Total life-cycle assessment of PEM fuel cell car

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Abstract

Most life-cycle assessments of fuel cells, fuel cell vehicles and other hydrogen technologies to date have focussed on single issues, such as air pollution or greenhouse gas emissions. The current investigation aims to be more comprehensive, by looking at specific technology in actual production, with the aim to create

1) an inventory of substances with potential harm, from PEM fuel cell production, over the system in which it is used to final disposition,
2) an impact analysis including environmental effects, health effects and less tangible social effects,
3) a damage assessment accounted in terms of actual physical damage,
4) an assessment in comparative terms, weighing the different damage contributions on a common scale as far as possible, and
5) suggesting alternative procedures during production, materials choice, conditions of use, and finally decommissioning, that will reduce those impacts deemed critical, eventually by formulating norms and regulation to govern the use of fuel cells in society.

Keywords: PEM fuel cell, fuel cell passenger car, life-cycle analysis, externality assessment

1. Introduction

The field of life-cycle analysis (LCA) and subsequent assessment has passed through several phases, from the first applications for individual product approval to the much broader work required for giving decision-makers proper tools for making choices between different future paths of industrial and social development. The most comprehensive list of items to include in a life-cycle analysis mention the following, without claiming the list to be complete [1,2]:

- *Economic impacts*, as seen from point of view of the owner (private economy) or from society (public economy, including considerations of employment and balance of foreign payments).
- *Environmental impacts,* e.g. land use, noise, visual impact, pollution of air, water, soil and biota, on a local, regional or global scale, including climate change induced by emissions of greenhouse gases or ozone depleting substances.
- *Social impacts,* including health impacts, accident risks, effect on work environment and satisfaction of human needs.
- *Security impacts,* including terror actions, misuse as well as supply security issues.
- *Resilience,* i.e. sensitivity to system failures, planning uncertainty and future changes in value and impact assessments.

- *Impact on development*, i.e. furthering or countering the development goals of society (assuming that such exist, as they usually do at least for currently less developed nations).
- *Political impacts*, including requirements for control, regulation and centralisation of decision-making.

In order to analyse some (or all) of these impacts, including upstream and downstream components relative to the system or device of primary interest, it is necessary to establish an inventory of substances and processes of relevance, to assess their individual impacts, first in physical terms (emissions, etc.) and then in damage terms (injuries, disease, death, etc.). The outcome will be in different units, or in some cases non-quantifiable, and must be submitted to an assessment by decision-makers or by public debate [1]. Only in some cases may it be meaningful to convert different impacts into common units (such as *euro* or "environmental points"). This involves many difficult issues, as damage often occur at other places or times than the benefits of using the technology. For instance, one would have to estimate the cost to society of accidentally losing one member (the "statistical value of a life"), which has spurred discussion on whether to use the insurance "cost" of a life in Western Europe to assess a life lost in a Columbian coal mine, rather than a Columbian value, perhaps corrected by use of purchase parity conversion [2]. If the impacts are kept in different units, the assessment is said to be "multivariate".

2. Context of fuel cell analysis

The passenger cars selected for this LCA study have the features listed in Table 1. The Daimler-Chrysler f-cell is the first fuel cell passenger car to enter the stage of limited series production (estimated at 60-80 units) for demonstration in Japan [6] and subsequently in Europe and the USA. It follows the Citaro fuel cell bus entering a similar phase in 2003 (demonstration in Europe of a small series of about 30 units). The f-cell car is based on a slightly longer version of the commercial A2 series of Mercedes-Benz gasoline and diesel fuel cars, and Table 1 reflects the limited data available at this time. The two non-fuel-cell cars studied for comparison are a Toyota Camry gasoline/Otto engine car used as a typical US year-2000 vehicle in a previous life-cycle study [3,7], and the Lupo 3L TDI Diesel car topping the European list for mixed driving efficiency [4,5]. Table 1 gives a gross material usage survey, as well as the weight and fuel consumption details to be used in the life-cycle analysis.

3. Environmental impact analysis

Table 2 gives the environmental LCA data for these cars, in terms of energy used and emissions occurring during the phases of the vehicle life-cycle, based on the studies mentioned with addition of own calculations and estimates. The impacts are given in physical units as required for the LCA inventory, and will subsequently be translated into concrete impacts on health and environment, including global warming effects. Of particular interest are the impacts from manufacture and use of the fuel cell component in the f-cell car. Figure 1 indicates the main steps in manufacture of a proton exchange membrane (PEM) fuel cell stack for automotive purposes.

Several components in the fuel cell assembly are not significantly different from components found in other industrial products (metals, carbon as fibre or graphite, plastics) and their life-cycle impacts may be taken from generic studies. However, there are notable exceptions: First, the use of a polymer membrane (e.g. perfluorinated ionomers [15], hydrocarbon-based [16] or using organic materials [17]) in each cell unit may cause special concerns regarding decommissioning or recycling [18]. Usually, recycling is difficult and incineration recommended, although in some cases, care should be taken to separate difficult materials such as Pd used with organic

Table 1. Basic vehicle data used

Passenger car (1-5 persons plus luggage) **Description**	average USA, 2000 Otto engine Toyota Camry	best Europe, 2000 common-rail Diesel VW Lupo 3L	35 MPa H_2 fuel PEMFC/elec. motor DaimlerChrysler f-cell	*unit*	*reference*
Bare mass (body, chassis)	930	570	800	kg	3,4,7,est.
Propulsion system mass	340	220	600	kg	3,est.
Battery mass	12	10	40	kg	3,4, est.
Fuel and container/handling mass	<40	<35	3+100	kg	3,4, est.
Proper mass (unloaded)	1300	825	1589	kg	4,5,6
Mass of steel		410		kg	4
Mass of plastics, rubber		130		kg	4
Mass of light metals		130		kg	4
Load mass	<350	<340	<340	kg	3,4
Total mass (occupancy: 2, 0.67 full tank)	1440	980	1725	kg	3,4
Coefficient of rolling resistance	0.009	0.006	0.006		3,est.
Drag coefficient	0.33	0.25	0.25		3,4
Auxiliary power	0.7	0.6	1	kW	3,est.
Engine/fuel cell rating	109	45	85	kW	3,5,6
Electric motor rating			65	kW	5,6
Battery rating		4/732	20/78 (?)	kW/Wh	5,6
Reformer efficiency (not applicable)					
Engine/fuel cell efficiency*	0.38	0.52	0.68		3,7,calc.
Gear and transmission efficiency*	0.5	0.7	0.6		3,est.
Electric motor efficiency			0.8		3
Fuel use*	2.73	1.08	0.65	MJ/km	3,7,calc.
Fuel use*	12	33		km/l	3,4,5
Fuel to wheel efficiency*	0.15	0.19	0.31		3,calc.

* For standard mixed driving cycle. Fuel to wheel efficiency is the work performed by the car to overcome air and road friction, plus the net work performed against gravity and for acceleration/deceleration, all divided by the fuel input (note that this efficiency concept varies linearly with the combined drag and rolling resistance).
? Nickel metal hydride battery, 6.5 Ah quoted in [6] appears too small

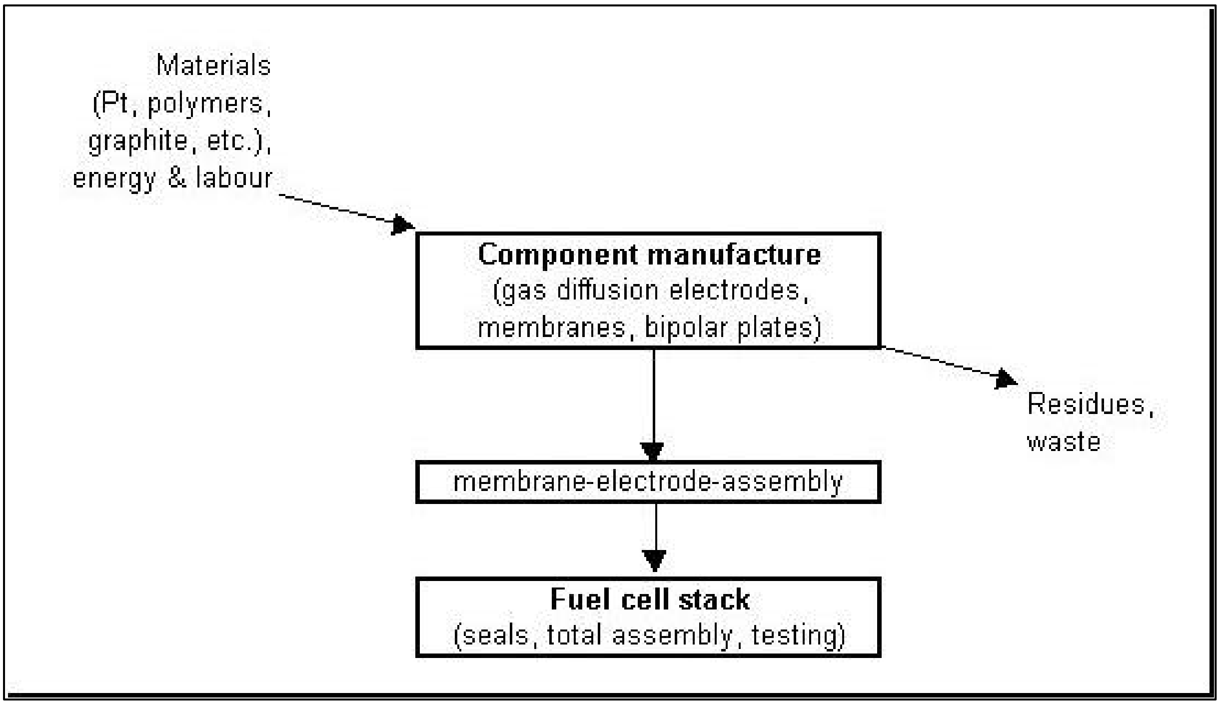

Figure 1. Flow of life-cycle path for the industrial manufacture of PEM fuel cell stacks.

Table 2. Environmental life-cycle impacts

Passenger car (1-5 persons plus luggage)	average USA, 2000	best Europe, 2000	H_2 from natural gas	H_2 from wind surplus		
LCA environmental impacts	Otto engine	common-rail Diesel	PEMFC/elec. motor	PEMFC/elec. motor		
life-cycle emissions	Toyota Camry	VW Lupo 3L	DaimlerChrysler f-cell	DaimlerChrysler f-cell	*unit*	*ref.*
Car manufacture		production+materials	total/FC stack			
Energy use	87	37+51	93/?, 178/80 §	93/?, 178/80	GJ	7,4,9
Greenhouse gas emissions	1.7	0.5+0.5	1.7/?, 2.8/1.4 §	1.7/?, 2.8/1.4 §	tC_{eq}	7,4,9
SO_2 emissions		1.6+10.0	36/14.5 §	36/14.5 §	kg	4,8
CO emissions			?/1.7	?/1.7	kg	8
NO_x emissions		1.8+4.6	?/14.5	?/14.5	kg	4,8
non-methane volatile organic compounds		2.0+1.3	?/1.7	?/1.7	kg	4,8
Particulate matter emissions		0.3+4.0	?/2.6	?/2.6	kg	4,8
Benzene			?/2.3	?/2.3	g	8
Benz(a)pyrine			?/0.034	?/0.034	g	8
Fuel production (for 300000km)						
Energy use	156	67	150	150	GJ	4,7
Greenhouse gas emissions	3.6	0.4	7	0	tC_{eq}	4,7
SO_2		9		0	kg	4
NO_x		40		0	kg	4
non-methane volatile organic compounds		60		0	kg	4
Particulate matter		1		0	kg	4
Pd (if reformer is used)						
Lifetime operation (15y, 300000km) ¤		incl. decomm. est.:				
Energy use	819	324	195	195	GJ	3,4
Greenhouse gas emissions	16.1	6.5	0	0	tC_{eq}	3,4
SO_2		1.6	0	0	kg	4
CO		30	0	0	kg	4
NO_x		75	0	0	kg	4
non-methane volatile organic compounds		2.7	0	0	kg	4
Particulate matter		6	0	0	kg	4
PAH		1.5	0	0	kg	4
N_2O: effect on stratospheric ozone	13	1	~0	0	kg	4,calc.
Decommissioning (not estimated separately)						
Totals						
Energy use	1062	479	523	523	GJ	3,4,7,9
Greenhouse gas emissions	21.4	7.9	9.8	2.8	tC_{eq}	3,4,7,9
SO_2	61	22.2	36	36	kg	4,8
CO		30			kg	4,8
NO_x	70	121			kg	4,8
non-methane volatile organic compounds		66			kg	4,8
Particulate matter	12	11.3			kg	4,8

§ Pt manufacture (assumed in South Africa) accounts for 30% of energy, 40% of greenhouse gases and 67% of acidification, with no recycling assumed [8]

¤ Maintenance impacts not estimated

membranes before burning. Second, while the steel and carbon contents of the bipolar plates can easily be reused or in the case of carbon incinerated, there are again small amounts of special materials requiring care. The most important among these is Pt used as a catalyst at each electrode, possibly as a compound with other metals. Pt cause strongly negative impacts due to the emissions during extraction and purifying, particularly in Third World plants with modest environmental experience, such as the case study of South African platinum made in ref. [8].

The effect of these impacts can be greatly reduced, if Pt is recovered and reused, as all heavy metals should be. The fuel cell vehicle considered in this study use hydrogen directly. If reformation of methanol or gasoline is used, additional impacts will derive from the reformer, including often quite large impacts from catalyst such as Pd, which again should be recycled as fully as possible.

No separate data have been found for decommissioning impacts, although VW [4] claims to have included them under "lifetime operation". In Denmark, cars delivered to a recycling station pay a fee of about 500 euro, assumed to cover the decommissioning costs minus income from selling extracted parts for re-use. European regulation is discussed, where decommissioning is part of the initial purchase price and the manufacturer is obliged to optimise assembly for decommissioning and to take the vehicle back at the end of service, for maximum recycling.

Table 3. Social life-cycle impacts

Passenger car (1-5 persons plus luggage)# **LCA social impacts and other environmental impacts**	average USA, 2000 Otto engine Toyota Camry	best Europe, 2000 common-rail Diesel VW Lupo 3L	H_2 from natural gas PEMFC/elec. motor DaimlerChrysler f-cell	H_2 from wind surplus PEMFC/elec. motor DaimlerChrysler f-cell	*unit*	*ref.*
Car manufacture/decommissioning						
Job creation	0.3	0.3	1.8	1.8	person-year	1
Occupational risk: death	0.0001	0.0001	0.0005	0.0005		1,12
Occupational risk: severe injury	0.003	0.002	0.015	0.015		1,12
Occupational risk: minor injury	0.015	0.013	0.08	0.08		1,12
Maintenance						
Job creation	0.3	0.3				1
Occuparional risks (death/major/minor injury)	0.0001/0.003/0.015	0.0001/0.002/0.013				1,12
Driving						
Accidents (death/severe injury)£	0.005/0.050	0.005/0.050	0.005/0.050	0.005/0.050		1
Stress/inconveniences	some	some	some	some		1
Mobility	advanced	advanced	advanced	advanced		
Time use as social factor (different perception by individuals)						
Noise (economic quantification in Table 5)	some	some	less	less		1
Visual impacts (of cars in environment; different perception by individuals)						
Impacts from road infrastructure (road construction, maintenance, visual impacts: estimated in monetary terms in Table 5)						
Impacts from car infrastructure (service, repair, traffic police & courts, insurance: mostly included in cost given in Table 4)						

all figures for service life of 15 years, 300000 km
£ Statistics for Denmark has been used

Table 4. Economic life-cycle impacts

Passenger car (1-5 persons plus luggage) **LCA economic impacts** life expectancy: 15 years, 300000 km	average USA, 2000 Otto engine Toyota Camry	best Europe, 2000 common-rail Diesel VW Lupo 3L	H_2 from natural gas PEMFC/elec. motor DaimlerChrysler f-cell	H_2 from wind surplus PEMFC/elec. motor DaimlerChrysler f-cell	*unit*	*ref.*
Direct economy						
Car (estimated cost without taxes/subsidies)	15000	13000	80000¤	80000¤	euro	est.
roads (monetary evaluation in Table 5)						
Fuel cost (at filling station, stable price*, no tax)	15000	5455	12675	12675	euro	est.
Service and maintenance	15000	13000	80000	80000	euro	est.
Decommissioning (becoming included in purchase price)						
Time use (of time that could have been paid, depends on individual case)						
Reference cost of satisfying mobility needs	35000	35000	35000	35000	euro	public tr.
Ressource use						
See materials in Table 1, recycling will modify these)						
Balance of labour and trade						
Job intensity (near 50% local, even if no local car or fuel production)						
Import and export fractions (varying between countries)						

* Oil price staying at current level, hydrogen price dropping linearly from 100 to 30 euro/GJ (projected for 50000 vehicle penetration [13]) during the 15y period, initial cost of hydrogen filling stations not included.
¤ Small series cost is reflected; the current 85kW PEMFC stack cost is about 10000 euro (with ~2500 euro projected for 2025) [14].

The Volkswagen report [4] is a detailed and site-specific LCA for the manufacturing plant at Wolfsburg including materials and water delivered to or coming out of the plant. It is centred on the Golf cars, but the scaling for application to Lupo made here has in gross terms already been made in the VW environmental report [4].

3. Social and economic impact analysis

Table 3 gives occupational risks during the life cycles of the vehicles, based on standard industrial data (i.e. the impacts are proportional to cost). The job content is based on statistics from the energy sector in Denmark [1]. The rate of accidents on the road are taken from several Danish studies and is considerably higher in some parts of the world. Evaluation of the health and injury impacts are again based on several Danish studies (references in [1]), as are the less tangible visual and noise impacts (estimated by hedonic pricing), and the inconveniences such as children having to be supervised when near public roads, or pedestrians in general having to use roundabouts to get to street crossings with traffic lights, where also the waiting time is valued.

Cars need roads for driving, and the road infrastructure is thus an "externality" to vehicle LCA, which has to be evaluated along with the car operation infrastructure. This is done in monetary terms based on [1] and included in Tables 4 and 5. Table 4 gives the direct costs involved (and for comparison the cost of public transportation), without including any of the substantial taxes and/or subsidies characterising the actual consumer costs in many countries. The cost of the f-cell car is not available at the present time, but has been taken as that of the corresponding A2 plus a fuel cell stack is taken as 100 euro/kW, and the other hydrogen handling and storage costs are assumed to be similar to that of the stack. Finally, a factor of two is applied due to the small series of production. This price distribution is similar to the one known for the Citaro fuel cell bus (Evobus project meeting 2001, EC Bruxelles). Maintenance costs are taken as a fixed fraction of capital cost and thus large for the f-cell car (hardly unrealistic for a new construction). The hydrogen cost is that of production from natural gas, ramped down as a function of time. It does not include the initial high cost of establishing hydrogen filling stations. No separate estimate is made for the cost of producing hydrogen from wind, discussed in [19]. The fuel price for gasoline and diesel fuel has been taken at the current level, disregarding possible increases during the period of operating the vehicles.

Table 5. Externality assessment

Passenger car (1-5 persons plus luggage) **Life-cycle assessment** externality monetising exercise	average USA, 2000 Otto engine Toyota Camry	best Europe, 2000 common-rail Diesel VW Lupo 3L	H_2 from natural gas PEMFC/elec. motor DaimlerChrysler f-cell	H_2 from wind surplus PEMFC/elec. motor DaimlerChrysler f-cell	*unit*	*ref.*
Vehicle-related environmental emissions (based on Table 2)						
Human health impacts	38100	14000-40000#	22500§	22500§	euro	1
Global climate impacts*	32100	12000	14700	4200	euro	1
Quantified social impacts (based on Tables 3,4)						
Occupational health risks	648	632	3241	3241	euro	1
Traffic accidents, incl. rescue & hospital costs	31200¤	31200¤	31200¤	31200¤	euro	1
Traffic noise	9000	9000	5000	5000	euro	1,est.
Road infrastructure (envir. & visual impacts)	28000	28000	28000	28000	euro	1
Inconvenience (to children, pedestrians etc.)	30000	30000	30000	30000	euro	1

* Mainly caused by tropical diseases and with accidental deaths valued by European standards (3 Meuro/death), cf. discussion in [1]

The upper estimate is due to possible increased impacts associated with NO_x compared to earlier valuations (may be reduced by NO_x exhaust cleaning)

§ Can be reduced by recycling of Pt [8]

¤ About half of this number is from the 3 Meuro valuation of accidental death.

4. Overall assessment

The total externality costs (i.e. those not reflected in direct consumer costs) are summarised in Table 5. This involves translating the impacts from physical units to common monetary units, with the problems inherent in such an approach, notably valuing the loss of a human life to society. The caveats are associated with the fact, that impacts such as accidental deaths are not always occurring in the same society that harvests the benefits of car driving. These issues have been discussed, e.g. in [2].

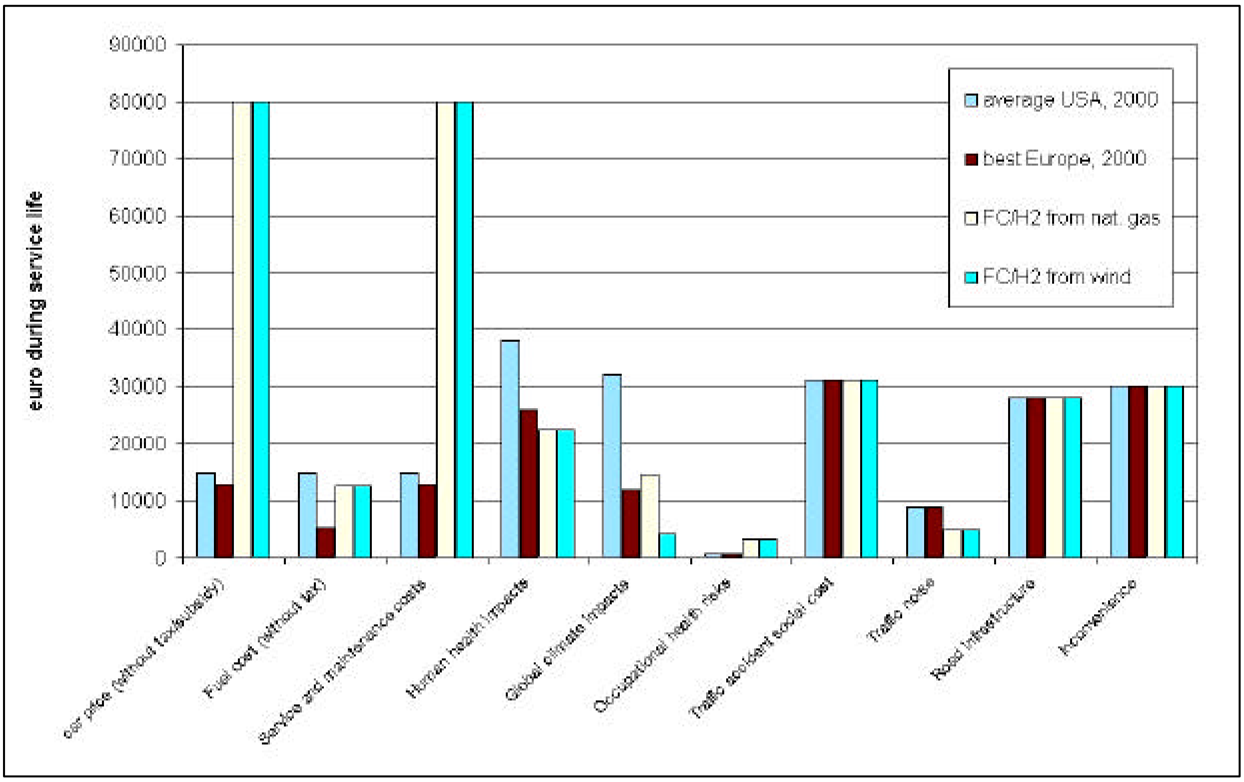

Figure 2. Summary of monetised life-cycle impacts from Tables 4 and 5.

All monetised impacts are summarised in Figure 2, for the three vehicles considered. A very large fraction of the impacts derive from road infrastructure, traffic accidents and annoyance. These are identical for all vehicles, except for noise that is smaller for hydrogen vehicles. The other large contribution is from emissions of pollutants to the air. They are in part from manufacture and maintenance, and in case of the gasoline and diesel cars from emissions in breathing height, despite attempts of exhaust cleaning (much less efficient than for central power plants). This component is larger for the average car than for the Lupo 3L, as is the fuel cost. Regarding greenhouse gas emissions, the f-cell car using hydrogen from natural gas is no better than the Lupo, but with hydrogen from renewable energy sources the advantage is substantial.
This report is based on material derived from an ongoing project [20].

6. References

[1] Kuemmel, B., Nielsen, S., Sørensen, B. (1997). Life-cycle analysis of energy systems. Roskilde University Press, 216 pp.
[2] Sørensen, B. (2004). Renewable Energy, 3rd edition. Elsevier Science (2nd ed. 2000, 1st ed. 1979, Academic Press, London).
[3] Weiss, M., Heywood, J., Drake, E., Schafer, A., AuYeung, F. (2000). On the road 2020. Report MIT EL 00-003, Laboratory for Energy and Environment, Massachussetts Institute of Technology, Cambridge MA.
[4] VW Environmental Report 2001/2002 (2002). Mobility and Sustainability; Schweimer, G., Levin, M. (2001). Life cycle inventory for the Golf A4 (internal report), Volkswagen AG.
[5] VW Technical Data (2003). Lupo 3 litre TDI, Volkswagen AG, Wolfsburg.
[6] Corporate Communications Dept. (2003). Press Release 16/10/03, Tokyo Gas Co., Ltd.

[7] Weiss, M., Heywood, J., Schafer, A., Natarajan, V. (2003). Comparative assessment of fuel cell cars. Report LFEE 2003-001 RP, Massachussetts Institute of Technology, Cambridge, MA.

[8] Pehnt, M. (2001). Life-cycle assessment of fuel cell stacks. *Int. J. Hydrogen Energy*, **26**, 91-101.

[9] Pehnt, M. (2003). Life-cycle analysis of fuel cell system components. Vol. 4, ch. 94 in "Handbook of Fuel Cells - Fundamentals, Technology and Applications (Vielstich, W., Gasteiger, H., Lamm, A., eds.), 1293-1317. John Wiley & Sons, New York.

[10] Fleischer, T., Oertel, D. (2003). Fuel Cells - impact and consequences of fuel cells technology on sustainable development. Report EUR 20681 EN, European Commission JRC, Sevilla.

[11] Berthold, O., Bünger, U., Niebauer, P., Schindler, P., Schurig, V., Weindorf, W. (1999). Analyse von Einsatzmöglichkeiten und Rahmenbedingungen von Brennstoffzellen in Haushalten and im Kleinverbrauch in Deutschland und Berlin. Ludwig-Bölkow Systemtechnik GmbH, Ottobrun.

[12] European Commission (1995). ExternE: Externalities of Energy, vols. 1-6. Reports EUR 16520-16525 EN, DGXII, Luxembourg.

[13] Jeong, K., Oh, B. (2002). Fuel economy and life-cycle cost analysis of a fuel cell hybrid vehicle. *J. Power Sources*, **105**, 58-65.

[14] Sørensen, B. (1998). Brint (Strategy note from Danish Hydrogen Committee). Danish Energy Agency, Copenhagen; Tsuchiya, H., Kobayashi, O. (2004). Mass production cost of PEM fuel cell by learning curve. *Int. J. Hydrogen Energy* (in press).

[15] Barbi, V., Funari, S., Gehrke, R., Scharnagl, N., Stribeck, N. (2003). Nanostructure of Nafion membrane material as a function of mechanical load studied by SAXS. *Polymer*, **44**, 4853-4861.

[16] Kreuer, K. (2003). Hydrocarbon membranes. Vol. 3, ch. 33 in "Handbook of Fuel Cells - Fundamentals, Technology and Applications (Vielstich, W., Gasteiger, H., Lamm, A., eds.), 420-435. John Wiley & Sons, New York.

[17] Evans, B., O'Neill, H., Malyvanh, V., Lee, I., Woodward, J. (2003). Palladium-bacterial cellulose membranes for fuel cells. *Biosensors and Bioelectronics*, **18**, 917-923.

[18] Handley, C., Brandon, N., van der Vorst, R. (2002). Impact of the European vehicle waste directive on end-of-life options for polymer electrolyte fuel cells. *J. Power Sources*, **106**, 344-352.

[19] Sørensen, B., Petersen, A., Juhl, C., Ravn, H., Søndergren, C., Simonsen, P., Jørgensen, K., Nielsen, L., Larsen, H., Morthorst, P., Schleisner, L., Sørensen, F., Pedersen, T. (2004). Hydrogen as an energy carrier: scenarios for future use of hydrogen in the Danish energy system. *Int. J. Hydrogen Energy*, **29**, 23-32; Full Report in Danish, Text #390 (2001), Roskilde University Institute 2, http://mmf.ruc.dk/energy

[20] Sørensen, B. (2005). Hydrogen and Fuel Cells. Academic/Elsevier (under preparation).