition of the catalyst ink and waste minimization (alternative cutting procedures such as laser cutting, optimized GDE geometries) lead to an increase of PGMs yields to up to 99%.
- Recycling of catalysts. Efficient recycling is necessary for economic and ecological reasons. An efficient recycling system has already been established in automobile exhaust catalyst recycling. Recycling catalysts can reduce environmental impacts for PGM production by a factor of 20 (primary energy demand) to 100 (SO_2 emissions).[30] 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 German decommissioned vehicles are exported to Eastern European countries) and the distribution of PGM in the fuel cell. So far, 52% of car catalysts in Germany are recycled.[31] 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 the stacks to car owners or deposits that 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.
- Recycling of components. In addition to PGM recycling, components such as the flow plates and membranes in stationary stacks can be reused or used in

other applications (e.g., membranes for desalination or heavy metal removal).

- Maximizing efficiency. Of course, maximizing efficiency by improving cell and balance of plant performance reduces the required PGM loading due to a reduction of the required active fuel cell area.
- Using "greener electricity" for the production process.
- The elimination of components and their integration into the stack (for instance humidifiers, air compressors, reformers (direct methanol fuel cell) and flow management).

2.4 Operation of fuel cell vehicles

For conventional vehicles based on internal combustion engines (ICEs), fuel combustion and the concomitant CO_2 emissions as well as direct exhaust emissions from incomplete combustion and nitrogen oxidation are of relevance for the assessment of the use phase along with other impacts, such as tire wear or noise emission.

For fuel cell vehicles, exhaust gas emissions are low (gasoline), almost (methanol) or entirely (hydrogen) zero with the important assumption that for fuel cell vehicles using gasoline or methanol as a fuel, cold start and evaporative emissions will be further reduced. Therefore, the question of the environmental characteristics of the use phase reduces to the question of the fuel consumption of these vehicles.

Various studies have investigated the fuel consumption (Table 2). Mainly, these studies have had to be based on modeling of the vehicle because little experience from existing cars has been gained so far. A number of parameters determine the fuel economy (Table 1). In Table 2, the main assumptions in various studies are summarized and the environmental aspects considered are given. Also indicated in the table are the fuel economy ratios (ICE fuel consumption/fuel cell fuel consumption) achieved in these reports as indicated in Figure 7.

Of particular importance is the driving cycle chosen for the evaluation. Thomas has shown that, due to the different efficiency profiles of the power trains as a function of the load, the fuel economy ratio for the same systems can vary from 3.7 (Japanese city cycle) to 1.8 (environmental protection agency US 06 cycle).[32] With increasing stop and go or acceleration at high speeds, the fuel economy ratio decreases due to the lower full load efficiency of fuel cell systems.

For the determination of fuel economy changes, the characteristics of the baseline gasoline vehicles are also important. Whereas most of the American studies assume rather high fuel consumptions due to heavier vehicles and less efficient, oversized engines, gasoline consumptions assumed in the European studies are well below that. In these studies, mainly future improved gasoline or diesel vehicle concepts are considered, which have already been demonstrated on the market but which have not yet diffused into the market on a large scale. For instance for a compact sized car, the 3–1 $100\,km^{-1}$ ($1\,MJ\,km^{-1}$) vehicle is state of the art but far from average fuel economies. For the reasons summarized above, most European studies calculate significantly lower fuel economy ratios.

In addition, in Europe mainly compact sized cars are investigated. However, the potential fuel reduction of fuel cells compared to ICEs for larger cars may be higher because the power trains of these cars typically have a higher mass specific power. Therefore, the fuel cell system operates less frequently in regions of lower system

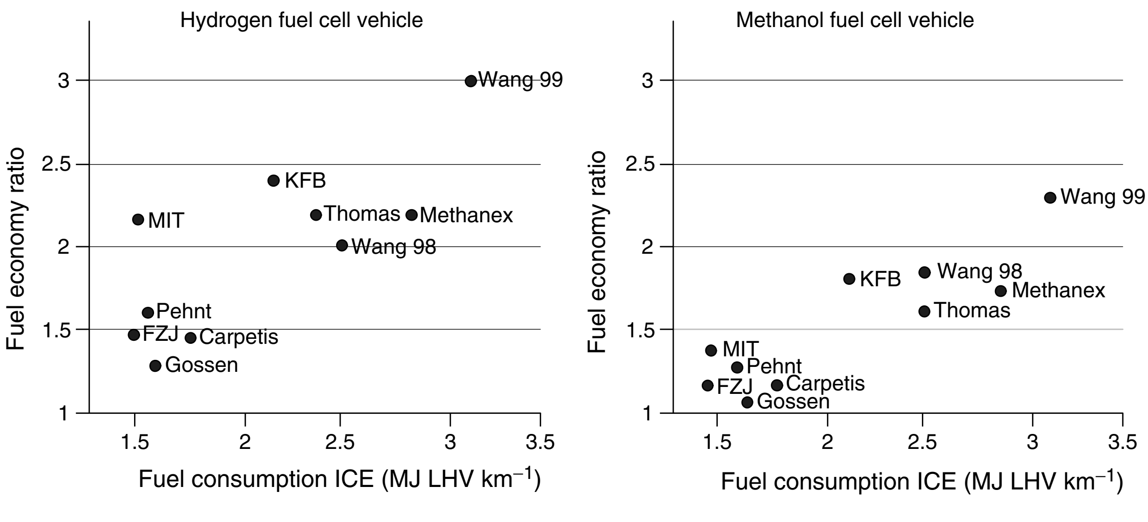


Figure 7. Fuel economy ratio (fuel consumption ICE/fuel consumption fuel cell) in various studies (for references see Table 2).

Table 1. Important parameters for calculating fuel cell vehicle fuel economies.

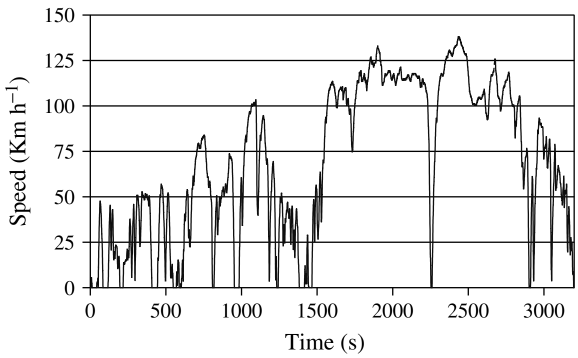
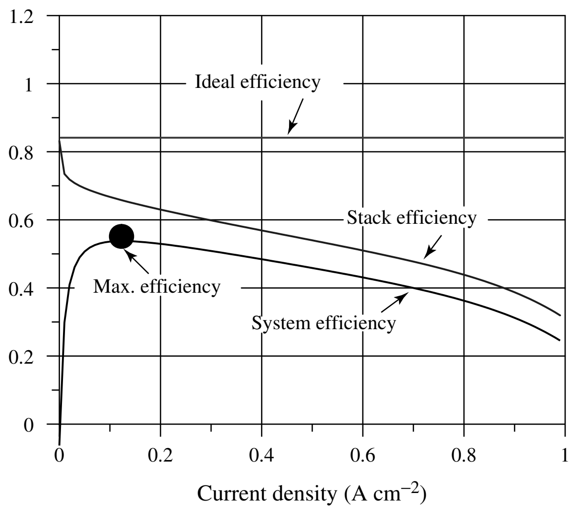
Parameter	Subparameter	Comments	Illustration
Mechanical energy demand	Mass	Light weight materials; weight of power train, incremental weight of fuel cell system	
	Rolling resistance Air resistance		
	Driving character-ristics/driving cycle	More dynamic driving cycles lead to shifts in favor of ICEs	
Efficiencies of system components	Polarization curve	Operation point is important: offset between maximum efficiency and maximum power	
	Reformer (MeOH) Parasitic loads		
Power management	Battery	Avoid full load or idle operation; cold start	
	Brake energy recovery		

Table 2. Review of input parameters, fuel economy ratios and analyzed environmental impacts in various studies.[a]

	Time frame	General vehicle and study parameters							ICE	
		Weight of body, chassis and driver (kg)	Incremental weight of FC compared to ICE (kg)			Air drag (cW A m^2)	Rolling res coeff.	Driving cycle	Gasoline consumption (MJ LHV km^{-1})	Emission level
			CH_2	MeOH	Gasoline					
Thomas (2000)		Ford sable (aluminum intensive)						Faster EPA	2.53	
Methanex (2000)	2010		−9	106	103			Faster 55/45	2.90	–
Wang (1998)	2010	Fuel economy ratio from literature						55/45	2.53	
Wang (1999)	2010	Fuel economy ratio from literature						55/45	3.16	Tier 2
GM (2001)		Full size pickup truck; data proprietary							3.76	Tier 2 bin 5
Pembina (2000)		Mercedes A class						55/45	2.36	
Ekdunge (1997)		1130	260	305						
ifeu/FZJ (1999a)	2010	825	42	115		0.6	0.008	NEDC highway	1.33	Euro 4
ifeu/FZJ (1999b)								NEDC highway	1.89	Euro 4
Carpetis (2000)	2005–2010	950	370	570	670	0.61	0.01	NEDC + highway	1.78	Euro 4
Pehnt (2002)	2010	825	320	410	–	0.6	0.008	NEDC + highway	1.60	Euro 4
Gossen (2000a)	longterm	957(tot)	85	185	–	0.58	0.0095	NEDC	1.52	Euro 4
Gossen (2000b)								Hyzem	1.65	Euro 4
MIT (2000)	2020	981	78	139	222	0.486	0.008	55/45	1.75	
KFB (2000)	2010	1418	90	226	–		0.008	55/45	2.20	

Table 2. (*continued*).

	Fuel economy ratio			General Information on Study			Comments	Ref.
	ICE fuel/FC fuel consumption							
	CH_2	MeOH	Gasoline	Vehicle production considered?	Fuel chains?	Environmental impacts considered		
Thomas (2000)	2.2	1.62 (best case)						[32]
Methanex (2000)	2.2	1.74	1.45	streamlined	yes	PE, GHG	Very high MeOH reformer efficiency (89.5%); almost equal values for production of ICE and FC vehicles; 75% efficiency of MeOH production	[24]
Wang (1998)	2	1.85	–	no	yes	PE, GHG		[33]
Wang (1999)	2.8–3.15	2.1–2.5	1.75–2	no	yes	PE, GHG, VOC, CO, NO_x, SO_x, PM10	Values represent "incremental" and leap-forward scenarios, respectively	[34]
GM (2001)	2.13*	1.5*	1.346*	no	yes	PE, GHG		[35]
Pembina (2000)	2.62	1.74	1.12	no	yes			[37]
Ekdunge (1997)	1.54					PE, GHG, some pollution		[38]
ifeu/FZJ (1999a)	1.66	1.25	–	no	yes	PE, GHG, A, E, C, SS, OD		[14]
ifeu/FZJ (1999b)	1.26	1.05	–	no	yes	PE, GHG, A, E, C, SS, OD		[14]
Carpetis (2000)	1.46	1.19	1	no	yes	PE, GHG, NO_x, NMVOC		[55]
Pehnt (2002)	1.55	1.27	–	yes	yes	PE, GHG, A, E, C, SS, OD	Baseline ICE vehicle is an improved gasoline vehicle	[15]
Gossen (2000a)	1.58	1.4	–	no	no	fuel consumption		[54]
Gossen (2000b)	1.31	1.13	–	no	no	fuel consumption		[54]
MIT (2000)	2.17	1.32	0.98	streamlined	yes	PE, GHG	Compared to advanced ICE, the economy ratios would be 1.92, 1.16 and 0.86 for hydrogen, methanol and gasoline FCV, respectively	[23]
KFB (2000)	2.4	1.8		no	no			[53]

[a]NEDC, New European driving cycle; Hyzem, European cycle combining dynamic urban, nonurban and highway parts; 55/45, 55% FUDS, 45% highway cycle. PE, primary energy; GHG, greenhouse gas emissions; A, acidification; E, eutrophication; C, carcinogenity; SS, summer smog; OD, ozone depletion; NMVOC, nonmethane volatile organic compounds; FCV, fuel cell vehicle.

*Higher, if charge sustaining hybrid electric vehicle is assumed.

efficiency. On the other hand, the additional weight of the fuel cell drive train might offset this advantage.

The calculated fuel economy ratios show the large bandwidth of results depending on the circumstances even if the same model is applied. In Ref. [33] a change in fuel economy ratio of 2 and 1.85 for H_2 and methanol fuel cell vehicles, respectively, is calculated with a 30-mpg baseline gasoline vehicle, whereas in Ref. [34] ratios of 2.8–3.15 (H_2) and 2.1–2.5 (methanol), respectively, are presented. In the most recent study by General Motors, co-authored by the Argonne National Laboratory, economy ratios of 2.13 (H_2) and 1.5 (methanol) were calculated (Table 2).[35]

In conclusion, the reduction of fuel consumption due to the use of fuel cell power trains remains an open question of very high relevance. First pilot vehicles and fleet operations should be analyzed to support the results of the model calculations. However, the rapid ICE development is a serious challenge for fuel cell vehicles with fuel economy ratios of <1.5 becoming realistic.

2.5 The conventional competitors

Future developments will also focus on optimizing conventional vehicles. More stringent emission levels in many nations have led to intensive research in the optimization of ICE vehicles. Catalysts and emission control systems, direct injection, downsizing/supercharging and valve control are only a few examples of future ICE development.[36] Therefore, LCAs should consider this future improvement potential and compare fuel cell vehicles not only to average ICE vehicles, but also to future car generations.

2.6 The total picture

In the following, results from the different life-cycle stages are put together to obtain a complete picture of the performance of the different power train and fuel options.

2.6.1 GHG

The evaluation of GHG emissions in the various studies can principally be divided into two classes. Studies assuming low or no additional weight of fuel cell drive trains, low fuel consumption of fuel cells, efficient upstream fuel supply and rather high gasoline consumption for competing vehicles result in a significant GHG advantage for all fuel cell types. An example for this is shown in Figure 8(right).

For most European studies, which also assume clear improvements in future ICE vehicles, GHG emissions of hydrogen fuel cell cars are lower than those of future gasoline or diesel cars in the case of hydrogen. Figure 8(left) shows an example LCA for this class of studies. If the production of the vehicle is not considered (fossil) H_2 fuel cell cars in that study are about 30% more greenhouse friendly based on the average driving cycle chosen for analysis. However, the higher production impacts (even assuming PGM recycling) reduce that advantage to 12% compared to future improved gasoline vehicles. The fuel cell car shows clear GHG advantages for innovative H_2 production paths, such as the Kværner CB& H process or electrolysis with electricity from renewable primary energy carriers.

However, the H_2 can also be used in ICE vehicles. These vehicles have comparable efficiencies to gasoline ICE engines and, therefore, lower efficiencies than fuel cell

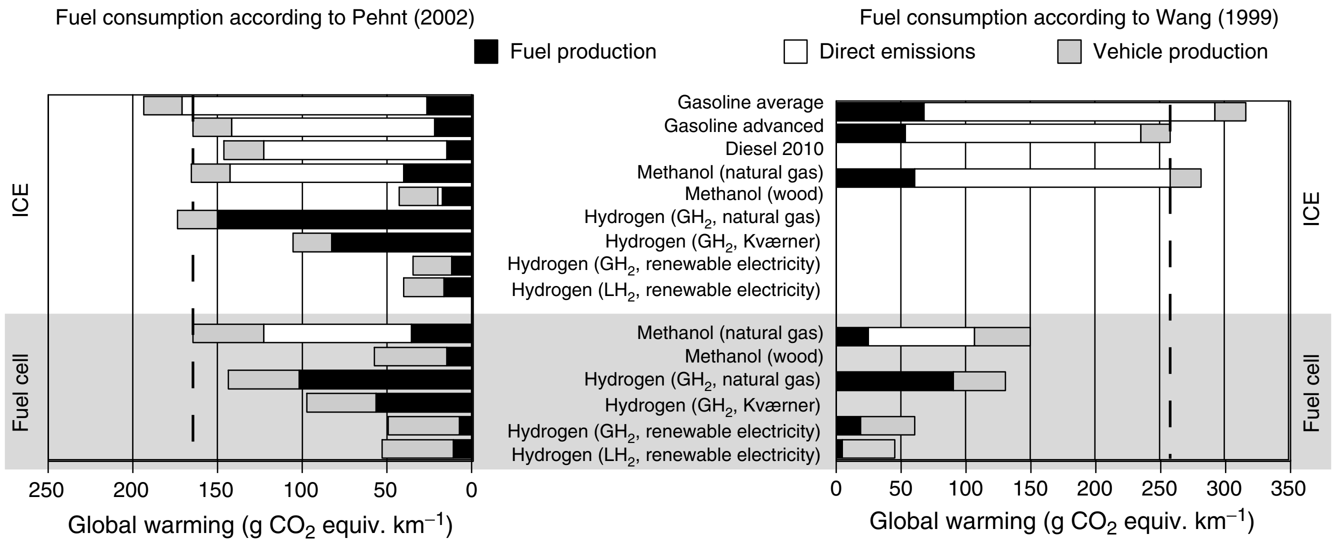


Figure 8. GHG emissions of different power train and fuel options. (Data sources: left, Ref. [15], hydrogen ICE according to Ref. [14]; right, fuel consumption and fuel chains according to Ref. [20], vehicle production from Ref. [15].)

vehicles. The exhaust emissions of these vehicles are – even without any catalyst – significantly lower (criteria pollutant without NO_x) or lower (NO_x) than in conventional ICEs. On the other hand, their production is less environmentally costly. The competition of ICE in this impact category, thus, remains a challenge for fuel cell vehicles.

Figure 8(left) also shows that for methanol fuel cell vehicles, direct emissions are lower due to a better power train efficiency. Unfortunately, methanol production is less efficient than today's gasoline and diesel production. Therefore, the share of fuel supply in Figure 8 is higher. In addition, production of the methanol fuel cell vehicle leads to higher impacts (higher than for H_2 because of additional components, particularly the PGMs for the catalytic refomer burner and an eventual membrane gas clean-up). Methanol produced from wood prevents the increase in GHG emissions. It should be mentioned that methanol can also be used in the ICEs.

In conclusion, there is still uncertainty about the degree of GHG reduction that fuel cell vehicles can offer in this market segment especially if fuel consumption is based on model calculations only. Therefore, it is strongly recommended to accompany the fuel cell development process with iterative LCAs to account for future developments and verify the "real" reduction potential of fuel cells.

2.6.2 Other environmental impacts

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, acidification from the energy chain and production is well below the gasoline ICE with the exception of the LH_2 transported by heavy oil tankers (Figure 9). For methanol, there is no clear advantage. The acidification of the production of fuel cell cars mainly stems from SO_2 from PGM production. For other impact categories, where SO_2 is insignificant (e.g., eutrophication and carcinogenity), the advantages of fuel cell cars are more pronounced.

Carcinogenic emissions mainly occur in the diesel engine. For the particle emission level, the Euro 4 emission standard was chosen as a basis. Biomass based fuel chains also show high impacts. This is due to the wood production (chain saws, further processing) and shows that it is necessary to base such investigations on the full life-cycle. It has to be recognized, however, that the Euro 4 emission standard is quite strict and that, therefore, the absolute emission level of Figure 9 is not very high.

2.7 Conclusions

Fuel cells offer advantages in many different impact categories. However, competition from conventional ICEs is getting stronger due to the developments of more stringent emission legislation and strict requirements regarding fuel consumption. Therefore, introducing fuel cell vehicles in large numbers must be accompanied with an effort to introduce renewable fuels as well as an efficient recycling system for the ecologically relevant vehicle components.

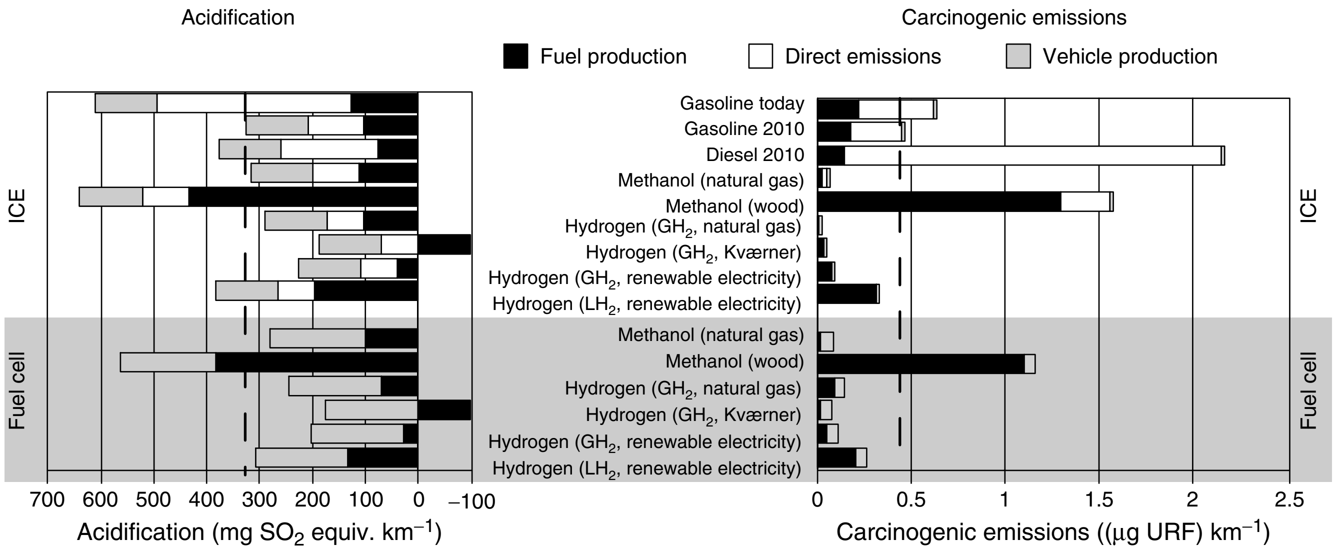


Figure 9. Acidification and carcinogenic emissions of different power train and fuel options. Data from Ref. [15]. High acidification of methanol from wood is caused by purge gas burnt in an engine CHP; these emissions can be avoided by different process options.[15] High carcinogenic emissions of methanol from wood caused by wood supply (chain saws, etc.). Negative emissions of Kværner hydrogen from carbon black credit. Fuel cell vehicle: 75% overall PGM recycling rate assumed.

In addition, data uncertainty regarding the fuel economy of future vehicle concepts is large. This leads to quite opposite conclusions in the different studies. To give an idea of the diverging conclusions, some citations are listed: "Thus the GHG advantage of fuel cell vehicles compared with conventional high efficiency competitors will only be maintained with certain hydrogen supply options...,"[37] "the greatest reduction in GHG would be from the use of compressed hydrogen manufacture by steam methane reforming of natural gas. The next greatest reductions come from centralized liquid hydrogen plants and from methanol reformed to hydrogen,"[24] "in general, ICE hybrids appear to have advantages over fuel cell hybrids with respect to life-cycle GHG emissions, energy efficiency and vehicle cost, but the differences are within the uncertainties of our results and depend on the source of fuel energy,"[23] "when the total energy chain is considered, the ICE is still ahead of the fuel cell. This may change, however."[38]

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

It is important to note that fuel cell vehicles offer other advantages in promoting the introduction of this power train, e.g., the simple realization of brake energy recovery with an adequate storage device, the compatibility with drive-by-wire or autopilot technologies, innovative safety concepts that can be realized with electric vehicles and higher user comfort and acceleration. In addition, auxiliary power unit applications, especially in trucks, can be an extremely attractive option for fuel cell use, given that efficiencies of current automobile electricity generators are as low as 5%.

3 STATIONARY SYSTEMS

3.1 Overview

Fuel cells can be applied in various stationary applications, ranging from 1-kW_{el} systems for domestic heating, combined heat and power production (CHP) for district heating or large buildings, up to megawatt applications for industrial cogeneration and electricity production without cogeneration. In each of these applications, different conventional systems are already well established, e.g., gas engine CHP, gas turbines or combined cycle power plants. The environmental assessment must, therefore, distinguish between the applications and compare fuel cells to different competitors (see Figure 10).

An early study carried out a streamlined LCA of fuel cell power production.[39] Some data, like the production of plants, was not available at that time. In addition, some of the fuel cell efficiencies were set very optimistically (phosphoric acid fuel cell (PAFC) ($200\,kW_{el}$) total $\eta =$ 85%; large solid oxide fuel cell (SOFC) power plant $\eta_{el} = 74-80\%$), whereas the parameters of the conventional systems were quite pessimistic (gas turbine ($1\,MW_{el}$) $\eta_{el} =$ 26%; large gas engine ($1\,MW_{el}$) $\eta_{el} = 36\%$). Ref. [40] assessed cumulated energy demands of a SOFC power plant. In Refs. [15, 16] an attempt has been made to combine LCAs of production, first using experimental evidence from existing pilot plants and performance data.

3.2 Production of fuel

3.2.1 *Natural gas*

In the near- and mid-term future, natural gas will be the fuel of choice for stationary applications. The life-cycle of natural gas comprises the exploration and extraction and the processing and transport to the consumer. LCAs of the natural gas supply must be carried out specifically for each country. Parameters of influence are, for instance:

- The transport mode and distance (pipeline distance, transportation as liquid natural gas, etc.);
- The specific energy requirements for compression and processing;
- The methane leakages in long-distance and the local distribution pipelines; this issue has been raised in connection with Russian natural gas where, due to the extreme climate and the poor pipeline conditions, leakage rates between 1 and 10% have been published.[41–45] The high GWP of methane leads to a significant influence of that leakage rate;
- SO_2 emission factors for the processing of sour natural gas.

The efficiency of (gaseous) natural gas supply is usually very high. For German industrial customers, for instance, the efficiency varies between 98% (Dutch natural gas) and 87% (Russian natural gas has a lower efficiency due to transportation).[8]

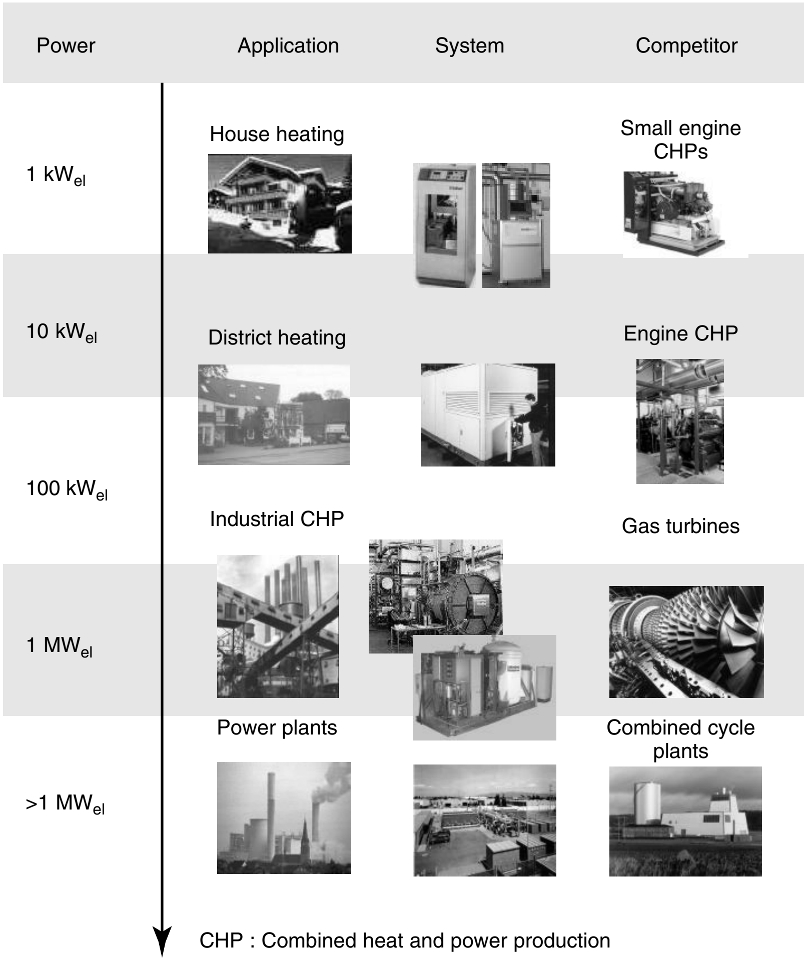


Figure 10. Applications, systems and competitors of stationary fuel cells.

3.2.2 Renewable fuels

For long-term applications, biogen and other renewable fuels are considered suitable for the use in fuel cells. Options include gasification of wood and other biomass,[9] anaerobic digestion of biowaste, sewage, manure, etc.[46] In the latter case, fuel cells are also attractive because of the low heat to power ratio. In many biogas plants, for instance, part of the heat produced in the cogeneration plant has to be wasted due to a lack of heat demand. Electricity, in contrast, can easily be fed into the grid. Generally, most applications (household, offices, industries) will have reduced heat consumption in the future due to energy savings, whereas electricity consumption will grow or at least stay constant.

3.3 Production of the power plant

In the following, the production of polymer electrolyte fuel cell (PEFC) and SOFC power plants will be presented. For other fuel cell technologies, LCAs of the system production have not yet been published.

3.3.1 PEFC

For the production of PEFC power plants, an LCA has been carried out in Refs. [15, 25]. Principally, the same comments as for mobile systems are applicable. However, although the environmental impacts of stationary fuel cell stacks per kilowatt are higher than those of mobile stacks due to the higher weight and catalyst loading, the higher impacts of the stationary stack per power unit (kW) are more than offset by the longer life-time (40 000 h instead of 4000 plus the potential to recycle part of the stacks, e.g., the flow field plates) when moving towards impacts per energy unit (kWh).

Assuming a similar balance of plant as the PAFC, a streamlined LCA was carried out for the total CHP system fired with natural gas including the periphery of the system.[15] To most impact categories, production of the *total* system, assuming PGM recycling of 90% (a higher rate than mobile systems because of the higher loading and the limited number of systems), contributes less than 8% of the life-cycle emissions. If no PGM were recycled, production would contribute less than 13%. Therefore, in stationary PEFC systems, the impacts of stack production are of much less relative importance than in mobile systems.

3.3.2 SOFC

Manufacturing SOFCs involves a number of rather unconventional 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).

Manufacturing SOFCs has only been assessed in two studies[15, 40] (and Ref. [47] mainly based on Ref. [40] which calculates cumulative energy demands for the materials). Due to the early publication date, only aggregated and preliminary data were available. Ref. [47] calculates unusually high impacts of the manufacturing process. In Ref. [15] industrial LCA data on the materials were available. However, not the current tubular stack design, but a planar stack was evaluated. The stack production process is shown in detail in Figure 11.

In Figure 12, the primary energy demand, the GWP and the acidification per kg of SOFC relevant 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 (for instance for yttrium and lanthanum).[15] 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 PGMs for PEFCs below).

Figure 13(a) shows that for systems of the first generation (no recycling), the stack is responsible for a large proportion of the total impacts of system production. This is partly due to the lower lifetime of the stack: it has to be exchanged during the life-time of the total system.

Further analysis of the contribution of different processes to the stack production (Figure 13b) reveals that in this planar design investigated, chromium used for the bipolar plates is a critical material. But also the electricity used for electrochemical etching, sintering and other process steps is of relevance, although large-scale series production was considered when calculating throughputs and energy demands.

To consider the possibility of recycling, the further assessment in Ref. [15] did not assess a system of first generation, but assumed recycling of 90% of the bipolar plate material.

3.4 Operation of fuel cell power plants

3.4.1 Direct emissions

The operation of fuel cell power plants leads to minimal direct emissions due to relatively low (compared to combustion engines or turbines) operating temperatures (leading to almost zero thermal NO_x emissions) and gas clean-up requirements (e.g., the required SO_2 removal).

The emissions are typically dependent on the load.[48] Only for PAFC is detailed emission data available. Averaging over load factors higher than 50% results in emission factors from the reformer burner as given in Table 3.

As a first order approximation, these emissions can be applied to all natural gas reforming stationary plants as long as the fuel, the reformer type and temperature and fuel utilization are comparable. Generally, these emissions are very low in comparison with emissions from other life-cycle stages so that the uncertainty is not very relevant for the total results.

It is important to consider emission developments in the conventional systems as well. Improved three-way catalysts for gas engines, low-NO_x combustion chambers and other primary and secondary measures for gas turbines as well as NO_x and SO_2 abatement technologies for large power plants have drastically reduced exhaust emissions. Estimates of future power plant generations are presented, for instance, in Refs. [12, 15, 49, 50].

3.4.2 Electrical efficiency

Essential for the LCA of the systems are the assumed electrical and thermal efficiencies, which differ very much according to the system and the fuel cell type as described in the subsequent sections.

The potentially high electrical efficiency of fuel cell power plants is one of the major advantages of these systems. For each power range, fuel cells offer higher efficiencies than the conventional competitors (Figure 14).

Table 3. Emission factors of a number of ONSI PAFCs per kWh_{el} and per MJ LHV fuel input. (Reproduced from Dienhart, Pehnt and Nitsch (1999).[49])

	$mg\,kWh_{el}^{-1}$	$mg\,MJ_{in}^{-1}$
CO	15	1.7
NO_x	8	0.9
SO_2	0	0
NMVOC[a]	2.5	0.3
CH_4	75	8.3
Particles	0	0

[a]NMVOC, nonmethane volatile organic compounds.

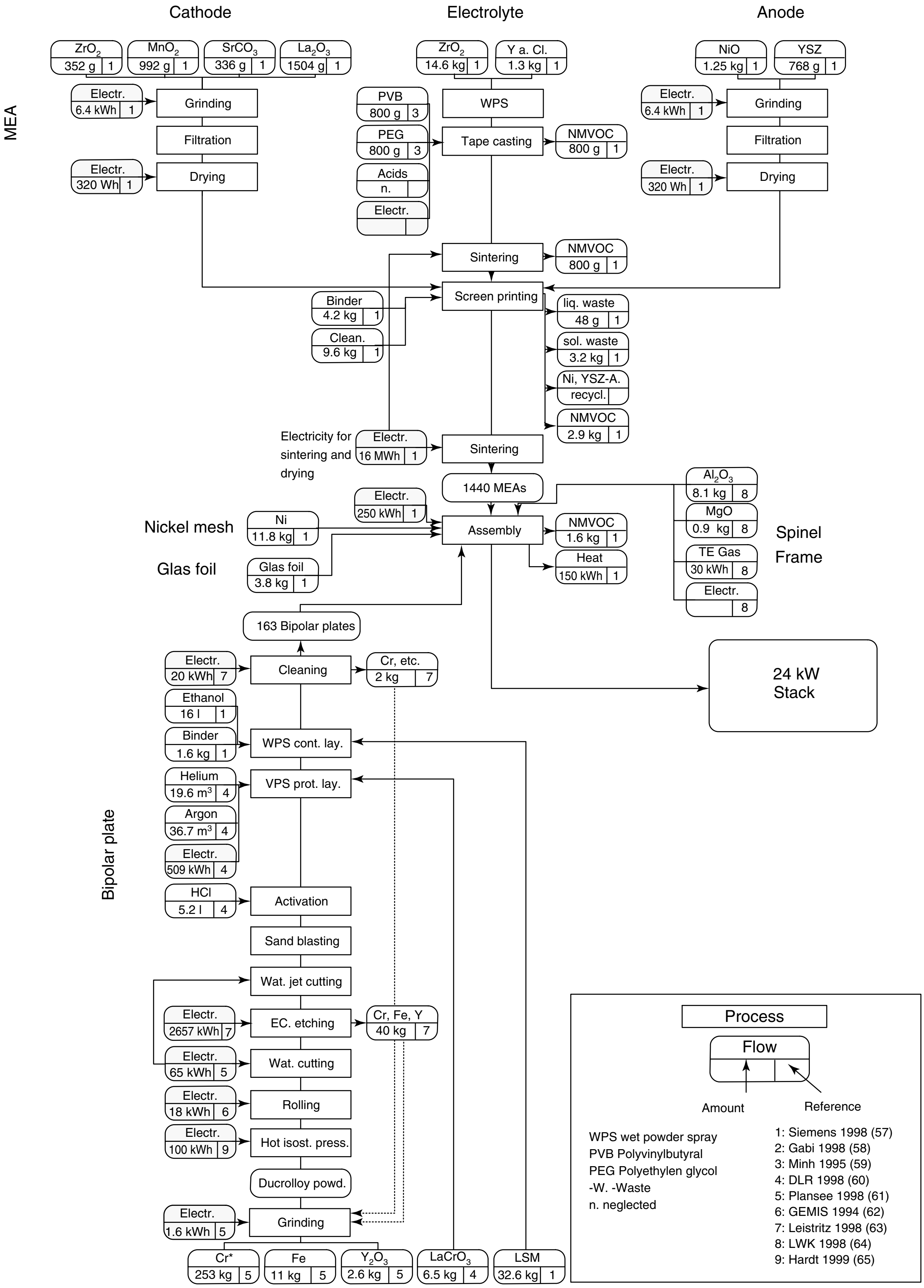


Figure 11. SOFC stack production process used for the LCA in Ref. [15]. MEA: membrane electrode assembly.

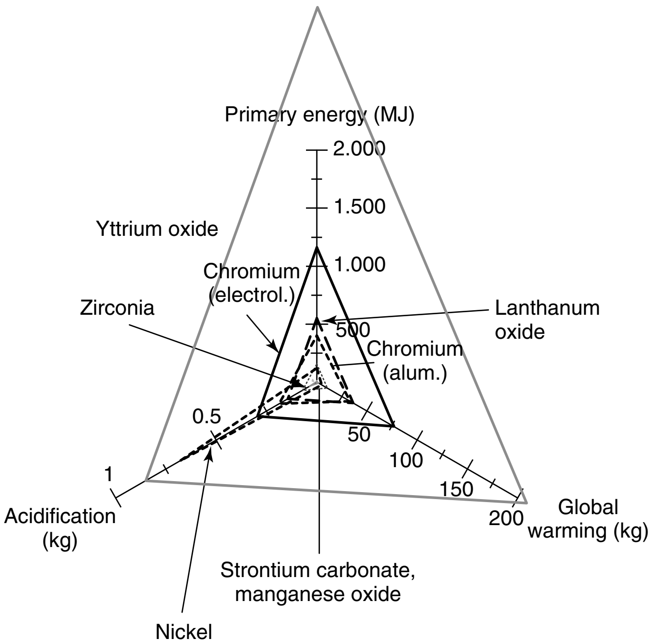


Figure 12. Selected environmental impacts associated with the production of 1 kg of different SOFC relevant materials.

It has to be mentioned that for fuel cells, these numbers present target values, whereas the demonstration plants do not yet reach these numbers. For conventional systems, future optimization potentials are also included in Figure 14 as the upper boundaries of the boxes.

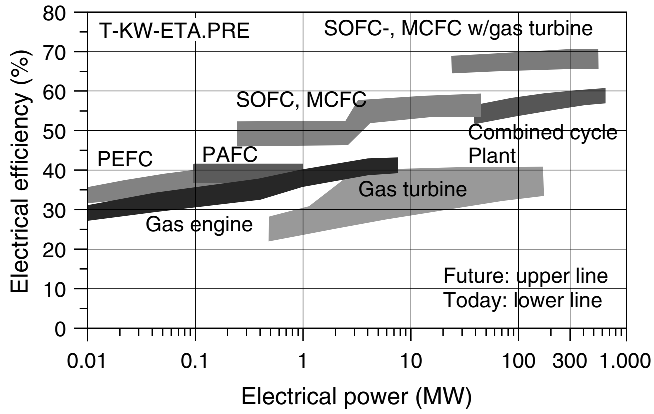


Figure 14. Electrical efficiencies of fuel cell power plants and conventional competitors (fuel: natural gas).

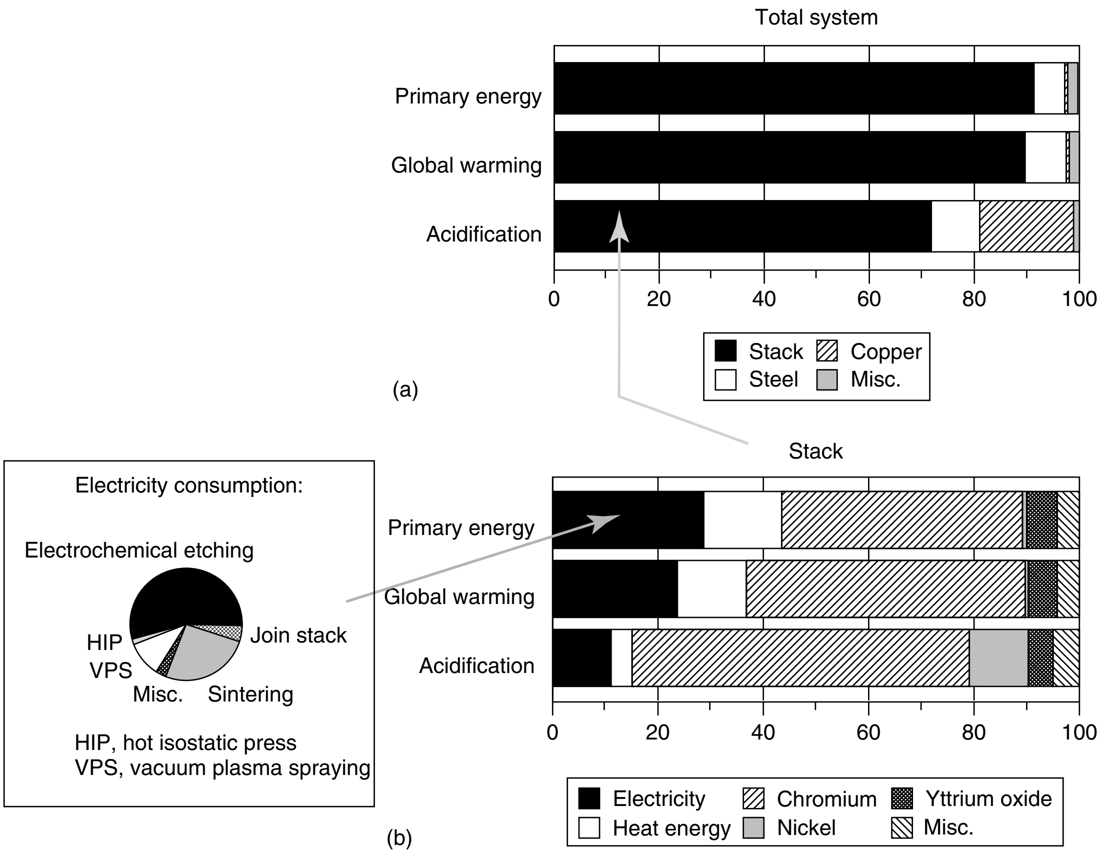


Figure 13. Selected environmental impacts from a SOFC system (above) and stack (below) production (planar Siemens design, 200 kW_{el} system, no recycling, parameters scaled for large-series production).

Referring to natural gas as a fuel, in the low power range, PEFCs have electrical efficiencies in the order of 32–35% for house heating systems and 40% in the 100 kW_{el} range. In a large number of demonstration projects, these numbers have already been demonstrated with PAFCs. In some systems, especially of the early generations, however, degradation effects lowered the lifetime efficiency.

High-temperature fuel cells offer efficiencies of 50% when used in lower power regimes. 47% have already been demonstrated in the Netherlands SOFC demonstration system as well as in the Bielefeld (Germany) molten carbonate fuel cell. In future, coupling fuel cells with gas turbines to use exhaust heat promises efficiencies of up to 68% at the beginning of the operation, with expected degradation to 62–64% at the end of life.

However, conventional systems are constantly being optimized. In the US advanced turbine programme, for instance, gas turbines in the MW range have reached electrical efficiencies of more than 40%. Also, combined cycle plants reach average efficiencies of 58–60%, with 65% (without degradation) being forecast by some researches. This means that the competition is getting tougher.

It is worth mentioning, however, that even in the 3–10 MW power regime, the efficiencies of fuel cell systems would exceed those of large 100–400 MW combined cycle power plants. A detailed investigation of current and future prospects of efficiency development can be found in Ref. [49]. For systems operated not at a fixed operation point, but with variable load, the efficiency as a function of the load is of relevance as well. For instance, for a district heating application in Ref. [15] a PEFC was modeled using average load data from a district heating system. As long as the system does not fall below a certain minimum power, the electrical efficiency increases with decreasing load. Similar to the driving cycle in the mobile application, therefore, the application dependent load characteristics should be considered. High-temperature fuel cells will, however, mainly be operated at fixed operating conditions.

3.4.3 Thermal/total efficiency

For CHP, the thermal efficiency is also of importance. The thermal efficiencies of conventional systems have been a key parameter for past optimization of the systems.[15] Gas engines, for instance, can reach total efficiencies of up to 100% (LHV) due to use of the condensing heat. In practice, more than 90% total efficiency is realistic. Combined cycle CHP plants can also reach thermal efficiencies of 50% resulting in total efficiencies of nearly 90%.

Thermal efficiency is, of course, a function of the temperature of the heat medium. If only steam is needed, as in many industrial applications, it will be lower than for a low-temperature district or house heating system. Also, thermal efficiency is a function of the load. Generally, current target values for most fuel cell systems are approximately 80% total efficiency. To successfully compete with conventional systems, future work should also focus on increasing thermal efficiencies by using the reformer exhaust heat and other heat sources.

3.5 The total picture

In Figure 15, different environmental impacts of fuel cell energy production including all life-cycle stages compared to competitors are represented as assessed in Ref. [15]. Note that in order to present the numbers in one diagram and in order to show the specific importance of the respective environmental impact, the values were normalized by dividing by the daily environmental impact per capita ("person equivalents"). Also, the heat produced in cogeneration systems is credited with a modern natural gas burner. That means that if the system produces x kWh of electricity and y kWh of heat simultaneously, the impacts of producing y kWh of heat with a modern natural gas are subtracted from the total impacts because this heat production is substituted by the cogeneration system.

It is obvious that high-temperature fuel cells in this application offer significant advantages compared to the competing technologies. Considering the GWP, 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 (see previous discussion).

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 combined cycle (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 3 MW_{el} power range produces less GHGs 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 optimized. This is even more important for PEFCs in the 100 kW_{el} range where engine CHPs show total efficiencies of more than 90% (LHV) because the heat of condensation is used. However, the development of high-efficiency centralized electricity production based on fuel cells decreases the gap between cogeneration and noncogeneration plants.

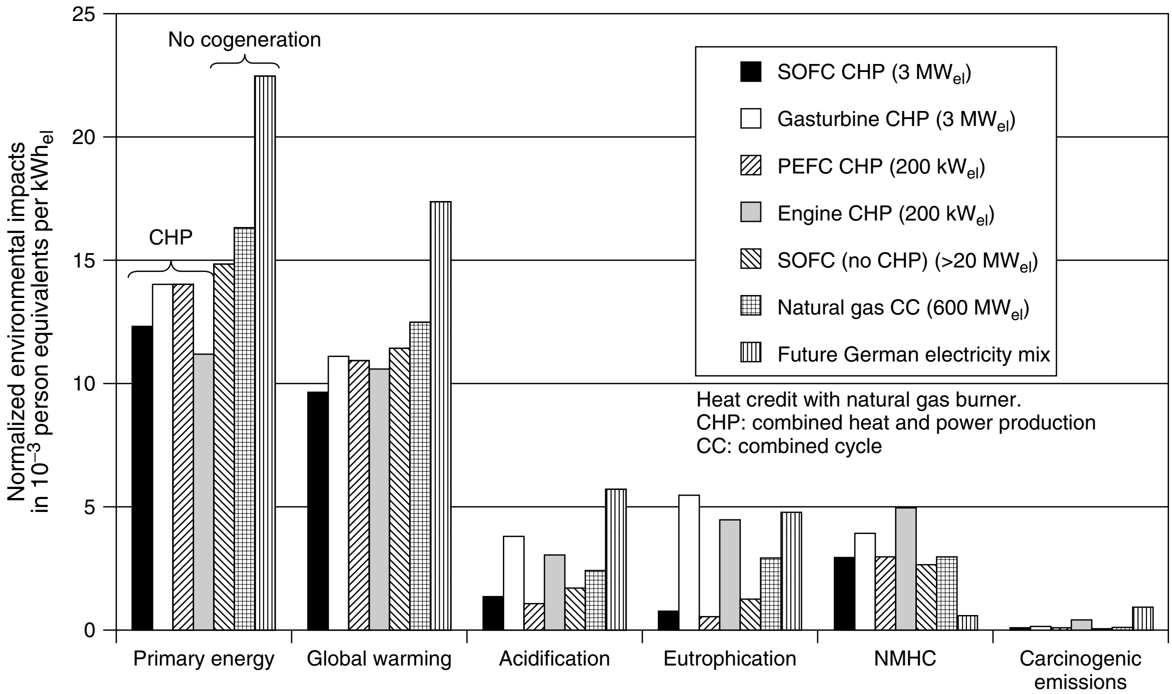


Figure 15. Total environmental impacts of energy production with fuel cells and conventional competitors. All impacts are related to the functional unit, 1 kWh_{el}. If heat is coproduced it is credited with a modern natural gas burner. All data is normalized to person equivalents by dividing the impacts by the average per capita impact in Germany. (10×10^{-3} person equivalents equal 4.93 MJ primary energy; 361 g CO_2 equiv.; 1.46 g SO_2 equiv.; 0.153 g $PO_4{}^{3-}$ equiv.; 0.625 g NMHC; 2.54 e 6 g unit risk factor carcinogenic emissions.)

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 optimum size of such plants will be at lower power. The introduction of fuel cells means the continuation of the process of decentralization of power production, which started with high-efficiency gas turbines, small 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. This can be seen from Figure 16 where the contribution of the life-cycle stages to total life-cycle impacts are shown. For acidification, the relative contribution of production 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 electrochemical etching of the interconnects) and the chromium for the planar interconnects. For tubular SOFCs, the environmental impacts from production are different.

A second example compares a SOFC using synthesis gas from wood gasification with a gas turbine using the same gas and the German electricity mix from Figure 13 (Figure 17). It can be seen that the primary energy demand and the GHG emissions can be drastically reduced by both the SOFC and the gas turbine. The advantages of fuel cells when coupled with biogen fuels are, on the one hand, the more efficient use of the often restricted biomass potentials and, on the other hand, prevention of increased emission level, which is typical for many other biomass based energy converting systems. In addition, low heat-to-power ratios are advantageous if the external heat demand is limited as is often the case in biogas plants.[46] Additionally, a trend towards higher electricity compared to heat demand can be observed in industry.

4 PORTABLE SYSTEMS

The environmental benefits from portable applications differ significantly from the other application areas. Portable systems usually compete with (rechargable) batteries to power laptops, telecommunication devices and other portable electronic devices or with gasoline or diesel power generators. The rapidly growing market – in 2006 more than 6 billion portable devices can be expected[51] – points to a potentially high ecological relevance. However, no LCA has so far been carried out in this field. Some general remarks can be made nevertheless.

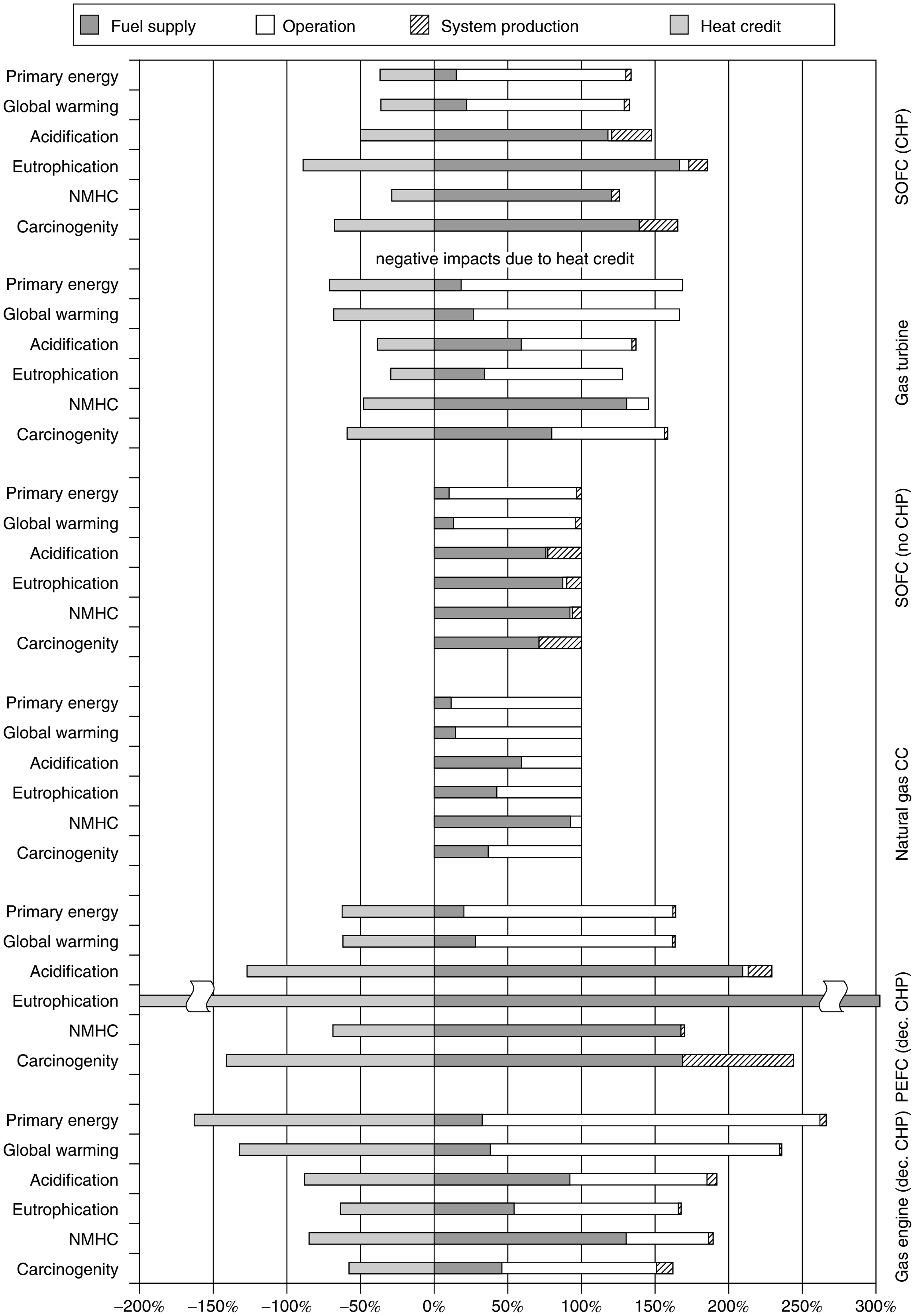


Figure 16. Contribution of life-cycle stages to total environmental impacts to the systems of Figure 15. Bars are scaled in such a way that positive impacts minus heat credit yields 100%.

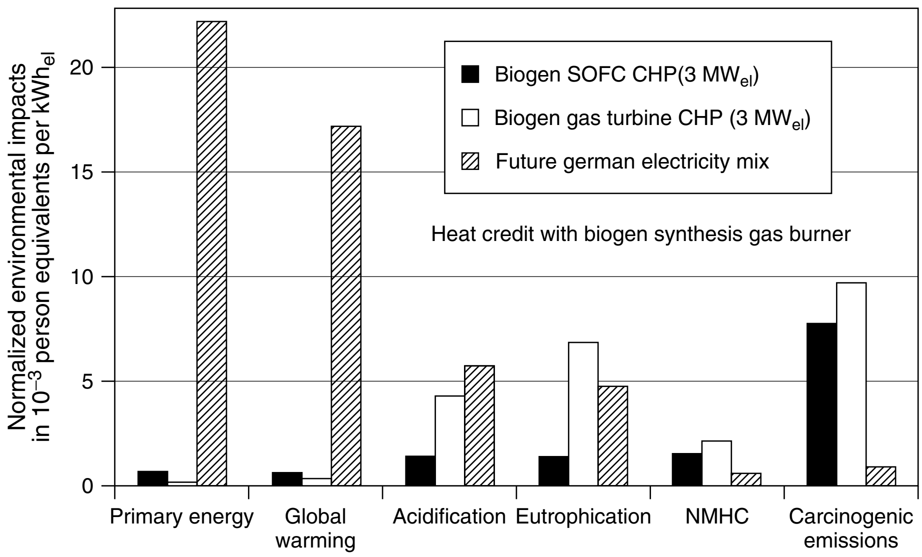


Figure 17. Total environmental impacts of energy production converting synthesis gas from gasified wood in a SOFC and a gas turbine compared to the future (2010) German electricity mix. All impacts are related to the functional unit 1 kWh_{el}. If heat is coproduced it is credited with a modern gas burner using the same synthesis gas. All data are normalized to person equivalents by dividing the impacts by the average per capita impact in Germany (see Figure 15).

Batteries contain ecologically critical materials such as cadmium, lead or mercury. In many countries, disposal of batteries is the main source of heavy metal contamination of waste disposal sites. It is estimated that in 2001, 500 million rechargable batteries were discarded. Additionally, the production of batteries consumes up to 500 times the energy contained in the battery itself. In the life-cycle of the fuel cell system, the production supply will play a less important role than the substitution of batteries. As fuel cell systems will have longer lifetimes and offer the potential of catalyst recycling, the net effect will be clearly positive.

Portable fuel cell systems also compete with gasoline or diesel generators. These small systems have an efficiency of typically 10% compared to fuel cells of a similar size with efficiencies between 20 and 28% depending on the load factor.[52] In addition, clear reductions in the noise level can be achieved.

5 OUTLOOK AND SUMMARY

Fuel cells are promising energy converters for mobile, portable and stationary applications. For an environmental evaluation of new technologies, however, an investigation of the complete life-cycle is necessary to ensure that no environmental aspect is neglected (LCA).

LCAs of mobile fuel cell applications show that this technology offers advantages in many different environmental impact categories. However, the competition of conventional power trains is increasing due to the developments of more stringent emission legislation and strict requirements regarding fuel consumption. In addition, the production of fuel cell vehicles is more environmentally relevant than the production of ICE cars, partly due to the large amount of catalyst materials employed in fuel cell vehicles. Also, data uncertainty regarding weight and fuel economy of future vehicle concepts is large. For hydrogen fuel cell vehicles, for instance, the calculated fuel economy ratios (=fuel consumption ICE vehicle/fuel consumption fuel cell vehicle) vary between 1.3 and 3. Consequently, the calculated climate gas reductions differ significantly in the various studies. A German study, for instance, calculates reductions of GHG emissions by 15% when hydrogen (from natural gas) fuel cell vehicles replace future improved gasoline vehicles and when the production of the vehicle is taken into account. In some American studies, the calculated GHG benefits are higher. The fuel cell car shows clear GHG advantages for innovative hydrogen production paths, such as electrolysis with electricity from renewable primary energy carriers or biomass gasification. However, in this case renewable hydrogen can also be used in ICE vehicles with similar GHG emission levels.

For fossil methanol fuel cell vehicles, the majority of studies do not determine a significant global warming advantage compared to the conventional competitors. To achieve CO_2 reductions, methanol produced from biogen primary energy would be required.

For other environmental impacts, such as acidification or summer smog, the fuel and vehicle production determine the minimum life-cycle impacts. In any case, based on a life-cycle perspective, the fuel cell car is not a zero emission vehicle. Introducing fuel cell vehicles in large numbers must, therefore, be accompanied with an effort to introduce renewable fuels as well as an efficient recycling system for the ecologically relevant vehicle components.

In stationary applications, the potentially high electrical efficiency of fuel cell power plants, especially high-temperature fuel cells, leads to clear resource and GHG emissions advantages compared to the competing technologies. An SOFC/gas turbine system in CHP as calculated in one study emits 12% less GHG emissions than a future gas turbine and 47% less than a future German electricity mix. 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 combined cycle plant. The acidifying emissions in the case of SOFCs stem almost exclusively from the energy chain and the production of the system which is considerably less relevant than in mobile applications due to the higher life time of the systems.

Further advantages could be achieved if not only the electrical, but the total efficiency were simultaneously optimized. This is particularly important for low temperature fuel cells in CHP applications where some engine CHP plants show total efficiencies of more than 90%.

In portable applications, the main environmental benefit will be the elimination of heavy metal-containing batteries and higher electrical efficiencies compared to gasoline or diesel generators with drastically reduced noise levels.

Future developments will bring some radical changes with respect to materials, concepts and applications, but also with respect to the framework – deregulated electricity markets, increasing pressure on climate policy or emission control, etc. – in which fuel cells have to be established. Therefore, LCAs at such an early stage of the market development can only be considered preliminary. They help to recognise ecological weak points or bottlenecks and to gradually improve process and system development. However, it is an essential requirement to accompany the ongoing research and development with iterative LCAs and help decision-makers as well as companies to make decisions under the constraint of limited information on power plant and power train technologies, fuel options, materials or operating conditions.

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REFERENCES

1. ISO 14040, 'Environmental Management – Life Cycle Assessment – Principles and Framework', International Organization for Standardization, Geneva, Switzerland (1997).
2. R. Heijungs, J. B. Guinee, G. Huppes, R. M. Lankreijer, H. A. U. D. Haes and A. W. Sleeswijk, 'Environmental Life-cycle Assessment of Products. Guide and Backgrounds', Center of Environmental Science, Leiden (1992).
3. H. Wenzel, M. Hauschild and L. Alting, 'Methodology, Tools and Case Studies in Product Development', "Environmental Assessment of Products", Vol. 1, Chapman & Hall, London (1997).
4. R. Frischknecht, A. Braunschweig, P. Suter and P. Hofstetter, *Environ. Impact Assess. Rev.*, **20** (2000).
5. B. Solberg-Johansen, R. Clift and A. Jeapes, *Int. J. Life-cycle Assess.*, **2**, 16 (1997).
6. ISO 14042, 'Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment', International Organization for Standardization, Geneva, Switzerland (2000).
7. Acurex, 'Evaluation of Fuel-Cycle Emissions on a Reactivity Basis', Acurex Environmental Corporation, Mountain View (1996).
8. J. Borken, A. Patyk and G. A. Reinhardt, 'Basisdaten für ökologische Bilanzierungen' (Data for LCAs, in German), Vieweg, Braunschweig, Wiesbaden (1999).
9. T. Dreier, 'Biogene Kraftstoffe. Energetische, ökologische und ökonomische Analyze. IfE Schriftenreihe Heft 38', TU München, München (1999).
10. M. Ekelund, A. Johansson, A. Brandberg and A. Roth, 'The Life of Fuels. Motor Fuels from Source to End Use', Vattenfall AB, Ecotraffic AB, Stockholm (1992).
11. R. Frischknecht (Ed), 'Ökoinventare von Energiesystemen. Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz' (Life-cycle Inventories of Energy Systems), Zürich (1996).
12. GEMIS, 'Gesamt-Emissions-Modell Integrierter Systeme Version 3.08', Öko-Institut E.V., Darmstadt, Freiburg (1998).
13. M. P. Gover, S. A. Collins, G. S. Hitchcock, D. P. Moon and G. T. Wilkins, 'Alternative Road Transport Fuels – A Preliminary Life-cycle Study for the UK', ETSU, Oxon, UK (1996).
14. A. Patyk and U. Höpfner, 'Ökologischer Vergleich von Kraftfahrzeugen mit verschiedenen Antriebsenergien unter besonderer Berücksichtigung der Brennstoffzelle' (Environmental Comparison of Vehicles with Different Power Trains), Report

for the Office of Technology Assessment of the German Parliament, Institut für Energie- und Umweltforschung, Heidelberg (1999).

15. M. Pehnt, 'Ganzheitliche Bilanzierung von Brennstoffzellen in der Energie- und Verkehrstechnik' (Life-cycle Assessment of Fuel Cells in Mobile and Stationary Applications), Ph.D. Dissertation, VDI–Verlag Fortschrittsberichte, Vol. 6 No. 476, Düsseldorf (2002).
16. M. Pehnt, 'Life-cycle Assessment of Fuel Cells and Relevant Fuel Chains', in "Proceeding of Hyforum 2000 International Hydrogen Energy Forum", Munich, pp. 387–396 (2000).
17. G. Reinhardt and G. Zemanek, 'Ökobilanz Bioenergieträger: Basisdaten, Ergebnisse, Bewertungen' (Life-cycle Assessment of Bioenergy), Erich Schmidt, Berlin (2000).
18. A. Röder, 'Vergleich regenerativer Energiesysteme bezüglich Kosten, Treibhausgasemissionen, Ressourcenverbrauch', Diplomar Thesis, Paul-Scherrer-Institut and ETH Zürich (1997).
19. U. Wagner, B. Geiger, H. Frey and T. Schedl, 'Untersuchung von Prozeßketten einer Wasserstoff-Energiewirtschaft' (Analysis of Process Chains of a Hydrogen Economy), TU München (1995).
20. M. Q. Wang, 'Greet 1.5–Transportation Fuel-Cycle Model', Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, Argonne, IL (1999).
21. O. Finkenwirth, M. Pehnt and T. Marheineke, 'Life-cycle Assessment of Innovative Hydrogen Production Paths', in "Proceedings of Hyforum 2000 International Hydrogen Energy Forum", pp. 161–171, Munich (2000).
22. P. Spath and M. Mann, 'A Complete Look at the Overall Environmental Impacts of Hydrogen Production", Hyforum 2000, Munich (2000).
23. M. A. Weiss, J. B. Heywood, E. M. Drake, A. Schafer and F. F. AuYeung, 'On the Road in 2020. A life-cycle Analysis of New Automobile Technologies', Massachusetts Institute of Technology, Cambridge, MA (2000).
24. STC, 'Assessment of Emissions of Greenhouse Gases from Fuel Cell Vehicles. Prepared for Methanex Corporation', Delta BC, Canada (2000).
25. M. Pehnt, *Int. J. Hydrogen Energy*, **26**, 91 (2001).
26. G. W. Schweimer, 'Sachbilanz des 3 Liter Lupo', Volkswagen AG, Wolfsburg (1999).
27. 'Platinum 1999', Johnson Matthey, London (1999).
28. C. Hochfeld, 'Bilanzierung der Umweltauswirkungen bei der Gewinnung von Platingruppen-Metallen für PKW-Abgaskatalysatoren' (Environmental Impacts of Platinum Group Metals for Catalysts), Diploma Thesis, Technische Universität Berlin (1997).
29. I. Råde, 'Requirement and Availability of Scarce Metals for Fuel-Cell and Battery Electric Vehicles', Dissertation Thesis, Chalmers University of Technology and Göteborg University (2001).
30. M. Schuckert, M. Harsch, P. Eyerer, K. Saur and C. Kaniut, 'Optimization of Three-Way Catalyst Systems by Life-Cycle Engineering Approach', SAE paper (1998).
31. C. Hagelüken, 'Der Kreislauf der Platinmetalle – Recycling von Autoabgaskatalysatoren' (The Platinum Cycle), 8. Duisburger Recyclingtage, Duisburg (1998).
32. C. E. Thomas, 'On Future Fuels: A Comparison of Options', in "On Energies-of-Change – The Hydrogen Solution", C.-J. Winter (Ed), Gerling-Akademie Verlag, München, pp. 50–66 (2000).
33. M. Q. Wang, 'Fuel-Cycle Greenhouse Gas Emissions Impacts of Alternative Transportation Fuels and Advanced Vehicle Technologies', Presentation at the Annual Meeting of the Transportation Research Board, Washington, DC (1998).
34. M. Q. Wang and H.-S. Huang, 'A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas', Argonne National Laboratory, Argonne, IL (1999).
35. 'Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems. North American Analysis, Report with cooperation of General Motors Corporation, Argonne National Laboratory, BP Amoco, ExxonMobil, Shell, General Motors (2001).
36. M. Pehnt, 'Ökologische Nachhaltigkeitspotenziale von Antrieben und Kraftstoffen' (Ecological Sustainability Potentials of Power Trains and Fuels). Report for the HGF project, in "Global zukunftsfähige Entwicklung. Perspektiven für Deutschland", DLR–Institut für Technische Thermodynamik, Stuttgart (2001). www.dlr.de/TT/system/projects/nachhaltige_Entwicklung
37. Pembina, 'Climate-Friendly Hydrogen Fuel: A Comparison of the Life-cycle Greenhouse Gas Emissions for Selected Fuel Cell Vehicle Hydrogen Production Systems', Pembina Institute, Drayton Valley, Canada (2000).
38. P. Ekdunge and M. Raberg, *Int. J. Hydrogen Energy*, **23**, 381 (1998).
39. D. Hart and A. Bauen, 'Further Assessment of the Environmental Characteristics of Fuel Cells and Competing Technologies', Department of Trade and Industry, London (1997).
40. P. Zapp, 'Ganzheitliche Material- und Energiefluß analyze von SOFC Hochtemperaturbrennstoffzellen' (Life-cycle Material and Energy Analysis of SOFC High Temperature Fuel Cells), Dissertation Thesis, Universität-Gesamthochschule Essen (1997).
41. J. V. Dedikov, G. S. Akopova, N. G. Gladkaja, A. S. Piotrovskij, V. A. Markellov, S. S. Salichov, H. Kaesler, A. Ramm, A. M. V. Blumencron and J. Lelieveld, *Atmos. Environ.*, **33**, 3291 (1999).
42. W. Zittel, 'Untersuchung zum Kenntnisstand über Methanemissionen beim Export von Erdgas aus Ruß land nach Deutschland, Endbericht', Ludwig-Bölkow-Systemtechnik, Ottobrunn (1997).
43. Methane leakages, IfE, in [44].
44. P. Biedermann, H. Dienhart, T. Dreier, T. Grube, B. Höhlein, R. Menzer, J. Nitsch, M. Pehnt and U. Wagner, 'Ganzheitliche Systemuntersuchung zur Energiewandlung durch Brennstoffzellen. Abschlußbericht des Forschungszentrum Jülich, des Deutschen Zentrums für Luft- und Raumfahrt und der Technischen Universität München', Forschungsvereinigung Verbrennungskraftmaschinen E.V., Frankfurt (1998).
45. 'VDEW-GEMIS-Datensatz. Energiebedarf und Emissionen von Kraftwerken und Prozessen', VDEW, Fichtner Development Engineering, Stuttgart (1996).

46. M. Pehnt, ‘Life-cycle Assessment of Biomass Fuels for Fuel Cell and Engine Combined Heat and Power Production. Biomass for Energy and Industry’, 10th European Conference and Technology Exhibition, Würzburg, Germany, June 8–11 (1998).
47. P. Olausson, ‘Life-cycle Assessment of an SOFC/GT Process’, Thesis, Department of Heat and Power Engineering, Lund Institute of Technology (1999).
48. NYSERDA, ‘200-kW Fuel Cell Monitoring and Evaluation Program. Final Report’, New York (1997).
49. H. Dienhart, M. Pehnt and J. Nitsch, ‘Analyze von Einsatzmöglichkeiten und Rahmenbedingungen verschiedener Brennstoffzellensysteme in Industrie und zentraler öffentlicher Stromversorgung’ (Analysis of the Framework and the Applications of Fuel Cells in Industry and Central Electricity Production), Report for the Office for Technology Assessment of the German Parliament, DLR–Institut für Technische Thermodynamik, Stuttgart (1999).
50. R. Dones, U. Gantner, S. Hirschberg, G. Doka and I. Knoepfel, ‘Environmental Inventory for Future Electricity Supply Systems for Switzerland’, Paul-Scherrer-Institut, ETH Zürich, Villigen, Switzerland (1996).
51. Technology Assessment Project, ‘Brennstoffzellen-Technologie’ (Fuel Cell Technology), Office for Technology Assessment of the German Parliament, TAB Report No. 67, Berlin (2000).
52. J. Scholta and M. Zedda, ‘Forschungsverbund Sonnenenergie’, in “Zukunftstechnologie Brennstoffzelle”, pp. 26–31 (2000).
53. K. G. Duleep, ‘Cost and Fuel Efficiency of 2010 Cars’, in “The Costs and Benefits of Electric Vehicles. Should Battery, Hybrid and Fuel-cell Vehicles be Publicly Supported in Sweden? Report of the KFB, Department of Economics, Göteborg University”, F. Carlsson and O. Johansson-Stenman (Eds), Göteborg (2000).
54. F. Gossen, ‘Der Brennstoffzellenantrieb im Vergleich zu konventionellen Antrieben’ (The Fuel Cell Power Train Compared to Conventional Power Trains), IIR Konferenz Brennstoffzellen, Stuttgart (2000).
55. C. Carpetis, ‘Globale Umweltvorteile bei Nutzung von Elektroantrieben (mit Brennstoffzellen und/oder Batterien) im Vergleich zu Antrieben mit Verbrennungsmotor’ (Global Environmental Advantages of the Use of Electric Power Trains), STB Report No 22, Deutsches Zentrum für Luft- und Raumfahrt, Institut für Technische Thermodynamik, Stuttgart (2000).