D8 Report on Environmental Impacts of the Hydrogen Society

Scientific report

Results of Work Package 2 (Task 2.5) of the HySociety project

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1 Executive Summary

The following report addresses the environmental impacts of a hydrogen society. Aspects like a comparison of a hydrogen society with conventional solutions using fossil fuels based on information obtained through a life-cycle analysis, the impacts on CO_2 emissions focusing on the Kyoto protocol (climate change), urban air quality and noise and other environmental topics are treated.

In the first task, a review is conducted of all recent and publicly available Life Cycle Assessments (LCAs) and/or Well-to-Wheel (WTW) studies of the production and use of hydrogen in various applications. The review focuses on LCAs and on mobile hydrogen applications rather than WTW studies, because the latter are also part of other work packages in the HySociety project (see report deliverable D4 of the HySociety project). In general, the WTW and LCA methodology is 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 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, geographical differences, system boundaries, etc. 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 and there is quite a wide range in the estimates between several studies.
- The results of LCA studies that have compared a petrol car with a hydrogen fuel cell car and include the fuel life cycle, the use of the vehicle and the vehicle production gave the following range of outcomes:

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

  - For centrally produced hydrogen through steam methane reforming (SMR) the reduction in GHG emissions during the full life cycle is in the range of 3 till 60 %.
  - 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 SOx and NOx)

  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 main contribution comes from the amount of Pt (platinum) 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 %.

  Dust and Eutrophication

  Very few studies have addressed these issues; therefore we were not able to make a comparison.

- Hybridisation offers more benefits for ICE cars than for the more efficient FC cars.

Recommendations for future LCA studies are to pay more 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 in LCA.

It has to be mentioned, that two hydrogen scenarios have been developed in the scope of the HySociety project and that the resulting impacts on CO_2-emissions as well as on energy efficiency impacts are a topic which is discussed within deliverable D5 of the HySociety project (see report on D5). Based on the calculation of economic and environmental impacts of single hydrogen energy chains, expert judgements and the creation of an economic framework a hydrogen scenario was built up assuming a hydrogen penetration of 20% of the total stationary and mobile energy demand for EU-25 in 2030. Steam reforming of gas, followed by coal gasification and to a limited extend also by electrolysis of electricity from renewable energy carriers are the most promising hydrogen production option for 2030 under the selected evaluation criteria. Compared to a reference case without hydrogen an emission reduction of 420.5 Mt of CO_2 emissions (10 % of the total CO_2 emissions in 2030) can be reached, mainly affected by CO_2 capture and sequestration technologies and the use of renewable energy carriers. However, the sequestration of CO_2 remains a controversial topic. Moreover not all technical challenges are solved for CO_2-capture and sequestration today.

Noise is a serious issue in Europe while road traffic is responsible for the highest percentage of the population exposed to noise. Fortunately, the hydrogen society would not have an important impact on noise level if only limited attention is paid on some aspects and devices. It could even be a progress factor towards a less noisy environment, especially in urban area.

Hydrogen use implies new equipments that are in general technologically improved and less noisy. Fuel cell vehicles offer benefits, over comparable petrol-driven propulsion systems, only at low speeds since tyre rolling resistance is the dominant source of noise at speeds above 40-50 km/h. The likely penetration of hydrogen in captive fleet and thus in buses and Light Duty Vehicles which are among the noisiest in urban circulation, will improve the environmental noise quality. Introduction of fuel cell vehicles would make a noticeable positive impact only in residential zones and urban area. Improvements will not have to be expected along large main roads.

A following analysis quantifies the reduction of pollutant emissions like NO_X, SO_2, CO etc. in urban areas for different hydrogen penetration rates. One major outcome is that hydrogen can make a significant contribution to the reduction of pollutants at the point of use. Thus transport based on hydrogen helps to reduce air pollution in urban areas. On the other hand, emissions occur at the point of hydrogen production if fossil fuels are used. The overall reduction of air pollution is therefore strongly dependent on the used primary energy carrier. If renewable energy sources are used, the pollutant can be reduced significantly.

The last analysis deals with the environmental, health and safety risks of hydrogen. Hydrogen is widely used as a chemical feedstock. Certain risks are associated with the use of hydrogen as a fuel, but it can be handled in a safe way and appears nor to be more dangerous than conventional fuels. Hydrogen does not affect human health, as it is neither toxic nor carcinogenic. With respect to environmental issues, it is likely that substituting fossil fuels by hydrogen will have a positive environmental impact by reducing both photochemical smog and mitigating climate change.

2 Review of Hydrogen LCA's for the Hysociety Project

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2.1 Introduction

In the HySociety project the item of Life Cycle Assessment (LCA) is addressed in WP 2.5. During the kick-off meeting it was decided that there was no need to make another new LCA study because of the large number of recent studies existing already. A second reason was the fact that Hysociety is no fundamental research project but should be considered more like a "study about the studies" in order to create an overview.

So the work performed is a review of all recent and publicly available LCA and/or Well-to-Wheel (WTW) studies. Shortly after starting this task it was also decided that the focus should be more on LCA studies than on WTW studies because the latter are already covered by work in other work packages within Hysociety. Nonetheless some WTW have been reviewed as well as a reference and to understand the differences in both approaches.

2.2 Collection and review of literature sources

In this study, literature regarding the complete life cycle of hydrogen as a fuel for mobile, stationary and portable applications was collected and reviewed. In general, literature published before 1998 was not considered, unless it was found to have considerable added value.

In a first step a consultation of all network partners of Hysociety was performed by e-mail to gather relevant studies.

In a second step several ways to find relevant references were explored. Scientific search engines such as Science Direct, Scifinder were used. The following journals were searched through individually: International Journal of Hydrogen Energy, International Journal of LCA, Journal of Power Sources, Energy Policy and Transportation Research. The internet was searched using keywords such as LCA, hydrogen, fuel cell, storage, production, use, life cycle etc.

Finally, we obtained many studies through references listed in key literature (e.g. Pehnt, Contadini, GM, …).

After a first evaluation round of all collected literature, 66 articles or reports were selected for the reviewing process.

For each study a review sheet was made containing the following aspects:

- general information:
  - title of the report or article;
  - author(s) of the report or article;
  - institute/company where the author works;
  - sponsor of the study;
  - journal or report details;
  - publication year;
  - number of pages;
  - short description of contents;
- LCA or WTW related information:
  - region for which the results are valid;
  - year for which the results are valid;
  - goal of the LCA or WTW;
  - system and system boundaries;
  - data origin;
  - impacts discussed in the study;
  - how was the impact assessment conducted;
  - transparency of data;
  - transparency of impact assessment;
  - ISO complicity (for LCA's);
  - conclusions of the report or article.

The list of literature is shown in Annex A, while an example of the review sheets are shown in Annex B.

2.3 Statistics

Almost 90 % of all literature reviewed during the scope of this project was published between 2000 and 2004. A few studies published in the period 1997-1999 were also included because they were deemed to be still relevant.

About 30 % of the studies were only about the production of hydrogen as a fuel, independent from the intended application. 30 % was about the WTW and 40 % was a complete life cycle study. The difference between these last two is the fact that the full life cycle studies study a wider system and include for example production and recycling of the vehicle, production of hydrogen distribution infrastructure, etcetera.

The majority of the studies were about mobile applications (almost 60 %). In 17 % of the studies, mobile as well as stationary and/or remote applications were discussed. 7 % of the studies discussed only stationary applications. 2 studies (3 %) are focussed mainly on the manufacturing of fuel cells. 14 % of the studies did not discuss any application but only discussed the production of hydrogen.

27 % of the literature investigated energy use and greenhouse gasses as environmental impacts. 73 % of the studies also investigated other impacts, such as acidification, particulate matter, resource use, emissions of criteria pollutants etcetera. It must be noted that some of these studies were only life cycle inventories. Very few studies have reported on all impact categories frequently used in LCA studies and very few studies have performed a weighting step.

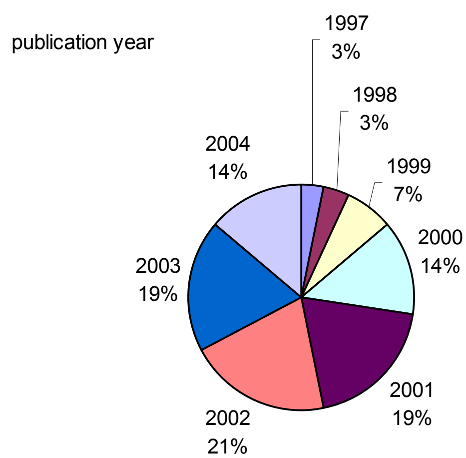


Figure 1: Publication year statistics

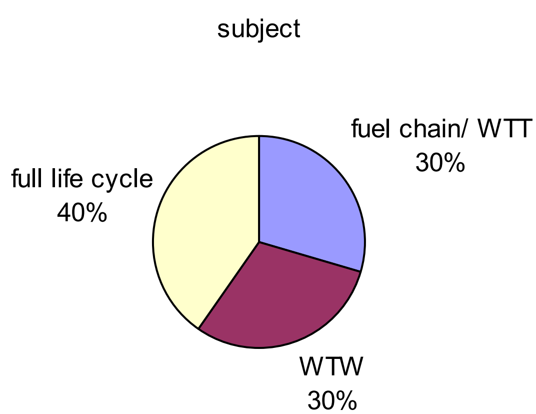


Figure 2: Subject statistics

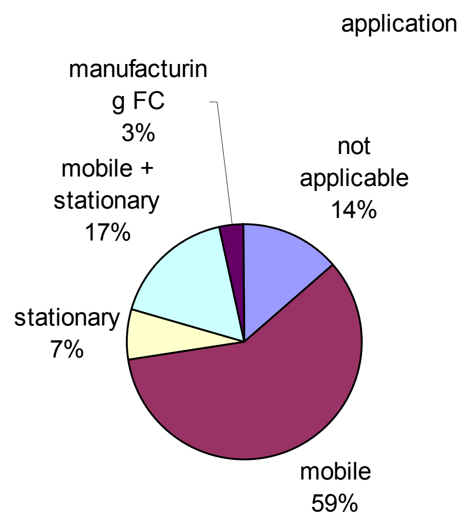


Figure 3: Application statistics

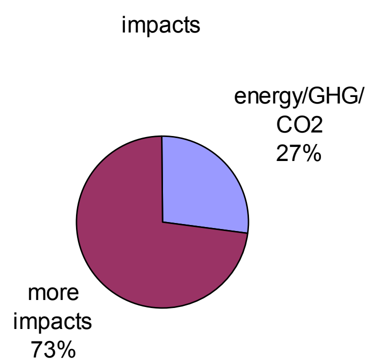


Figure 4: Impacts statistics

2.4 LCA methodology versus WTW methodology

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 studies are general studies 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.

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 (2004) 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 (2004) 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.

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.

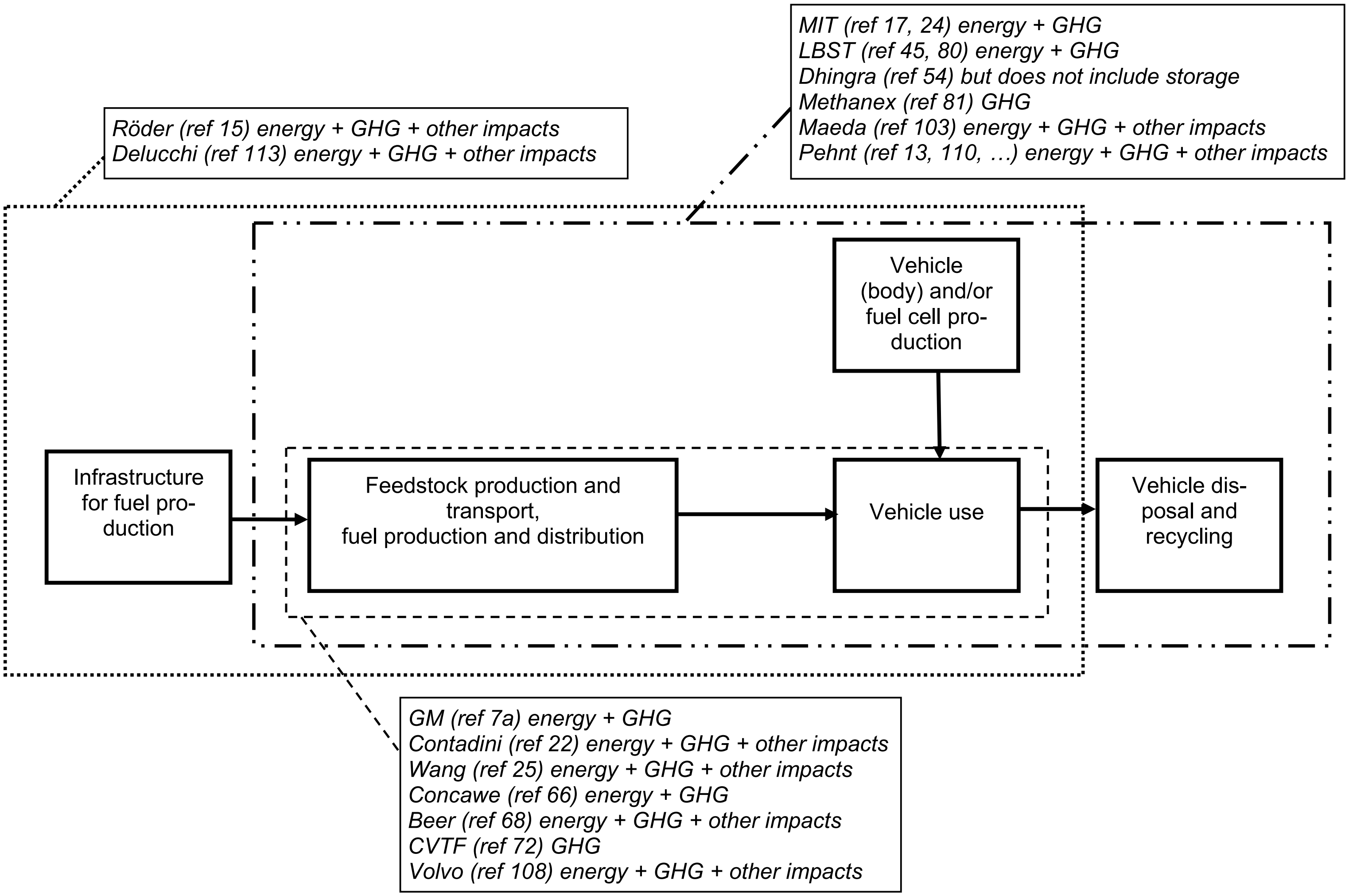


Figure 5: System boundaries for a selection of the reviewed studies

2.5 LCA conclusions versus WTW conclusions

The LCA studies give a wider view on the total system. In the use-phase of a vehicle the fuel cell car is of course attractive because of its higher efficiency and much lower emissions. But the amount of additional "environmental" investments in materials and production processes for fuel cells, storage systems and maybe on-board reformers is not included in WTW studies. That's why the differences between hydrogen applications and conventional systems are more pronounced in WTW studies and less pronounced in LCA studies.

LCA studies draw attention to important contributors such as: fuel tank (weight, materials and production processes, boil-off losses), precious metals (e.g. Pt and Pd), and the life time of membranes. Especially the production of the precious metals contributes significantly to impacts such as acidification and particulate matter. There is a Japanese study (ref 103) that states that fuel cell cars today score higher on acidification and particulate matter than petrol cars, mainly because of the amount of precious metals used. Most other studies use projections in the future and assume a reduction in used amounts of precious metals. As might be expected estimations by different people will lead to different results. For the mentioned 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.

2.6 Conclusions and recommendations

In general, the WTW and LCA methodology is 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.

However, the final results from different studies with different assumptions are often not easy to compare, because of differences in:

- scope;
- reference year of technology;
- geographical differences;
- system boundaries;
- estimated life time of fuel cell components;
- for mobile applications
  - vehicle type (car, light truck, bus);
  - vehicle range (number of km without refilling);
  - vehicle weight;
  - vehicle life time;
  - driving cycle.

The differences in the level of detail of reporting (documents vary from 1 – 400 pages) also do not ease comparisons.

Because the reporting is usually performed on an aggregated level and not all underlying calculations are transparently reported, one can not always clarify the exact reasons for (small) differences in the final results.

Taking account of the aspects complicating a comparison of results from different studies described above, the following conclusions have been drawn:

- Most studies have a very large scope (great number of fuels and technologies studied), hydrogen is often one (small) part of the study.
- Regarding the applications of hydrogen, most studies concern mobile applications, there is less attention for stationary applications and only few studies are focused on fuel cell manufacturing.
- Few LCA studies claim to be conform ISO standards or even mention them, most of them still put GHG as the central issue.
- WTW studies focus on the fuel chain production and distribution routes and the emissions during use of the vehicles. LCA studies also include the production and end-of life phase of the products and sometimes also the infrastructure for fuel production and distribution.
- Around the year 2000 there were only a few WTW studies and LCA studies, the latter covering a wider system and more impact categories. Today there exists a larger variety of studies for different systems and more combinations of impact categories.
- Hybridisation offers more benefits for ICE cars than for the more efficient FC cars.
- The use of renewable energy sources for the production of hydrogen can reduce impacts but the issues to be addressed are the amount of emissions from needed infrastructure and whether there will be enough capacity (land, locations) to produce them. Benefits from renewables can also be achieved in more conventional systems like e.g. ICE, electricity production, heating applications.
- The studies about the hydrogen production routes seem to be offering more consensus than the studies about the applications. There are still explainable differences between different continents/countries such as the USA, Japan, Europe and Canada.
- 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.

- Indirect processes such as vehicle manufacturing, tire and brake wear, etcetera can contribute significantly to some impact categories, therefore it is important to take the whole life cycle into account.
- WTW studies and LCA studies, comparing hydrogen applications with conventional solutions, experience the same type of difficulties: how to estimate the future impacts of a technology that today is in its prototype phase with existing conventional systems that are also still improving. Most studies take a future reference year and include predictions based on expert opinions, learning curve trends, making comparisons to technological developments in similar applications etc. Only 2 studies work with distributions instead of single data points as a means to deal with the inherent uncertainties (Contadini 2002 (ref 22) and Wang 2002 (ref 2)).
- Comparing hydrogen fuel cell systems to conventional petrol, the balance between emissions in the use phase and emissions in the production/distribution phase clearly changes: much lower impacts in the use phase and higher impacts in the production phase of the vehicle, while the impacts from the production of hydrogen are very dependent on the energy sources.
- 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 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 SOx and NOx)

  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 %.

Dust and Eutrophication

Very few studies have addressed these issues, therefore we were not able to make a comparison.

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 comparative LCA's. In this LCA review there is only one reference that assessed hydrogen as a fuel in ICE (Röder 2001, ref 15).

2.7 Recommended literature Chapter 2

After having reviewed many documents, we recommend the following references for readers with more detailed interest in the subject of Life Cycle Assessment related to hydrogen applications:

Ahlvik, Peter; Brandberg, Ake: Well-to-wheel efficiency for alternative fuels from natural gas or biomass. Ecotraffic, Swedish National Road Administration, Publication 2001:85 (ref 11)

Altmann, M.; Blandow, V.; Niebauer, Dr. P.; Schindler, J.; Schurig, V.; Weindorf, W.; Wurster, R.; Zittel, Dr. W.: Vergleich verschiedener Antriebskonzepte im Individualverkehr im Hinblick auf Energie- und Kraftstoffeinsparung. Studie im Auftrag des Bayerischen Staatministeriums für Landesentwicklung und Umweltfragen, Endbericht, L-B-Systemtechnik, April 2002 (ref 80)

Beer, T.; Grant, T.; Morgan, G.; Lapszewicz, J.; Anyon, P.; Edwards, J.; Nelson, P.; Watson, H.; Williams, D.: 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, 2001 (ref 68)

Contadini, J. Fernando, Ph.D: Life cycle assessment of fuel cell vehicles – Dealing with uncertainties. Dissertation, Office of Graduate Studies, University of California at Davis, 2002 (ref 22)

Delucchi, Mark A.: A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials. MAIN REPORT, ITS-Davis, Publication No. UCD-ITS-RR-03-17-MAIN REPORT, December 2003 (ref 113)

GM: Well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel/vehicle systems – a European study. 27 September 2002 (ref 7a)

Karakousis, Vasilis: Environmental emissions of SOFC and SPFC system manufacture and disposal. A study conducted for the UK DTI Fuel Cell Programme, ETSU, 2000 (ref 32)

Pehnt, Dipl.-Phys. Martin: Ganzheitliche Bilanzierung von Brennstoffzellen in der Energie- und Verkehrstechnik. Fortschritt-Berichte VDI Reihe 6 Nr. 476, Heidelberg (ref 110)

Röder, Alexander: Integration of Life-cycle assessment and energy planning models for the evaluation of Car power trains and Fuels. Dissertation submitted to the Swiss Federal Institute of Technology for the degree of Doctor of Natural Sciences, Zürich, 2001 (ref 15)

Wang, M.Q.; Huang, H.S.: A full fuel-cycle analysis of energy and emissions impacts of transportation fuels produced from natural gas. Center for Transportation Research, Argonne National Laboratory, ANL/ESD-40, 1999 (ref 25)

Weiss, Malcom A.; Heywood, John B.; Drake, Elisabeth M.; Schafer, Andreas; AuYeung, Felix F.: On the road in 2020: A life-cycle analysis of new automobile technologies. Energy Laboratory report No. MIT EL-00-003, Energy Laboratory, MIT, Cambridge, MA, 2000 (ref 24)

2.8 Executive summary

This chapter describes the result of the LCA review as part of WP 2.5 of the Hysociety project. 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 are 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. After a first selection, 66 articles or reports entered the reviewing process. For each study a review sheet was made containing the following aspects:

- general information: title, author(s), institute/company, sponsor, journal/publication details, publication year, number of pages, short description of contents
- LCA or WTW related information: region, year of technology, goal, system, data origin, impacts considered, assessment, transparency of data, transparency of impact assessment, ISO comformity (for LCA's), conclusions.

The number of studies has increased considerably since the year 2000. The majority of the studies concerns mobile applications. We see that the variety of chosen system boundaries is increasing. This concerns in particular the inclusion or exclusion of the vehicle production, the end-of-life of the vehicle and the infrastructure for fuel production.

27 % of the studies considered energy use and greenhouse gasses as environmental impacts, while 73 % of the studies also investigated a variety of other impacts. Very few studies claim to be ISO compliant and very few studies have performed a weighting step.

In general, the WTW and LCA methodology is 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.

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 FC, 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 SOx and NOx)

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.

2.9 Annex A: 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

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.

ref	author/institute	kind of study	reference
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
18	Spath	article	The environmental aspects of using renewables for hydrogen production compared to a fossil based system – a specific case study for a remote application, Pamela Spath, Ronny Glöckner and Cathy Grégoire Padró, DOES Workshop, International Workshop on the Design and Optimisation of Energy Systems, Delft, January 2003
19	Alternative fules contact	report	Market development of alternative fuels, Report of the Alternative Fuels Contact Group, December 2003
20	Spath	article	Life Cycle Assessment – An Environmental Comparison of Hydrogen Production from Steam Methane Reforming and Wind Electrolysis. Spath, P. L.; Mann, M. K. Hydrogen: The Common Thread. Proceedings of the 12th Annual U.S. Hydrogen Meeting, 6-8 March 2001, Washington, DC. Washington, DC: National Hydrogen Association; pp. 311-319; NREL Report No. 31870, 2001
22	Contadini	dissertation	Life cycle assessment of fuel cell vehicles – Dealing with uncertainties, J. Fernando Contadini, Ph.D. Dissertation, Office of Graduate Studies, University of California at Davis, 2002
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
25	Wang	report	A full fuel-cycle analysis of energy and emissions impacts of transportation fuels produced from natural gas, M.Q.Wang, H.S.Huang, Center for Transportation Research, Argonne National Laboratory, ANL/ESD-40, 1999
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

ref	author/institute	kind of study	reference
34	Bauen	article	Assessment of the environmental benefits of transport and stationary fuel cells, A. Bauen, D. Hart, Journal of Power Sources, 86, 482–494, 2000
35	Hart	article	Environmental benefits of transport and stationary fuel cells, D. Hart, G. Hörmandinger, Journal of Power Sources, 71, 348-353, 1998
38	Row	report	Life-Cycle Value Assessment (LCVA) of Fuel Supply Options for Fuel Cell Vehicles in Canada, J. Row et al., Pembina Institute, 2002
40	Lassaux	ext abstract	A comparative LCA of different proton exchange membrane fuel cells (PEMFC) and a microturbine for combined production of heat and electricity, S. Lassaux, extended abstract, 8th LCA Case Studies Symposium SETAC-Europe, 2000
41	Lassaux	ext abstract	Life cycle assessment of two renewable electricity buffer systems, S. Lassaux, 10th LCA case Studies Symposium SETAC-Europe, xxxx
45	Altmann	presentation	Hydrogen Fuel – Hydrogen Production, Energy Availability Potentials, Well-to-Wheel Emissions and Costs, Emission Scenarios, Climate Technologies Assessment Workshop, Brussels, Belgium, 24 September 2003, Matthias Altmann, L-B-Systemtechnik, Ottobrunn
48	Zittel	article	Der Einfluß von Wasserdampf auf das Klima, W. Zittel, M. Altmann, Ludwig-Bölkow-Systemtechnik GmbH, Veröffentlicht in ENERGIE, Jahrg. 45, Nr. 4, April 1994
49	Zittel	article	Molecular hydrogen and water vapour emissions in a global hydrogen energy economy, W. Zittel, M. Altmann, L-B-Systemtechnik, Published in the proceedings of the 11th World Hydrogen Energy Conference, Stuttgart, Germany, 1996
50	Zittel	report	Hydrogen in the Energy Sector, W. Zittel, R. Wurster, L-B-Systemtechnik Hyweb:Knowledge, 1996 http://www.hydrogen.org
51	Harris	report	Pathways for Natural gas into advanced vehicles, G. Harris, 2002
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
56	MacLean	article	Evaluating Automobile Fuel/Propulsion System Technologies, H. L. MacLean, L. B. Lave, J. Prog. Energy Comb. Science 29, in publicatie
63	Pehnt	article	Life-cycle assessment of fuel cell stacks, M. Pehnt, Int. Journal of Hydrogen Energy 26, 91-101, 2001
64	Pehnt	article	Assessing future energy and transport systems: the case of fuel cells – Part II: Environmental performance, Martin Pehnt, Int J LCA 8 (6) 365-378 (2003)
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

ref	author/institute	kind of study	reference
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
72	Cleaner Vehicles Task Force	report	The Report of the Alternative Fuels Group of the Cleaner Vehicles Task Force – An assessment of the Emissions Performance of Alternative and Conventional Fuels, January 2000
77	IEA	book	Automotive Fuels for the Future – the Search for Alternatives, Martijn van Walwijk, Mira Bückmann, Willemien P. Troelstra and Nils Elam, International Energy Agency, 1999
79	Altmann	report	Vergleich verschiedener Antriebskonzepte im Individualverkehr im Hinblick auf Energie- und Kraftstoffeinsparung, Studie im Auftrag des Bayerischen Staatministeriums für Landesentwicklung und Umweltfragen, Zusammenfassung des Endberichts, M. Altmann, V. Blandow, Dr. P. Niebauer, J. Schindler, V. Schurig, W. Weindorf, R. Wurster, Dr. W. Zittel, L-B-Systemtechnik, April 2002
80	Altmann	report	Vergleich verschiedener Antriebskonzepte im Individualverkehr im Hinblick auf Energie- und Kraftstoffeinsparung, Studie im Auftrag des Bayerischen Staatministeriums für Landesentwicklung und Umweltfragen, Endbericht, M. Altmann, V. Blandow, Dr. P. Niebauer, J. Schindler, V. Schurig, W. Weindorf, R. Wurster, Dr. W. Zittel, L-B-Systemtechnik, April 2002
81	S&T	report	Assessment of emissions of greenhouse gases from fuel cell vehicles, Prepared For: Methanex Corporation by (S&T)2 Consultants Inc., 5 June 2000
84	Koroneos	article	Life cycle assessment of hydrogen fuel production processes, C. Koroneos, A. Dompros, G. Roumbas, N. Moussiopoulos, Int. Journal of Hydrogen Energy 29, 1443-1450 (2004)
85	OECD	report	Can cars come clean? Strategies for low-emission vehicles, ISBN 92-64-10495-X, OECD, 2004
86	Pehnt	paper	Life cycle assessment of fuel cells and relevant fuel chains, M. Pehnt, to be published in Proceedings Hyforum The International Hydrogen Energy Forum 2000, 11th-15th September, Munich
87	Pehnt	paper	Ökobilanzen und Markteinritt von Brennstoffzellen im mobilen Einsatz (Life cycle assessment and market entry of mobile fuel cell systems), M. Pehnt, J. Nitsch, VDI-Konferenz "InnovativeFahrzeugeantribe", Dresden 26-27 October 2000
88	Patyk	paper	Umweltaspekte des Einsatzes von Brennstoffzellen und ihrer Energieträger, A. Patyk, Brennstoffzellen … effiziente energietechnik der zukunft – Tagung des Wirtschaftsministeriums Baden-Württemberg in zusammenarbeit mit dem DLR/Stuttgart und dem ZSW/Ulm, Friedrichshafen, 20-21 Juli 2000
91	Lunghi	article	Life-cycle-assessment of fuel-cells-based landfill-gas energy conversion technologies, P. Lunghi, R. Bove and U. Desideri, Journal of Power Sources, 131, 120-126 (2004)
93	Neelis	article	Exergetic life cycle analysis of hydrogen production and storage systems for automotive applications, M.L. Neelis, H.J. van der Kooi and J.J.C. Geerlings, International Journal of Hydrogen Energy, 29, 537-545 (2004)
96	Badin	article	Energy pathway analysis, a hydrogen fuel cycle framework for system studies, J.S. Badin and S. Tagore, International Journal of Hydrogen Energy, 22, 389-395 (1997)

ref	author/institute	kind of study	reference
97	MacLean	article	Life cycle assessment of automobile/fuel options, HL MacLean, LB Lave, Environmental Science and Technology, 37, 5445-5452 (2003)
98	Marquevich	article	Life cycle inventory analysis of hydrogen production by steam reforming process: comparison between vegetable oils and fossil fuels as feedstock, M. Marquevich, G.W. Sonnemann, F. Castells and D. Montane, Green Chemistry, 4, 414-423 (2002)
100	Heffelfinger	paper	Life cycle GHG emissions for FCVs in Japan, B. Heffelfinger, Proceedings of the international Conference on Greenhouse Gas Control Technologies, 6th Kyoto, Japan
101	Koroneos	paper	Hydrogen production via biomass gasification – a life cycle analy-sis approach, C. Koroneos, A. Dompros, G. Roumbas, N. Mous-siopoulos, Pyrolysis and gasification of Biomass and Waste, Pro-ceedings of an expert meeting, Strasbourg, France, 2002
103	Maeda	article	Life cycle assessment case study for fuel cell vehicle, H. Maeda, T. Moro, Y. Matsuno, M. Sagisaka, A. Inaba, Journal of Advanced Science, 13, 285-289 (2001)
106	Feng	article	The future of hydrogen infrastructure for fuel cell vehicles in China and a case of application in Beijing, W. Feng, S. Wang, W. Ni, C. Chen, International Journal of Hydrogen Energy, 29, 355-367, 2004
107a	Fischer	article	Life cycle assessment (LCA) and economic considerations of hydrogen including future scenarios, M. Fischer, M. Faltenbacher, P. Eyerer, M. Betz, M. Binder, VDI-Berichte 2003
107b	Fischer	article	Hydrogen as a fuel for urban transportation, M. Fischer, M. Shi-basaki, M. Faltenbacher, P. Eyerer, M. Betz, Hyforum 2004
108	Andersson	paper	Volvo environmental database for fuels, E. Andersson, SAE SP 2000
109	Spath	report	Life cycle assessment of renewable hydrogen production via Wind/Electrolysis, Milestone report, NREL/MP-560-35404, Pamela L. Spath and Margaret K. Mann, 2004
110	Pehnt	dissertation	Ganzheitliche Bilanzierung van Brennstoffzellen in der energie- und Verkehrstechnik, Dipl.-Phys. Martin Pehnt, Fortschritt-Berichte VDI Reihe 6 Nr. 476, Heidelberg
112	ESTO	report	Potential for Hydrogen as a Fuel for Transport in the Long Term (2020 – 2030) – Full Background Report, Matthias Altmann, Pat-rick Schmidt, Reinhold Wurster, Martin Zerta, Dr. Werner Zittel (edited by Hector Hernandez), Institute for Prospective Techno-logical Studies, European Commission Joint Research Centre, Technical Report Series EUR 21090 EN, March 2004
113	Delucchi	report	A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials. MAIN REPORT. Delucchi, Mark A. ITS-Davis. Publication No. UCD-ITS-RR-03-17-MAIN REPORT. December 2003.

2.10 Annex B: Example for a reference evaluation

For the complete list please contact VITO/ULg.

publication – ref 2	title	**Fuel choices for fuel-cell vehicles: well-to-wheels energy and emission impacts**
	authors	Michael Wang
	institute/company	Center for Transportation Research, Argonne National Laboratory
	sponsor	Office of Transportation technologies, US Department of Energy
	journal/report	Journal of Power Sources
	publication year	2002
	number of pages	14
	contents	* focus on fuel cell vehicles, but also hybrid electrical vehicles and standard gasoline car * 18 fuel pathways, of which 10 for hydrogen: central and decentral steam reforming of natural gas, electrolysis based on US electricity and central and decentral elecrolysis based on renewable energy, all of this for compressed and liquid hydrogen * the other fuel pathways include gasoline, diesel, compressed natural gas, methanol, ethanol, naphta, ... some of these are used to produce hydrogen onboard

subject	region	USA
	year	near-term future
	goal	WTW evaluation of energy and emissions of various fuel-cell fuels
	system	mile driven
		production of fuels, distribution of fuel to vehicle and use of vehicle (storage aboard vehicle and vehicle itself is not included)
	data origin	primary + secundary
		WTT: Argonne National Laboratory has collected own data from fuel producers over several years TTW: several studies were reviewed and distribution assumptions were made based on these studies
	impacts	total energy use changes (%), fossil energy use changes (%), petroleum use changes (%), GHG emissions changes (CO_2, CH_4 and N_2O)
	assessment	LCIA
		midpoint
		no weighting
	transparency of data	very transparant, sometimes reference is made to other reports about the GREET model from the same author
	transparency of impact assessment	transparant, sometimes reference is made to other reports about the GREET model from the same author
	ISO	no claim
	conclusions	* all hydrogen options have lower WTT efficiencies than standard gasoline vehicles, and therefore should have higher miles per gallon to achieve overall WTW energy efficiency gains * for some hydrogen options, the lower WTT efficiency is not offset by a higher miles per gallon, for others it is, so even efficient fuel cell vehicles may not achieve energy benefits if the fuel pathway is very inefficient * all fuel/vehicle systems except based on US electricity considerably reduce fossil energy use * all hydrogen pathways, but other fuel/vehicle systems as well, almost elimate petroleum use * all fuel/vehicle systems except for hydrogen produced from US electricity and decentral production of liquid hydrogen from natural gas (considerably) reduce GHG emissions by 40 to 60 %), especially if based on renewable fuel (more than 90 %) * fuel cells on hydrogen can reduce energy use and GHG emissions considerable but it depends on the pathway to produce the hydrogen (no US electricity or decentral production of liquid hydrogen from natural gas)

3 Noise

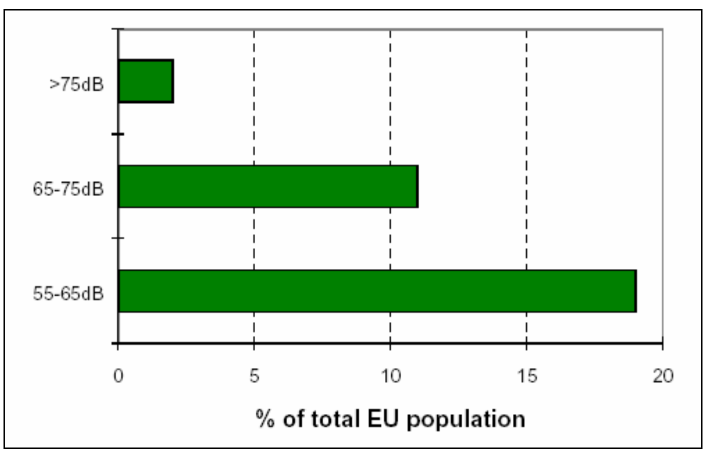
ULg Université de Liège

3.1 Introduction

3.1.1 Noise in Europe

Noise is a serious issue – levels above 40 Ldn dB(A) affect our well-being, while there is evidence that levels above 60 Ldn dB(A) can affect our physical and psychological health. While the last two decades have seen significant reductions in the noise produced by all sorts of vehicles, the rapid growth in transport – particularly air and road – has resulted in well over 120 million people in the EU being exposed to noise levels above 55 Ldn dB(A) on the front facade of their houses.

Some 10 million people in Europe are exposed to environmental noise levels that can result in hearing loss [3]. Road traffic is the predominant source of human exposure to noise, except for people living near airports and railway lines. In the EU, it is estimated that more than 30 % of citizens are exposed to road noise levels, and around 10 % to rail noise levels, above 55 Ldn dB(A) [1]. Around 65 % of the people in Europe, about 450 million, are exposed to noise levels leading to serious annoyance, speech interference and sleep disturbance [2].



Source: EEA, 1999

Figure 6: Share of population exposed to different road traffic noise levels (EU)

To avoid major nuisances and impairments (disruption of communication and sleep), further noise reductions to 59 dB(A) in the daytime and 49 dB(A) at night are required by UBA (German Federal Environmental Agency) in residential areas by 2010. The long-term targets for residential areas are noise levels below 55 dB(A) in the day and 45 dB(A) at night.

3.1.2 Regulation

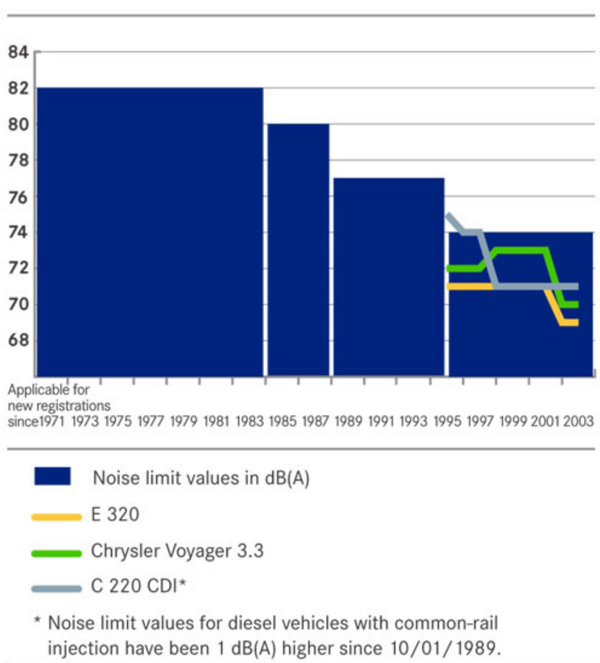
Existing noise control legislation of European Union can be divided into four categories. The noise emissions from **motor vehicles** are covered by two directives introducing sound level limits. Three directives limit noise emissions from **aeroplanes** by reference to the Convention on international Civil Aviation. Noise emission from **household appliances** has been the object of a framework directive on household appliances. The last sector, **construction equipment**, is based in the EEC conformity assessment procedure framework directive which led to the adoption of seven daughter directives on particular types of equipment.

In hydrogen society, the following categories are influential. They consist in vehicles, compressors, energy generators and household appliances.

3.1.2.1 Motor vehicles, motorcycles

Motor vehicles

Directive 70/157/EEC introduces limits on the sound levels of noise for road vehicle and gives requirements for measuring sound levels from exhaust systems and silencers. Several amendments, the latest by Directive 96/20/EC, have reduced these permissible sound levels. Limit values for eight types of passenger and goods vehicles range from 74 dB(A) to 80 dB(A).



Source: Daimler-Benz

Figure 7: Development of European noise limit values for passenger cars in dB(A).

Motorcycles

Directive 78/1015/EEC on motorcycles establishes limits for the permissible sound level of motorcycles and requirements for exhaust or intake silencer. Limit values are given for three categories of motorcycles and range from 75 dB(A) to 80 dB(A).

3.1.2.2 Permissible noise emission: Construction plant and equipment

Compressors

Directive 84/533/EEC lays down noise limits for the environment and related requirements for the issuance of an EEC type-examination certificate for compressors.

Power generators

Directive 84/536/EEC lays down noise limits and related requirements for the issuance of an EEC type-examination certificate for power generators.

3.1.2.3 Household appliances

Directive 86/594/EEC is a framework directive on airborne noise emitted by household appliances. It provides consumers and users with standards and procedures governing the provision of accurate information about the noise levels of household appliances by means of clear labels combined with other mandatory consumer information such as energy consumption levels.

3.2 Transition to hydrogen society

3.2.1 General remarks

A first remark consists in the fact that hydrogen launch implies new techniques, new equipments, new machineries which will be broadly better and thus will satisfy the noise abatement requirement. Everybody who bought recently a new dishwasher knows that. Secondly, hydrogen related techniques involve, from the noise point of view, compressors and boosters it and, as many fuel cells work at low temperature, powerful heat exchanger (this often means large, and sometimes, noisy fans).

The modification due to hydrogen applications can be evaluated in relation with the two scenarios A and B described before (Deliverable 5). They describe production, transport, refuelling and use of hydrogen in stationary and mobile applications.

It is likely that the captive fleets will be among the first commercial applications for fuel cells and hydrogen in vehicles. Captive fleets comprise some groups of cars, Light

Duty Vehicles (LDV) and buses. These two last categories are among the noisiest in urban circulation. According to Scenario A, hydrogen will be used by 50% of total LDV registrations and 80 % of total bus registrations.

3.2.2 Production plants

Centralized production plants will be located in industrial sites far from the inhabited zones. They don't comprise heavy or noisy machineries except boosters or compressors. These problems are generally well controlled on new industrial plants. On the other hand, **decentralized production plants** will be, in some cases, nearer to inhabitants. They also imply more varied modes of production: biomass gasification, wind on-shore and off-shore, solar-thermal and reforming from natural gas. Two specific aspects should be pointed out: (1) wood crushing can be a noisy activity which should be confined. (2) the problems of noise from on-shore wind mills are well known and finally do not appear to be the most crucial issue.

In addition, it is necessary to distinguish the noise problems involved in normal operation of the installations from those related to accidental behaviour, for example, from safety valve actuation, forced ventilation of the buildings, gas flaring, etc...

The noise problems of **on-site production** are similar to those in decentralized production, taking into account their limited size. Admission of the natural gas reformer is generally done at 30 bar, it would be wise to benefit from the existing pressure in the natural gas grid so to avoid useless compressions and associated noise.

3.2.3 Hydrogen transport

Hydrogen transport is envisaged by pipeline or by cryogenic truck. For the pipeline, an analogy can certainly be made with the distribution of natural gas which, although it involves compressors, does not create any noise trouble for the inhabitants.

With regard to the road transport, it is to note that, due to hydrogen low density (+/- 71 kg/m^3), a cryogenic truck can only transport a limited quantity of hydrogen. The consequence is that to transport the same quantity of energy as for example gas or oil, it will be necessary to make more trips with the trucks, and thus increase the noise pollution.

3.2.4 Refuelling

The last remark about hydrogen density also implies that refuelling will be more frequent, like the noise related to activity on a refuelling station (nozzle locking, pumps, doors closing, discussions,...); starting of compressors requires careful attention, especially at night.

3.2.5 Stationary application

Noise measurement of a PC25C fuel cell is reported at 65 dB(A) essentially due to the air conditioner [4]. This value is to be compared with Combined Heat Power of Caterpillar's GenSet 3408: 110 dB(A).

A maximum value of 58 dB at 10 meter is reported for the same type of fuel cell (PC25A) in the Gazel project [5]. Frequency analysis shows that the measured maximum level of 58 dB is located in the low frequencies (80 – 100 Hz). This level thus constitutes a real maximum as the low frequencies are most difficult to attenuate.

Others values [6] are notified for stationary appliances:

Company	Model	Noise
H Power Corp	RCU 1-10 kW – natural gas line or propane cylinder	65 dB(A) or less at one meter
Nuvera	1 kW hydrogen system	50 dB(A) at 3 feet
Nuvera	1 kW propane system	60 dB(A) at 3 feet
Nuvera	5 kW natural gas system	70 dB(A) at 3 feet
Plug Power Inc.	SU-1 System (residential) natural gas	< 70 dB(A) at 1 meter
Siemens Power Generation	SOFC 250 kW system CHP natural gas	65 dB(A) at 10 meters
Siemens Power Generation	SOFC 100 kW system CHP natural gas	65 dB(A) at 7 meters from unit
UTC Fuel Cells	PC25 PAFC system natural gas	60 db at 30 feet

Table 1: Extracts of stationary fuel cells – Operating info [6]

In conclusion, the fuel cell systems are less noisy compared with existing cogeneration plants based on internal combustion units; they are on the same order as residential boilers for the small units. Moreover, decentralized installations of Combined Heat and Power will make it possible to remove individual heating installations and their associated noise.

3.2.6 Hydrogen in Transport

Road traffic is responsible for the highest percentage of European population exposition to noise. This means that a main aim consists, beyond cutting primary fuel consumption and CO_2 emissions, in reducing noise levels.

However, fuel cell vehicles offer benefits, over comparable petrol-driven propulsion systems, only at low speeds since tyre rolling resistance is the dominant source of noise at speeds above 40-50 km/h. Introduction of fuel cell vehicles would make a noticeable positive impact only in urban area.

Fuel cell Cars

Limited data are available regarding noise emissions from fuel cell cars. First, dated (1995), findings [7] about an Energy Partners prototype are described where: *"the 'noisiest' component is the rotary vane type air compressor, which generates a noise level of about 85 dB at 1 m distance*". A second test [8] on the DaimlerChrysler fuel cell electric vehicle NECAR 4, a compact car based on the A-Class, shows a value of 69,3 dB(A) at 50km/h.

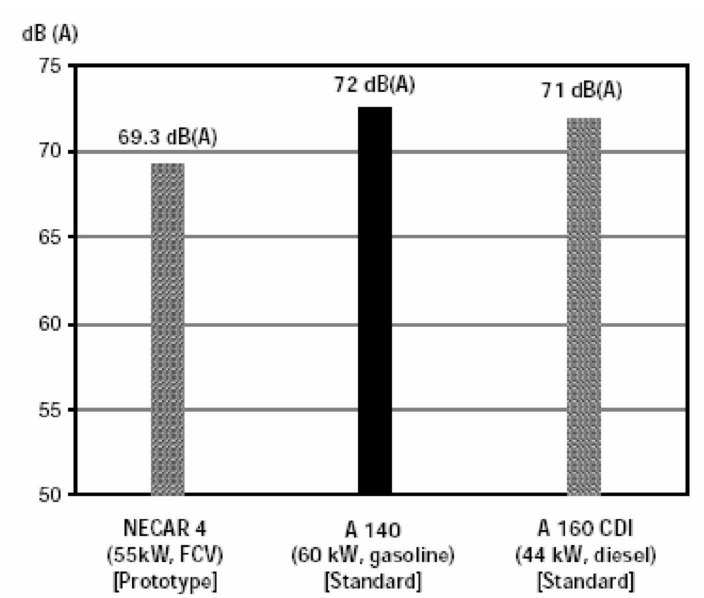


Figure 8: External noise emission of NECAR 4 and standard Mercedes-Benz A-Class vehicles at the standardized "accelerated passage" test (measured in IDIADA for the "accelerated passage" test, defined by the European regulation 70/157/EWG) [8]

Since fuel cell cars are powered by electricity, the noise levels measured for battery powered electric cars also provide a useful basis for evaluation. However, the findings indicate that for fuel cell vehicles we also need to consider noise from components (e.g. transformers, pumps and fans) not included in battery-powered electric vehicles.

Emissions from electric-powered cars and identical vehicles with conventional propulsion systems were measured in 1995, having regard for the conditions described above (*Eden et al., 1996 in [9])*. The following tests were all carried out under standard conditions on the ISO test track. Noise levels were measured under acceleration and at different constant speeds. The noise emissions measured for three pairs of vehicles are given in Figure 9.

The results presented show that electric cars are 2 to 7 dB(A) lower than the same models with internal combustion engines at low speeds and under acceleration. Difference is greatest because rolling noise is insubstantial at low speeds, so that engine noise is the dominant emission factor.

The noise amplifies under acceleration at higher speeds due to higher rolling noise. But even under acceleration from 50 km/h the noise level of the conventional car is around 1 to 2 dB(A) higher than that of the comparable electric car.

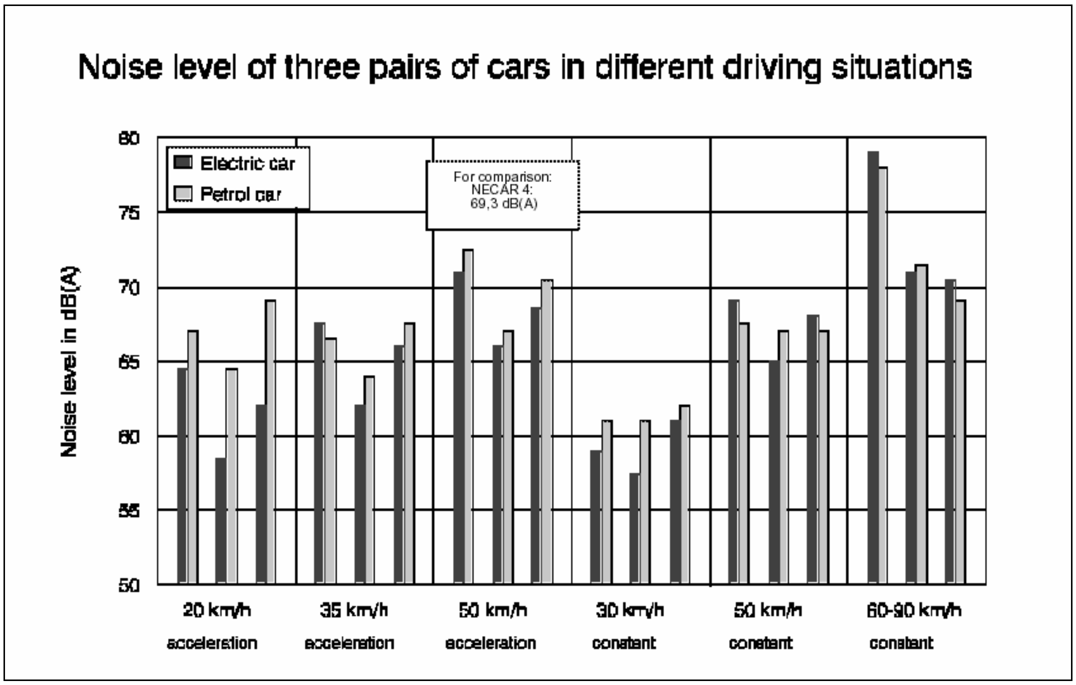


Figure 9: Noise level of three pairs of vehicles in different driving situations [9].

Since battery-powered electric cars, just like fuel cell vehicles (NECAR-4: 1 750 kg; Class A 140: 1 030 kg; Class A 170 CDI: 1 070 kg), are heavier than conventional cars and noise increases with weight, the difference is negative at speeds of 50 km/h and more. In other words, electric-powered vehicles with standard tyres may be 1 to 2 dB(A) louder than conventional cars at higher speeds up to 90 km/h.

Fuel cell buses

It is likely that urban buses will be among the first commercial applications for fuel cells and hydrogen in vehicles. This is due to the fact that urban buses are highly visible for the public, they contribute significantly to air pollution in urban areas, they have small limitations in weight and volume and fuelling is handled via a centralised infrastructure.

From the point of view of noise impression, this is a positive aspect since the results establish an important improvement of the fuel cell buses compared with the ICE vehicles. Taking into account that the impact of buses in urban area is more intense than the other vehicles, if the portion of buses operating on hydrogen and fuel cell is important, the effect on noise pollution will be more effective.

A study [10] presents a quantitative assessment of the local environmental benefits (and noise impact) of using fuel cell buses in comparison with EURO 5 diesel buses and compressed natural gas buses along a central bus route in Göteborg, Sweden, in 2006. The sound exposure level of a future fuel cell bus is unknown to the authors, but it is assumed to be at the same level of a present simple car. The used (for the study) sound exposure level (10 m) from the different bus technologies is 77.5 dB(A) for the diesel bus, 76.5 dB(A) for the natural gas bus, and 70.5 dB(a) for the fuel cell bus.

Matheny et al. [11] carried out measurement of interior and exterior noise of a 30 ft (9,1 m) liquid fuel phosphoric acid fuel cell (PAFC) transit bus. This bus was powered by a PAFC engine, which operates near ambient pressure and therefore requires no compressor/expander in the fuel cell engine. In the case of the bus tested the compressor (used for air brakes and other auxiliary equipment) caused the greatest noise increase outside, near the front of the bus.

Vehicle	Maximum Sound Pressure Levels at 2.5 m (dB(A))
Gillig 50’ (15 m) bus diesel(1995)	84
Orion 30’ (9.1 m) bus diesel (1989)	82
GMC 35’ (10.6 m) bus diesel (1983)	87
PAFC fuel cell bus 30’ (9.1 m)	73

Table 2: Sound pressure levels for various busses [11]

In a test of a Hybrid Fuel Cell Bus (Scania Hybrid PEM Fuel Cell Concept Bus), external noise emissions of the bus were measured [12]. The test was performed as an accelerated passage test, defined by the European regulation 70/157/EEC. In the test, the bus is accelerated to a speed of 50 km/h, which is held constant when it approaches the measuring area. As it enters, a full acceleration is performed during a 20 m long test (measuring) strip while the noise is measured at a specified distance on both side of the bus. The noise level is compared with the same bus type, but with its standard engine and driveline configuration. A comparison is also made with the present noise regulations (Figure 10).

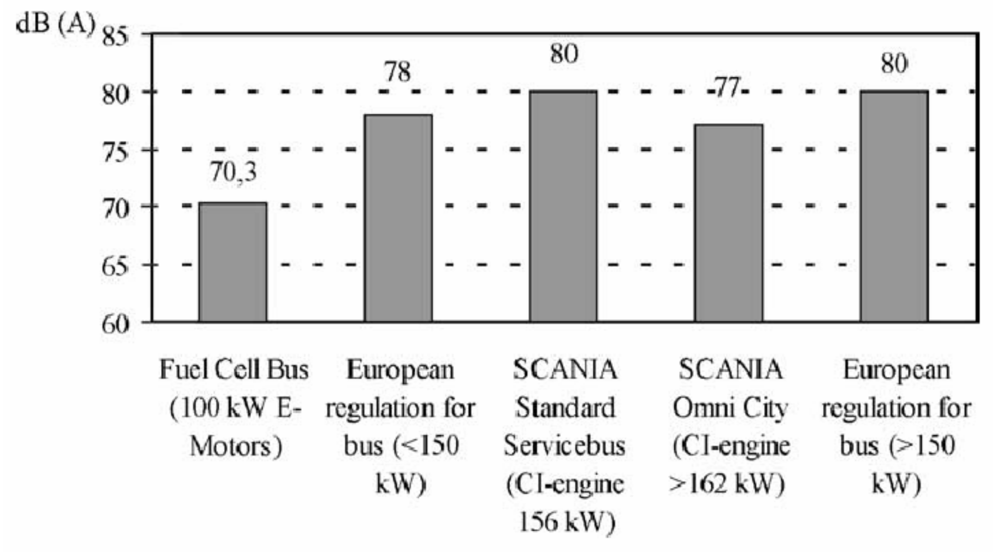


Figure 10: Results from noise measurements, defined by the European regulation 70/157/EEC [12]

All these data clearly point out that the noise characteristics of fuel cell vehicles offer many advantages. This is particularly the case when vehicles accelerate in actual road traffic situations. Where the noise can be attributed to individual vehicles, e.g. in purely residential areas, tangible improvements can be achieved by substituting fuel cell vehicles for their conventionally powered counterparts. The benefits in urban areas will be marked only if the proportion of the FC vehicles are substantial.

3.3 Summary and conclusions

Noise is a serious issue in Europe while road traffic is responsible for the highest percentage of the population exposed to noise.

Fortunately, the hydrogen society would not have an important impact on noise level if only limited attention is paid on some aspects and devices. It could even be a progress factor towards a less noisy environment, especially in urban area.

Hydrogen use implies new equipments that are in general technologically improved and less noisy. Fuel cell vehicles offer benefits, over comparable petrol-driven propulsion systems, only at low speeds since tyre rolling resistance is the dominant source of noise at speeds above 40-50 km/h. The likely penetration of hydrogen in captive fleet and thus in buses and Light Duty Vehicles which are among the noisiest in urban circulation, will improve the environmental noise quality.

Introduction of fuel cell vehicles would make a noticeable positive impact only in residential zones and urban area. Improvements will not have to be expected along large main roads.

3.4 References Chapter 3

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4 Local Air Quality

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4.1 Introduction

Urban air pollution is one of the most important environmental problems and is the result of human activities. Clean air is a gaseous mixture composed of nitrogen (78%), oxygen (21%), argon, carbon dioxide, ozone and other gases in smaller quantities (1%). Therefore atmospheric pollution may be defined as the emission of large quantities of substances that disturb the physical and chemical properties of air.

The main pollutants are classified into primary (they stay in the atmosphere just like they were originally emitted by the source; they are considered to be: sulphur oxides, carbon monoxide, nitrogen oxides, hydrocarbons and particles) and secondary pollutants (they form in the air when primary pollutants react or interact, such as photochemical oxidants like ozone or particles produced from precursor gases such as SO2, NOx (combination of nitrogen monoxide, NO, and nitrogen dioxide, $NO_{2)}$ and ammonia)

- Ground-level ozone, in ambient air, can affect human health, and damage crops, vegetation and materials. Ozone is not emitted directly, but is formed in the lower atmosphere by reaction of volatile organic compounds and NOX in the presence of sunlight.
- Exposure of particulate matter, measured as concentrations of PM10 or PM2.5 (particle diameter less than 10 and 2.5 µm respectively) in ambient air represents one of the largest human health risks from air pollution. Short-term inhalation of high concentrations may cause increased symptoms for asthmatics, respiratory symptoms, reduced lung capacity and even increased death rates. Harmful compounds in particulate form can damage materials.
- Sulphur dioxide (SO2) and nitrogen oxides (NOx) can have various adverse impacts on vegetation, human health, and materials.

This pollution has diverse causes and sources, such as industrial, commercial, agriculture and domestic activities. Combustion employed to obtain heat, electricity or movement is the process in which more pollutants are produced. So the higher concentration occurs mainly in the urban areas of Europe. It is estimated that between 1996 and 2001, 25-45% of the urban population was exposed to particles concentrations and 20-30% to ozone concentration in excess of the EU limit value [1].

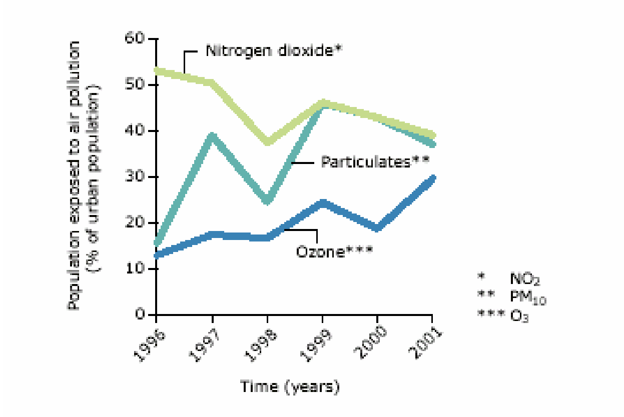

Figure 11: Population exposed to air pollution [1]

The present tendency is the reduction of both ozone and fine particles emissions (by 30% and 36 % respectively in EU-15 from 1990 to 2001) thanks to the introduction of catalysts on new cars and to the implementation of the EU solvents directive to industrial process. But this reduction is not enough to reach target concentration over the whole Europe.

According to the European Environment Agency's 1999 report "Environment in the European Union at the turn of the century" nearly 40 million people living in the 115 larger European cities still experience levels over air quality guidelines for at least one pollutant.

The European Auto-Oil Programme II (AOPII) makes an assessment of the future trends in emissions and air quality. The scope of AOPII included all the main "conventional" pollutants for the period 1990-2020 in the EU15 but with a focus on ten "auto-oil" cities (see Table 3).

The AOPII base case for 2010 [3] resulted in a large improvement of urban air quality. However, exceedances of the various environmental objectives were still to be expected. The objectives for PM10, both short-term and long-term, as well as the NO_2 long-term objectives were projected to be most frequently exceeded in 2010.

Pollutant	Averaging period	1995 (a)	2010(b)
SO2	1 hour	*23%*	2%; *3-6%*
SO2	24 hours	*25%*	7%; *9-11%*
NO2	1 hour	*5%*	5%; *0%*
NO2	Calendar year	*65%*	5%; *20%*
PM_{10}	24 hours	*89%*	62%; *73%*
PM_{10}	Calendar year	*87%*	62%; *52%*
CO	8 hours	*14%*	*0.5-1.5%*
O3	Daily 8-h max	48%	6%
Benzene	Calendar year	*50%*	*13%*
Pb	Calendar year	*23%*	*0%*

(a) fraction estimated from UAQAM and OFIS model calculations
(b) fraction estimated from cQ, UAQAM and OFIS model calculators; results obtained by UAQAM are given in italics.

Table 3: Fraction (in %) of total urban population living in non-attainment cities [3]

It is important to show (following table) that, in the majority of the cities, remove road transport emissions is the key factor that reduce considerably the average NO2 concentration.

City	Average NO_2 concentration over central ten cells	Non-attributable secondary concentration	Average concentration after eliminating emissions from:			
			Road transport	Area sources	Large area sources	Other area
Athens	62	25	38	62	61	49
Berlin	20	6	15	19	19	12
Cologne	9	2	6	9	8	8
Dublin	22	4	7	21	19	20
Helsinki	25	6	9	25	25	23
London	39	16	27	32	39	36
Lyon	44	5	8	44	43	43
Madrid	28	2	3	28	28	28
Milan	36	12	17	34.	35	33
Utrecht	26	8	14	24	25	22

Table 4: Air quality effect of removing emissions from road transport and other sources in 2010, µg/m³ [3]

4.2 Forecast of pollutants emissions "Base case"

Several studies evaluated the future of the air quality in Europe. One of them [2] estimated the effect of H_2 in terms of its benefits to the environment with respect to two main issues, i.e. climate change and atmospheric pollution in urban areas. The estimation of benefits for atmospheric pollution in urban areas has be carried out, looking at the forecasts provided by the AUTOOIL Programme II [3].

The work of IPTS [2] is the basis of this "Hysociety" analysis [2]. The benefits of hydrogen on local air quality can be estimated in relation with the two scenarios A and B described before (Deliverable 5, task 2.2.). A first step consists in an evaluation of the base case emissions (and induced urban air quality) in 2030. On this base, the benefits of hydrogen use are estimated.

A first step consists in establishing the "base case" forecast of pollutants emissions. The best starting point is undoubtedly the Auto Oil II Program [3]. The final report gives forecasts limited to EU15 and to 2020 for the following pollutants: Nitrogen Oxides (NOx), Sulphur Oxides (SO2), Carbon Oxide (CO), Particulate Matter (PM10), Volatile Organic Compounds (VOC) and Benzene (C6H6).

The report [3] (data on spreadsheet can be found on [6]) gives emission data for the Corinair sectors[3] as:

- **Non-industrial combustion** plants: heat generation in other sectors than industry and energy.
- **Road transport**
- **Other mobile** sources and machinery: including operation of aircraft, ships, tractors, construction machinery, lawn mowers, military and other equipment

Our report focuses on the two first sectors which are the most significant in order to evaluate urban air pollution. Values for "other mobile" as the total for EU-15 are given for information.

The assessment for the particulate matter is less reliable than for the other pollutants. There are three categories of dust from road transport. The non-exhaust emissions are basically those from brake and tires wear. In our study, we don't consider the non-exhaust dust taking into account that hydrogen use in vehicles will not change these emissions.

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2 In addition, it is interesting to inform that many data on transport emissions and forecasts until 2020 could be found on the Tremove project [10].

3 CORINAIR: CO-oRdinated INformation on the Environment in the European Community – AIR. CORINAIR stands for a methodology in order to coordinate national inventories of the atmospheric emissions of specific pollutants (sulphur dioxide, nitrogen oxides and volatile organic compounds,…) released from eight important industrial and non-industrial activity sectors.

Nitrogen oxides **Emissions in kt**

EU15 sector totals	1990	1995	2000	2005	2010	2015	2020
Combustion: non-industry	571	584	596	608	620	620	620
Road transport	5865	5131	3925	2678	1631	1157	985
Other mobile	1771	1695	1619	1544	1468	1468	1468
EU15	**12824**	**11608**	**9920**	**8190**	**6661**	**6188**	**6015**

Table 5: Nitrogen oxides emissions

Sulphur dioxide **Emissions in kt**

EU15 sector totals	1990	1995	2000	2005	2010	2015	2020
Combustion: non-industry	1281	794	632	574	345	345	345
Road transport	127	143	85	18	18	18	18
Other mobile	323	188	176	179	197	197	197
EU15	**15996**	**9739**	**7489**	**6460**	**4817**	**4817**	**4817**

Table 6: Sulphur dioxide emissions

Carbon monoxide **Emissions in kt**

EU15 sector totals	1990	1995	2000	2005	2010	2015	2020
Combustion: non-industry	6775	5892	5901	5919	5962	5970	5953
Road transport	31362	26372	19280	12662	8407	5973	5048
Other mobile	1924	1905	1886	1866	1847	1828	1809
EU15	**50126**	**43903**	**36829**	**30180**	**25815**	**23294**	**22308**

Table 7: Carbon monoxide emissions

Particulate matter < 10 microns **Emissions in kt**

EU15 sector totals	1990	1995	2000	2005	2010	2015	2020
Combustion: non-industry	481	436	391	346	301	301	301
Road transport: Diesel exhaust	229	245	177	115	67	47	43
Road transport: Gasoline exhaust	88	68	36	34	35	37	40
Road transport: Non exhaust	33	41	47	53	58	63	68
Other mobile	25	24	24	23	23	23	23
EU15	**2322**	**2179**	**1939**	**1736**	**1548**	**1535**	**1538**

Table 8: Particulate matter emissions

Non methane volatile organic compounds **Emissions in kt**

EU15 sector totals	1990	1995	2000	2005	2010	2015	2020
Combustion: non-industry	655	654	652	650	649	649	649
Road transport	5415	4378	2828	1522	804	600	566
Other mobile	752	710	668	626	584	584	584
EU15	**13261**	**11821**	**9869**	**8160**	**7040**	**6835**	**6802**

Table 9: Non methane volatile organic compounds emissions

Benzene **Emissions in kt**

EU15 sector totals	1990	1995	2000	2005	2010	2015	2020
Combustion: non-industry	24	24	24	24	24	24	24
Road transport	200	163	79	42	23	17	16
Other mobile	25	24	22	21	19	19	19
EU15	**288**	**249**	**165**	**127**	**108**	**101**	**100**

Table 10: Benzene emissions

A summary of this data is presented in the following table. In spite of the fact that the temporal horizons are different (we have here forecasts for 2020, while the IPTS study [2] is about 2030), many discrepancies subsist even if we attempt to extrapolate values to 2030 (Table 12).

Extrapolations are to be performed to extend the evaluations to the EU25 and to 2030. The method used for the extrapolation to EU25 is the same as in the IPTS study [2], as the assumption is that there is no significant difference among the countries of EU25 and therefore the EU15 data can be used, the values being increased in proportion of the related energy consumptions for the residential, tertiary and transport sector.

Forecasts 2020

		Transport		Combustion: non-industry		Total	
Pollutant	unit	EU15	EU25	EU15	EU25	EU15	EU25
NOx	kton	985	1121	620	706	1605	1826
SO2	kton	18	20	345	393	363	413
CO	kton	5048	5743	5953	6773	11001	12517
PM10	kton	82	94	301	343	384	436
NMVOC	kton	566	644	649	738	1215	1382
C6H6	kton	16	18	24	27	39	45

Table 11: Extrapolation of EU15 emissions data to EU25

The method used for the extrapolation to 2030 is based on the shape of the curves. The figure below shows the asymptotic evolution of the emissions due to road transport.

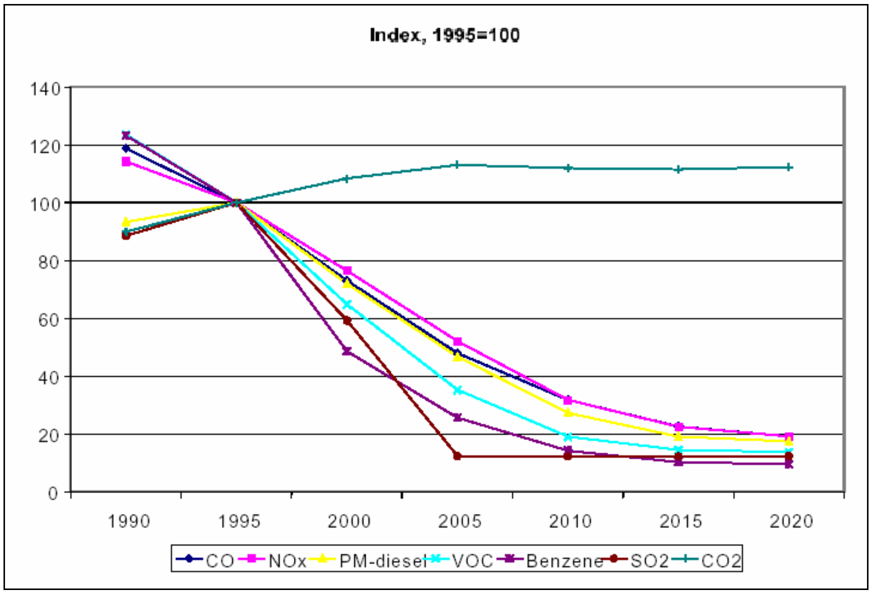

Figure 12: Road transport emissions in Europe [3].

The table below shows the data of forecast to 2030 for EU25.

Forecasts 2030

		Transport		Combustion: non-industry		Total	
Pollutant	unit	EU15	EU25	EU15	EU25	EU15	EU25
NOx	kton	639	728	620	705	1259	1433
SO2	kton	18	20	345	393	363	413
CO	kton	3198	3639	5948	6767	9146	10406
PM10	kton	79	90	301	343	380	433
NMVOC	kton	499	567	649	738	1147	1306
C6H6	kton	13	15	24	27	37	42

Table 12: Extrapolation of forecast emissions to 2030

4.3 Benefits of hydrogen use

In this context we introduce the use of new fuels like hydrogen to produce stationary and transport energy especially in the cities. The production of noxious pollutants is avoided when H_2 is burned or used in the fuel cells. Therefore H_2 is a promising energy vector in order to restore acceptable environmental conditions in the urban areas.

Regarding the improvement the local air quality in cities, hydrogen technologies are part of the so called "efficiency route". The efficiency route is based on the idea that is it possible to solve the environmental problems caused by transport by developing new and more efficient technology. More efficient engines, lighter materials, catalytic devices for cleaning exhaust and alternative fuels, as hydrogen, are examples embedded in this route. The beauty of this route is that we can travel more, while we pollute less at the same time.

The CUTE European project is an example of reaching sustainability with the efficiency route and hydrogen as alternative fuel. This project will investigate the potential of the new FC technology to reduce air polluting emissions like SO_2 and the summer smog caused by NOx and VOC in highly populated inner city areas [8]

Figure 13 gives a first indication of the NOx emissions along the life cycle of diesel, FC (NEBUS) and CNG busses. Please note that the graph shown here is based on literature data using German boundary conditions and that the bus production is not included.

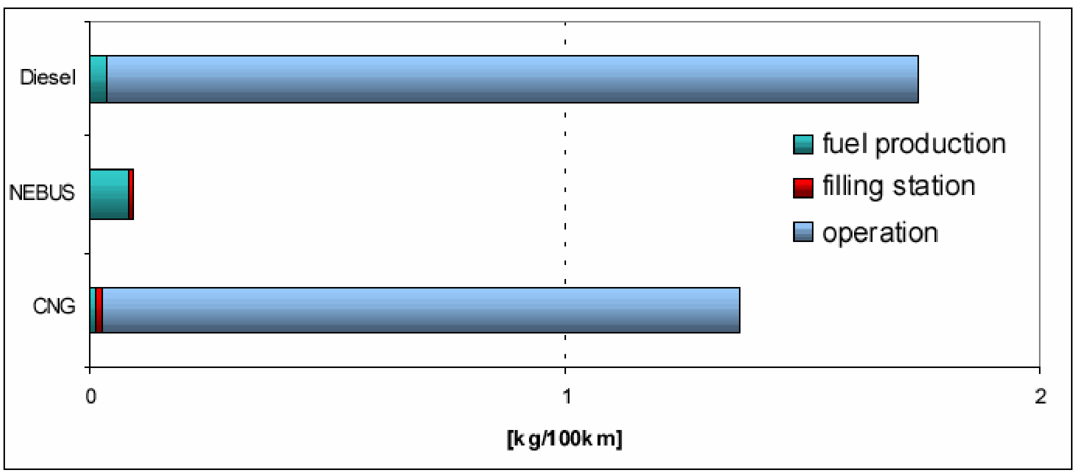

Figure 13: NOx emissions in urban drive cycle

Monitoring the emissions over the complete life cycle enables us to quantify the contribution of the new technology not only to emission reduction goals as stated out in the Kyoto Commitments but also on the air quality in comparison to conventional bus technologies.

The main traffic related emissions such as CO_2, NOx, PM, SO_2 and CO have a different environmental impact in different geographical areas. E.g. CO_2 emissions influence the climate on a global level, SO_2 emissions on a regional level and NOx and CO a local level. The emission of fine particles (PM) for example has a much higher environmental impact in an already emission stressed urban area with a high population density than in low populated rural area with little air pollution.

On the basis of previous forecasts (Table 14), the benefits of hydrogen use can be evaluated in relation with the two scenarios A and B described before. In the majority of cases, the great part of urban emissions, and the inherent air quality, is essentially due to the residential and transport sectors.

The benefits of hydrogen use will be respectively close to 20% and 5% (and in many cases more than 20%) of reduced emissions for the majority of pollutants.

In scenario A, 85 % of the hydrogen production is from fossil fuels (15 % from renewable sources). Thereof 80 % is produced in centralised plants with CO_2 capture and sequestration and 20 % in small, distributed plants via natural gas reforming.

In case of CO_2 sequestration, the presence of gaseous substances such as SO_2, NO_X and dust, have an impact on the viability of the CO_2 capture process. For instance, the presence of both SO_2 and/or NO_X in the flue gas can have damaging effects on some chemical scrubber-based systems. Thus, in the case of carbon capture, only a part of flue gas in the reformer process produces atmospheric pollutants, mainly NO_x emissions. The main part of hydrogen production is done in non-urban areas, with limited atmospheric emissions.

Decentralized (25 % of H_2 from fossil sources for mobile applications = 138 168 GWh) and on-site (20 % of H_2 from fossil sources for stationary applications = 372 458 GWh) hydrogen production from fossil fuels is considered via natural gas reforming. In both cases, no carbon capture and sequestration occur. Direct air emissions can be estimated. They are only significant for NO_x (and of course for CO_2). For reformer efficiency between 70 or 75 %, NO_x emission factor is 0.0762 g/kWh (H_2). This means more or less 10.5 ktonnes NO_x emissions from mobile applications and 28.4 ktonnes NOx emissions from stationary applications. These quantities are to be added to the results in Table 14, respectively for transport sector and for non-industry combustion.

The CO_2 emissions produced from biomass gasification are neutral otherwise other emissions are less known but would approximately be the same for SO_2, NO_x and PM_{10} as for natural gas. The dominant impact from the biomass fuel cycle is from emissions of NO_x, similar to that derived for natural gas. A rough estimate could be 5.4 ktonnes NO_x emissions from mobile applications and 14.8 ktonnes NO_x emissions from stationary applications. We can suppose that biomass gasification will not occur in urban areas, so that the impact on urban air quality will be negligible.

Both scenarios assume that hydrogen will be used in fuel cell application (stationary and transport). Air emissions in this case can be estimated to be insignificant. Scenario A assumes that 20 % of energy consumption of stationary sector (industry, tertiary and residential) comes from hydrogen. We can assume that industry will almost not use hydrogen. The main stream of hydrogen to stationary sector will go to residential and tertiary sector so that the share would be larger than 20 %. If we allocate the 2 190 929 GWh from hydrogen (20% share of the stationary sector) only to residential and tertiary sectors in the same proportion as the energy demand (respectively 61 and 39%), the part of hydrogen in these two sectors increases to 34 % of the energy demand.

Table 13 : Final Energy Demand by sector, Baseline scenario EU-25, 2030 [9] and allocation of hydrogen to residential and tertiary sectors for scenario A.

	Mtoe	GWh	H_2 allocation of 2 190 929 GWh %	H_2 allocation of 2 190 929 GWh GWh
industry	385.5	4 483 365		
residential	338.6	3 937 918	61%	1 333 301
tertiary	217.8	2 533 014	39%	857 628

Results are shown in the following table. Pollutants emissions from fuel cell application are considered as insignificant. Benefits of hydrogen introduction fluctuating between 25 to 33 % can be expected, depending on pollutant,. The worst result is for NOx , due to air emissions from natural gas reforming.

		Transport		Households		Total	
Pollutant	Unit	BAU	20% H2	BAU	20% H2	BAU	20% H2
NOx	kton	728	593	705	494	1433	1087
SO2	kton	20	16	393	259	413	275
CO	kton	3639	2.911	6767	4466	10406	7377
PM10	kton	90	72	343	226	433	298
NMVOC	kton	567	454	738	487	1306	941
C6H6	kton	15	12	27	18	42	30

Table 14: Forecasts of 2030 air emissions for EU25 in scenario “Business as usual” and scenario A

The same analysis can be made on scenario B as on scenario A, taking into account that production proportion are less favourable to environment (less carbon capture and sequestration and more decentralized and on site production) but that production and emissions quantities are less important.

In scenario B, 90 % of hydrogen production is from fossil fuels (10 % from renewable sources). Thereof 50 % is produced in centralised plants with CO_2 capture and sequestration and 50 % in small, distributed plants via natural gas reforming.

Decentralized and on-site production means more or less 3.7 ktonnes NO_x emissions from mobile applications and 21.8 ktonnes NO_x emissions from stationary applications. These quantities are to be added to the results in table 13, respectively for transport sector and for non-industry combustion. If we allocate the 547 732 GWh from hydrogen (5 % share of the stationary sector) only to residential and tertiary sectors in the same proportion as the energy demand (respectively 61 and 39%) the part of hydrogen in these two sectors increases to 8.5 % of the energy demand.

		Transport		Households		Total	
Pollutant	unit	BAU	5% H2	BAU	5% H2	BAU	5% H2
NOx	kton	728	692	705	667	1433	1.362
SO2	kton	20	19	393	360	413	379
CO	kton	3.639	3.457	6767	6192	10406	9449
PM10	kton	90	86	343	314	433	399
NMVOC	kton	567	539	738	675	1306	1214
C6H6	kton	15	14	27	25	42	39

Table 15: Forecasts of 2030 air emissions for EU25 in scenario “Business as usual” and scenario B

In this case, hydrogen benefit is obviously less important, from 5 to 8 % depending on pollutants.

In both scenarios, more in scenario B than in scenario A, hydrogen fuelled vehicles are above all in the public transport and in captive fleets. In scenario B, only a limited number of private hydrogen fuelled cars exist, located in congested areas in Germany, Great Britain, Spain, France and Italy. In these cases, the reduction impacts will be greater in cities.

It should also be stressed that AOPII has addressed only a limited number of targets in the context of existing air quality objectives. In the future it will be important to watch out for current or emerging problems associated with non-regulated pollutants such as polycyclic aromatic hydrocarbons (PAH), nitrous oxide (N_2O), formaldehyde, acetaldehyde, etc. For these substances also, hydrogen use will have a positive part since emissions of such substances are avoided at a local level.

4.4 Summary and conclusions

The introduction of hydrogen use by fuel cell vehicles in urban area will have a positive aspect on air emissions and on air quality. Impact on air quality will be similar to the introduction rate of hydrogen (5 or 20 % improvement according to the different scenarios). However, the increased penetration of hydrogen in urban areas, due to a greater use of public transport and captive fleets in cities with a better introduction of fuel cell technology in tertiary and residential sector, enhance hydrogen benefits to 33% in some cases.

Some emissions will occur in decentralized and on-site hydrogen production by methane reforming. However, impact will be very small and limited to NO_x emissions.

The production of hydrogen from fossil sources in a centralized way produces some emissions but, in all cases it is done with carbon capture and sequestration systems which imply a significant reduction of most pollutants. It will affect less polluted areas, some distance away from crowded cities.

Hydrogen production from biomass comes with emissions of $NO_{x.}$ Biomass gasification is not supposed to take place in urban areas, so that the impact on urban air quality will be negligible.

So the use of hydrogen will contribute to reinforce the current trend of decreasing the air pollution in general, with more intensity in urban areas.

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In addition, many documents related to AutooilII can be found from:

[9] http://europa.eu.int/comm/environment/autooil/

[10] A database with many details on the emissions due to transport and with forecasts about 2020: http://www.tremove.org/index.htm

5 Environmental, Health and Safety Risks of Hydrogen

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5.1 Introduction

All fuels, by their nature, present hazards to the environment, health and safety. However, these hazards vary widely between different fuel types, and suitable national and international standards are traditionally put into place to ensure that the fuels are handled as safely as possible. This section discusses a number of environmental, health and safety issues associated with the use of hydrogen.

5.2 Health and safety

Hydrogen has been in use as a fuel sporadically since the turn of the century. It has been in much more constant use as a chemical feedstock or industrial by-product, and every year more than 500 *billion* cubic metres of hydrogen are generated and used world-wide without major safety problems. In energy terms, this corresponds to over half of the United Kingdom’s yearly energy requirements.

Hydrogen is rarely used as a fuel outside the space industry, and so comparatively few rules and regulations apply to its widespread use in this way. However, working groups of the International Standards Organisation (ISO) and national standards bodies such as the German TÜV have explicitly begun to consider hydrogen as a fuel. There are also many standards applied to, for example, compressed gases, which have been applied directly in many of the hydrogen vehicle test programmes presently under way.

Although hydrogen has not been in widespread use as an energy carrier, the ‘town gas’ or coal gas that was prevalent before the introduction of natural gas networks in many areas consisted of large proportions of hydrogen. The percentage of hydrogen in this fuel was often 50% and sometimes as high as 70%. The widespread use of this fuel was not considered to pose particular environmental hazards. Hydrogen is also used routinely in industrial processes and used in both liquid and gaseous form. There is no indication that a properly designed hydrogen infrastructure for power and transport uses would pose any greater danger than conventional fuels. It should also be possible to transfer the experience of hydrogen use in larger-scale industrial installations to the emerging decentralised use of hydrogen as a fuel.

5.2.1 Hydrogen combustion

Hydrogen is both flammable and explosive under the right conditions, as are all fuels. It has a wider flammability and explosivity range than any other fuel when mixed with air, but it also has high lower flammability limits and dissipates upwards extremely rapidly, and does not form low-lying pools of explosive gas. In open spaces it is almost impossible to detonate hydrogen-air mixtures because of the high speed of dissipation, but explosions can occur if the gas is trapped in an enclosed area. The blast energy dissipated by the explosion varies depending on local conditions, but is generally lower than an equivalent amount (by energy) of a conventional liquid fuel. Hydrogen has a relatively high auto-ignition temperature, which makes it difficult to ignite a hydrogen/air mixture on the basis of heat alone without some additional ignition source. However, hydrogen like most fuels has a low ignition energy. Hydrogen burns with a light blue flame which is almost invisible in daylight, but easily visible in subdued light and in the dark.

General properties are shown below, with those of petrol and natural gas for comparison (**Error! Reference source not found.**).

Units	*Hydrogen*	*Natural gas*	*Petrol*
Lower Heating Value (MJ/kg)	120	50	44.5
Auto-ignition Temperature (°C)	585	540	228-501
Flame Temperature (°C)	2045	1875	2200
Limits of Flammability in Air (Vol. %)	4.0-75	5.3-15	1.0-7.6
Minimum Ignition Energy (μ J)	20	290	240
Limits of Detonation in Air (Vol. %)	13-65	6.3-13.5	1.1-3.3
Theoretical Explosive Energy (kg TNT/m^3 Gas)	2.02	7.03	44.22
Diffusion Coefficient in Air (cm^2/s)	0.61	0.16	0.05

Table 16: Fuel properties

5.2.2 Human health

Hydrogen is neither toxic nor carcinogenic, and forms no harmful compounds with other materials under normal conditions. It may cause asphyxiation if present in high enough concentrations as not enough oxygen will then be available to the subject. It is also difficult to detect as it is colourless, odourless and tasteless. However, ingestion is not considered a potential route for exposure, and there are no known toxicological or ecological effects.

Use of hydrogen in enclosed spaces must be accompanied by adequate ventilation and, in certain circumstances, by hydrogen sensors. The addition of conventional sulphur containing additives used with natural gas may pose a problem to fuel cell operation because of catalyst poisoning. However, hydrogen dissipates rapidly and thus passive ventilation is adequate in many cases to ensure that no flammable build-up can take place. In unconfined areas risk of asphyxiation is almost negligible due to the high buoyancy and diffusivity of hydrogen.

Hydrogen derived from reforming of other fossil fuels is typically accompanied by nitrogen, carbon dioxide, carbon monoxide and other trace gases, which are also generally odourless, colourless and tasteless. Carbon monoxide is poisonous and potentially flammable and explosive. So, where hydrogen is produced from fossil fuels and carbon monoxide is produced, its levels need to be monitored.

Pure hydrogen may affect metal and other surfaces by making them brittle, particularly under cryogenic conditions. Liquid hydrogen is extremely cold (-253°C) and contact with the skin may cause severe burns. However, in an open environment contact is unlikely to take place because of the so-called *Leidenfrost* effect, where the high temperature difference between the liquid hydrogen and the skin causes hydrogen boil-off and forms an insulating gaseous layer between the two.

5.2.3 Effects of wide-scale use

Generally the risks associated with widespread use of hydrogen will be limited to the area in which the hydrogen is produced and stored and, in the case of transport applications, the area where the hydrogen vehicles are in use. Hydrogen production, even at small scales, gives rise to similar hazards to a conventional hydrogen production plant and must conform to existing standards. These include operation at set distances from other fuels, sources of flame, vegetation and other potential hazards. In addition, walls may be required to ensure the area is separated from areas with other types of use.

Storage of gaseous hydrogen gives rise to a potential combustion hazard. Hydrogen from any leak in the tank will dissipate rapidly upwards and should itself present only a small hazard. Should it burst into flame then this will be almost invisible and thus could be difficult to avoid. However, the flame also burns very rapidly and the fire itself should burn out rapidly. Hydrogen flames radiate almost no heat, making them easy to approach unwittingly, but also causing very little secondary damage.

In use, the hydrogen is also likely to be in compressed form. Tanks will most likely be on top of buses – very safe in the event of a crash – and in similarly safe positions in other vehicles. Modelling and testing has shown that an explosion is almost impossible in open-air conditions, though hazards may arise in tunnels and other enclosed spaces. Hydrogen is currently stored in vehicles using tanks whose design is based on long experience in producing vehicle tanks for high pressure compressed natural gas. The tanks have been subjected to extreme tests – including dropping them long distances onto concrete and firing bullets at them. The safety standards for these tanks are extremely high.

5.2.4 Standards

Standards are under development for hydrogen systems from two key perspectives – health and safety and commonality. ISO TC 197 is currently developing standards in areas such as compressed hydrogen cylinders and refuelling nozzles, with active participation from the Hydrogen Research Institute in Quebec, the National Hydrogen association in Washington, DC and some European groups.

Commonality, and the generation of standards to ensure that vehicles produced in one place, for example, are usable in another, is much more complex. In general, hydrogen vehicles have been built to whatever standards have been felt applicable, and then application made to the local authorities on a specialised basis.

As yet, however, there are almost no worldwide regulations under which common development can take place. The European Integrated Hydrogen Project worked towards standardisation in Europe, and members are also active in the ISO Programmes. However, it may take several years before suitable standards are in place for road-going vehicles, not least because agreement of all the relevant bodies takes a significant amount of time. Undated information on international standards relating to hydrogen safety can be found at http://www.hydrogensafety.info/.

5.3 Atmospheric impacts of hydrogen

Molecular hydrogen (H_2) is a naturally-occurring trace component of the lower atmosphere, with a present concentration of about 500ppbv (Tromp et al. 2003). It is a key part of atmospheric chemical cycles of water and various pollutants and greenhouse gases. Its budget is influenced by anthropogenic emissions, such as car exhaust, but is dominated by photochemical reactions in the atmosphere and uptake in the soils. H_2 concentration in the lower atmosphere is currently increasing at a rate of 5ppbv per year, about two thirds from direct emissions from fossil and biomass combustion and a third from the photochemical oxidation of volatile organic compounds.

The largest sources of hydrogen are (a) direct hydrogen emission and (b) oxidation of methane and isoprene. Motor vehicle exhausts and biomass burning are the largest direct emission sources, but much of the hydrogen in the atmosphere has come from methane and isoprene oxidation through atmospheric chemistry processes.

The interactions between sources and sinks is not fully understood (Zittel et al. date, Tromp et al 2003). However, a significant increase in molecular hydrogen emissions in the troposphere will lead to part of the molecular hydrogen reacting with hydroxyl radicals in the troposphere and in an important share of the emissions moving up and mixing with stratospheric air.

Molecular hydrogen can contribute to the following environmental issues:

- ground-level and tropospheric ozone production affecting air quality and acting as a greenhouse gas;
- stratospheric ozone chemistry affecting the ozone layer and climate change.

5.3.1 Ground level and tropospheric ozone production and radiative forcing

Ozone has an effect on air quality and global warming, being the 3rd most important greenhouse gas after methane and CO_2. Ozone is not emitted directly into the troposphere, but is a secondary photochemical pollutant usually formed from the sunlight-initiated oxidation of volatile organic compounds (VOC), for example hydrocarbons in the presence of nitrogen oxides (NO_x). The atmospheric chemistry of H_2 and its impact on ozone formation and radiative forcing agents is complex and a matter of ongoing research. The reaction of H_2 molecules with OH radicals reduces the radicals' potential to react with hydrocarbons and thus increases the potential for ozone formation. However, this also leads to a reduction in the concentration of methane, a potent greenhouse gas. The direct oxidation of hydrogen molecules leads to the formation of water and ozone, water vapour also being a potent greenhouse gas. However, both of these reactions are slow and biologically-driven soil deposition acts as a sink for atmospheric hydrogen. The quantities of hydrogen that may be emitted to the atmosphere are unlikely to be cause for concern: assuming that all fossil fuel consumption were replaced by H_2 and that even as much as 1% of that H_2 were to leak to the atmosphere, its climate impact would be 0.6% that of the fossil-based system it replaced (Derwent, R, 2004).

Derwent *et al.* [2001] have used the STOCHEM global 3-D tropospheric chemistry model to calculate the indirect effects of hydrogen (and also CO, CH_4, NO_x) on climate change. In Table IV of their paper (reproduced in **Error! Reference source not found.** below), they presented global warming potentials that resulted from changes in (a) the OH radical concentration and its affect on methane; (b) the O_3 produced and (c) the CO_2 produced in the complete oxidation of methane and carbon monoxide.

Tropospheric ozone precursor	GWP from impact on CH_4 concentrations	GWP from changes to O_3 concentrations	GWP from changes to CO_2 produced during oxidation
Methane (CH_4)	20.0	3.3	2.4
Surface nitrogen oxides In NH (NO_x)	-8.5	13	
Surface nitrogen oxides In SH (NO_x)	-24.0	39	
Aircraft nitrogen oxides (NO_x)	-65.9	343	
Carbon monoxide (CO)	1.0	0.6	1.6
Hydrogen (H_2)	3.4	2.4	

Table 17: Global warming potentials for three radiative forcing mechanisms for a range of different emission pulses of tropospheric ozone precursors over a 100-year time horizon [relative to the gwp(direct co2) = 1]

Each GWP has been expressed relative to an emission pulse of 1 Tg (as CH_4, NO_x, CO, CO_2 and H_2).

As noted by Derwent et al. (2001), the GWP(O_3) values for methane, CO and H_2, on a mass basis, are heavily influenced by the low molecular weight of hydrogen. On a molar basis, the relative radiative forcing indices change order and become 4:14:53 respectively.

5.3.2 Water vapour in the lower atmosphere

Water vapour emissions from hydrogen use would be negligible compared to existing global water vapour cycles even if all energy conversion were to be based on hydrogen. Also, water vapour emissions from a transition to hydrogen would only marginally influence local or regional water cycles. As an example, the conversion of all road transport from fossil fuels to hydrogen would increase water vapour emissions from transport by about 2.5 times, and water emissions from converting all road transport to hydrogen in a city like Munich would still be an order of magnitude less than water vapour emissions from the cooling tower of a 1GW thermal power plant.

5.3.3 Water vapour and oxides of nitrogen in the stratosphere

While it has been claimed that the migration of tropospheric H_2 to the stratosphere may result in its 'moistening' as H_2 is oxidised to water. The result of this could be a cooling of the lower stratosphere and the disturbance of ozone chemistry, in particular a decrease in stratospheric ozone through a compounding effect to that of chlorofluorocarbons. However, the quantities of H_2 likely to be released under an efficient hydrogen economy should be small and the build up of a hydrogen economy will take decades, during which the ozone layer may have largely recovered from the negative effect of chlorofluorocarbon emissions. The effect of hydrogen releases in the troposphere may thus have a negligible effect on stratospheric ozone. (Science article and letters)

The release of water vapour emissions in the stratosphere, through the use of hydrogen in aviation for example, may have more important impacts. Burning hydrogen produces 2.6 times the amount (mass) of water vapour as burning kerosene with equal energy content. The greenhouse effect of water varies greatly with altitude. Above approximately 6000m, where water vapour condenses and freezes to form thin ice clouds, the greenhouse effect per molecule is greater for water than for CO_2. Carbon dioxide has a much greater residence time, however: approximately 100 years, independent of altitude, compared to 3-4 days at ground level and 0.5-1 year in the stratosphere for H_2O. There is general consensus that the combined radiative forcing of emissions from LH_2 fuelled aircraft would be much lower than from kerosene. There is disagreement about critical altitudes, however: Some commentators, such as Heinz et al and Contreraz et al state that the effect of water vapour at current subsonic altitudes will be 'negligible' or 'not significant', whereas Pohl et al believe that emissions from LH_2 aircraft flying above 10km would exceed those from kerosene aircraft. Consequently Pohl believes that flight altitudes will have to be reduced to below 10km where ‘the greenhouse effect is very close to zero.’

Finally, the high-temperature combustion of H_2 in air would result in emissions of oxides of nitrogen. To reduce emissions of NO_x, new combustion concepts are required that take full advantage of hydrogen’s particular properties. These include the possibility for lean-burn low temperature combustion, short dwell times, and fuel/air homogeneity. In the 1990s the European-Canadian “Euro-Quebec Hydro-Hydrogen Pilot Project” successfully proved that very low NO_x emissions are possible from practical LH_2 jet engines.

On balance it is likely that substituting hydrogen for fossils fuels will have a positive environmental impact in reducing both photochemical smog and climate change. There could be an adverse impact on the ozone layer but this is likely to be small, though potentially more significant if hydrogen was to be used widely as an aviation fuel. However the highly complex nature of chemical reactions in the atmosphere means that extensive modelling would be required to verify some of these assumptions.

5.4 Summary and conclusions

The use of hydrogen as a fuel needs to address environmental issues other than climate change, as well as health and safety issues. A properly designed hydrogen infrastructure for power and transport uses is not likely to pose greater danger than conventional fuels. A fundamental requirement is the implementation of suitable safety standards for hydrogen energy related equipment and applications. Training of qualified personnel dealing with hydrogen energy applications will also be important to ensure safety. It should be possible to transfer the experience of hydrogen use in larger-scale industrial installations to the emerging decentralised use of hydrogen as a fuel.

Molecular hydrogen can contribute to ground-level and tropospheric ozone production affecting air quality and acting as a greenhouse gas and to stratospheric ozone chemistry affecting the ozone layer and climate change. These are areas that require further research. However, the quantities of hydrogen that may be emitted to the atmosphere are unlikely to be cause for concern. Water vapour emissions from hydrogen use would be negligible compared to existing global water vapour cycles even if all energy conversion were to be based on hydrogen. Also, water vapour emissions from a transition to hydrogen would only marginally influence local or regional water cycles. There could be an adverse impact on the ozone layer but this is likely to be small, though potentially more significant if hydrogen was to be used widely as an aviation fuel.

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