Hydrogen and its Applications :
Review of Life Cycle Assessment Studies and Well-to-Wheel Studies.

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Abstract

This paper describes a review study, conducted in the context of the 5th EU Framework Program in a project called Hysociety (contractnr. NNE5-2001-641). All recent and publicly available Life Cycle Assessments (LCA's) and Well-to-Wheel (WTW) studies of the production and use of hydrogen in various stationary and mobile applications have been reviewed. In general terms, the WTW and LCA methodology are similar, the main differences are that LCA covers a wider range of environmental impacts and usually also covers a wider system, including at least the production of the vehicle and the fuel cell. Very few LCA studies claim to be ISO compliant (a well accepted international standard for LCA studies).

The final results from different studies with different assumptions are often not easy to compare, because of differences in scope (chosen impacts), reference year of technology (2000, 2012, 2020), geographical differences, system boundaries, etc. Nonetheless the following main conclusion (about mobile hydrogen applications) was drawn from this review. LCA studies draw special attention to important contributors such as: fuel tank (weight), precious metals (e.g. Pt and Pd), life time of membranes. Especially the production of the precious metals contributes significantly to impacts such as acidification and particulate matter and there is quite a wide range in the estimates between several studies.

The most important recommendation for future LCA studies is to pay more attention to high uncertainty areas like the fuel tank, the amount of precious metals in fuel cells and the life time of membranes.

Key words

Hydrogen, LCA , Well-To-Wheel

Introduction

A review of all recent and publicly available Life Cycle Assessment (LCA) and/or Well-to-Wheel (WTW) studies on the production and use of hydrogen in various applications was conducted. The focus of the review was on LCA rather than on WTW studies, because the latter were also part of other work packages in the Hysociety project.

Literature on the environmental effects caused by the complete life cycle of hydrogen as a fuel for use in mobile, stationary and portable applications was collected using different sources (the Hysociety network, scientific literature, internet, own database). In general, literature published before 1998 was not considered, unless it was found to have considerable added value. At the end more than 100 articles were included in the review (see Annex).

Literature statistics

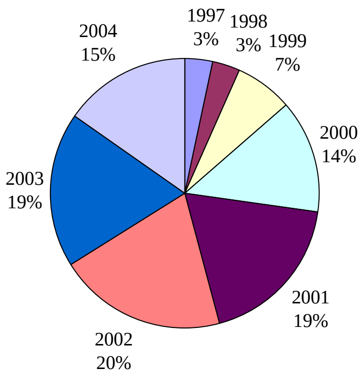

Figure 1: Publication year statistics

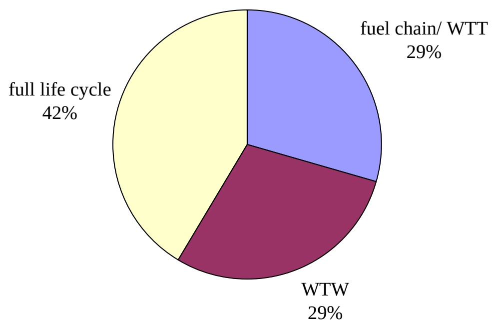

Figure 2: Subject statistics (WTT= Well-To-Tank, WTW= Well-To-Wheel)

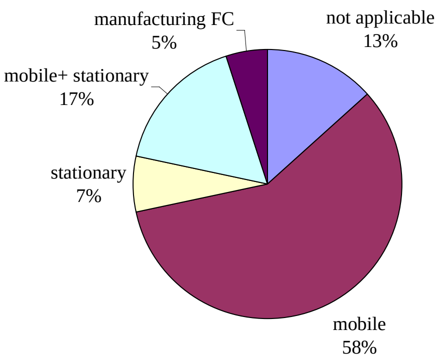

Figure 3: Application statistics (FC=fuel cell)

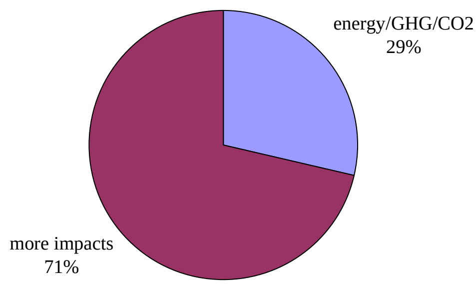

Figure 4: Impacts statistics

The number of studies has increased considerably since the year 2000 (figure 1). 40 % of the studies cover the full life cycle whereas the other 60 % cover a smaller system (figure 2). The majority of the studies concerns mobile applications (figure 3). 29 % of the studies considered energy use and greenhouse gasses (GHG) as environmental impacts, while 71 % of the studies also investigated a variety of other impacts (figure 4). Very few studies claim to be ISO compliant and very few studies have performed a weighting step.

Methodological comparison of LCA and WTW studies

The approaches and practicalities of WTW and LCA studies show similarities as well as differences :

Scope

WTW studies are specific studies aimed at transport applications. LCA is a general methodology that can be applied to any kind of system or product.

System boundaries

WTW studies typically focus on the production and distribution of different fuels and on the emissions of vehicles during use.
LCA studies typically focus on full life cycles of products or product systems. Applied to transport they typically include the three phases of a vehicle (production, use and end-of-life) and also the production and distribution processes of the needed fuels. Production of infrastructure is often not included because of less relevance (this is no absolute statement).

Impacts

WTW studies typically include GHG emissions (contributions from CO_2, N_2O and CH_4) and an energy (efficiency) indicator.
LCA studies usually include more impact categories than WTW studies, such as acidification, eutrophication, ozone layer depletion, carcinogenics etc.

Figure 5 shows the differences in system boundaries and included impacts for several of the reviewed studies. During the last years the variety of systems and impacts studied has been growing.

Data sources

Looking at the participants of WTW studies they typically have good access to primary data sources (from the suppliers/producers).
LCA studies typically make use of commercial databases that make use of both primary and secondary data (from literature).

Standardisation

WTW studies show similarities among each other but are not standardized yet.

For LCA there exists a range of ISO standards (14040, 14041, 14042, 14043). Unfortunately, very few studies claim to follow these standards.

Allocation

If a unit process delivers two or more useful products, and the studied product system uses only one of these products, the needed input flows and resulting output flows should be partitioned among the products.
The CONCAWE WTW study (Ref. 66) explains that this should be avoided whenever possible and prefers to avoid this allocation by assuming that all energy and emissions of the unit process are going to the main product and by giving a credit to the transport system equal to the energy and emissions saved by not producing the product that is most likely to be replaced.
In the ISO standards for LCA (2000) a similar approach is followed: try to avoid allocation first by f.i. system expansion. If this is not possible than the options are allocation based on physical or eventually economic considerations.

Marginal approach

In the CONCAWE WTW study (Ref. 66) it is mentioned that within the WTT approach they prefer to work with the so-called marginal approach. This means for instance that when an alternative product system uses more electricity, the extra emissions should not be counted as the average emissions for electricity but only the emissions produced by the technology that is most likely to be used to produce this extra amount of electricity (which is more likely to be a more environmentally friendly technology).

In the LCA community the marginal approach has been debated probably for many years before the first WTW studies appeared. The existing databases are not really prepared for this and as long as the influence caused by the specific product system on the total societal system is small, one might wonder whether there is such a clear correlation (there will be a large number of little positive and negative changes in society that have to be summed up). When the size of the studied system (like the transport system) compared to the total society is relatively large there are better arguments to assume that the marginal approach is more correct.

Conclusions from review

The final results from different studies with different assumptions are often not easy to compare, because of differences in scope (chosen impacts), reference year of technology, geographical differences, system boundaries, estimated life time of components from fuel cell, and for mobile applications vehicle type, vehicle driving range, vehicle weight, vehicle life time and driving cycle.

Nonetheless the following main conclusions (about mobile hydrogen applications) can be drawn from this review:

- LCA studies draw attention to important contributors such as: fuel tank (weight), precious metals (e.g. Pt and Pd), life time of membranes. Especially the production of the precious metals contributes significantly to impacts such as acidification and particulate matter. For these hot spots, there is quite a wide range in the estimates between several studies: the additional weight of a fuel cell car differs from 0 till 300 kg, these differences in estimates are also reflected in the price estimates for e.g. the on-board storage of hydrogen which can vary about a factor 3.

- Comparing petrol cars with fuel cell cars with the technology of approx. the year 2000, the reduction in GHG over the full life cycle is still limited, mainly because of the still high amounts of precious materials used to produce the fuel cell and of the storage technology for hydrogen. For acidification the impacts are even higher. This comparison concerns a rather well engineered technology with a new hydrogen fuel cell technology still under development. Most studies make comparisons for the year 2010 and later and are based on assumptions for future technological developments for both the petrol/diesel cars and (hydrogen) fuel cell cars. These studies report a higher reduction for GHG and also a reduction for acidification.
- The results of LCA studies that have compared a petrol car with a Hydrogen Fuel Cell car and that at least included the fuel life cycle, the use of the vehicle and the vehicle production and discussed impacts like global warming, acidification, eutrophication, smog and dust gave the following range of outcomes:

  Global warming (mainly caused by CO_2, CH_4 and N_2O)

  – For centrally produced hydrogen through SMR (Steam Methane Reforming) the reduction in GHG emissions during the full life cycle is in the range of 3 till 60 %. The lowest score relates to a study with reference year of technology 2001 (where there is still 180 gram of Pt needed in the fuel cell).

  – For locally produced hydrogen the reduction in GHG is usually a bit less but the range is similar: 8 till 52 %.

  – For hydrogen produced from renewables sources (solar energy, hydropower, biomass, wind power) the reduction is in the range of 53 till 85 %.

  Acidification (mainly caused by SO_x and NO_x)

  For centrally produced hydrogen through SMR the change in acidifying emissions during the full life cycle is in the range of 25 % reduction till 600 % increase. The 25 % scores relate to studies with a more long term reference year of technology and the 600 % increase relates to a study with 2000 as reference year for the FC car. The main contribution comes from the amount of Pt needed for the production of the fuel cell.

  Smog (mainly caused by VOC’s)

  – For centrally produced hydrogen through SMR the reduction in smog forming emissions during the full life cycle is in the range of 47-75 %.

  – For hydrogen produced by renewables (solar energy, hydropower, biomass, wind power) the reduction is in the range of 70 till 85 %.

Recommendations for future LCA studies are to pay most attention to high uncertainty area’s like the fuel tank, the amount of precious metals in fuel cells and the life time of membranes. Another recommendation is to include the option of hydrogen as a fuel in ICE cars more often in LCA.

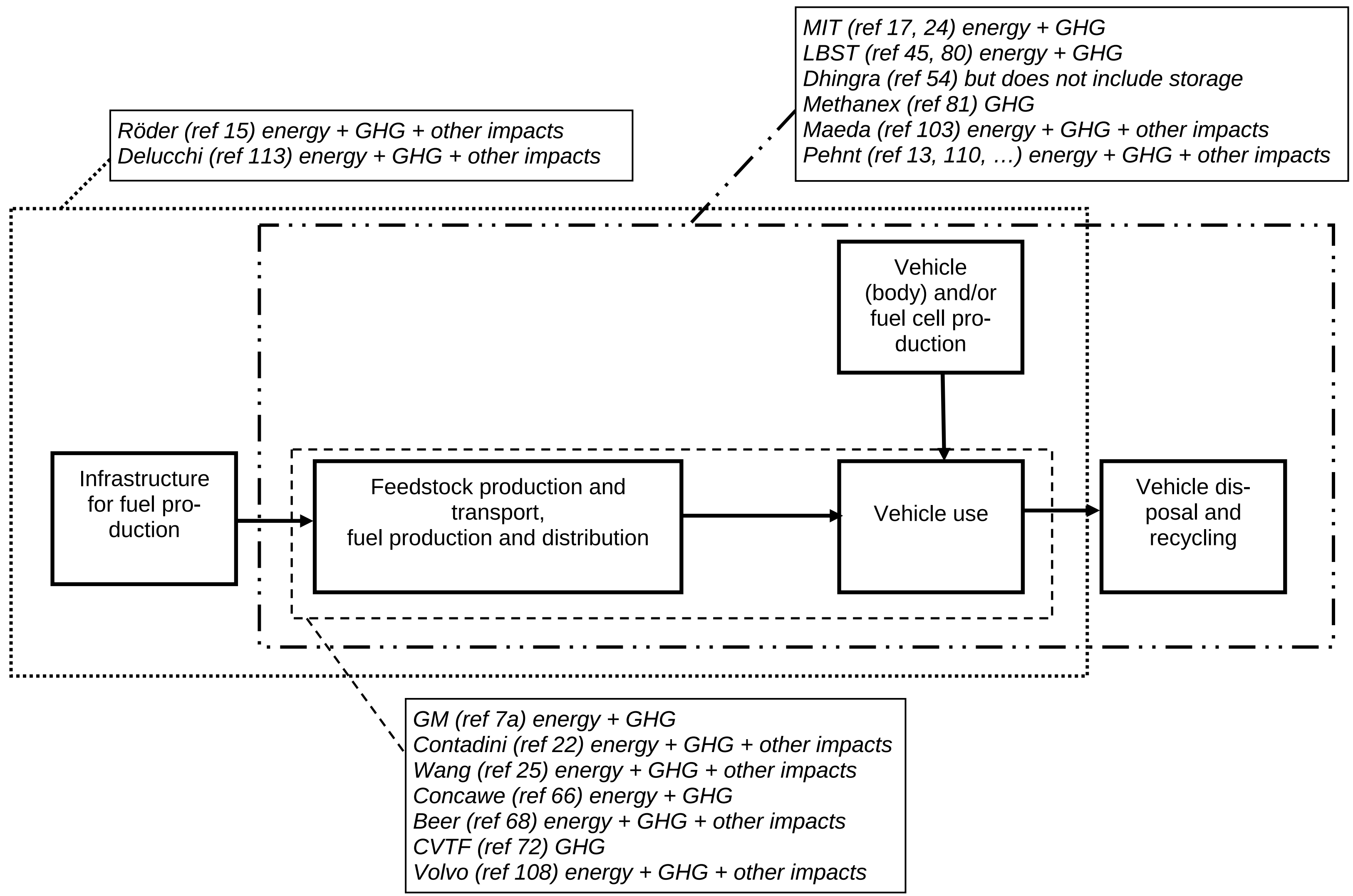

Figure 5: System boundaries for a selection of the reviewed studies

Annex : List of literature[1]

ref	author/ institute	kind of study	reference
2	Wang	article	Fuel choices for fuel-cell vehicles: well-to-wheels energy and emission impacts, Michael Wang, Journal of Power Sources 112, 307-321 (2002)
3	White	article	Life-cycle impact assessment of a one kW fuel cell system, Philip White, Debbie Driscoll and Stuart Cowan, 25 September 2001
4	Pehnt	article	Assessing future energy and transport systems: the case of fuel cells – Part I: methodological aspects, Martin Pehnt, Int J LCA 8 (5) 283-289 (2003)
7	GM	report	GM Well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel/vehicle systems – a European study, 27 September 2002
10	Spath	article	Life cycle assessment of hydrogen production via natural gas steam reforming, Pamela L. Spath, Margaret K. Mann, NREL/TP-570-27637, 2001
11	Ahlvik	report	Well-to-wheel efficiency For alternative fuels from natural gas or biomass, Peter Ahlvik and Ake Brandberg, Ecotraffic, Swedish National Road Administration, Publikation 2001:85
13	Pehnt	article	Life-cycle analysis of fuel cell system components, Martin Pehnt, Handbook of fuel cells – Fundamentals, Technology and Applications, Volume 4, Part 13, pp 1293-1317, 2003
15	Röder	dissertation	Integration of Life-cycle assessment and energy planning models for the evaluation of Car powertrains and Fuels, Alexander Röder, dissertation submitted to the Swiss Federal Institute of Technology for the degree of Doctor of Natural Sciences, Zürich, 2001
16	Patyk	article	Life cycle analysis of biofuels for transportation used in fuel cells and conventional technologies under European conditions, Andreas Patyk and Guido A. Reinhardt, IFEU
17	Weiss	report	Comparative Assessment of Fuel Cell Cars, Malcolm A. Weiss, John B. Heywood, Andreas Schafer and Vinod K. Natarajan, MIT LFEE 2003-001 RP, 2003
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[1] Some numbers are missing from the list. These were originally assigned to references which were later deemed to be irrelevant for the purpose of this study or to be similar to other studies which were already reviewed.

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24	Weiss	report	ON THE ROAD IN 2020: A life-cycle analysis of new automobile technologies, Malcolm A. Weiss, John B. Heywood, Elisabeth M. Drake, Andreas Schafer, and Felix F. AuYeung, Energy Laboratory report No. MIT EL-00-003, Energy Laboratory, MIT, Cambridge, MA, 2000
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26	Wang	report	Greet 1.5 – Transportation fuel-cycle model, M.Q. Wang, Center for Transportation Research, Argonne National Laboratory, ANL/ESD-39, 1999
27	Wang	report	Development and use of GREET 1,6 Fuel-Cycle model for transportation fuels and vehicle technologies, M.Q.Wang, Center for Transportation Research, Argonne National Laboratory, ANL/ESD/TM-163, 2001
29	Hart	description	Initial assessment of the environmental characteristics of fuel cells and competing technologies, a study conducted for the UK DTI Fuel Cell Programme by David Hart and Günter Hörmandinger under contract to WS Atkins and ETSU, 1997
30	Hart	description	Further assessment of the environmental characteristics of fuel cells and competing technologies, a study conducted for the UK DTI Fuel Cell Programme by Ausilio Bauen and David Hart under contract to WS Atkins and ETSU, 1998
32	Karakousis	report	Environmental emissions of SOFC and SPFC system manufacture and disposal, a study conducted for the UK DTI Fuel Cell Programme by Vasilis Karakousis et al. under contract to ETSU, 2000
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54	SAE	article	Environmental Evaluation of Direct Hydrogen and Reformer Based Fuel Cell Vehicles, R. Dhingra, SAE 2002-01-0094, 2002
55	SAE	article	Investigation of Hydrogen Carriers for Fuel-Cell Based Transportation, S. E. Gay-Desharnais, J.-Y. Routex, M. Holtzapple, M. Ehsani, SAE 2002-01-0097, 2002
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66	JRC, Concawe, Eucar	report	Well-to-wheels analysis of future automotive fuels and powertrains in the European context – Well-to-wheels report version 1b, Concawe, Eucar and JRC, January 2004 (+ deelreporten en appendices)
67	Elam	report	Agreement on the Production and Utilization of Hydrogen 2001 Annual Report, IEA/H2/AR-01 IEA, Carolyn C. Elam, National Renewable Energy Laboratory, 2001
68	Beer	report	Comparison of transport fuels, Final Report (EV45A/2/F3C) to the Australian Greenhouse Office on the Stage 2 Study of Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles, T. Beer, T. Grant, G. Morgan, J. Lapszewicz, P. Anyon, J. Edwards, P. Nelson, H. Watson & D. Williams, 2001
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