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Life Cycle Assessment of Fuel Cell Systems

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1 Abstract

Due to the efficient and (almost) zero emission operation of fuel cells, they are particularly attractive for application in the transportation sector and in stationary power conversion. 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. In this "cradle-to-grave approach", not only the use phase, but also the supply of the fuel and the production and disposal/recycling of the vehicle or power plant have to be considered. The appropriate instrument for this task is Life Cycle Assessment (LCA).

This chapter presents LCAs of fuel cells in mobile and stationary applications with different fuel options and compares them to conventional power train or plant options focussing on different environmental aspects such as use of resources, global warming, acidification and emission of carcinogenic substances. For this purpose, the future developments of the fuel cell competitors, e. g. internal combustion engines, gas turbines, combined cycle plants etc., have to be taken into account as well.

In vehicle applications, special focus is paid to the question of the best fuel which is of high importance for the performance of fuel cell vehicles. Also the production of the required materials, e. g. catalyst materials, and system components will be described and assessed.

In stationary systems, cogeneration applications using low and high-temperature fuel cells are investigated thoroughly.

2 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 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 eletric 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).

Figure 1 next to here

With the increasing environmental operation standards of modern energy conversion systems, the up- and downstream processes, e. g. fuel supply or system production, become increasingly relevant. While, for instance, in conventional road vehicles, the production of the vehicle only contributes 10 % to the life cycle greenhouse gas 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.

2.1 Brief Introduction to LCA

The instrument to assess these environmental impacts is called life cycle assessment (LCA). In the past ten years, the use of LCA has grown rapidly. Parallel to this development, an international standardisation process was started with ISO norms 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.

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

Figure 2 next to here

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 in- 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 below).

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 which are carefully recorded. While flows within the boundaries of the system are the “commodities” or “commodity flows”, flows across boundaries are called the “elementary flows”. The latter can be emissions (pollutants), energy carriers or other raw materials (resources). The main product or the co-products, energy carriers, accessories, wastes and emissions into air, water or soil are outputs leaving the system boundaries.

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 output flows to the biosphere to so-called impact categories, such as the global warming potential, by multiplication with characterisation factors.

The development of impact categories with relevant characterisation factors has been discussed intensively in [2] with more recent developments published in the International Journal of Life Cycle Assessment and other publications. Impact categories include

- the *depletion of abiotic resources,* for instance fossil energy carriers and uranium, metals or other materials.
- the *depletion of biotic resources* as a measure of overexploitation.
- the *global warming potential (GWP).* The emission of greenhouse gases (GHG) 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 global warming potential can be attributed to these anthropogenic climate gases which evaluate the effectivity in increasing the temperature relative to carbon dioxide for a given reference time. Most recent GWPs are published by the Intergovernmental Panel on Climate Change.
- the *depletion of stratospheric ozone* particularly by chlorinated and brominated compounds, nitrous oxide, and indirectly by the greenhouse effect. The ozone depletion is quantified using the ozone depletion potential with CFC-11 as reference substance.
- the *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 operationalised 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 sulphur dioxide as a reference [2].

- the *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. The 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].
- the emission of *ecotoxic and human toxic substances*, e. g. pesticides, heavy metals, carcinogenic substances. For these complex impact categories, a number of different quantifications have been tried [3].
- the *emission of radioactive substances* [4,5].
- other impact categories, such as land use, noise, waste and odour.

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

- a *normalisation*, 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 valuesphere, i. e. the perceived seriousness of ecological damage.

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

2.2 Goal and Scope of this Article

The goal of this article 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 which require further research or practical experience with power plants or vehicles.

3 Mobile Applications

3.1 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 focussed on applications in passenger vehicles. The following chapter will therefore focus on this application. A few remarks, however, shall be made regarding other possible applications.

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 signifance. 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.

Railways. The use of fuel cells in railways is considered particularly for not electrified railway lines. In electric trains, the use of fuel cells is generally less attractive than in busses 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 busses: 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**.

In the following, results of different LCAs of passenger vehicles are reviewed.

3.2 Production of the Fuel

3.2.1 General Aspects

The question of the "right" fuel is of high importance for the overall assessment 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 chapter – but also the environmental impacts for the different fuels are of importance.

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 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 also reduces these impacts to low inputs of fossil energy along the production chain.

The *efficiencies and impacts of processing* are of importance as well. 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.

Fuel chains have been assessed in a number of different studies focussing on different environmental impacts, countries and applications [7-20].

3.2.2 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 AS 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 H_2 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 [21] using LCA.

Figure 3 next to here

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 byproduct. As base case, [22] assumes extremely optimistic 89 % (HHV; steam exported) whereas [19] assumes 70 %. In [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 accout, 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, one kWh wind electricity, fed into the German electricity grid, presently avoids 700 g 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 avoids

320 g. In the next 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, also the supply of hydrogen has to be considered to determine its related emissions and effects to the environment. As an example, Figure 4 compares different transport scenarios of hydrogen produced in Norway from renewable electricity and subsequently transported to Germany [15]. 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 GHG 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 emissions of the LH_2 tanker and, if heavy oil is used as fuel for the tankers, the SO_2 emissions.

Figure 4 next to here

3.2.3 Methanol

Methanol is under consideration as a "liquid hydrogen storage". If produced from natural gas, the efficiency of the methanol conversion plant is of main importance for the overall impact, especially for the primary energy demand and the greenhouse gas (GHG) emissions. Efficiencies of average plants (LHV methanol/LHV natural gas) are well below 65 % leading to CO_2 emissions in the order of 30 to 40 g CO_2/MJ 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]. It is important that not the efficiency at the optimum operating point is of interest in LCAs, but the efficiency averaged over the life-time including degradation effects, start-ups after maintenance, etc. In addition, the marginal efficiency improvements lead to overproportionally high incremental costs thus making efficiently produced methanol clearly more expensive.

Methanol can also be produced using biogen synthesis gases, such as from 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].

3.2.4 Gasoline and Diesel

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

3.3 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 to 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 [15,25], an effort has been made to calculate impacts from fuel cell vehicle production in as much detail as possible. The LCA of *fuel cell stack production* in [15,25] was carried out 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) (Figure 5).

Figure 5 next to here

Due to the early stage of development, the *balance-of-plant* materials could only be roughly estimated. Of particular importance are the PGM for catalyst materials in the stack, the reformer and an eventual Pd/Ag membrane for gas clean-up (with methanol as a fuel).

The *production of the car body and the conventional vehicle* in [25] is taken from [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 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.

Analysing 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 platinum group metals (PGM) used as catalysts. PGM are mainly produced 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, the mining of PGM results in significant environmental interventions particularly because of the 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 [25,28].

Figure 6 next to here

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 half 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 the efforts to reduce the weight of the flow plates. These 13 % are partly caused by the graphite production itself and partly by the use of a resin impregnant.

Improvement potentials as identified in [25] include

- The *reduction of PGM loading.* Compared to earlier stack generations the PGM loading has already been reduced substantially from 8 mg/cm^2 to 1 mg/cm^2 and 0.3 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 a rapid, global introduction of fuel cells occurs, recycling becomes a main issue also because of the ressource situation (for further information on PGM ressources refer to [29]).
- *Maximizing the PGM yield* during production. The yield of PGM 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 PGM yields to up to 99 %.
- *Recycling of catalysts.* An 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 the environmental impacts for PGM production by a factor 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 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 [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 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.

- *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 the efficiency*. Of course, maximizing the 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).

3.4 Operation of Fuel Cell Vehicles

For conventional vehicles based on internal combustion engines, the fuel combustion and the concomitant CO_2 emissions as well as the 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 1). Mainly, these studies had to be based on modelling 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, main assumptions in various studies are summarised and the environmental aspects considered are given. Also indicated in the table are the achieved fuel economy ratios (ICE fuel economy/FC fuel economy) in these reports as indicated in Figure 7.

Table 1 next to here

Table 2 next to here

Figure 7 next to here

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 (EPA US 06 cycle) [32]. With increasing stop and go or accelaration at high speeds, the fuel economy ratio decreases due to the lower full load efficiency of fuel cell systems.

For the determination of the fuel economy changes, also the characteristics of the baseline gasoline vehicles are 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 are demonstrated on the market already but which have not yet diffused into the market on a large scale. For instance for a compact sized car, the 3l/100 km (1 MJ/km) vehicle is state of the art but far from average fuel economies. For the reasons summarised 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 is 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 efficiency. Also, the assumptions regarding additional weight of the fuel cell drive train differ significantly.

The calculated fuel economy ratios show the large bandwidth of results depending on the circumstances even if the same model is applied. In [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 [34], ratios of 2.8 to 3.15 (H_2) and 2.1 to 2.5 (methanol), respectively, are presented. In the most recent study by General Motors coauthored by 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 analysed 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 < 1.5 becoming realistic.

3.5 The Conventional Competitors

Future developments will also focus on optimising conventional vehicles. More stringent emission levels in many nations lead to intensive research in the optimisation 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.

3.6 The Total Picture

In the following, the 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.

3.6.1 Greenhouse Gas Emissions (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 the 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 of future ICE vehicles, the 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 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 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 Next to here

Figure 8 (left) also shows that for methanol fuel cell vehicles, the direct emissions are lower due to a better power train efficiency. Unfortunately, methanol production is less efficient than todays gasoline and diesel production. Therefore, the share of „fuel supply“ in Figure 8 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 clean-up). Methanol produced from wood avoids the increase in GHG emissions. It should be mentioned that methanol can also be used in the internal combustion engine.

In **conclusion**, there is still uncertainty about the degree of GHG reduction fuel cell vehicles can offer in this market segment. Especially, the 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.

3.6.2 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, the acidification from the energy chain and production is well below the gasoline ICE with the exception of the LH_2 transported with a heavy oil tanker (Figure 9 left). 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. The 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 recognised, however, that the Euro 4 emission standard is quite strict and that therefore, the absolute emission level of Figure 9 is not very high.

Figure 9 next to here

3.7 Conclusions

Fuel cells offer advantages in many different impact categories. However, the competition of 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.

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 greenhouse gas advantage of FCVs 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 SMR 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 the gasoline and diesel vehicles, possess significant improvement potentials. Once mass reduction and reduction of rolling and air resistance are realised, 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 optimised 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 < 20 % partial load is avoided which is important because the fuel cell system has an optimum efficiency at partial load > 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 promoting the introduction of this power train, e. g. the simple realisation of brake energy recovery with an adequate storage device, the compatibility with drive-by-wire or autopilot technologies, innovative safety concepts that can be realised with electric vehicles, and higher user comfort and acceleration. In addition, auxiliary power unit (APU) applications, especially in trucks, can be an extremely attractive option for fuel cell use given the efficiencies of current automobile electricity generators as low as 5 %.

4 Stationary Systems

4.1 Overview

Fuel cells can be applied in various stationary applications, ranging from one kW_{el} systems for domestic heating, combined heat and power production (CHP) for district heating or large buildings, up to MW 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.

Figure 10 next to here

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

4.2 Production of the Fuel

4.2.1 Natural gas

In the near and midterm future, natural gas will be the fuel of choice for stationary applications. The life-cycle of natural gas comprises the exploration and extraction, 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 of the long-distance and the local distribution pipelines; this issue has been raised for 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 global warming potential of methane leads to a significant influence of that leakage rate;
- and the 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; lower efficiency due to transportation) [8].

4.2.2 Renewable Fuels

For longterm 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. The electricity, in contrast, can easily be fed into the grid. Generally, in 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.

4.3 Production of the Power Plant

In the following, the production of PEFC and SOFC power plants will be presented. For other fuel cell technologies, LCAs of the system production have not yet been carried out.

4.3.1 PEFC

For the production of PEFC power plants, an LCA has been carried out in [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 hours instead of 4,000 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 phosphoric acid fuel cell, 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, the 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, the 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.

4.3.2 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 SOFC has only been assessed in two studies [40] (and [47] mainly based on [40]) calculates cumulative energy demands for the materials. Due to the early publication date, only aggregated and preliminary data was available. [47] calculates unusually high impacts of the manufacturing process. In [15], industrial LCA data on the materials was 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.

Figure 11 next to here

In Figure 12, the primary energy demand, the global warming potential 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 platinum group metals for PEFCs below).

Figure 12 next to here

Figure 13 shows that 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 analysing the contribution of different processes to the stack production (Figure 13 below) 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.

Figure 13 next to here

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

4.4 Operation of Fuel Cell Power Plants

4.4.1 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, detailed emission data is available. Averaging over load factors higher than 50 % results in emission factors from the reformer burner as given in Table 3.

Table 3 next to here

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 the fuel utilisation 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 3-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 the exhaust emissions. Estimates of future power plant generations are presented, for instance, in [12,15,49,50].

4.4.2 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). 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 optimisation potentials are also included in Figure 14 as the upper boundaries of the boxes.

Figure 14 next to here

Refering to natural gas as a fuel, in the low power range, PEFC have electrical efficiencies in the order of 32 to 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) MCFC. In future, coupling fuel cells with gas turbines to use the exhaust heat promises efficiencies of up to 68 % at the beginning of the operation, with expected degradation to 62-64 % at the end of the life.

However, conventional systems are constantly optimised. 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 [49]. For systems operated not 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 [15], a PEFC was modelled 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.

4.4.3 Thermal/total efficiency

For combined heat and power production, the thermal efficiency is of importance as well. The thermal efficiencies of conventional systems have been a key parameter for past optimisation 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 are realistic. Combined cycle CHP plants can also reach thermal efficiencies of 50 % resulting in total efficiencies of nearly 90 %.

The 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, the 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 the conventional systems, future work should also focus on increasing thermal efficiencies by using the reformer exhaust heat and other heat sources.

4.5 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 [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 normalised 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 electricity and y kWh heat simultaneously, the impacts of producing y kWh heat with a modern natural gas are subtracted from the total impacts because this heat production is substituted by the cogeneration system.

Figure 15 next to here

It is obvious that high-temperature fuel cells in this application offer significant advantages compared to the competing technologies. Considering the global warming potential, an 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 above).

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 3 MW_{el} power range produces less greenhouse gases than an 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 more than 90 % (LHV) because 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 optimum 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, 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 electro-chemical etching of the interconnects) and the chromium for the planar interconnects. For tubular SOFCs, the environmental impacts from production are different.

Figure 16 next to here

A second example compares an 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, avoiding an increased emission level which is typical for many other biomass based energy converting systems. In addition, low heat-to-power ratios are advantegeous if the external heat demand is limited as is often the case in biogas plants [46]. Additionally, a trend towards higher electricty compared to heat demand can be observed in industry.

Figure 17 next to here

5 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. Batteries contain ecologically critically 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 will be disposed of. 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 supply of the production will play a less important role than the substitution of batteries. As the fuel cell systems will have longer life times 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 similar size with efficiencies between 20 to 28 % depending on the load factor [52]. In addition, clear reductions in the noise level can be achieved.

6 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 (Life Cycle Assessment 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 getting stronger 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 internal combustion engine (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 greenhouse gas (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 H_2 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 the 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 ressource and GHG advantages compared to the competing technologies. An SOFC/gas turbine system in combined heat and power production (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 optimised. This is particularly important for low temperature fuel cells in CHP applications where some engine CHP plants show total effiencies 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.

The future development 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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[58] GaBi_3, 'Ganzheitliche Bilanzierung. Software-Plattform zur Ganzheitlichen Bilanzierung', Institut für Kunststoffprüfung und Kunststoffkunde der Universität Stuttgart, Stuttgart (1998).

[59] N. Q. Minh and T. Takahashi, 'Science and Technology of Ceramic Fuel Cells', Elsevier, Amsterdam (1995).

[60] DLR, Personal Communication Mr R Ruckdäschel, Institute for Technical Thermodynamics, German Aerospace Center Stuttgart (1998).

[61] Plansee, Personal Communication Mr M Janousek, Plansee AG Reutte (Austria) (1998).

[62] GEMIS, 'Gesamt-Emissions-Modell Integrierter Systeme (GEMIS) Version 2.1, Endbericht', Öko-Institut, Darmstadt u. a. (1994).

[63] Leistritz, Personal Communication Dr. M. Baumgärtner, Leistritz AG Nürnberg (1998).

[64] LWK, Personal Communication Dr. W Schultze, LWK Plasmakeramik (1998).

[65] R. Hardt, Personal Communication Mr Hardt, Industriekontor Hardt, Düsseldorf (1999).

8 Table and Figure legends

Table 1 Important parameters for calculating fuel cell vehicle fuel economies

Table 2 Review of input parameters, fuel economy ratios and analysed environmental impacts in various studies

Table 3 Emission factors of a number of ONSI PAFCs per kWh_{el} and per MJ LHV fuel input [49]

Figure 1 The life cycle of fuel cells

Figure 2 Life Cycle Assessment according to [1]

Figure 3 Selected hydrogen production and supply paths [21]

Figure 4 Comparison of GHG emissions and acidification for different transport scenarios of renewable hydrogen (normalised to GH_2 with high voltage direct current (HVDC) transmission)

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.

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

Figure 8 Greenhouse gas emissions of different power train and fuel options. Data sources: Left: [15]. H_2 ICE according to [14]. Right: Fuel consumption and fuel chains according to [20], vehicle production from [15].

Figure 9 Acidification and carcinogenic emissions of different power train and fuel options. Data from [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 H_2 from carbon black credit.

Figure 10 Applications, systems and competitors of stationary fuel cells

Figure 11 SOFC stack production process used for the LCA in [15]

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

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

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

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 normalised 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 eq.; 1.46 g SO_2 eq.; 0.153 g PO_4^{3-} eq.; 0.625 g NMHC; 2.54 e-6 g*URF carcinogenic emissions

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 %.

9 Tables

Table 1

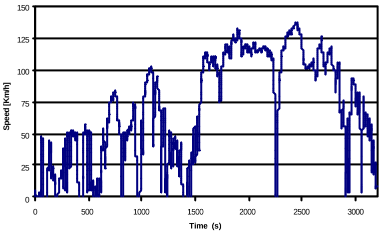
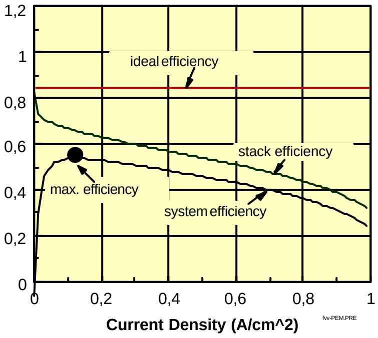
<table>
<tr><th>Parameter</th><th>Subparameter</th><th>Comments</th><th>Illustration</th></tr>
<tr><td rowspan="4">Mechanical energy demand</td><td>Mass</td><td>- Leight weight materials
- Weight of power train, incremental weight of fuel cell system</td><td></td></tr>
<tr><td>Rolling resistance</td><td></td><td></td></tr>
<tr><td>Air resistance</td><td></td><td></td></tr>
<tr><td>Driving characteristics/ driving cycle</td><td>- more dynamic driving cycles lead to shifts in favor of ICEs</td><td>
</td></tr>
<tr><td rowspan="3">Efficiencies of system components</td><td>Polarization curve</td><td>Operation point is important: Offset between maximum efficiency and maximum power</td><td rowspan="3">
</td></tr>
<tr><td>Reformer (MeOH)</td><td></td></tr>
<tr><td>Parasitic loads</td><td></td></tr>
<tr><td rowspan="2">Power management</td><td>Battery</td><td>- avoid full load or idle operation
- cold start</td><td></td></tr>
<tr><td>Brake energy recovery</td><td></td><td></td></tr>
</table>

Table 2

	Time Frame	General Vehicle and Study Parameters							ICE		Fuel Economy Ratio			General Information on Study			Comments	Ref.#
		Weight of Body & Chassis & Driver	Incremental Weight of FC compared to ICE			Air Drag	Rolling Res. Coeff.	Driving Cycle	Gasoline Consumption	Emission Level	ICE Fuel Consumption/FC Fuel Consumption			Vehicle Production Considered?	Fuel Chains?	Environmental Impacts Considered		
			CH2	MeOH	Gasoline	cW*A					CH2	MeOH	Gasoline					
		kg	kg	kg		m2			MJ LHV/km									
Thomas 2000		Ford Sable (Aluminum intensive)						faster EPA	2,53		2,2	1.62 (best case)						[32]
Methanex 2000	2020		approx. 0	200	200			faster 55/45	2,90	-	2,2	1,74	1,45	streamlined	yes	PE, GHG	very high MeOH reformer effici. (89,5 %). Almost equal values for production of ICE and FC vehicles. 75 % efficiency of MeOH production.	[24]
Wang 1998	2010	Fuel Economy Ratio from Literature						55/45	2,53		2	1,85	-	no	yes	PE, GHG		[33]
Wang 1999	2010	Fuel Economy Ratio from Literature						55/45	3,16	Tier 2	2.8-3.15	2.1-2.5	1.75-2.25	no	yes	PE, GHG, VOC, CO, NOx, SOx, PM10	Values represent "incremental" and "leap-forward" scenarios, respectively.	[34]
GM 2001		full size pickup truck. Data proprietory							3,76	Tier 2 Bin 5	2.13 *	1.5 *	1.346 *	no	yes	PE, GHG		[35]
Pembina 2000		Mercedes A class						55/45	2,36		2,62	1,74	1,12	no	yes			[37]
Ekdunge 1997		1130	260	305												PE, GHG, some pollut.		[38]
ifeu/FZJ 1999	2010	825	42	115		0.6	0.008	NEDC	1,33	Euro 4	1,66	1,25	-	no	yes	PE, GHG, A, E, C, SS, OD		[14], [55]
								highway	1,89	Euro 4	1,26	1,05	-	no	yes	PE, GHG, A, E, C, SS, OD		
Carpetis 2000	2005-2010	950	370	570	670	0.61	0.01	NEDC + highway	1,78	Euro 4	1,46	1,19	1	no	yes	PE, GHG, NOx, NMVOC		[56]
Pehnt 2001	2010	825	320	410	-	0.6	0.008	NEDC + highway	1,60	Euro 4	1,55	1,27	-	detailed	yes	PE, GHG, A, E, C, SS, OD	baseline ICE vehicle is an improved gasoline vehicle	[15]
Gossen 2000	longterm	957 (tot)	85	185	-	0.58	0.0095	NEDC	1,52	Euro 4	1,58	1,22	-	no	no	Fuel Consumption		[54]
								Hyzem	1,65	Euro 4	1,31	1,13	-	no	no	Fuel Consumption		
MIT 2000	2020	892	78	139	222	0.396	0.006	55/45	1,54		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	2010	1418	90	226	-		0.008	55/45	2,20		2,4	1,8	-	no	no			[53]

NEDC: New European Driving Cycle, Hyzem: European Cycle combining dynamic urban, non-urban and highway parts, 55/45: 55 % FUDS, 45 % highway cycle

PE Primary Energy, GHG Greenhouse Gas Emissions, A Acidification, E Eutrophication, C Carcinogenity, SS Sommer smog, OD Ozon Depletion.   * higher, if charge sustaining hybrid electric vehicle is assumed

Table 3

	mg/kWh$_{el}$	mg/MJ$_{in}$
CO	15	1.7
NO_x	8	0.9
SO_2	0	0
NMVOC	2.5	0.3
CH_4	75	8.3
Particles	0	0

10 Figures

Figure 1

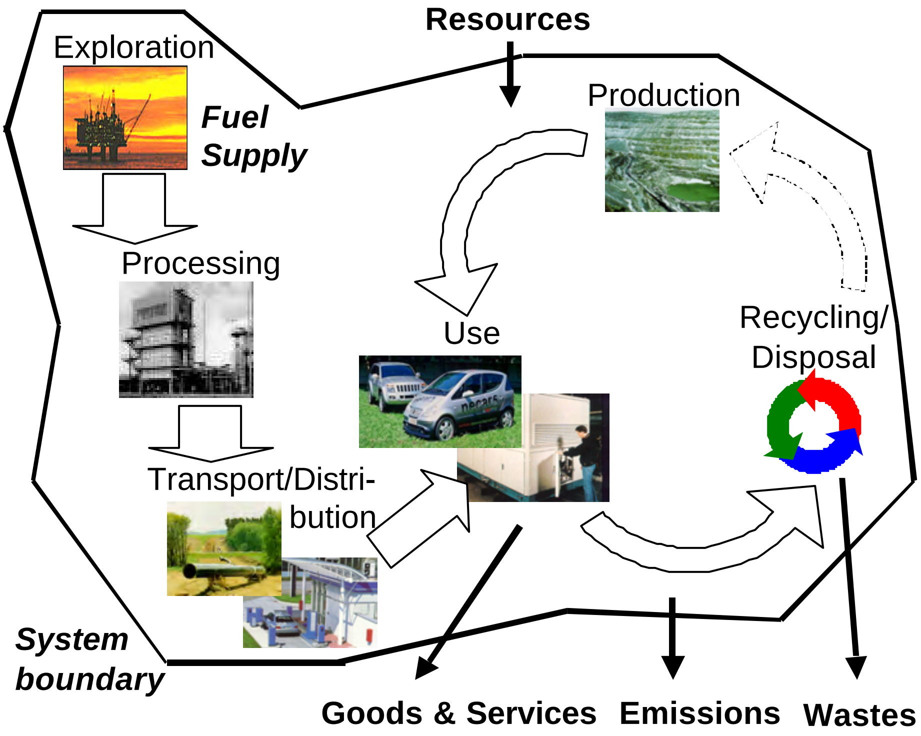


Figure 2

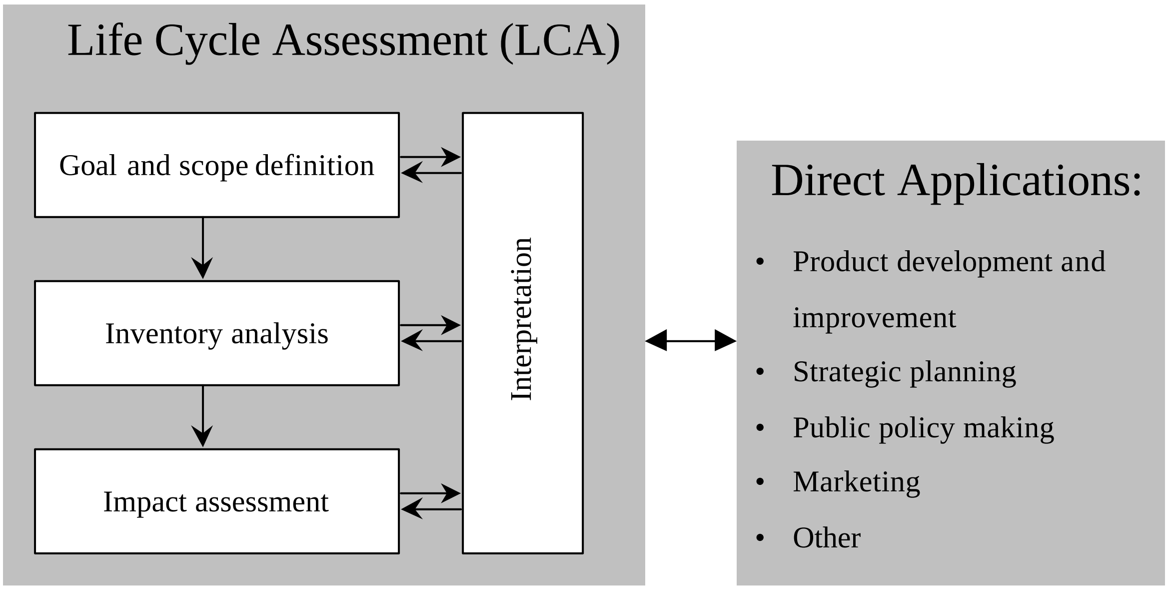

Life Cycle Assessment (LCA)
Goal and scope definition
Inventory analysis
Impact assessment
Interpretation
Direct Applications:
Product development and improvement
Strategic planning
Public policy making
Marketing
Other

Figure 3

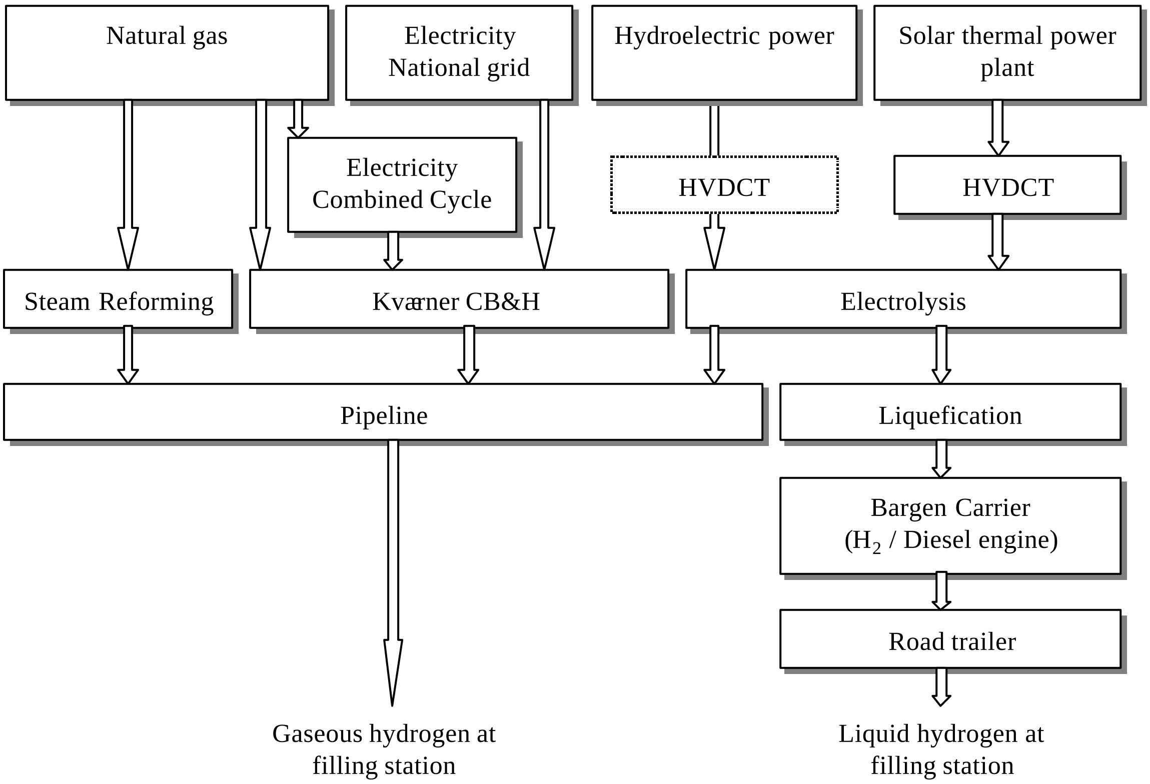

Natural gas
Electricity National grid
Hydroelectric power
Solar thermal power plant
Electricity Combined Cycle
HVDCT
HVDCT
Steam Reforming
Kværner CB&H
Electrolysis
Pipeline
Liquefication
Bargen Carrier (H2 / Diesel engine)
Road trailer
Gaseous hydrogen at filling station
Liquid hydrogen at filling station

Figure 4

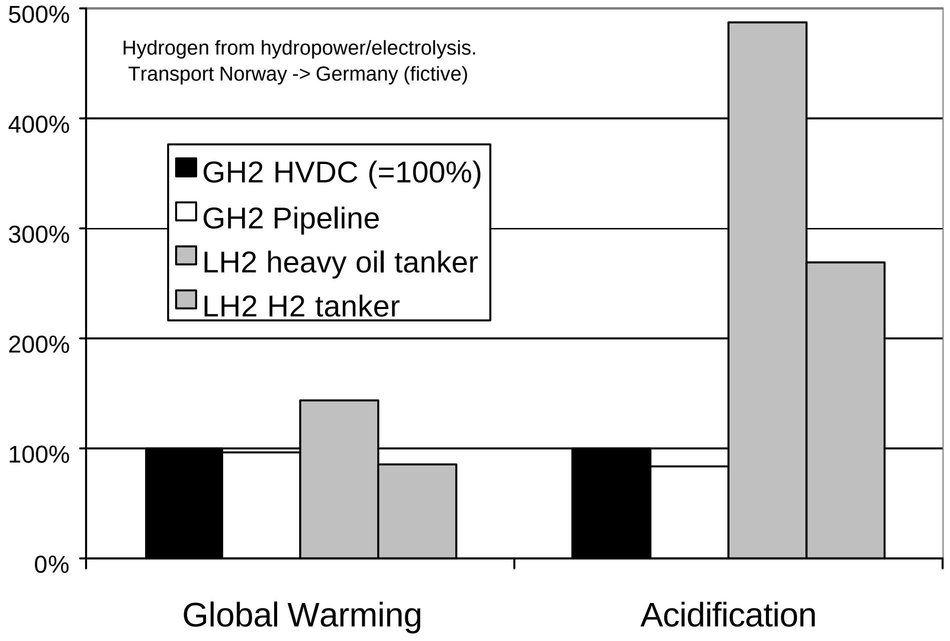

500%
400%
300%
200%
100%
0%
Hydrogen from hydropower/electrolysis.
Transport Norway -> Germany (fictive)
GH2 HVDC (=100%)
GH2 Pipeline
LH2 heavy oil tanker
LH2 H2 tanker
Global Warming
Acidification

Figure 5

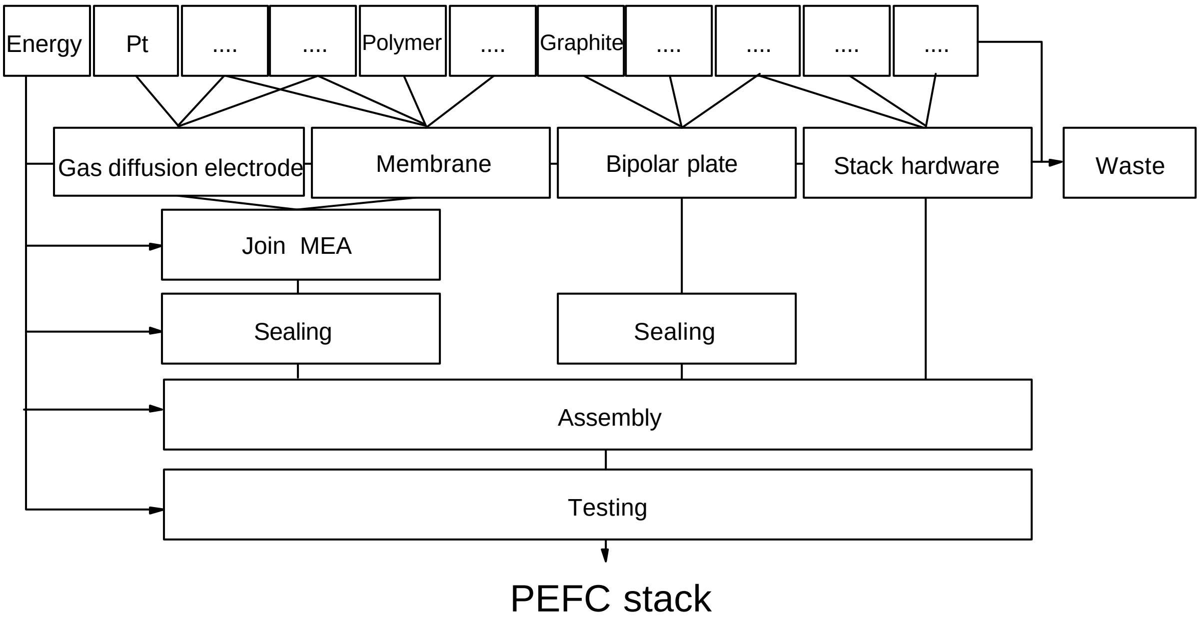

Energy
Pt
....
....
Polymer
....
Graphite
....
....
....
....
Gas diffusion electrode
Membrane
Bipolar plate
Stack hardware
Waste
Join MEA
Sealing
Sealing
Assembly
Testing
PEFC stack

Figure 6

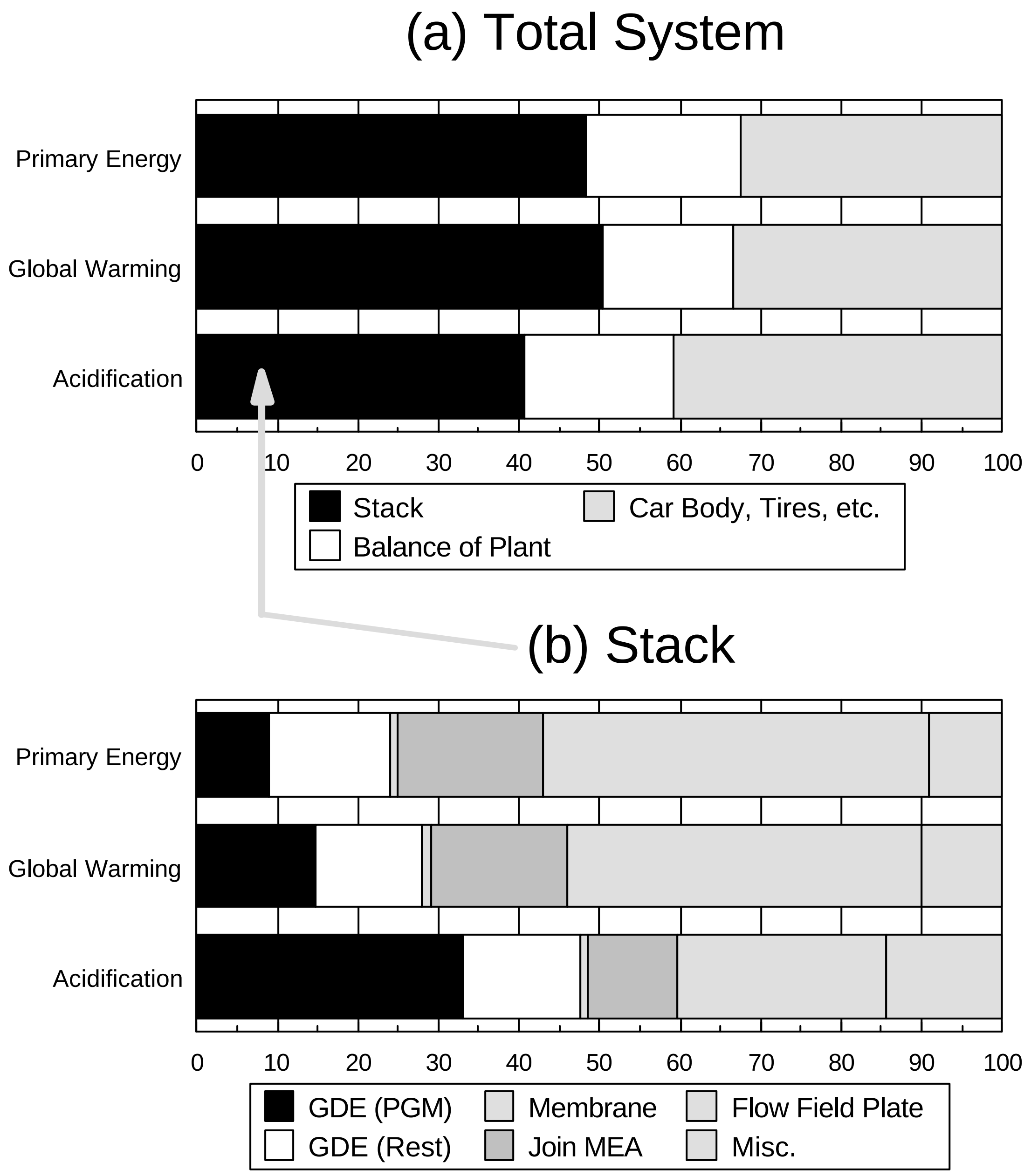

(a) Total System
Primary Energy
Global Warming
Acidification
0
10
20
30
40
50
60
70
80
90
100
Stack
Car Body, Tires, etc.
Balance of Plant
(b) Stack
Primary Energy
Global Warming
Acidification
0
10
20
30
40
50
60
70
80
90
100
GDE (PGM)
Membrane
Flow Field Plate
GDE (Rest)
Join MEA
Misc.

Figure 7

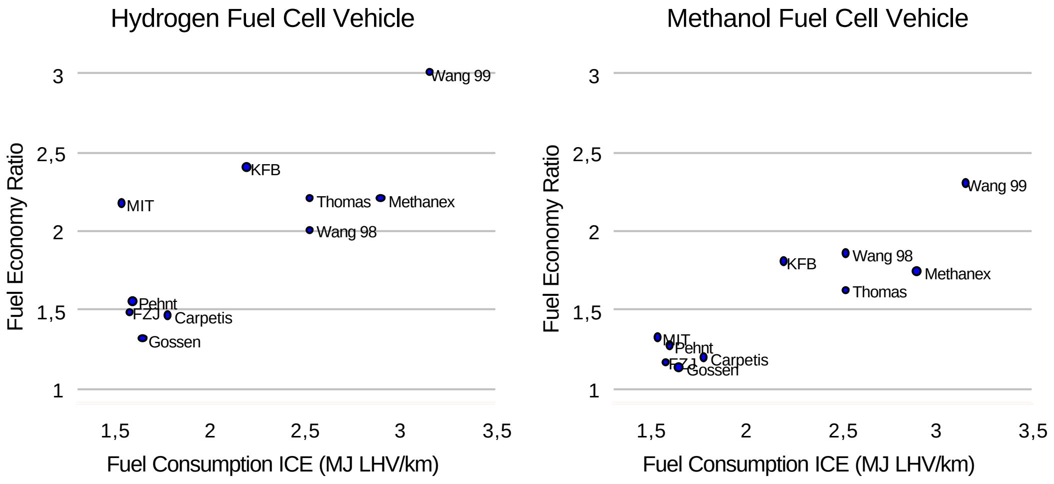

Hydrogen Fuel Cell Vehicle
Fuel Economy Ratio
3
2,5
2
1,5
1
Wang 99
KFB
MIT
Thomas
Methanex
Wang 98
Pehnt
FZJ
Carpetis
Gossen
1,5
2
2,5
3
3,5
Fuel Consumption ICE (MJ LHV/km)
Methanol Fuel Cell Vehicle
Fuel Economy Ratio
3
2,5
2
1,5
1
Wang 99
KFB
Wang 98
Methanex
Thomas
MIT
Pehnt
FZJ
Carpetis
Gossen
1,5
2
2,5
3
3,5
Fuel Consumption ICE (MJ LHV/km)

Figure 8

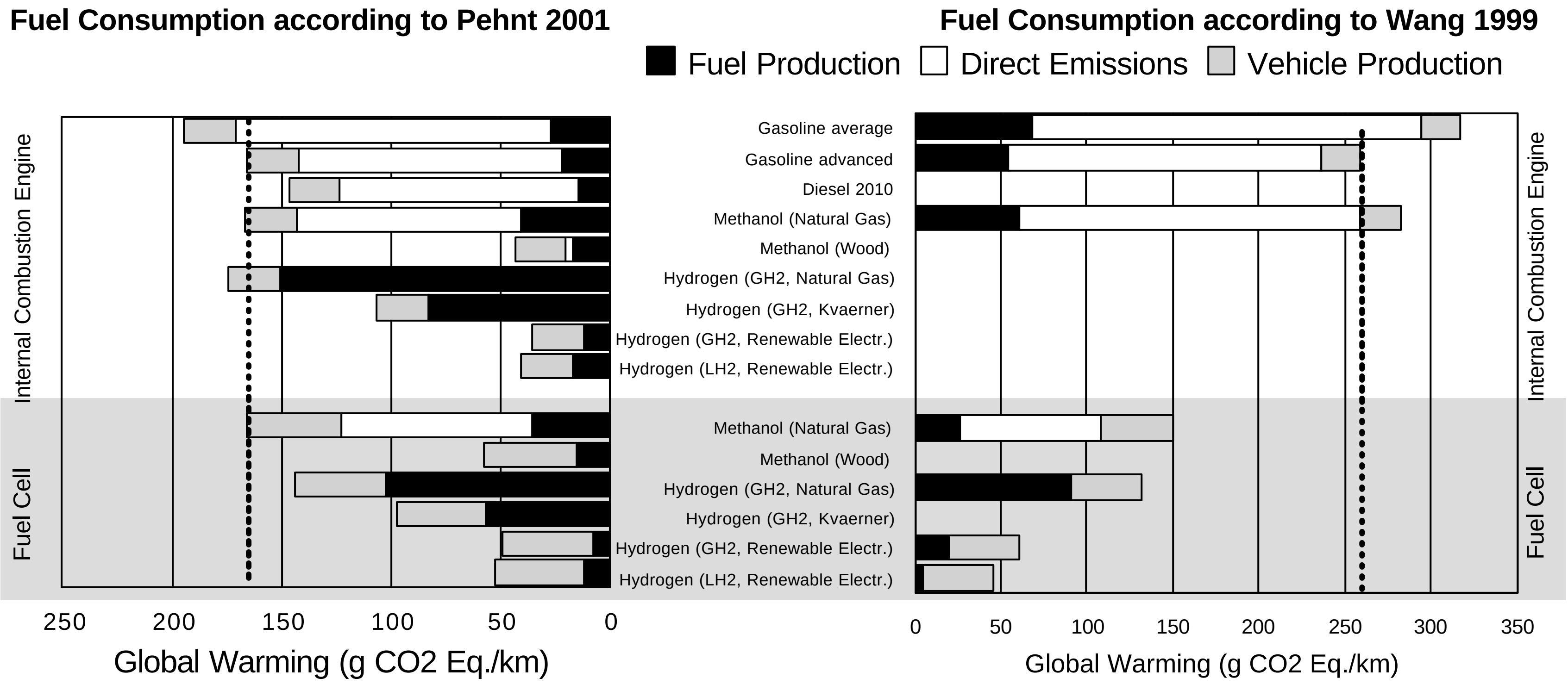
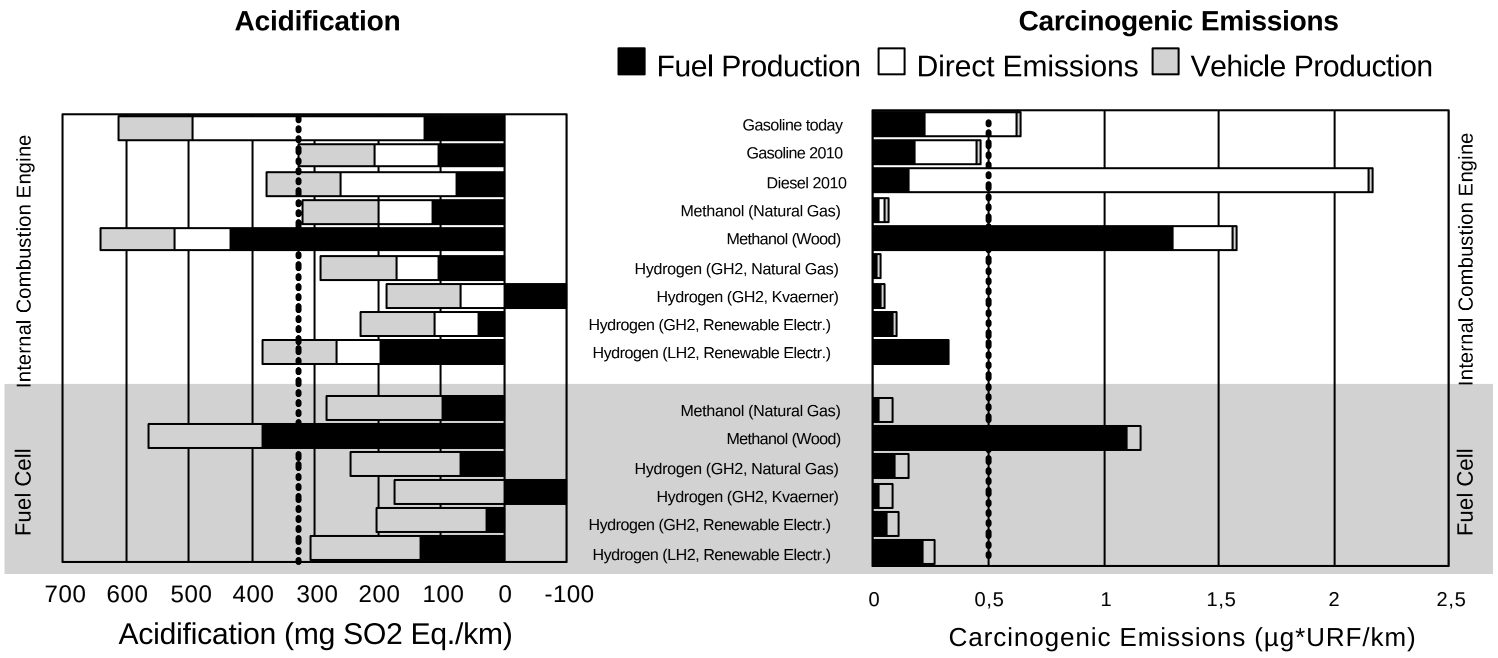

Fuel Consumption according to Pehnt 2001
Fuel Consumption according to Wang 1999
■ Fuel Production
☐ Direct Emissions
▨ Vehicle Production
Internal Combustion Engine
Fuel Cell
Gasoline average
Gasoline advanced
Diesel 2010
Methanol (Natural Gas)
Methanol (Wood)
Hydrogen (GH2, Natural Gas)
Hydrogen (GH2, Kvaerner)
Hydrogen (GH2, Renewable Electr.)
Hydrogen (LH2, Renewable Electr.)
Methanol (Natural Gas)
Methanol (Wood)
Hydrogen (GH2, Natural Gas)
Hydrogen (GH2, Kvaerner)
Hydrogen (GH2, Renewable Electr.)
Hydrogen (LH2, Renewable Electr.)
250
200
150
100
50
0
Global Warming (g CO2 Eq./km)
0
50
100
150
200
250
300
350
Global Warming (g CO2 Eq./km)
Internal Combustion Engine
Fuel Cell

Figure 9



(Line shift only in pdf document)

Figure 10

Power

Application

System

Competitor

$1\ kW_{el}$

House Heating

Small Engine CHPs

$10\ kW_{el}$

District Heating

Engine CHP

$100\ kW_{el}$

Industrial CHP

Gas Turbines

$1\ MW_{el}$

Power Plants

Combined Cycle Plants

$>1\ MW_{el}$

CHP: Combined Heat and Power Production

M. Pehnt

Figure 11

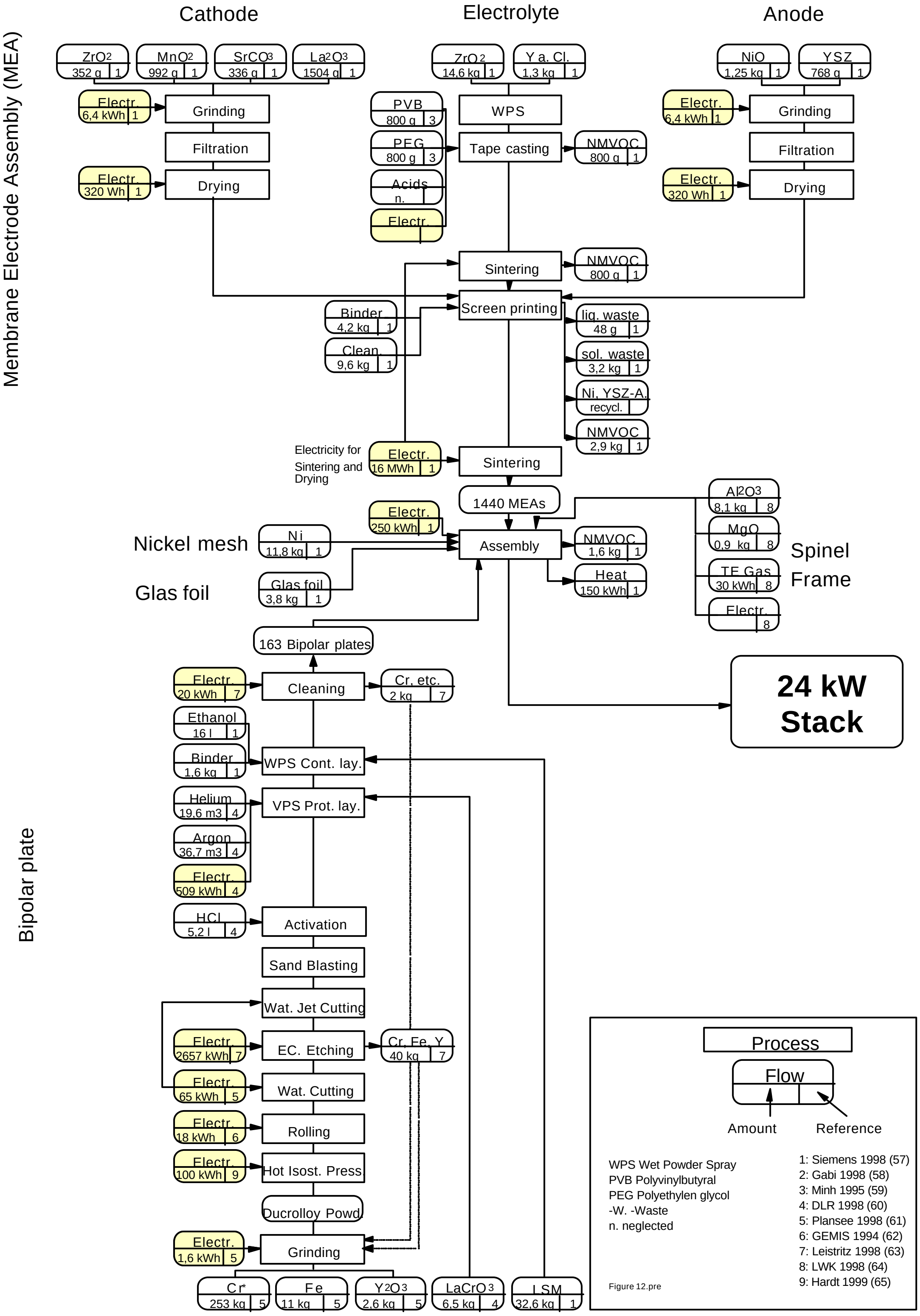

Membrane Electrode Assembly (MEA)
Cathode
Electrolyte
Anode
ZrO2 352 g 1
MnO2 992 g 1
SrCO3 336 g 1
La2O3 1504 g 1
Electr. 6,4 kWh 1
Grinding
Filtration
Electr. 320 Wh 1
Drying
ZrO2 14,6 kg 1
Y a. Cl. 1,3 kg 1
PVB 800 g 3
PEG 800 g 3
Acids n.
Electr.
WPS
Tape casting
NMVOC 800 g 1
Sintering
NMVOC 800 g 1
NiO 1,25 kg 1
YSZ 768 g 1
Electr. 6,4 kWh 1
Grinding
Filtration
Electr. 320 Wh 1
Drying
Screen printing
Binder 4,2 kg 1
Clean. 9,6 kg 1
liq. waste 48 g 1
sol. waste 3,2 kg 1
Ni, YSZ-A. recycl.
NMVOC 2,9 kg 1
Electricity for Sintering and Drying
Electr. 16 MWh 1
Sintering
1440 MEAs
Electr. 250 kWh 1
Nickel mesh
Ni 11,8 kg 1
Glas foil
Glas foil 3,8 kg 1
Assembly
NMVOC 1,6 kg 1
Heat 150 kWh 1
Al2O3 8,1 kg 8
MgO 0,9 kg 8
TE Gas 30 kWh 8
Electr. 8
Spinel Frame
163 Bipolar plates
24 kW Stack
Bipolar plate
Electr. 20 kWh 7
Cleaning
Cr, etc. 2 kg 7
Ethanol 16 l 1
Binder 1,6 kg 1
WPS Cont. lay.
Helium 19,6 m3 4
Argon 36,7 m3 4
Electr. 509 kWh 4
VPS Prot. lay.
HCl 5,2 l 4
Activation
Sand Blasting
Wat. Jet Cutting
Electr. 2657 kWh 7
EC. Etching
Cr, Fe, Y 40 kg 7
Electr. 65 kWh 5
Wat. Cutting
Electr. 18 kWh 6
Rolling
Electr. 100 kWh 9
Hot Isost. Press
Ducrolloy Powd.
Electr. 1,6 kWh 5
Grinding
Cr 253 kg 5
Fe 11 kg 5
Y2O3 2,6 kg 5
LaCrO3 6,5 kg 4
LSM 32,6 kg 1
Process
Flow
Amount
Reference
WPS Wet Powder Spray
PVB Polyvinylbutyral
PEG Polyethylen glycol
-W. -Waste
n. neglected
1: Siemens 1998 (57)
2: Gabi 1998 (58)
3: Minh 1995 (59)
4: DLR 1998 (60)
5: Plansee 1998 (61)
6: GEMIS 1994 (62)
7: Leistritz 1998 (63)
8: LWK 1998 (64)
9: Hardt 1999 (65)
Figure 12.pre

Figure 12

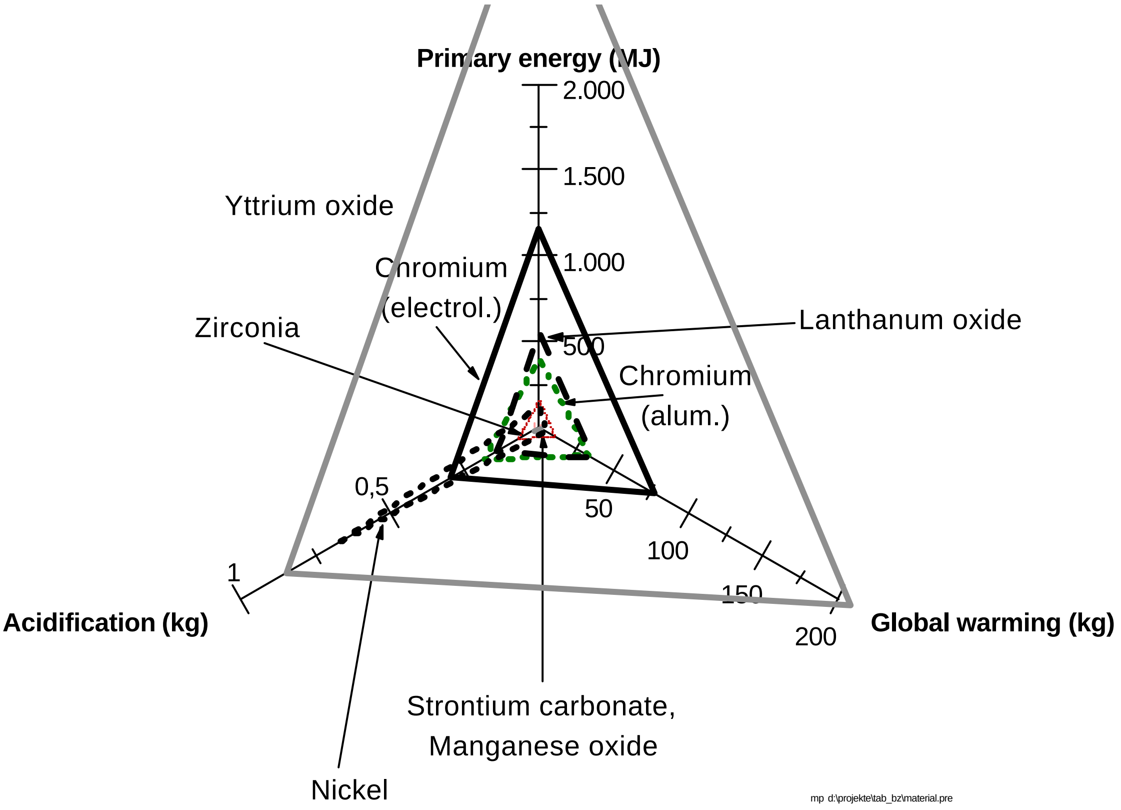

Primary energy (MJ)
2.000
1.500
1.000
500
Yttrium oxide
Chromium (electrol.)
Zirconia
Lanthanum oxide
Chromium (alum.)
0,5
1
50
100
150
200
Acidification (kg)
Global warming (kg)
Strontium carbonate, Manganese oxide
Nickel
mp d:\projekte\tab_bz\material.pre

Figure 13

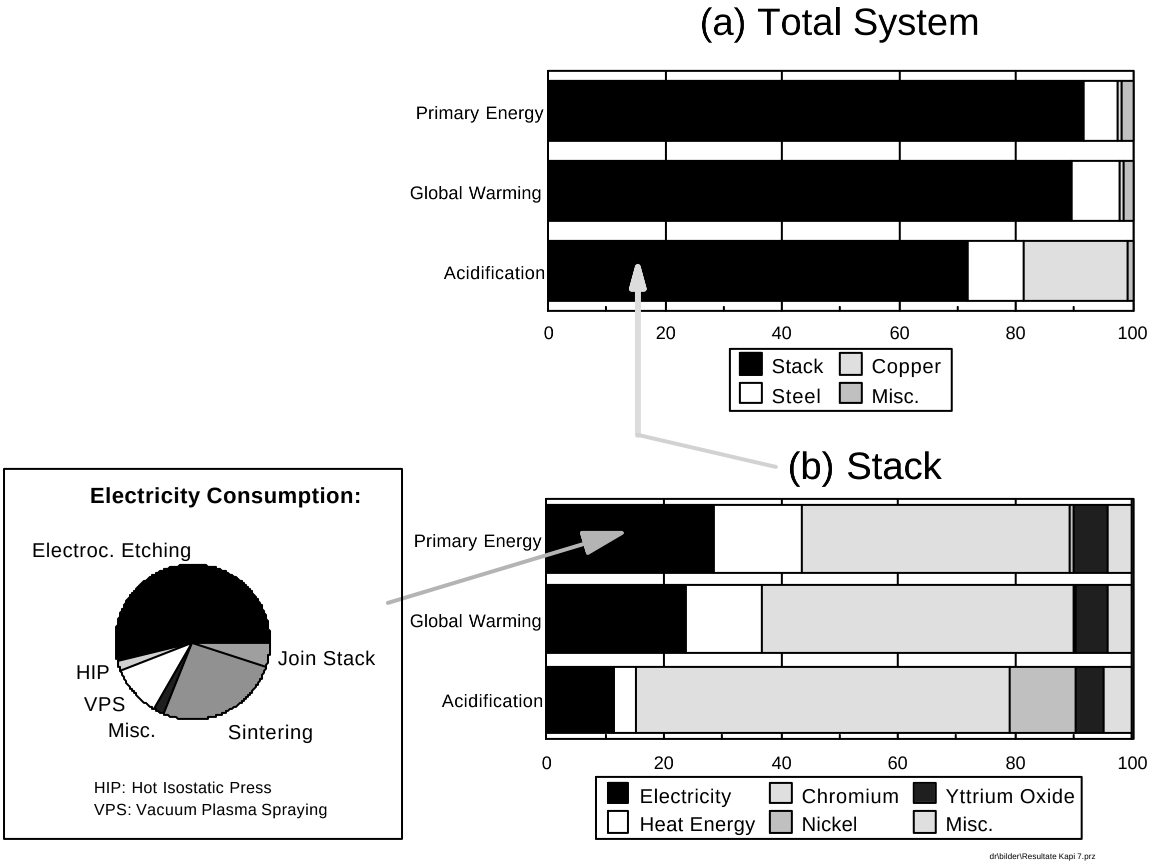

(a) Total System
Primary Energy
Global Warming
Acidification
0
20
40
60
80
100
Stack
Copper
Steel
Misc.
(b) Stack
Primary Energy
Global Warming
Acidification
0
20
40
60
80
100
Electricity
Chromium
Yttrium Oxide
Heat Energy
Nickel
Misc.
Electricity Consumption:
Electroc. Etching
Join Stack
HIP
VPS
Misc.
Sintering
HIP: Hot Isostatic Press
VPS: Vacuum Plasma Spraying
dr\bilder\Resultate Kapi 7.prz

Figure 14

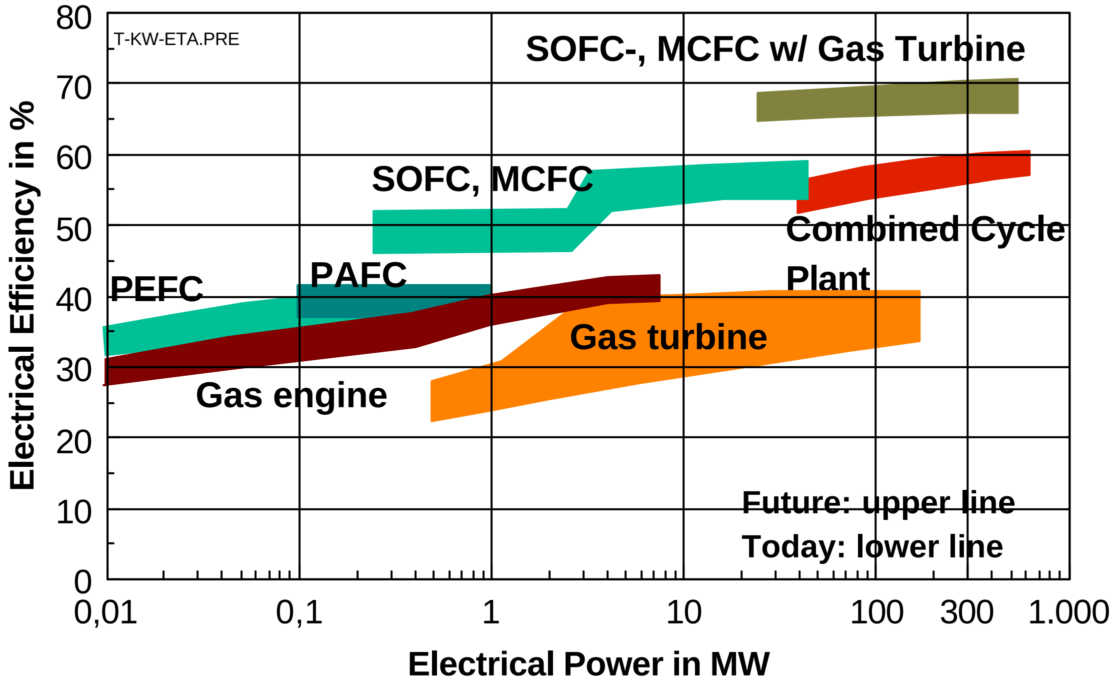

T-KW-ETA.PRE
SOFC-, MCFC w/ Gas Turbine
SOFC, MCFC
Combined Cycle
Plant
PEFC
PAFC
Gas turbine
Gas engine
Future: upper line
Today: lower line
Electrical Efficiency in %
0
10
20
30
40
50
60
70
80
0,01
0,1
1
10
100
300
1.000
Electrical Power in MW

Figure 15

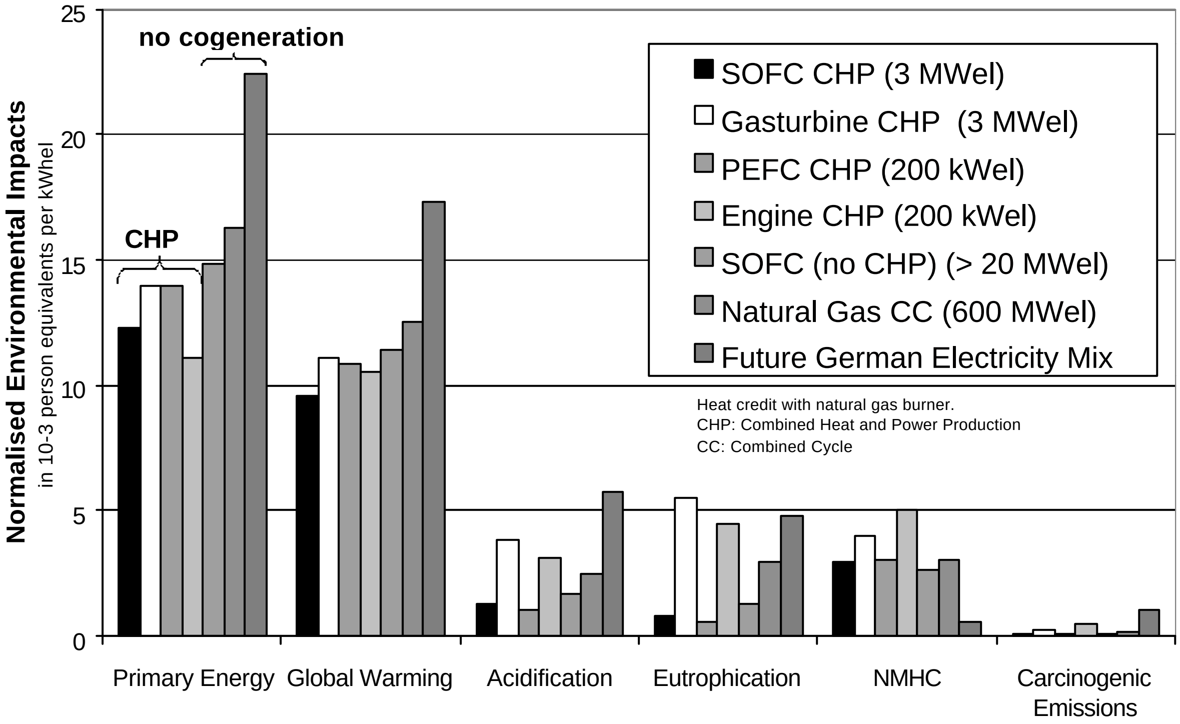

no cogeneration
CHP
Normalised Environmental Impacts
in 10-3 person equivalents per kWhel
25
20
15
10
5
0
SOFC CHP (3 MWel)
Gasturbine CHP (3 MWel)
PEFC CHP (200 kWel)
Engine CHP (200 kWel)
SOFC (no CHP) (> 20 MWel)
Natural Gas CC (600 MWel)
Future German Electricity Mix
Heat credit with natural gas burner.
CHP: Combined Heat and Power Production
CC: Combined Cycle
Primary Energy
Global Warming
Acidification
Eutrophication
NMHC
Carcinogenic Emissions

Figure 16

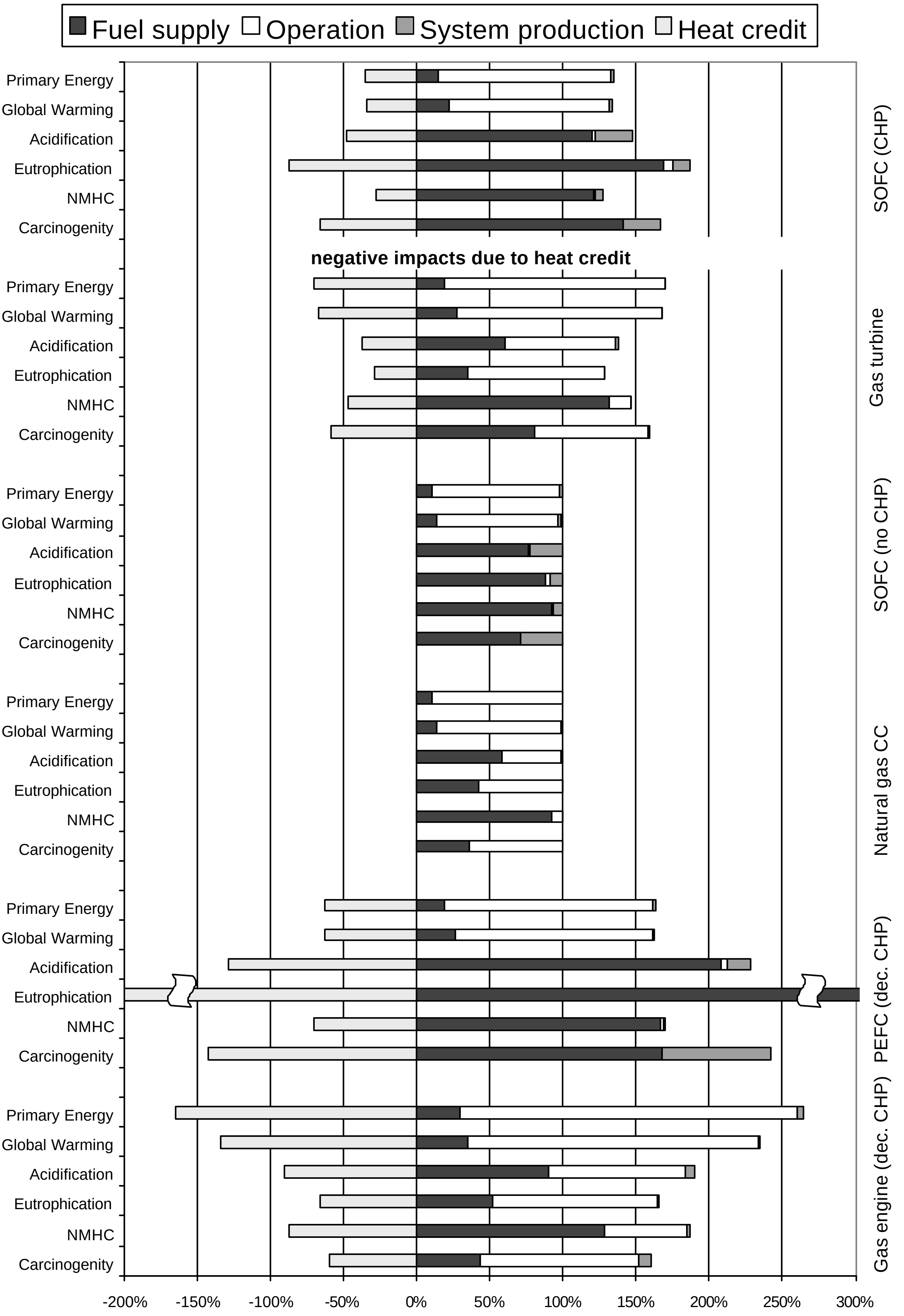
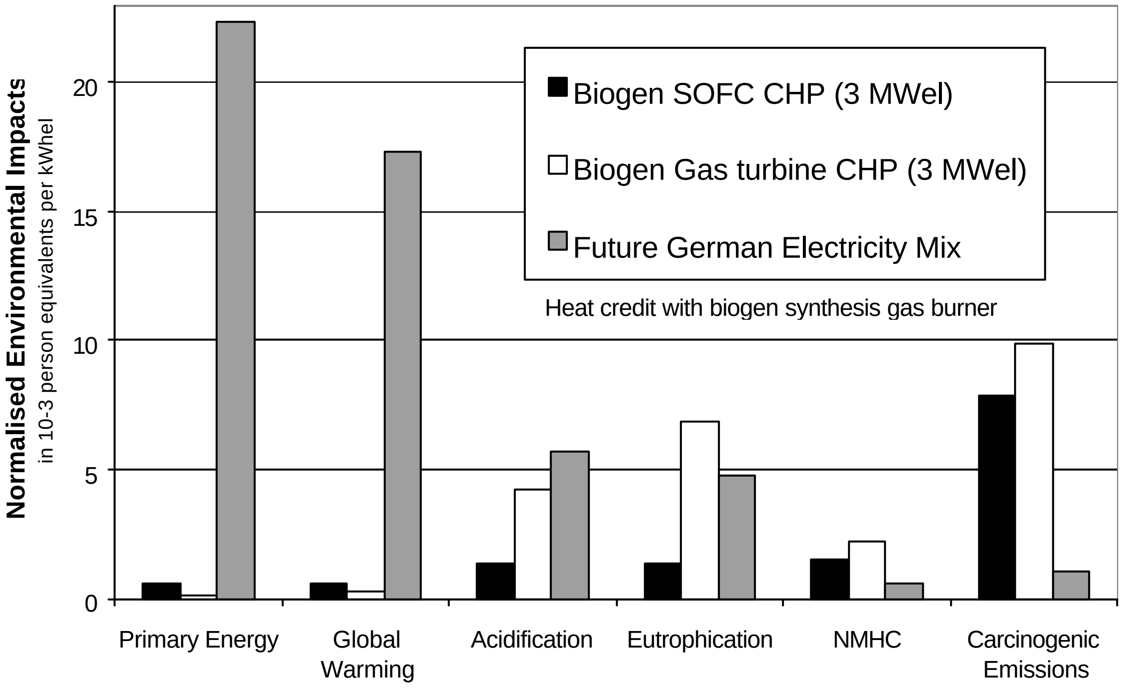

Fuel supply
Operation
System production
Heat credit
Primary Energy
Global Warming
Acidification
Eutrophication
NMHC
Carcinogenity
SOFC (CHP)
negative impacts due to heat credit
Gas turbine
SOFC (no CHP)
Natural gas CC
PEFC (dec. CHP)
Gas engine (dec. CHP)
-200%
-150%
-100%
-50%
0%
50%
100%
150%
200%
250%
300%

Figure 17


Normalised Environmental Impacts
in 10-3 person equivalents per kWhel
20
15
10
5
0
■ Biogen SOFC CHP (3 MWel)
□ Biogen Gas turbine CHP (3 MWel)
▨ Future German Electricity Mix
Heat credit with biogen synthesis gas burner
Primary Energy
Global Warming
Acidification
Eutrophication
NMHC
Carcinogenic Emissions

[23,38,53-56]