Max-Planck-Institut für Meteorologie
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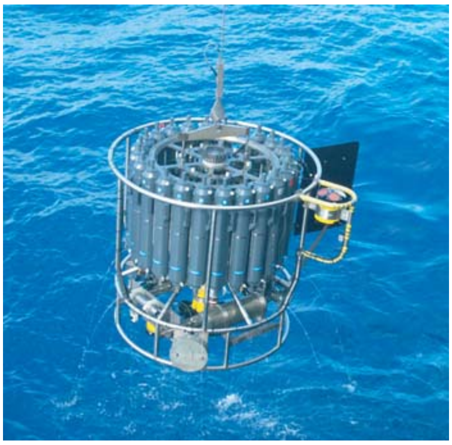
HyCARE
Hydrogen Energy Chances and Risks for the Environment

Proceedings of the 2nd HyCARE meeting,

Laxenburg, Austria, 19-20 Dec 2005

Edited by Martin G. Schultz and Malte Schwoon



Berichte zur Erdsystemforschung 25/2005

Reports on Earth System Science

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HyCARE

Hydrogen Energy
Chances and Risks for the Environment

A forum to discuss the European research strategy concerning the environmental impacts of a future hydrogen economy

Proceedings of the 2nd HyCARE meeting, Laxenburg, Austria, 19-20 Dec 2005
Edited by Martin G. Schultz and Malte Schwoon

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The second HyCARE meeting in Laxenburg, Austria, Dec 19-20, 2005, was organized around four main themes related to the chances of hydrogen as a future energy carrier and the present-day and potential future budgets of hydrogen in the atmosphere. This report summarizes the meeting presentations and discussions and is based on extended abstracts (or short abstracts where these are not available) sent by the meeting participants. With this second meeting, HyCARE successfully established itself as a major international forum for all environmental aspects related to hydrogen energy. Further information on the initiative including the proceedings from the first and the second HyCARE meeting can be found on the web pages http://www.fz-juelich.de/hycare/. To contact HyCARE, please send email to m.schultz@fz-juelich.de.

HyCARE is sponsored by the ACCENT network of Excellence under the topic of Atmospheric Sustainability. ACCENT is funded by the European Commission through FP6, Prority 1.1.6.3 Global Change and Ecosystems.

ACCENT
ATMOSPHERIC COMPOSITION CHANGE
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Executive Summary

With its second symposium in Laxenburg, Austria, the Hydrogen Energy – Chances and Risks for the Environment (HyCARE) platform further strengthened its role as a broad international discussion forum where environmental scientists, energy systems analysts, manufacturers and suppliers of fuell cells, hydrogen, or hydrogen-fueled applications, and policy makers meet and exchange their knowledge and their viewpoints on the future of the global energy systems and the implications on the environment. The first HyCARE meeting in Hamburg, December 2004, had produced a general overview about research into hydrogen in the environment. Its proceedings can be downloaded from http://www.fz-juelich.de/icg/icg-ii/hycare/material/.

The second meeting in contrast placed more emphasis on the scenarios for developing hydrogen as a key component in the energy supply chains and in particular aimed at discussing hydrogen versus other energy alternatives, particularly in the mobile sector. This special focus was intended to provide earth system scientists with more specific background information to plan their future impact calculations. Updates on the development of atmospheric hydrogen measurements and models as well as opportunities for future funding of HyCARE related environmental research projects were also given and provided valuable information to energy analysts and economists.

The two-day meeting was structured into four sessions:
1. Atmospheric chemistry, the global budget of hydrogen and its past and possible future trends
2. Pathways into a hydrogen economy and their possible consequences for greenhouse gas and air pollutant emissions
3. Atmospheric chemistry-climate interactions in relation to potential future emission changes in a hydrogen economy
4. Costs and benefits of hydrogen energy in relation to alternative energy scenarios

In addition, a moderated discussion on "Chances and risks of the hydrogen economy" involving four distinguished panelists was held as a final event.

The form of the meeting was changed compared to the first symposium in that the number of oral presentations was slightly reduced in order to give more room for posters and the moderated discussion. Four invited keynote presentations provided a general overview about the individual sessions, and these were complemented by some shorter presentations on specific studies or topics. The open form of the meeting and the discussions was kept and once again turned out to be highly fruitful, leading to interesting debate.

In the future, HyCARE will be managed by the research center Jülich in Germany. The HyCARE co-ordinator, Martin Schultz, assumes a new position in this institution which has a long tradition in fuel cell and energy research as well as in atmospheric chemistry research. This new environment should provide additional stimuli to the further growth of the HyCARE initiative.

During the Laxenburg meeting, the participants also elected a new steering group, which now consists of the following members:

- Dr. Martin Schultz, Forschungszentrum Jülich (co-ordinator)
- Dr. Stefan Berger, Adam Opel GmbH, Rüsselsheim
- Dr. Heinz Hass, Ford Motor Company, Aachen
- Dr. Jean-Francois Larivé, CONCAWE, Brussels
- Dr. Thomas Röckmann, Univ. Utrecht

- Prof. Ulrich Schmidt, Univ. Frankfurt
- Prof. Frode Stordal, Univ. Oslo
- Dr. Markus Amann, IIASA, Laxenburg

The responsibilities of the steering group include the promotion of the HyCARE initiative and its objectives, the definition of the HyCARE work plan, preparation of the annual HyCARE workshop, and the review of HyCARE documents. The present steering group will act until a new group is elected which is scheduled for the next HyCARE symposium in 2007.

The next HyCARE meeting has been tentatively scheduled to take place in Brussels in July 2007. For further information, please watch the HyCARE web pages at http://www.fz-juelich.de/hycare/.

Extended Abstracts

Session 1: Atmospheric Chemistry, the Global Budget of Hydrogen and Its Past and Possible Future Trends

Open Questions about the Atmospheric Hydrogen Cycle

Thomas Röckmann, Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Princetonplein 5, 3508TA Utrecht, Netherlands

Research about the atmospheric cycle of H_2 has been neglected in the past decades, and has only recently reached new attention. This is mainly due to a worldwide initiative for moving from a fossil-fuel-based economy to a hydrogen-based economy. Although the effect on the environment is expected to be beneficial, also potential environmental problems from leakage of H_2 have been identified.

However, recent studies have revealed that the knowledge of the “natural” hydrogen budget, in particular the strengths of the individual sources and sinks, is quite limited. At this time we still have the chance to thoroughly study the global cycle of hydrogen before the anticipated strong anthropogenic perturbation takes place. I will highlight in my presentation some of the largest unknowns in the global hydrogen cycle and discuss strategies to improve our knowledge of those terms.

Calibration of Atmospheric Hydrogen Measurements

Armin Jordan, Max-Planck-Institute for Biogeochemistry, Hans-Knöll-Str. 10, 07745 Jena, Germany

Molecular hydrogen is being analysed at a number of different laboratories. As there is no common calibration scale and internal calibration scales established independently are used for quantification. Conversion factors of different scales are largely unknown. This introduces large uncertainties when comparing atmospheric hydrogen records measured by different programs.

One main problem that has inhibited the setup of a hydrogen scale is that commonly used containers for trace gas reference standards are aluminium cylinders (Luxfer). These cylinders tend to produce hydrogen and hence lead to significant concentration changes in the gas.

To provide a check for potential drifts of a laboratory's internal calibration standards a method to regularly prepare reference gas mixtures by a one step dilution is now being tested. Ultrapure hydrogen is filled in a sample loop connected to a two-position Valco valve. By switching the valve the sample loop contents are isolated and then connected to a high pressure cylinder with hydrogen-free air and an evacuated 6 L aluminium cylinder. After evacuating the inter-connecting lines the sample loop is put in line and the hydrogen transferred to the mixing cylinder.

First results will be presented that demonstrate that this approach may help to improve hydrogen calibrations.

Methods to Determine Regional Sources and Sinks of H_2 from Continuous Observations

Samuel Hammer and Ingeborg Levin Institut für Umweltphysik der Universität Heidelberg, Im Neuenheimer Feld 229, 69120 Heidelberg

1. Introduction:

Global atmospheric budget estimates of molecular hydrogen have been performed in the last years by a number of groups (Sanderson et al., 2003; Hauglustaine and Ehhalt, 2002; Novelli et al., 1999), who identified two major direct sources of H_2: Combustion from technological sources (e.g. automotive exhausts) and biomass burning. Oceanic emissions and nitrogen fixation are only minor sources. In addition H_2 is produced in the atmosphere via oxidation of CH_4 and NMHC (Non Methane HydroCarbons), which themselves are emitted from various anthropogenic and natural sources. The budget is closed by two main sinks: the oxidation of H_2 initiated by reaction with the OH radical and soil uptake, the latter is believed to be the dominating part. The present uncertainties in the budget are large, and it is therefore difficult to assess the impacts of potential future changes. This study presents methods to estimate the combustion sources as well as the soil sink on the regional scale, derived from continuous observations of boundary layer air in Heidelberg.

2. Sampling location and Instrumentation:

Heidelberg (49°24' N, 8°42' E, 116m a.s.l., 130000 inhabitants) is located in the Rhine valley in South West Germany. The air sampled from the roof of the Institute's building (~ 20m above local ground) is influenced by anthropogenic emissions of the Rhine-Neckar area with an important industrial region at Mannheim-Ludwigshafen, about 20km west of the sampling site. Biogenic influences come from agricultural areas in the Rhine valley and close to the campus where the Institute is located, as well as from a region of extended forests and grasslands east of Heidelberg. In 2005 the gas chromatographic (GC) system consisting of one HP 5890II and one Trace Analytics RGA-3 instrument has been modified to allow for a quasi-continuous parallel determination of mixing ratios of CO_2, CH_4, CO, H_2, N_2O and SF_6. At least one ambient air injection is measured every 15 minutes. The H_2 mixing ratios determined in Heidelberg are linked to the CSIRO scale within 1-2%. The precision of the H_2 measurements is generally better than 1%. ^{222}Rn is monitored on a half hourly basis, via its daughter activity with the static filter method (Levin et al., 2002).

3. Estimate of the combustion source of H_2:

Since CO and H_2 are both produced during incomplete combustion they share their anthropogenic sources. In Figure 1 a typical winter situation for both tracer mixing ratios is shown. The concentrations of CO and H_2 are very well correlated, reflecting similar sources as well as atmospheric mixing conditions. Both gases exhibit clear rush hour peaks during the morning and the afternoon hours. These rush hour situations can be used to determine the H_2/CO ratio for traffic emissions in the Heidelberg region. We applied a linear regression to all morning rush hour periods (6h to 10h am) for the year 2005, and calculated a mean H_2/CO ratio for all rush hours which fulfil the following criteria:

1. More than 71% data coverage during the rush hour for both gases
2. correlation coefficient $R^2 > 0.75$
3. CO peak more than 50% above the respective background level.

Approximately 30% of all days in 2005 fulfil these criteria and lead to a mean H_2/CO ratio of 0.32 ± 0.07. This H_2/CO emission ratio can be used in combination with CO emissions inventories for the catchment area of the Heidelberg sampling site to derive a bottom-up estimate of the H_2 flux from car exhausts.

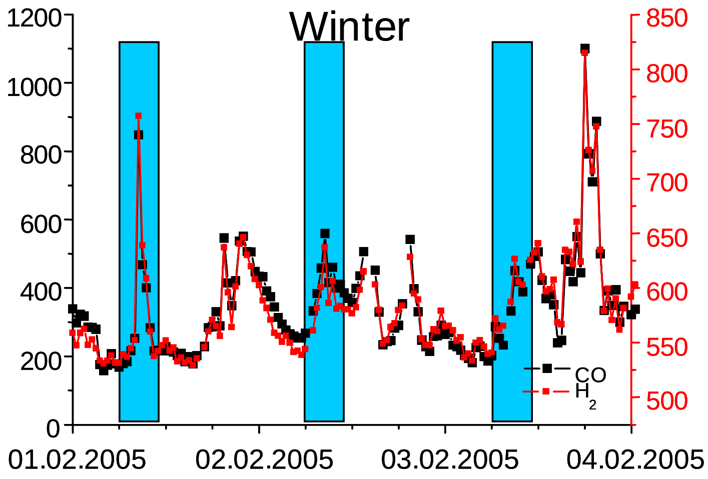


Figure 1: Typical winter situation for CO (black, left scale in ppb) and H_2 (red, right scale in ppb) mixing ratios measured in Heidelberg. Blue shaded areas mark morning (6h to 10h am) rush hours.

4. Estimate of the H_2 soil sink with the ^{222}Rn tracer method:

The idea to use ^{222}Rn as a tracer to parameterise vertical mixing and calculate fluxes of greenhouse gases between soil and atmosphere has been successfully applied for methane by Levin et al. (1999) and for N_2O by Schmidt et al. (2001). The fundamental idea of the ^{222}Rn tracer method is, that ^{222}Rn as a decay product of natural ^{238}U is emitted from all soils at a more or less constant rate. In the atmosphere the ^{222}Rn activity is solely controlled by radioactive decay and atmospheric dilution. In a one dimensional box model approach the temporal concentration change of ^{222}Rn can be expressed using the following equation:

$$\frac{\Delta c_{Rn}}{\Delta t} = \frac{j_{Rn}}{H(t)} - \lambda_{Rn} \cdot c_{Rn} \qquad (1)$$

With j_{Rn} being the ^{222}Rn flux from the soil to the atmosphere and H(t) being the box height which approximates the inversion layer height. The radioactive decay of ^{222}Rn as an ultimate sink for ^{222}Rn has been taken into account be subtracting $\lambda_{Rn} \cdot C_{Rn}$. For H_2 a similar equation can be applied without a radioactive sink.

$$\frac{\Delta c_{H_2}}{\Delta t} = \frac{j_{H_2}}{H(t)} \qquad (2)$$

The unknown inversion layer height, which is the same for ^{222}Rn and H_2, is eliminated be combining equation (1) and (2) and solving it for the H_2 flux j_{H2}.

$$j_{H_2} = j_{Rn} \frac{\Delta c_{H_2}}{\Delta c_{Rn}} \qquad (3)$$

This simple model (neglects any transport over the box boundary at H) is only applicable during relatively stable inversion conditions. Therefore, only nocturnal inversion situations were chosen to investigate temporal concentration changes of H_2 and ^{222}Rn. Corrections for the radioactive decay of ^{222}Rn in Eq.(3) have been neglected since this correction accounts only to 3-4% for a typical night time inversion. Since ^{222}Rn has a constant soil source, increasing ^{222}Rn activity during night times are expected. For H_2, the opposite should be true: a decrease of H_2 concentrations is supposed to be observed during stable nights. In Figure 2 summer situations with pronounced diurnal cycles for both gases is shown.

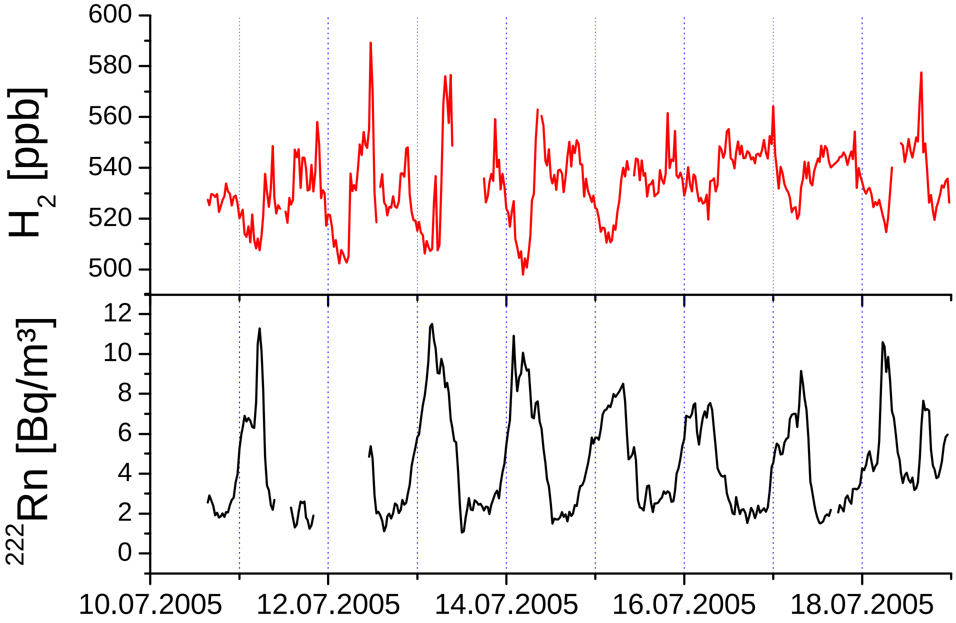


Figure 2: H_2 concentrations (upper panel) and ^{222}Rn activity (lower panel) in Heidelberg in summer 2005. Both tracers show pronounced diurnal cycles which are anti-correlated during night, reflecting once a soil source (^{222}Rn) and once a soil sink (H_2).

The advantage of using direct atmospheric measurements to estimate the H_2 soil sink, in contrast to closed chamber techniques is, that a much larger catchment area and thus many different soil types are considered and average fluxes can be calculated from Eq.(3).

5. Summary:

The combination of CO and H_2 measurements provide an opportunity to estimate the proportions of the anthropogenic H_2 source. The comparison of H_2 and ^{222}Rn offers a new possibility to assess the H_2 soil sink.

6. References

Hauglustaine, D.A. and Ehhalt, D.H., (2002). A three-dimensional model of molecular hydrogen in the troposphere. J. Geophys. Res., 107 D17, 4330 ACH41-16

Levin, I., M. Born, M. Cuntz, U. Langendörfer, S. Mantsch, T. Naegler, M. Schmidt, A. Varlagin, S. Verclas and D. Wagenbach, (2002). Observations of atmospheric variability and soil exhalation rate of Radon-222 at a Russian forest site: Technical approach and deployment for boundary layer studies. Tellus 54B, 462-475.

Levin, I., H. Glatzel-Mattheier, T. Marik, M. Cuntz, M. Schmidt and D. E. Worthy, (1999). Verification of German methane emission inventories and their recent changes based on atmospheric observations, J. Geophys. Res., 104(D3), 3447-3456.

Novelli, P.C., et al., (1999). Molecular hydrogen in the troposphere: Global distribution and budget. J. Geophys. Res. 104: 30427-30444.

Sanderson, M.G. et al., (2003). Simulation of global Hydrogen levels using a Lagrangiean Three Dimensional model, J. Atmos. Chem., 46, 15-28.

Schmidt M., H. Glatzel-Mattheier, H. Sartorious, D. E. Worthy and I. Levin, (2001). Western European N_2O emissions: A top-down approach based on atmospheric observations. J. Geophys. Res., 106(D6), 5507-5516.

EU Framework Programme 7

Ib Troen, DG Research – Global Change & Ecosystems Unit, European Commission, Rue de la Loi, B-1049 Brussels, Belgium

The presentation provided a general overview about the planning of the 7th EU framework programme and highlighted the areas where research into hydrogen energy and environmental research are foreseen. Detailed information about the EU and its research oriented activities can be found on the following web pages.

EU research:
http://europa.eu.int/comm/research

Seventh Framework Programme:
http://europa.eu.int/comm/research/future/index_en.cfm

Information on research programmes and projects:
http://www.cordis.lu/

RTD info magazine:
http://europa.eu.int/comm/research/rtdinfo/

Information requests:
research@cec.eu.int

Road Traffic Hydrogen Emissions from a Tunnel Study

Martin K. Vollmer, Martin Steinbacher, Stefan Reimann, Niklas Jürgens, Empa, Ueberlandstr. 129, 8600 Duebendorf, Switzerland

Molecular hydrogen (H_2) was measured along with carbon monoxide (CO) and carbon dioxide (CO_2) during a road tunnel campaign in 3 km long Gubrist Tunnel, Switzerland. Because traffic for the two directions is directed through 2 separated bores, and because active ventilation is absent from these bores, the experimental setup becomes relatively simple. Trace gas concentrations were measured at the entrance and at the exit of the east-bound bore and vehicle emissions were calculated using wind speed measurements and traffic counting instruments. H_2 concentrations at the exit followed the daily pattern of vehicle frequency and reached maximum concentrations of ~ 15 ppm during rush-hour traffic. Mean results for H_2 and CO emissions were calculated over a ~3 week observational period comprising ~1 mio vehicles. Preliminary emission factors for H_2 are ~45 mg km^{-1} veh^{-1} and for CO 1.4 g km^{-1} veh^{-1}. The resulting H_2/CO molecular ratio of 0.46 (~0.03 on a weight basis) is similar to literature results from pollution studies which did not separate road traffic from other combustion processes. We are planning to complement our results by measurements of H_2 and CO emissions from single vehicles with various engine technologies on dynamometer test stands. Using these results will help to better understand the variability of H_2 emission and may aid at improving a scaling of the H_2 emissions to CO on a global basis.

Global Modelling of the Atmospheric Hydrogen Budget

Nicola Warwick and John Pyle, Centre for Atmospheric Science, Chemistry Dept., University of Cambridge, Lensfield Road, Cambridge, CB2 1EW, UK

Before future H_2 emissions can be accurately estimated (e.g. for a hydrogen economy), we need to understand hydrogen in the air today. At ~500 ppb, the current background hydrogen mixing ratio is more than double the estimated pre-industrial concentration, likely due to man-made emissions from the fossil fuel industry and biomass burning. So far, only a few studies have modelled hydrogen in the atmosphere and the current H_2 budget is not well understood. Major uncertainties in the hydrogen budget include production from the atmospheric destruction of hydrocarbons and the magnitude of the soil sink. Model simulations of today's hydrogen budget have been performed using individual coloured source tracers with the aim of understanding and improving our knowledge of present-day hydrogen sources and sinks.

Atmospheric hydrogen has been incorporated in the 3D atmospheric model, p-TOMCAT. The main sources and sinks of hydrogen include emissions from biomass burning and industry (there is also a small source from the ocean and nitrogen fixation by legumes), photochemical production from the photolysis of formaldehyde (HCHO), and destruction by reaction with atmospheric OH or microbes in the soil. The model includes a simple chemistry scheme, where the OH and HCHO fields required to calculate the source and sink of hydrogen are prescribed and taken from a 'full chemistry' version of p-TOMCAT.
The hydrogen soil sink is dependent on the land type (derived using the Olson database) and soil moisture (obtained from the European Centre for Medium Weather Forecasting, ECMWF). Surface emissions of H_2 are prescribed and calculated using present-day IPCC emission scenarios for CO and H_2/CO emission ratios. Hydrogen simulations are performed using ECMWF wind analyses for 1998 at a resolution of ~2.8° in horizontal, and 31 vertical levels to 10 hPa.

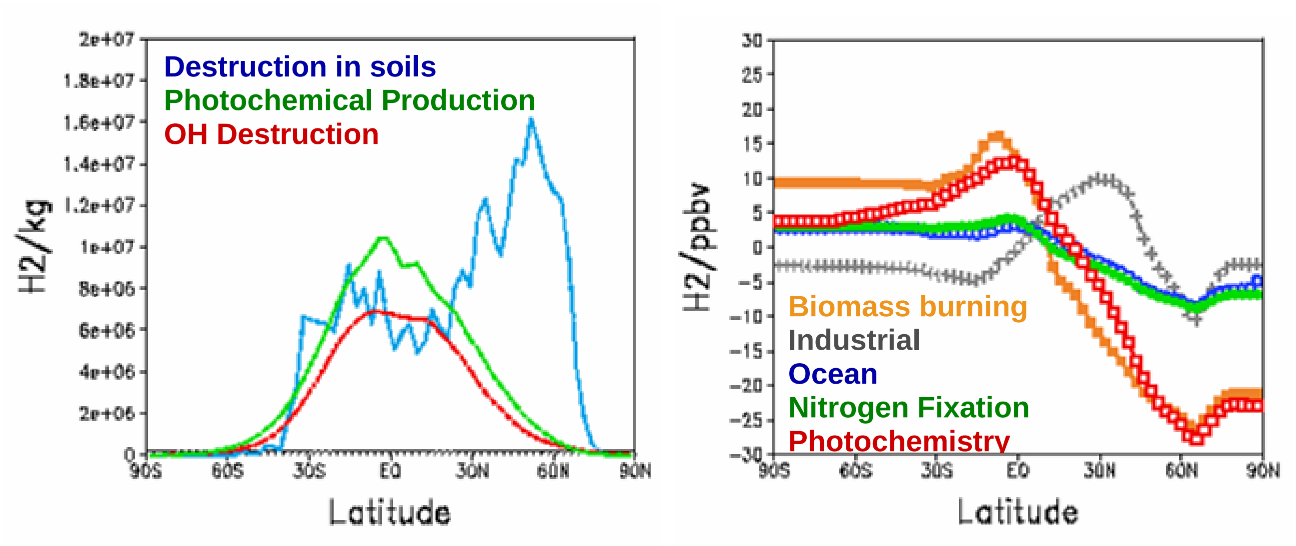
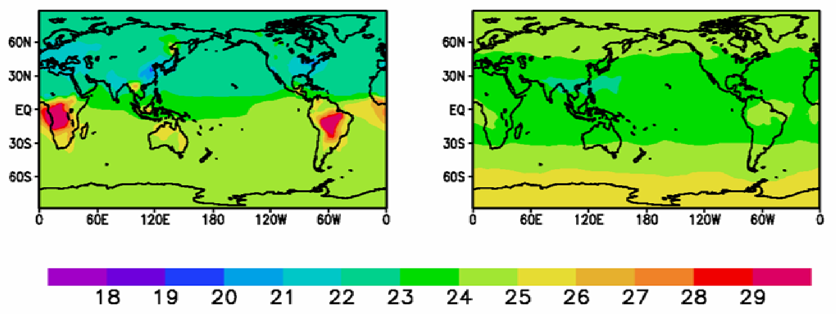
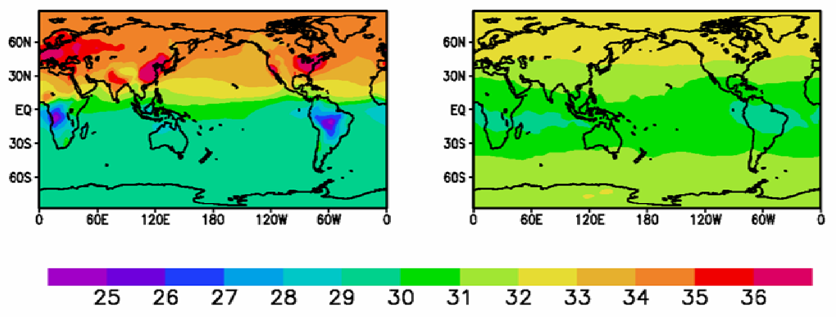


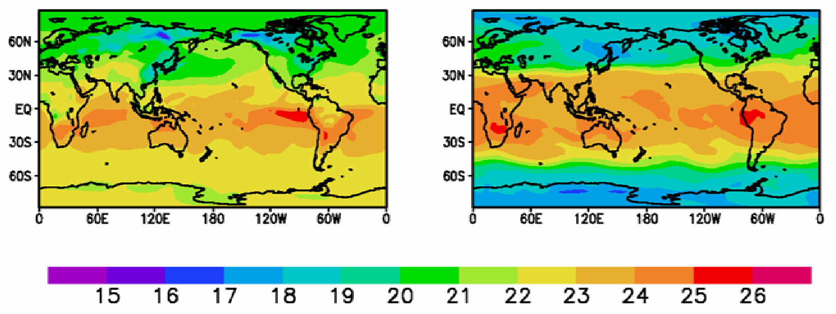
Figure 1 – The modelled latitudinal distribution of hydrogen production and loss (left) and the latitudinal gradient of surface atmospheric hydrogen coloured by source (right). The industrial source of hydrogen peaks in northern mid-latitudes, where the majority of emissions are located. Both biomass burning and the photochemical source of hydrogen peak in the tropics, again where the largest sources are located, and show a minimum in high northern latitudes due to the the large magnitude of the soil sink in this location (see left).



(a) % H_2 from biomass burning



(b) % H_2 from industry



(c) % H_2 from photochemistry

Figure 2 – The percentage of total hydrogen emitted from biomass burning, industry and photochemistry in the model at the surface (left) and 200 hPa (right). Hydrogen emitted from industrial processes, predominantly in the Northern Hemisphere contributes the largest proportion to total hydrogen in the model.

Measurements of H_2 Deposition to Forest Soil in Southern Finland

Marko Lallo, Tuula Aalto, Tuomas Laurila and Juha Hatakka, Finnish Meteorological Institute, Climate and Global Change Research, P.O.Box 503, 00101 Helsinki, Finland

Introduction

The interest to hydrogen economy has opened possibilities to enhance understanding of the hydrogen cycle including soil and atmosphere. The expected increase of the use of hydrogen as a fuel promotes a need to find out current levels of the atmospheric hydrogen both at urban and rural locations. This is partly due to better understanding of atmospheric processes and partly interest to utilize fuel cell as a power source for new cars (Rahn et. al, 2003; Schultz et. al, 2003). The global interest is towards decreasing greenhouse gas emissions. The major companies in the field of car industry have committed to develop hydrogen powered cars.

Processes which affect the hydrogen uptake to soil are largely unknown. There are assumptions that enzymatic activities of soil hydrogenases are responsible for hydrogen consumption. The soil moisture affects to the hydrogen flux rate. Hydrogen is also formed in nitrogen fixation process (Conrad and Seiler, 1985).

Methods

Field chamber measurements were accomplished in urban park location (at Helsinki) and in rural forest area in peat soil (at Loppi). Measurements were started on August 2005 and continued until winter. There were six measurement points at Loppi. One measurement location was placed to forest drain to find out the effect of water level to hydrogen flux. At Helsinki there were two measurement locations.

Measurements were performed using a chamber with an aluminium cover. The cover was attached to chamber during sample collection period of 20 minutes. Sample interval was 2 – 4 minutes and plastic syringes of a volume 20 ml was used to take samples. Chambers were embedded about 10 cm to the soil. Chamber dimensions were 0,60 m x 0,60 m.

Hydrogen deposition rates were obtained using Peak Performer 1 instrument which uses on HgO reduction gas method (Schmidt and Seiler, 1970). In order to separate hydrogen and carbon monoxide from each other, the sample gas is delivered through two columns, the first one is scrubber column for removing carbon monoxide, moisture and some hydrocarbons, the second is analytical column. Both columns are maintained at constant temperature of 105 °C and mercury oxide bed is temperature controlled to 265 °C.

Results

Based on the hydrogen deposition measurements the soil fluxes were estimated. The flux values were calculated using linear curve fitting method and taking into account first three or four measurement points to determine the slope. During the period of August to September, hydrogen flux values were generally at 8 – 12 nmol m-2 s-1. After September, the flux values were decreased to level 4 – 6 nmol m-2 s-1 at Helsinki while at Loppi there were no significant changes. The decrease of temperature to near-freezing values seems to lower hydrogen deposition rates. The drain location at Loppi is different compared to other measurement points. Hydrogen flux values were much lower there due to high water table level.

Table 1: Hydrogen deposition fluxes at Loppi and Helsinki

	Measurement sites			
	Helsinki	Loppi	Loppi (drain)	Air temp.
Day	Flux (nmol m-2 s-1)			C°
17.8	-10.2	-	-	18
18.8	-8.7	-	-	19
19.8	-9.8	-	-	18
29.8	-10.9	-	-	17
6.9	-9.2	-	-	18
7.9	-10.5	-	-	20
8.9	-	-11.1	-0.2	17
6.10	-	-9.3	-0.6	11
28.10	-5.8	-	-	5
24.11	-	-7.5	-0.2	5
2.12	-4.8	-	-	5
23.12.	-5.6	-	-	-0.5

In Figure 1, the concentration values are shown as time series inside a closed chamber. Values are based on measurements during one day on August and on December. In summer conditions the concentration decreases more rapidly than in winter. In winter time low temperatures and freezing seem to prevent hydrogen flux to soil.

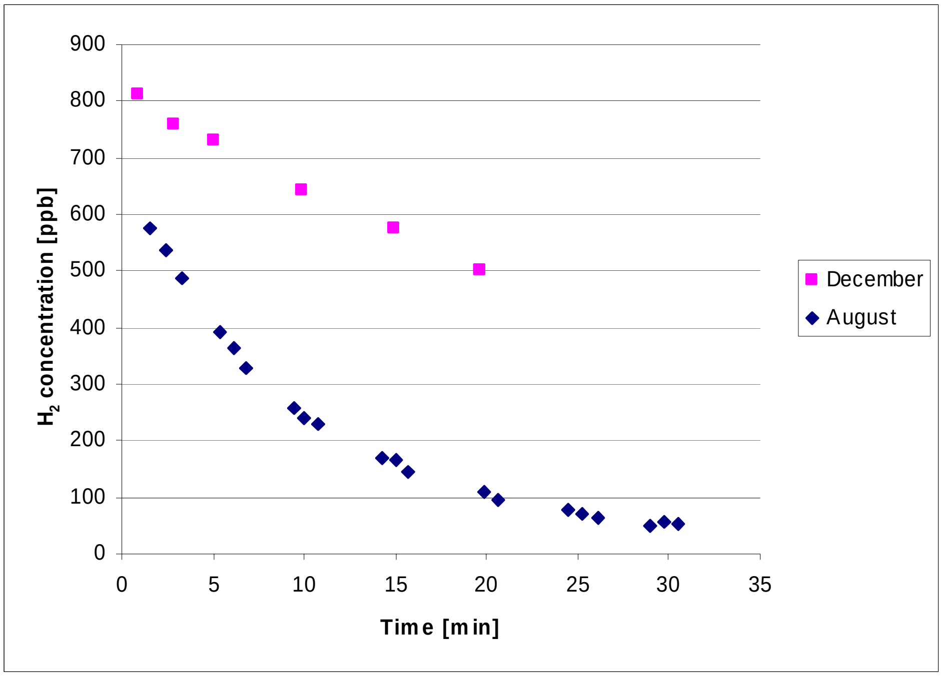


Figure 1: Comparison of summer and winter time measurements

Acknowledgement

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References

Conrad, R., Seiler, W., (1985). Influence of Temperature, Moisture and Organic Carbon on the Flux of H_2 and CO Between Soil and Atmosphere: Field Studies in Subtropical Regions, J. Geophys. Res., 90(D3), pp. 5699-5709.

Rahn, T., Eller, J. M., Boering, K. A., Wennberg, P. O., McCarthy, M. C., Tyler, S., Schauffler, S., Donnelly, S., Atlas, E., (2002). Extreme deuterium enrichment in stratospheric hydrogen and the global atmospheric budget of H_2, Nature, 424, pp. 918-921.

Schmidt, U., Seiler, W., (1970). A New Method for Recording Molecular Hydrogen in Atmospheric Air, J. Geophys. Res., 75(9), pp. 1713-1716.

Schultz, M. G., Diehl, T., Brasseur, G. P., Zittel, W., (2003). Air Pollution and Climate Forcing: Impacts of a Global Hydrogen Economy, Science, 302, pp. 624-627.

Modeling of Hydrogen in the Troposphere by LMDz-INCA and the Hints on Sources and Sinks of Hydrogen

Y. Li and D.A. Hauglustaine, Laboratory of Climat and Environmental Science (LSCE), Gif-sur-Yvette, France

Hydrogen is an important species in the atmosphere, which primarily has an impact on the water vapor content and ozone depletion in the stratosphere and a potential impact on OH in troposphere. However, hydrogen sources and sinks are not yet well understood, especially the deposition of hydrogen. We made a simulation by LMDz-INCA with full NMHC chemistry and hydrogen deposition rescaled from soil respiration from ORCHIDEE and compared the results of hydrogen and CO with the surface measurements of CMDL. Since CO and H_2 have similar sources, the seasonal variations of CO and H_2 are similar in the northern polar region, with a small phase change. However, they have different seasonal variations in the southern hemisphere, where hydrogen maxima occurred in winter and hydrogen minima occurred in summer. The hydrogen budget of both northern and southern hemispheres suggested that the main processes influencing hydrogen seasonal variation are dry deposition and transport. We will also present the results from sensitivity studies, with different dry depositions and emissions. In the upcoming work, we will inverse the hydrogen modeling to estimate hydrogen sources and sinks, using a large package of hydrogen measurements from CMDL and CSIRO stations and other stations.

A Global Modelling Study of Atmospheric Hydrogen from 1960 to 2000

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In the framework of the European RETRO project, we are presently conducting comprehensive long-term 3D global simulations of atmospheric pollutant species including hydrogen. New emission inventories were generated for the project (Figure 1), and the model results are being analysed for trends in tropospheric ozone and precursor concentrations in order to distinguish between natural and anthropogenic factors influencing background surface ozone concentrations. Three different global chemistry transport models were employed to simulate the 41-year period from 1960 to 2000. Meteorological fields were provided from the European Centre for Medium Range Weather Forecast Reanalysis ERA-40.

Here, we analyse first simulation results for CO and H_2 for the 1960-2000 time period from the MOZECH chemistry general circulation model developed at the Max Planck Institute for Meteorology in Hamburg. As shown in Figure 2, the model generally underestimates CO (at least in the northern hemisphere) and it overestimates H_2. On the other hand, the seasonal cycle and variability of these two gases are well reproduced for many sites around the globe. The model high bias for H_2 is likely due to an overestimate of the emission source strength while we relate the CO low bias to an excessive oxidation by OH radicals. A significant trend can be observed throughout the period from 1960 to 1990, thereafter many sites show either a small negative trend or no trend at all. Figure 3 shows decadal average surface mixing ratios for the 1960s and 1990s. It should be noted that model results after 1991 are erroneous because of an error in the biomass burning emission inventory. Nevertheless, for some sites, the simulations capture the interannual variability rather well.

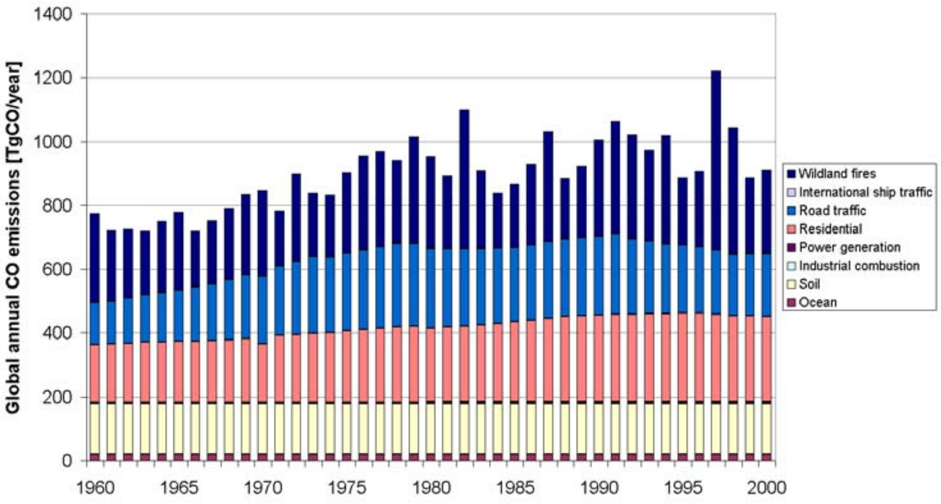
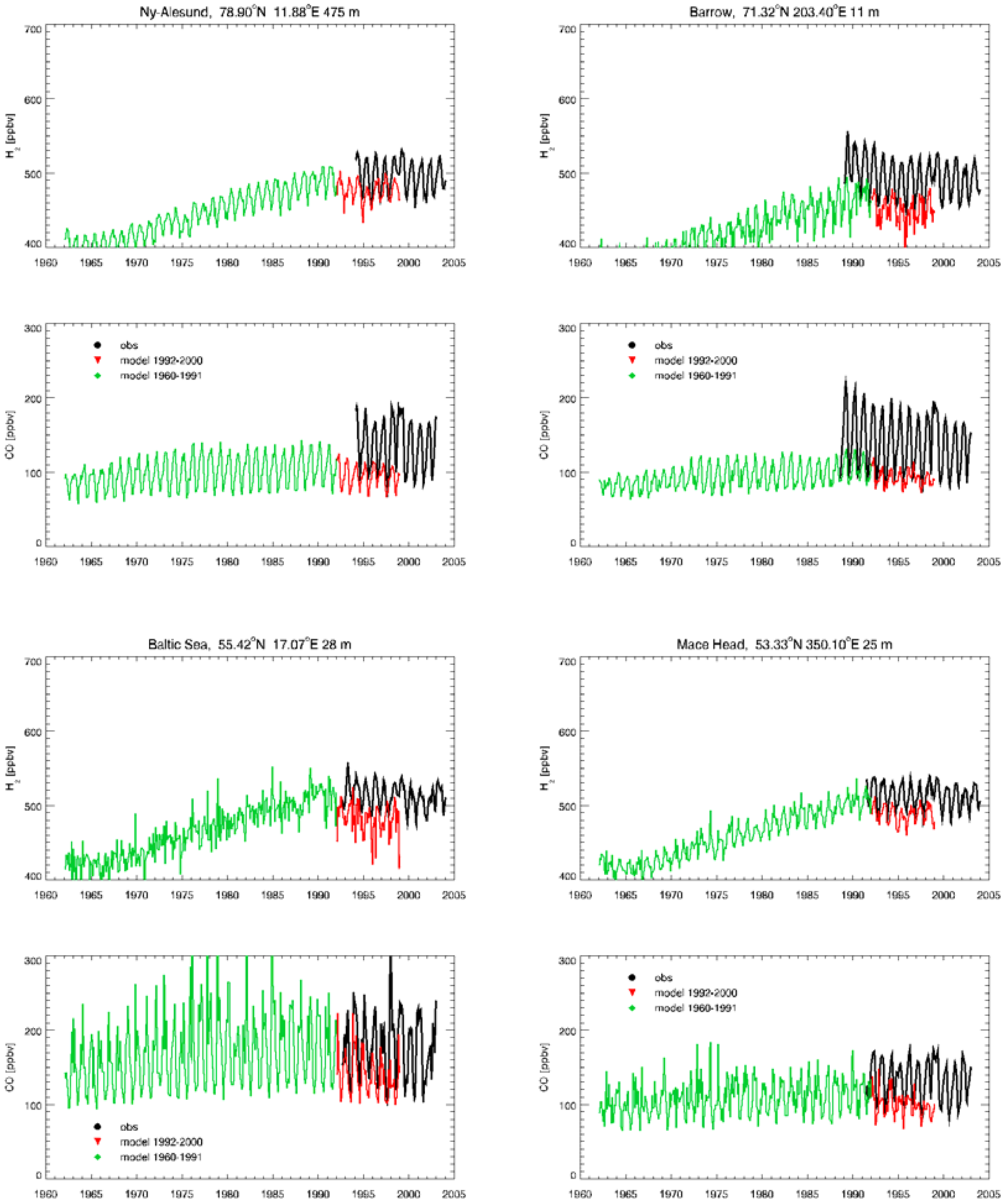


Figure 1: RETRO global carbon monoxide emission trends 1960-2000


Ny-Alesund, 78.90°N 11.88°E 475 m

Barrow, 71.32°N 203.40°E 11 m

Baltic Sea, 55.42°N 17.07°E 28 m

Mace Head, 53.33°N 350.10°E 25 m

Figure 2: Comparison of simulated and observed hydrogen and carbon monoxide concentrations for selected stations from the Climate Monitoring and Diagnostics Laboratory (CMDL). Note that simulated H_2 concentrations were scaled with a factor of 0.85 and that simulation results after 1991 contain an erroneous inventory for biomass burning

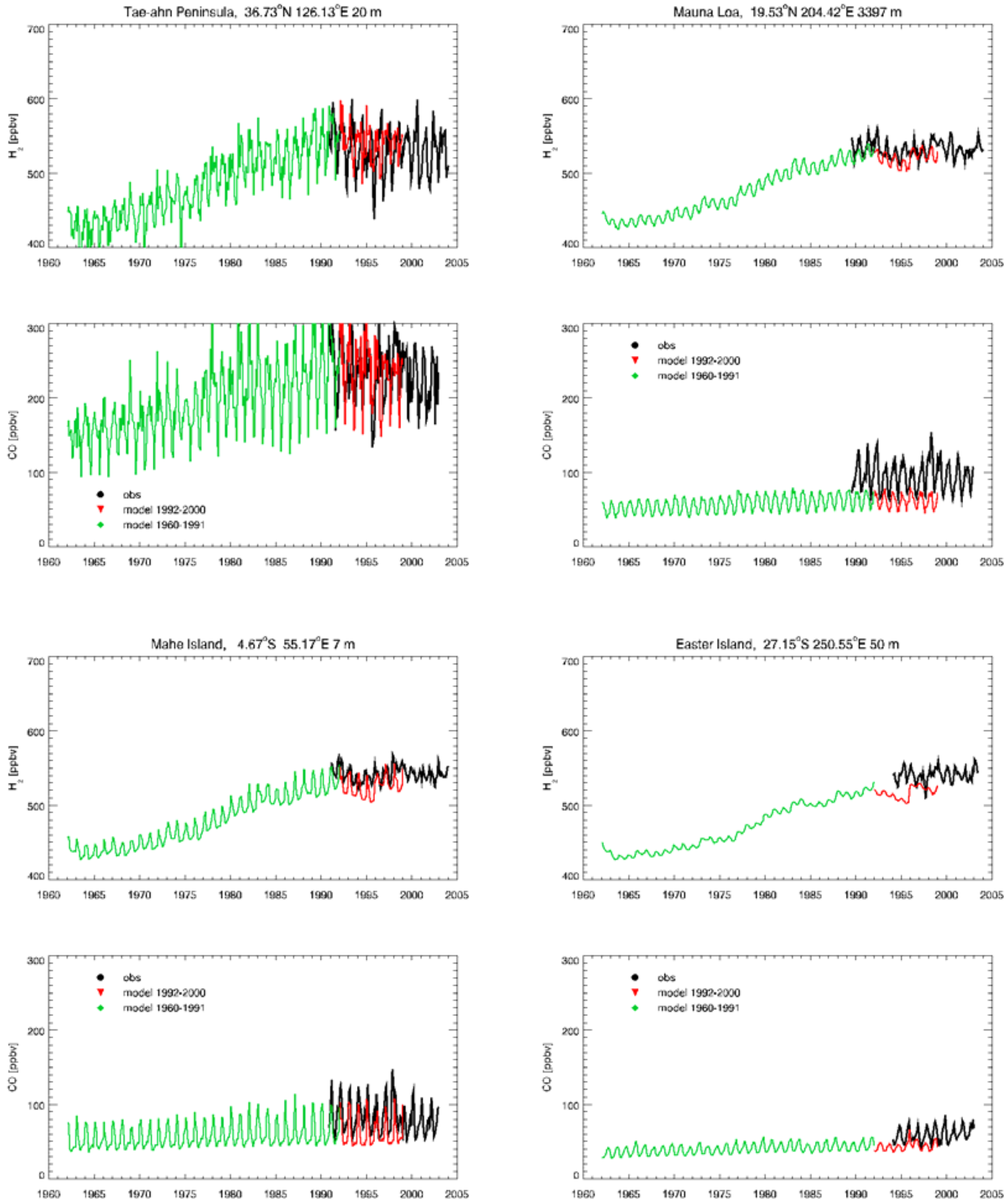
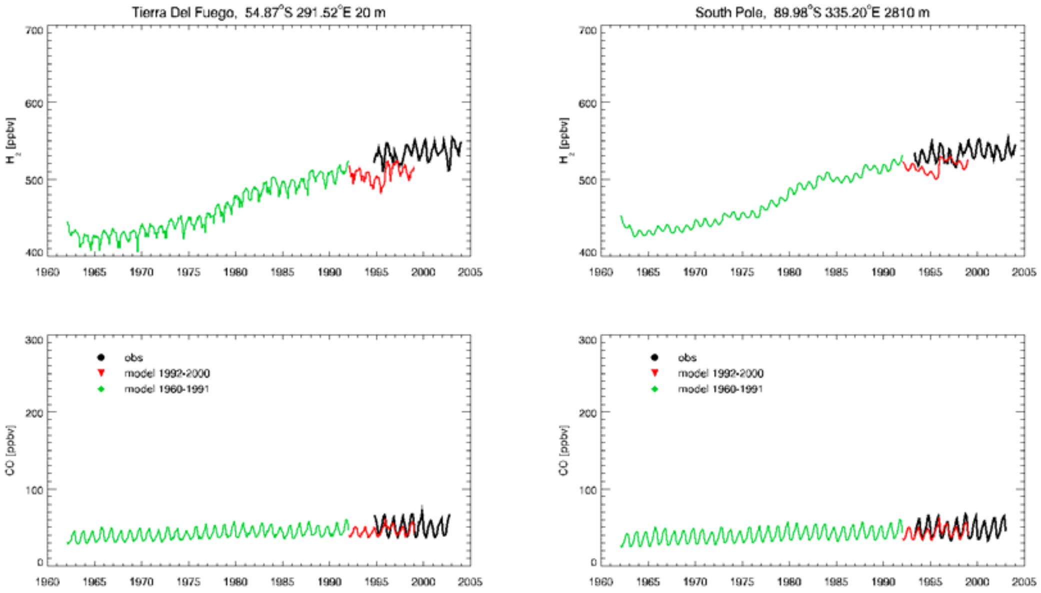


Figure 2, continued



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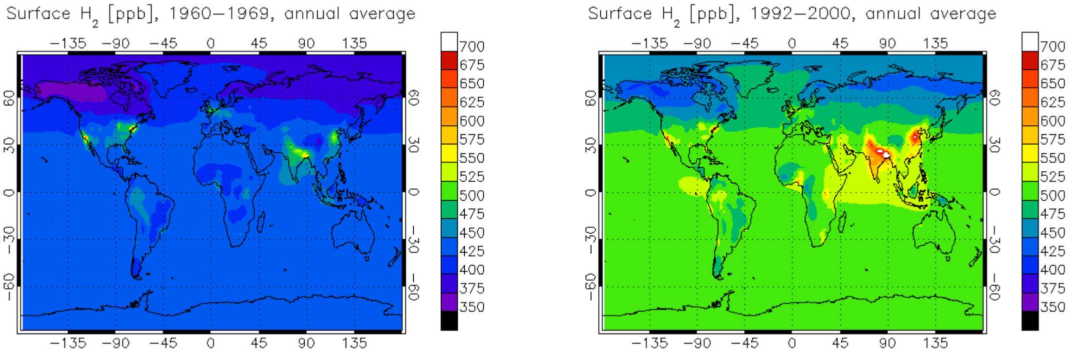

Figure 3: Decadal averages of simulated surface H_2 mixing ratios for the 1960s and 1990s

EUROHYDROS: A Proposal for a European Monitoring Network and Budget Studies of Atmospheric Hydrogen

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EUROHYDROS is a proposal which has been recently submitted to the European Commission. It aims at establishing a European Network for atmospheric observations of molecular Hydrogen and budget studies of this compound. It is further planned to put in place a new and consistent calibration scale for molecular Hydrogen. The proposed observational network will be presented. Measurement station range from clean air observatories for atmospheric background to moderately polluted (e.g. urban outflow) and urban (i.e. polluted) sites. This will enable to improve the understanding of hydrogen in the global background atmosphere and of the impact of European emissions on the present day atmosphere. Budget investigations are planned by studying specific sources and sinks of molecular hydrogen, by model calculations using a wide range of different model approaches and by observations of the atmospheric D/H ratios, which are controlled by the different sources and sinks. The Proposal further includes some studies to assess the impact of atmospheric hydrogen on the present day atmosphere and some exploratory studies will be carried out to investigate these impacts under changed atmospheric hydrogen levels, associated with the use of hydrogen as a carrier of economy.

Updating the results on the effects of conventional fuelled aircraft on cirrus and contrail cirrus

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1. Introduction

Recent studies on the effects of aviation on cirrus clouds (Zerefos et al., 2003; Minnis et al., 2004; Stordal et al 2005; Stubenrauch and Schumann, 2005) have shown evidence of increasing trends in cirrus/high cloud coverage over congested air traffic locations in possible association with aviation activities.

Zerefos et al. (2003) after removing correlations related to natural perturbations (such as ENSO, QBO, NAO and tropopause temperatures) found a statistically significant positive correlation (+0.7) between decadal changes in cirrus cloud cover (CCC) and aviation fuel consumption along the latitude belt centred at the North Atlantic air traffic corridor, providing an independent test of possible impact of aviation on contrail cirrus formation.

Minnis et al. (2004) found that seasonal cirrus changes over the United States were generally consistent with the annual cycle of contrail coverage and frequency lending additional evidence to the role of contrails in the observed trend. It was concluded that the U.S. cirrus trends were most likely due to air traffic.

In Europe, Stordal et al. (2005) found indications of a trend of about 1–2% cloud cover per decade due to aircraft, in reasonable agreement with previous studies. Even though they found moderate correlations between trends in cirrus cloud cover and aircraft density data, as many other factors could have also contributed to changes in cirrus, they still regarded their results to be indicative of an impact of aircraft on cirrus amount.

Stubenrauch and Schumann (2005) analysed TOVS Path–B satellite data of seasonal mean effective high cloud amount and relative humidity for the period 1987 to 1995 and compared trends in cirrus coverage in situations favourable for contrail formation to trends in general and to those favourable for cirrus, separately over regions with heavy air traffic and with low air traffic. In conclusion, they found a weak but significant decadal increase of cirrus in regions where air traffic is very high for situations in which the air is cold and humid enough to let contrails form.

Sausen et al. (2005) showed that the radiative forcing from aviation induced cirrus clouds might be as large as the present estimate of the total radiative forcing (without cirrus). The aircraft induced cirrus cover over Europe is about ten times larger than that of linear contrails in the same region. Radiative forcing from the additional cirrus may be more than 10 times higher than that of linear contrails and aviation induced CO_2 increases (Mannstein and Schumann, 2005).

In this study, updated through 2004 long–term changes in (CCC) are correlated with aviation travelled distance in 2000 over the northern middle latitudes and the tropics in order to examine whether updated trends in cirrus clouds continue to be positively correlated with aviation activities in the northern middle latitudes. Since changes in cirrus clouds could result from a variety of processes including aviation, (CCC) changes were also correlated with corresponding changes in upper–tropospheric natural parameters, which could have affected the long–term variability of natural cirrus clouds. The natural parameters that were examined in relation to cirrus clouds are vertical velocities and relative humidity at 300 hPa, a pressure level that was considered in this study to represent an altitude level with high air traffic.

2. Data sets

2.1 ISCCP cloud data

Mean monthly cirrus cloud data from the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schiffer, 1999) were used to calculate long–term changes in (CCC) from 1984 to 2004. The data are based on observations from the suite of operational geostationary and polar orbiting satellites. Visible radiances are used to retrieve the optical thickness of clouds and infrared radiances to retrieve cloud top temperature and pressure. The D2 dataset used in this study has a spatial resolution of 280 km (2.5° at the equator) and provides monthly averages of cloud properties of fifteen different cloud types. The cloud types are derived based on radiometric definitions that rely on cloud optical thickness and cloud top pressure. Cirrus clouds are defined as those with optical thickness less than 3.6 and cloud top pressure less than 440 mb.

To overcome the effect of seasonal variations in the estimated trends, all trends were calculated after removing variations related to the seasonal cycle of the data. (CCC) data were deseasonalized by subtracting the long–term monthly mean (1984–2004) pertaining to the same calendar month. All trends have been evaluated as to their statistical significance by applying the t–test of each trend against the null hypothesis of no–trend for the appropriate number of degrees of freedom. In order to minimize the impact of the Mt. Pinatubo eruption on the satellite retrievals, (CCC) data taken between 1991 and 1992 were not used in our analysis.

2.2 NCEP Reanalysis data

Vertical velocities and relative humidity at 300 hPa were analysed from the NCEP Reanalysis data sets[1] for the period 1984–2004. NCEP provides mean monthly gridded values of various atmospheric and surface parameters on 2.5°x2.5° grid boxes (90°N–90°S, 0°E–357.5°E) from 1/1/1948 (1958 for some variables) until present. These variables are averages of instantaneous values at the 4 reference times; 0,6,12 and 18z over the averaging period (month). For brevity in this study, the terms (VV300) and (RH300) were used to indicate the vertical velocities and relative humidity at 300 hPa respectively. (RH300) is relative humidity with respect to liquid water.

2.3 Air traffic data

The air traffic density over the globe was examined using the travelled distance per grid cell inventory for the year 2000 as determined by the TRADEOFF emission datasets[2]. All data are provided on a basic 1°x1° latitude/longitude grid. The vertical resolution in all cases is 2000 feet (610m) in even spacing. The data are arranged in columns as follows: Column 1: longitude (degrees), Column 2: latitude (degrees), Column 3: level number, Column 4: km travelled per grid cell (km/month), Column 5: fuel used per grid cell (kg/month) and Column 6: NOx emission (as NO_2) (kg/month). The bottom level nearest the ground is “level 0”, which includes emissions from ground to 2000 feet, and so on. There are totally 19 altitude levels (level 0 corresponds to the ground; level 19 corresponds to 11590 m altitude). In this study we made use of altitude levels 16–19 which correspond to 9760–11590 m height. Emission calculations are based on the ANCAT/EC2 movements database but with the FAST model (i.e. for 1991/1992). Thus, as in ANCAT, the data are for the months 1, 4, 7 and 10 (January, April, July and October). Each month is representative of a quarter year, so that month 1 should be used for January, February and March. The sum of the data files multiplied by three results in the annual emission/fuel/distances.

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[1] http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.derived.html

[2] http://www.iac.ethz.ch/tradeoff/database)

3. Results and discussion

Fig. 1a shows the global distribution of linear trends in deseasonalized monthly mean (CCC) from January 1984 to December 2004 (in % cloud cover per decade) based on linear regression analysis at each individual grid box. The respective linear trends in (VV300) and (RH300) from NCEP are shown in Figs. 1b and 1c, respectively. As can be seen from Fig. 1a, the geographical distribution of linear trends in (CCC) is similar to that published by Stordal et al. (2005) who made use of the same cloud data set (their Fig. 2). It also appears that there are discontinuities on the spatial distribution of the derived trends at the borders between areas which are "viewed" by different ISCCP satellites, as a result of the satellite zenith angle dependence in the detection of high clouds in combination with the changing satellite positions and numbers of satellites operating over the years (Stordal et al., 2005). These discontinuities could result in uncertainties in the calculations of trends and therefore care should be taken when drawing conclusions regarding the trends at the borders between areas which are "observed" by different satellites.

In the northern middle latitudes, (CCC) increased over United States of America, western North Atlantic and Western Europe and decreased over East Asia, Japan and the western part of the North Pacific. In the tropics, increases in (CCC) are observed over the tropical North American corridors, central Africa and Indian Ocean whereas decreases are observed over South America, South Atlantic, Australia and Thailand. These negative trends, over low air traffic areas, follow the negative course of global trends in (CCC) observed over most of the northern middle latitudes and over the tropics (about –0.5% cloud cover per decade). Our findings regarding the cirrus trends over USA, western North Atlantic, South America, Africa and Asia are similar to those published by Minnis et al. (2004). The respective (RH300) from NCEP decreased over Europe, the US, Asia and the temperate ocean regions in fully agreement with the results published by Minnis et al. (2004). Over much of the Tropics, northern China, south western United States and adjacent waters we find negative trends in (RH300) in contrast to the findings by Minnis et al. (2004) who found increases in those areas.

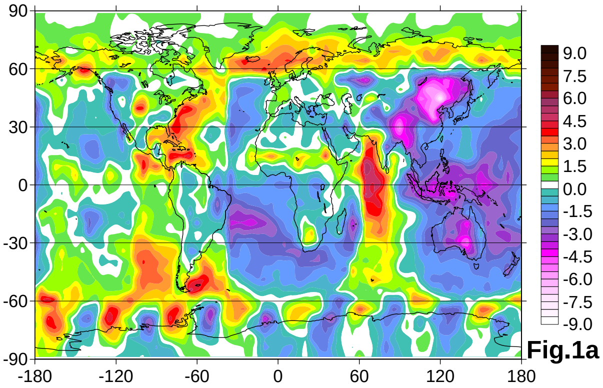


Fig.1a

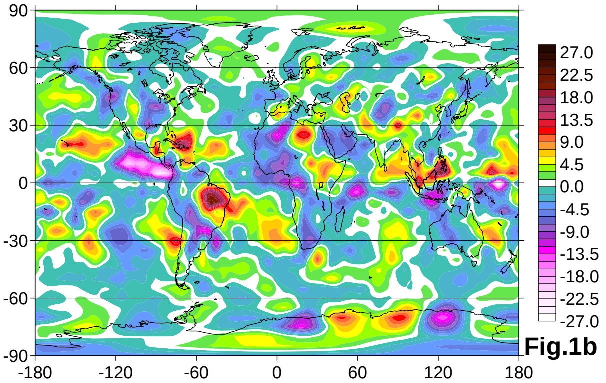


Fig.1b

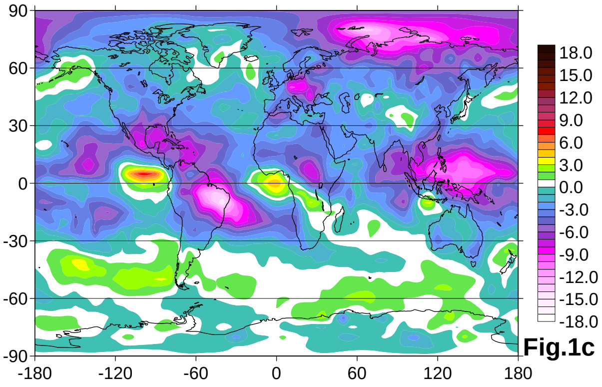


Fig.1c

Figure 1: (a). Updated through 2004 linear trends in deseasonalized monthly mean (CCC) from January 1984 to December 2004 from ISCCP (in % cloud cover per decade). (b) Same as (a) but for the (VV300) from NCEP (in mPa/s per decade). (c) Same as (a) but for the (RH300) from NCEP (in % per decade). Regions with no trend are shown with white colour.

Fig. 2 shows the spatial distribution of aviation travelled distance per grid cell at 9760–11590 m height in the wintertime (January, February and March) (in km per month). Regions with more than 40.000 travelled km per grid cell by highflying air traffic are shown with green, orange, red and brown colours while regions with less than 40.000 km per grid cell are shown with yellow, blue and pale yellow colours. In the northern middle latitudes congested air traffic regions are evident over United States of America, Europe, East Asia and Japan whereas over the ocean the heaviest air traffic routes are mainly observed over the North Atlantic and North Pacific. In the northern sub–tropics, regions with high air traffic are mainly found over the Thailand air corridors (5°N–25°N, 90°E–120°E) and over the tropical North American air traffic routes.

In order to investigate whether updated through 2004 changes in (CCC) continue to be correlated with air traffic, aiming at quantifying possible changes in cirrus cloudiness due to contrail formation by aviation, we have spatially correlated the updated trends in (CCC) with travelled distance by aviation in 2000 over locations that correspond to different air traffic load. Since cirrus cloud changes could result from a variety of processes including aviation, (CCC) changes were also correlated with corresponding changes in (VV300) and (RH300). Fig. 3 shows the longitudinal distribution of long–term changes in (CCC) from 1984 to 2004 and of the travelled distance by aviation in 2000 in the wintertime (January, February and March), (a) over high air traffic locations in the middle latitudes (35°N–55°N) and (b) over low air traffic regions in the tropics (5°N–25°N).

As can be seen from Fig. 3a the updated through 2004 longitudinal distribution of long–term changes in (CCC) along the latitude belt centred at the North Atlantic air corridor, parallels the travelled distance curve from highflying air traffic (correlation coefficient, R=+0.6) in fully agreement with the results published by Zerefos et al. (2003). The positive correlation between the two variables suggests that the apparent increase of thin cirrus clouds, about 1.4% cloud cover over North America and 0.5% cloud cover over Europe, could be related to contrail formation by aviation. Over East Asia on the other hand, the trends in (CCC) are negative and could be related to negative trends in (RH300). Negative trends in (CCC) over East Asia were also observed by Minnis et al. (2004) and Stordal et al. (2005). In the summertime the correlation coefficient between (CCC) changes and air traffic is lower when compared to the wintertime but however the largest increases in (CCC) are found over the North Atlantic air flight corridor (~2.1% cloud cover per decade) (not shown here).

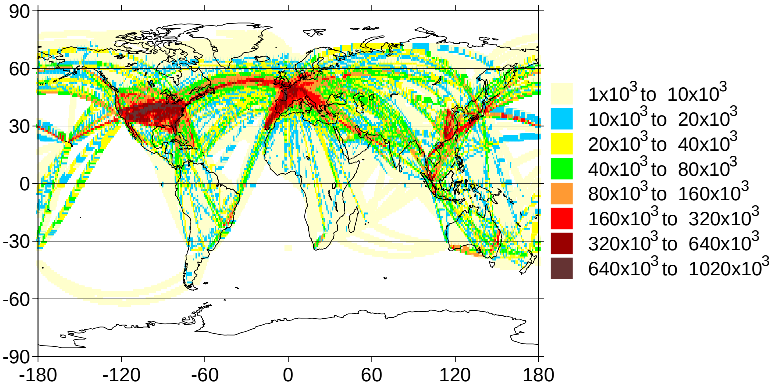
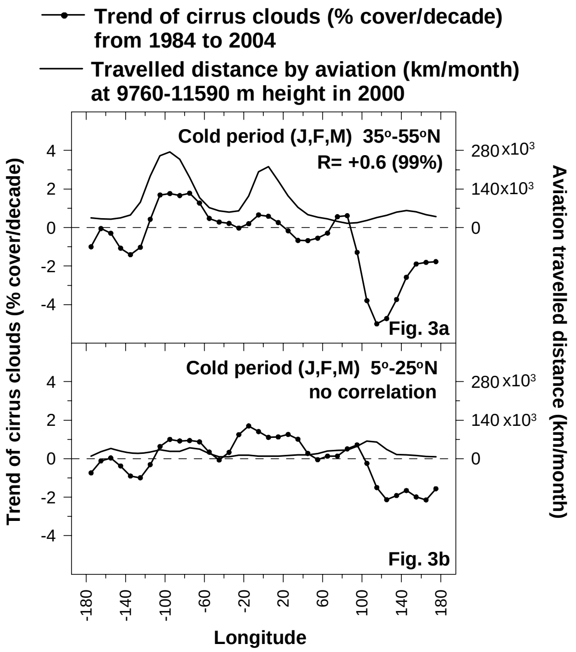
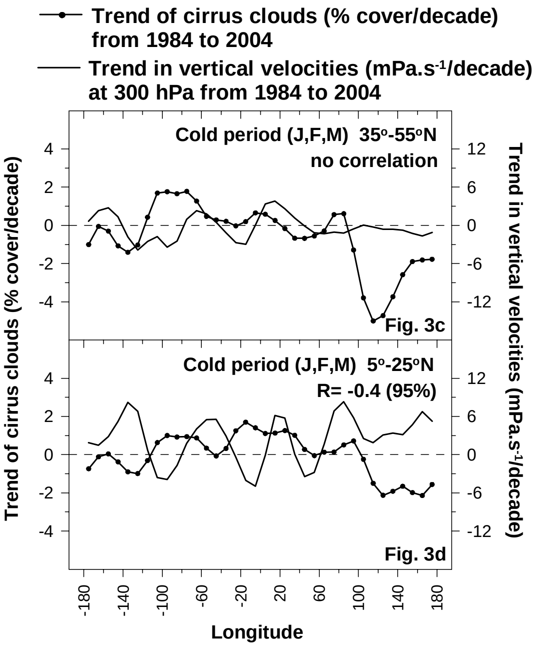


Figure 2: Travelled distance by aviation at 9760–11590 m height in 2000 in the wintertime (January, February and March) (in km/month).





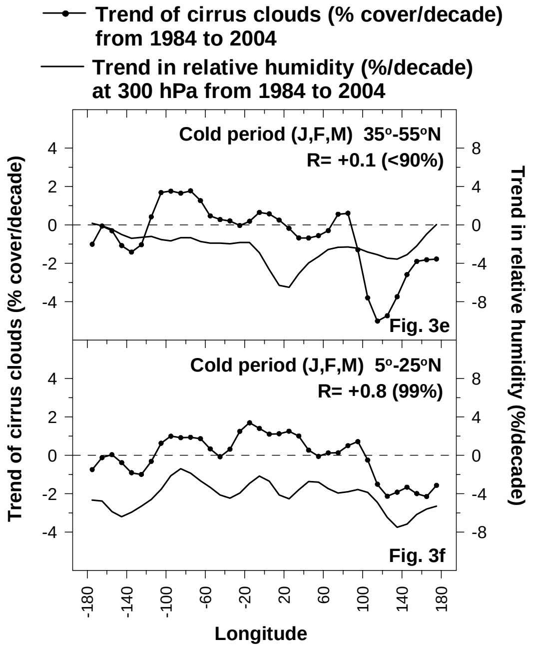


Figure 3: (a) Updated through 2004 longitudinal distribution of (CCC) trends from 1984 to 2004 and of travelled distance by aviation in 2000 in the wintertime (Jan, Feb, Mar), over heavy air traffic locations (35^{o}N–55^{o}N). (b) Same as (a) but for low air traffic locations (5^{o}N–25^{o}N). Values on the abscissa correspond to 36 equal regions of 10 degrees longitude, from west to east, in which (CCC) and travelled distance by aviation have been averaged for the two latitudinal belts. R is the correlation coefficient between the two lines. Values in brackets refer to statistical significance of each R. (c) Same as (a) but for (CCC) and (VV300) trends over 35^{o}N–55^{o}N. (d) Same as (b) but for (CCC) and (VV300) trends over 5^{o}N–25^{o}N. (e) Same as (a) but for (CCC) and (RH300) trends over 35^{o}N–55^{o}N. (f) Same as (b) but for (CCC) and (RH300) trends over 5^{o}N–25^{o}N.

At lower latitudes (5^{o}N–25^{o}N) our results are also consistent with those published by Zerefos et al. (2003). Although the air traffic density is much lower and the correlation is insignificant (Fig. 3b), the longitudinal variability of (CCC) is as high as over the middle latitudes. This is not a paradox but can be explained by the fact that in tropical latitudes, cirrus clouds are formed primarily from vertical water vapour transport by convective processes. As a result, tropical cirrus amounts are controlled by local temperature conditions and moisture sources and any trend in those conditions would leave a signature on the cirrus cloud field. Therefore, the tropical cirrus trends could reflect trends in the local temperature and moisture field. In the middle latitudes, on the other hand, cirrus cloud formation is controlled by baroclinic processes that are to a great extent independent of local conditions and depend on global wave patterns. Therefore, any localized modulation of middle latitude cirrus cloud properties would be related more strongly to microphysical rather than dynamical condition changes (Zerefos et al., 2003). The results are shown in Figs. 3c, 3d, 3e and 3f where it appears that the observed changes in (CCC) are significantly correlated with corresponding changes in (VV300) and (RH300) over the tropics (–0.4 and +0.8, respectively) but not over northern middle latitudes. Our findings on the positive trends in (CCC) over North America, Europe and North Atlantic due to air traffic are consistent with those published by Minnis et al. (2004), Stordal et al. (2005) and Stubenrauch and Schumann (2005), in spite of the differences in examined datasets and periods of records.

Conclusions

Long–term changes in cirrus cloud cover (CCC) from ISCCP updated to the year 2004 were correlated with aviation flown distance in 2000 by the TRADEOFF emission datasets and compared with corresponding changes in natural parameters (i.e. vertical velocities and relative humidity at 300 hPa from NCEP) at altitude levels with high air traffic. Results presented in this study generally confirm earlier findings on possible effects of aviation on cirrus cloud positive trends over congested air traffic regions (Zerefos et al., 2003). More specifically, long–term changes in (CCC) from 1984 to 2004 continue to be positively correlated (+0.6) with aviation travelled distance in 2000 over the northern middle latitudes but not over the tropics. This could be explained by the fact that the observed changes in (CCC) are significantly correlated with corresponding changes in (VV300) and (RH300) over the tropics (–0.4 and +0.8, respectively) but not over northern middle latitudes. Results from recent papers with the findings of this study were also discussed.

Acknowledgments

This study was conducted within the FP6 Integrated Project "Quantifying the Climate Impact of Global and European Transport Systems" (QUANTIFY, Contract No 003893–GOCE) and contributes to the ECATS Network of Excellence both funded by the European Commission. We acknowledge the assistance of Dr. Prodromos Zanis from the Research Centre of Atmospheric Physics and Climatology of the Academy of Athens for his assistance with the analysis of the NCEP Reanalysis data.

References

Mannstein, H., and U. Schumann, Aircraft induced contrail cirrus over Europe, Meteorol. Z., Vol. 14, No. 4, 549–554, 2005.

Minnis, P., J. K. Ayers, R. Palikonda, and D. Phan, Contrails, Cirrus Trends, and Climate, J. Climate, 17, 1671–1685, 2004.

Rossow, W. B., and R. A. Schiffer, Advances in understanding clouds from ISCCP, Bull. Amer. Meteor. Soc., 80, 2261–2287, 1999.

Sausen, R., I. Isaksen, V. Grewe, D. Hauglustaine, D. S. Lee, G. Myhre, M. O. Köhler, G. Pitari, U. Schumann, F. Stordal, and C. Zerefos, Aviation radiative forcing in 2000: An update on IPCC (1999), Meteorol. Z., Vol. 14, No. 4, 555–561, 2005.

Stordal, F., G. Myhre, E. J. G. Stordal, W. B. Rossow, D. S. Lee, D. W. Arlander, and T. Svendby, Is there a trend in cirrus clouds cover due to aircraft traffic?, Atmos. Chem. Phys., 5, 2155–2162, 2005.

Stubenrauch, C. J., and U. Schumann, Impact of air traffic on cirrus coverage, Geophys. Res. Lett., 32, L14813, doi: 10.1029/2005GL022707, 2005.

Zerefos, C. S., K. Eleftheratos, D. S. Balis, P. Zanis, G. Tselioudis, and C. Meleti, Evidence of impact of aviation on cirrus cloud formation, Atmos. Chem. Phys., 3, 1633–1644, 2003.

Session 2: Pathways into a Hydrogen Economy and Their Possible Consequences for Greenhouse Gas and Air Pollutant Emissions

Optimal Initial Distribution of Hydrogen Filling Stations

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Introduction

To launch fuel cell vehicles (FCVs) at the market at reasonably competitive prices would require further technological improvements and especially cost reductions from mass production. But car producers are probably reluctant to set up large-scale FCV production lines as long as there exists no sufficient initial hydrogen infrastructure, because demand for such cars crucially depends on fuel availability. Ignoring this start up problem, which is also termed the "chicken and egg problem of H_2 and FCVs", the majority of economic studies that focus on estimating the costs and/or the environmental benefits of pathways into a "H_2-economy" are basically best-case scenarios of a successful system switch. The standard approach is to assume a certain number of FCVs and estimate the necessary infrastructure investments to supply them or alternatively to take certain infrastructure developments as given and derive the number of FCVs that can be supplied (see, e.g., Schneider et al. (2004), Thomas et al. (1998), Moore and Raman (1998), Ogden (1999, 2002), Stromberger (2003), Mercuri et al. (2002), Sørensen et al. (2004), Oi and Wada (2004), Hart (2005)).

Explicit studies on the dynamics of the early stages of a H_2-infrastructure system and FCV driving are absent with the exception of a study by Stephan and Sullivan (2004), which suggests an agent-based model, in which drivers tend to buy a FCV, if they are frequently exposed to H_2 filling stations. Conversely, filling station owners add an H_2-pump if they observe sufficient FCV traffic. They test these behavioral assumptions in an artificial urban area with surroundings covering 160x160km. Within this area, commuters drive regularly to a specific business district and some other attractors. In this study, I take Stephan and Sullivan's behavioral model, and apply it to the real German trunk road system, in which artificial drivers make long distance trips. The model is used to analyze different initial distributions of H_2-pumps as, e.g., the "HyWay"-ring suggested by Hart (2005). Results suggest that trip modeling might be a helpful tool to optimize placement of H_2-pumps.

The model

The graphs in Figure 1 show the German trunk road network as used in the model, where the bold blue roads are expressways ("Autobahnen") and the red ones are highways ("Bundesstraßen"). All drivers are assumed to reside in one of about 200 cities with populations larger than 50,000 including a few bordering cities like Basel (Switzerland) or Strasbourg (France). The focus is on cities, because initial H_2-stations (this term is used from now on to refer to an existing filling station that adds an H_2-pump) are likely to be set up in larger urban areas, e.g., to supply buses in public transport or taxis. The labeled cities are the 15 largest German cities with respect to population and they are split in up to 8 city parts. In contrast to Stephan and Sullivan, long distance trips are modeled. The reason is that with current H_2 tank capacity, a range of more than 400km is no problem. This is enough for trips within a city. Thus, a few H_2-stations at arterial roads seem to be sufficient. However, the main benefit from car ownership is the flexibility to do spontaneous long distance trips. This is what people are believed to have in mind, when they state that they would buy an alternative fuel car if they were able to refuel it "everywhere".

To get a first approximation of long distance traveling behavior, a gravity model of transport is used (see, e.g., Erlander and Stewart, 1990), to identify the probability of intercity trips.

The gravity model implies that traffic between two cities increases with the size of the cities but decreases with distance. The model is calibrated using regional data from the German Federal Statistical Office (FSO-GOR) for population, inflow/outflow of commuters and tourist arrivals. It is calibrated to fit traffic counts from Lensing (2003).

Drivers make randomized trips according to the probabilities of the gravity model. During their trips they recognize the distance between H_2-stations on their way, no matter whether they drive a FCV or a conventional car. As long as this "H_2-distance" is lower then, e.g., 50km, they perceive this as sufficient coverage ("don't worry distance" = 50km). For greater distances drivers get worried about refueling. When a driver makes a decision to buy a new car, he checks, whether H_2 is available at his home city and if so, he trades off certain individual and social benefits from driving a FCV (including tax exemptions) against additional costs of the fuel cell system compared to an internal combustion engine (which decline with the number of FCVs sold due to learning by doing) and his refueling worries from trips during the last six month. In the central case, about 0.8 percent of all drivers would be willing to buy a FCV, given that they encounter H_2-stations every 50km. The numbers of newly registered cars and replaced old ones are fitted against data from the Federal Bureau of Motor Vehicles and Drivers (FBMVD, 2005a, 2005b), driving and refueling behavior is derived from the German Mobility Panel (GFMTBH, 2005).

As in Stephan and Sullivan, filling station owners add an H_2-pump, if they observe sufficient FCVs at their road and keep it for at least six month. Thereafter, they might remove it, if traffic has fallen below a certain threshold. A basic H_2 coverage within a city (H2-stations at selected arterial roads) is set up, if the number of potential FCV buyers, who would have bought a FCV, but didn't, because of the lack of H_2 in their home city, is high enough. Depending on the actual number of FCVs in the city later on, this basic H_2 coverage might also be removed.

Scenario assumptions and preliminary results

The upper left graph of Figure 1 shows an initial distribution of H_2-stations (blue "H") at trunk roads following the "HyWay"-ring suggested by Hart (2005) in a study for Linde AG. This ring connects major German car production clusters and cities with H_2-station demonstration projects. The distance between the stations does not exceed 50km. In the model runs, the connected cities are assumed to have a basic H_2 coverage at year 0 (which might be somewhere between 2010 and 2015). This initial H_2 coverage remains for at least 4 years, i.e. one election period. At the vehicle side, 0.8 percent of newly registered cars in these cities are assumed to be FCVs (this magnitude would imply for Germany that about one third of people with taxable income exceeding 100,000EUR per year would be willing to pay a significant premium for a FCV).

Figure 1 shows the resulting development of H_2-stations, given the initial "Linde scenario" distribution after 5, 10 and 15 years for a "don't worry distance (DWD)" of 100km, implying that refueling worries are extremely low. After 5 years, some H_2-stations particularly in the West and in the East have been deconstructed due to insufficient demand; while particularly in the South there has been a small increase in H_2-stations. Note that even after 15 years parts of the initial ring remain empty, while the connection between the two largest cities Berlin and Hamburg has been established. This indicates that the suggested initial ring distribution might be suboptimal.

Figure 2A shows the corresponding numbers of urban areas with basic H_2 coverage, trunk road H_2-stations and the cumulated number of FCVs sold. In Figure 2B, results are shown for a lower "don't worry distance" of 50km, representing a higher concern about refueling that seems to be more realistic. Here, the system is severely hit after the first 4 years, implying that the initial coverage was insufficient. In this scenario, given the initial H_2 coverage, FCVs would not enter the mass market for at least another 20 years. Figure 2C shows the development of H_2-infrastructure and FCVs if the same amount of trunk road H_2-stations and a similar coverage of urban H_2-stations relative to population is initially set up as a cluster in North Rhine-Westphalia. Even with people not being too concerned about refueling (DWD = 100km), such a clustered initial H_2-station distribution seems to be inappropriate to encourage substantial introduction of the new technologies. The DWD = 50km case shows an almost complete deconstruction of infrastructure after 4 years (Figure 2D) and can be seen as a failed introduction of H_2 and FCVs.

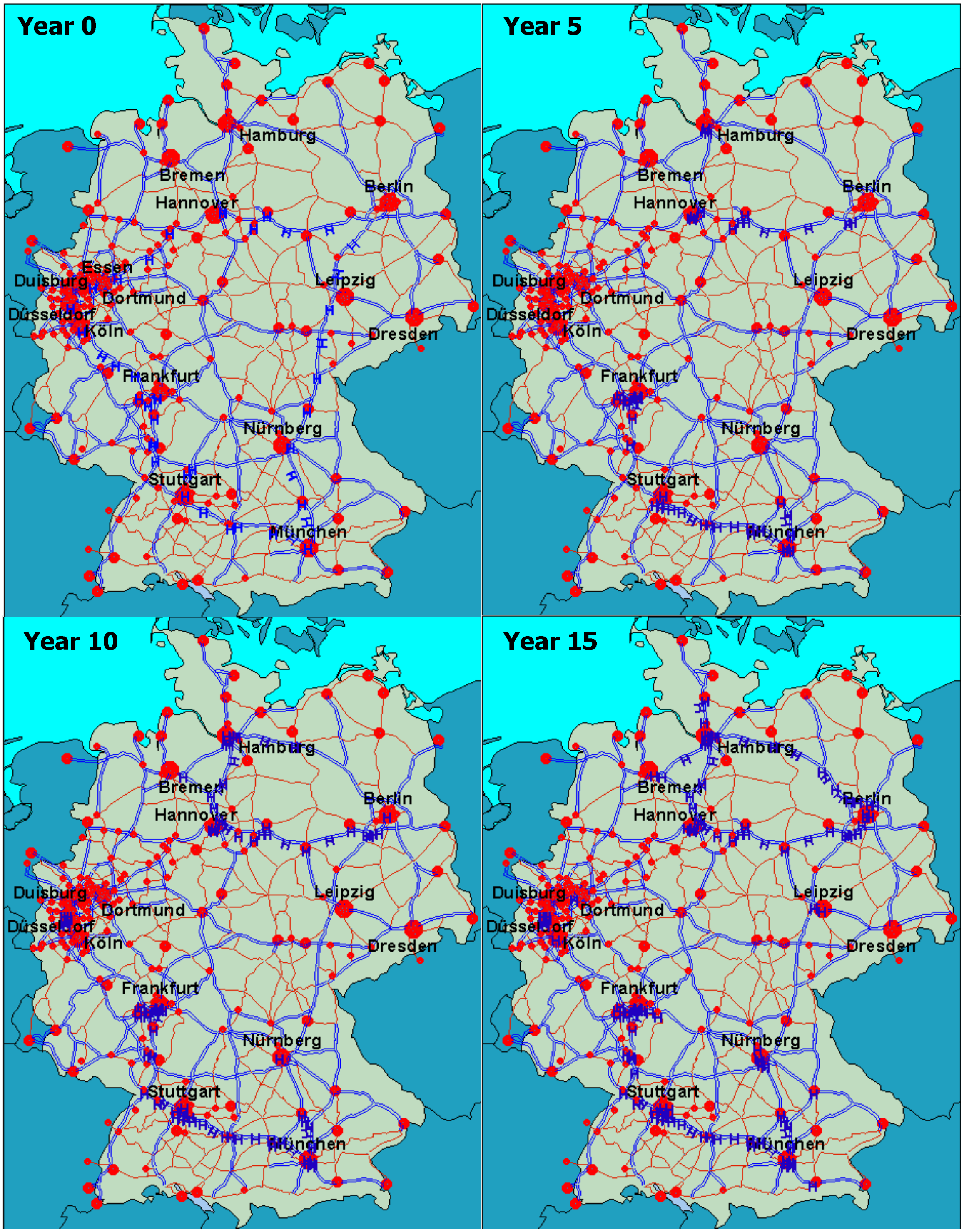

Figure 1: H_2-station development for Linde Scenario (DWD = 100km)

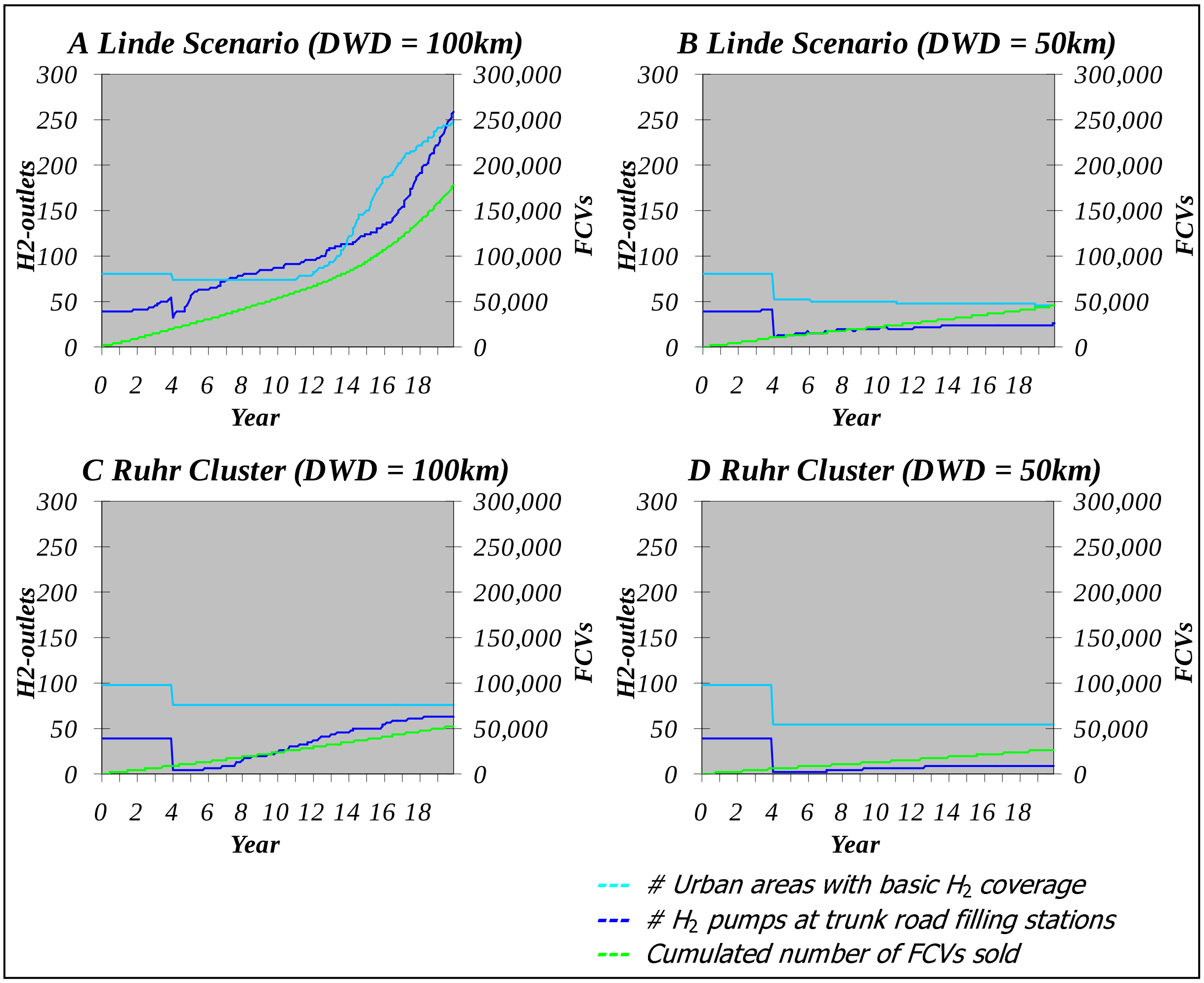

Figure 2: H_2-station development and cumulated number of FCVs (different scenarios)

Discussion

There must be at least some initial H_2-stations to overcome the chicken and egg problem associated with H_2 and FCVs (or with alternative fuels in general). To keep upfront infrastructure investments as low as possible, the initial distribution should include just as many H_2-stations as necessary to be self sustained, i.e. to "survive" until vehicle costs go down sufficiently, such that large scale demand for FCVs and H_2 arises. Such an initial H_2-stations system requires careful design, because inappropriate placement can lead to a collapse of major parts of the system due to the lack of hydrogen demand, endangering the whole introduction of the new technology. So far, the results of the model presented suggest that using agent based trip modeling provides a helpful tool to test different initial distributions for their potential success. An obvious next step will be to investigate the "natural" patterns of H_2-stations that emerge if the introduction of the new technologies is successful, even if unrealistically optimistic parameterizations (like the DWD = 100km case) are applied, because those patterns might actually be promising initial distributions.

Given the magnitude of infrastructure investments required to implement an alternative fuel system, savings from an optimized initial distribution should be significant. This calls for further research into this issue to overcome limitations of the current model: First of all, the trip distributions generated by the gravity model are "most likely distributions", but do not necessarily reflect real travel behavior, which is often characterized by specific habits or work requirements. Moreover, holiday trips to specific sights at the seaside or the Alps are not included and the same holds for trips abroad in general. Thus, a more complex travel model, perhaps on a European level would be preferable. Furthermore, the - to some extent - ad hoc parameterization of the agent behavior restricts the model to qualitative results from comparing different initial conditions. Finally, it would be desirable to increase the overall resolution of the model to also account for optimal H_2-station distributions within the cities.

References

Erlander, S. and Stewart, N.F., (1990). The Gravity Model in Transportation Analysis - Theory and Extensions. VSP, Utrecht, The Nederlands.

Federal Bureau of Motor Vehicles and Drivers FBMVD, (2005a). Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern am 1. Januar 2005 nach Zulassungsbezirken (Sonderheft 1). Statistische Mitteilungen - Reihe 2: Fahrzeugbestand (vehicle population), Kraftfahrt-Bundesamt, Flensburg, Germany.

Federal Bureau of Motor Vehicles and Drivers FBMVD, (2005b). Neuzulassungen - Besitzumschreibungen - Löschungen von Kraftfahrzeugen und Kraftfahrzeuganhängern im Jahr 2004 – Jahresband. Statistische Mitteilungen - Reihe 3: Fahrzeugzulassungen (vehicle registration), Kraftfahrt-Bundesamt, Flensburg, Germany.

Federal Statistical Office (FSO). GENESIS-Online regional. http://www.regionalstatistik.de.

German Federal Ministry of Transport, Building and Housing GFMTBH, (2005). Das Deutsche Mobilitätspanel (1994-2004) (The German Mobility Panel (1994-2004)). DLR, Clearing House for Transport Data and Transport Models, http://www.clearingstelle-verkehr.de.

Hart, D., (2005). The Economics of a European Hydrogen Automotive Infrastructure - A study for Linde AG. E4tech study, http://www.hydrogenday.com/WGAP/hydrogen/file/rwar-69wdr8.en.1/e4tech%20hydrogen%20study.pdf.

Irvine, F.O., (1993). Demand Equations for Individual New Car Models Estimated Using Transaction Prices with Implications for Regulatory Issues. Southern Economic Journal, 49 (3), 764-782.

Lensing, N., (2003). Straßenverkehrszählung 2000 - Ergebnisse (Traffic counts 2000 - results). Berichte der Bundesanstalt für Straßenwesen, Verkehrstechnik, Heft V 101.

Mercuri, R., Bauen, A., and Hart, D., (2002). Options for refuelling hydrogen fuel cell vehicles in Italy. Journal of Power Sources, 106, 353-363.

Moore, R.B. and Raman, V., (1998). Hydrogen Infrastructure for Fuel Cell Transportation. International Journal of Hydrogen Energy, 23 (7), 617-620.

Ogden, J., (1999). Prospects for building a hydrogen energy infrastructure. Annual Review of Energy and the Environment, 24, 227-279.

Ogden, J.M., (2002). Modeling Infrastructure for a Fossil Hydrogen Energy System with CO2 Sequestration. Paper prepared for the Sixth Greenhouse Gas Control Technologies Conference, Kyoto, Japan.

Oi, T. and Wada, K., (2004). Feasibility study on hydrogen refueling infrastructure for fuel cell vehicles using the off-peak power in Japan. International Journal of Hydrogen Energy, 29, 347-354.

Schneider, M.T., Schade, B., and Grupp, H., (2004). Innovation Process 'Fuel Cell Vehicle': What Strategy Promises to be Most Succesful? Technology Analysis & Strategic Management, 16 (2) 147-172.

Sørensen, B., Petersen, A.H., Juhl, C., Ravn, H., Sondergren, C., Simonsen, P., Jorgensen, K., Nielsen, L.H., Larsen, H.V., Morthorst, P.E., Schleisner, L., Sørensen, F., and Pedersen, T.E., (2004). Hydrogen as an energy carrier: scenarios for future use of hydrogen in the Danish energy system. International Journal of Hydrogen Energy, 29, 23-32.

Stephan C., and Sullivan, J., (2004). An Agent-Based Hydrogen Vehicle/Infrastructure Model. IEEE Proceedings of the 2004 Congress on Evolutionary Computation (vol. 2), Portland, USA.

Stromberger, R., (2003). Building up a gas station infrastructure to supply vehicles with hydrogen as an alternative fuel, taking technical, economic and ecological aspects into consideration. Abridged version of dissertation, Vienna University of Technology http://www.hydrogenhighway.ca.gov/tt/economy/stromberger.pdf.

Thomas, C.E., Kuhn, I.F., James, B.D., Lomax, F.D., and Baum, G.N., (1998). Affordable Hydrogen Supply Pathways for Fuel Cell Vehicles. International Journal of Hydrogen Energy, 23 (6) 507-516.

European Hydrogen Energy Roadmap (HyWays) – First Results from Simulation, Stakeholder Discussion and Evaluation

Dr. Stefan Berger, Adam Opel GmbH, on behalf of the HyWays Consortium

The aim of HyWays

HyWays is an integrated project, co-funded by research institutes, industry, national agencies and by the European Commission under the 6th Framework Programme. HyWays aims to develop a validated and well-accepted Roadmap for the introduction of hydrogen in the European energy system. The main characteristic of this Roadmap is that it reflects real life conditions by taking into account not only technological but also country specific institutional, geographic and socio/economic barriers and opportunities. Both stationary and mobile applications are addressed, including possible synergies ('spill over effects') between these applications. HyWays will systematically describe the future steps to be taken for large-scale introduction of hydrogen as an energy carrier in the power market and transport sector and as a storage medium for renewable energy. An Action Plan for the support of the introduction of hydrogen technologies will be derived from this Roadmap.

The HyWays process in brief

The implementation of advanced, highly innovative technologies such as hydrogen applications is not just a matter of achieving the right payback time. A transition towards a sustainable energy system involves changes on various levels. Therefore, the assessment framework includes the use of a well-balanced set of models addressing impacts on micro, meso and macro level, an actor analysis as well as an analysis of a hydrogen infrastructure build-up (Figure 1).

HyWays comprises two phases of 18 months each. In the first phase, an analysis of the introduction of hydrogen is performed for six countries (France, Germany, Greece, Italy, the Netherlands, and Norway). In the second phase, the analysis is carried out for another four countries (Finland, Poland, Spain, and United Kingdom).

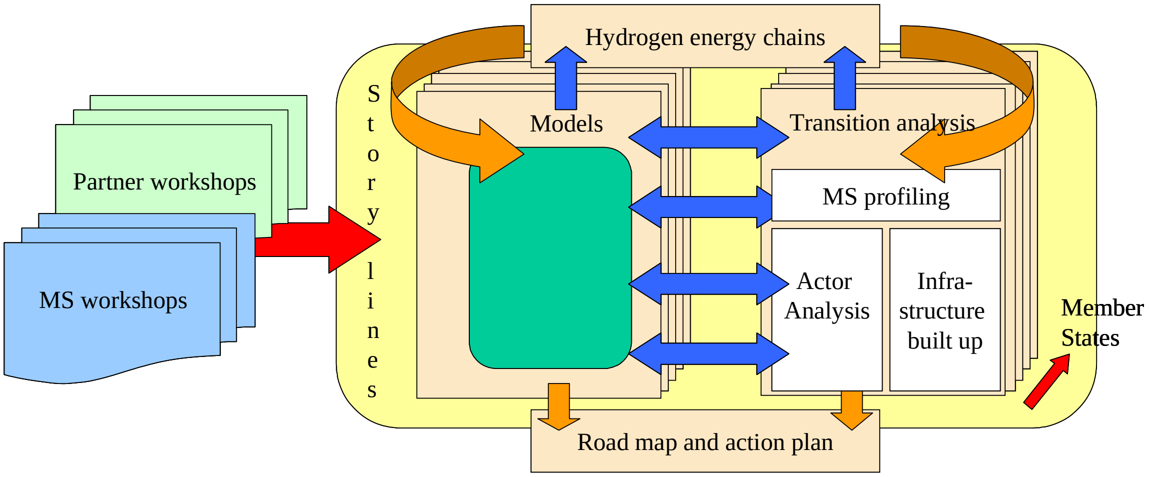

Figure 1: Schematic representation of the HyWays process

Validation workshops both within the consortium and with wider stakeholder groups in the participating countries play a crucial role in the HyWays process. The workshops serve as a platform to discuss and develop the methodology, collect the required input for the scientific analysis as well as for first order validation of results. The goal of the national stakeholder workshops is twofold:

- To collect information on stakeholder preferences and other country specific conditions. This information is used to modify the results of the scientific analysis in order to turn the 'optimal' pathways, from a strict techno-economic optimisation point of view, into realistic pathways that reflect real life conditions.

- To validate the results of HyWays and to give these stakeholders a say in the process of selecting energy chains and developing realistic and preferable pathways, thus improving the quality as well as the acceptance of the HyWays results.

Robust results from Phase I

In this phase of the project, few validated results are available. Nevertheless, some robust conclusions were drawn from the interactions with the various stakeholder groups. Both the model extensions as well as more detailed model results will be covered in HyWays publications to be published towards the end of the project or already posted in the publications area of the HyWays website http://www.hyways.de.

Energy chains selected

The definition and description of the hydrogen production, distribution, and consumption technologies in the E3-database (Agator, 2003) stand at the basis of the selection of country specific chains. The database provides a means of accessing all known techno-economical characteristics of hydrogen technologies, as well as a tool for energy chain analysis. In such an analysis, the energy efficiency, greenhouse gas emissions and costs for a particular chain are determined, from production to consumption of hydrogen.

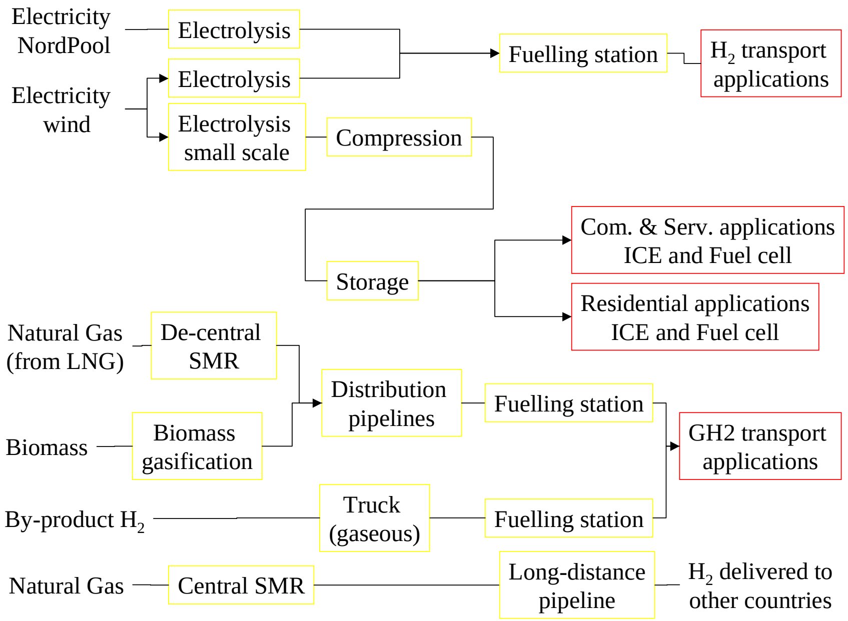

Figure 2: Example of hydrogen source-to-user and well-to-wheel chains (Norway)

The chain selection process for the six countries participating in Phase I combined the specific socio-political landscape of a country with the availability of information in the E3-database (Figure 2). The selection indicates that the countries share the view on the importance of transport applications. The use of hydrogen in the built environment for combined heat and power is viewed as relevant, albeit to a lesser extent in terms of size of hydrogen demand. A similar consensus can be observed on the choice of distribution options, with a main role for pipeline transport, and a limited role for trucks carrying liquefied hydrogen. In Italy, like in the US, for power production technologies in which hydrogen is temporarily produced, it is considered as an intermediate energy vector in the power sector. In the other countries this is still open for discussion.

The major distinction between the countries is in the selection of the production options, although even there the differences between the Member States are limited. All countries foresee a role for the production from natural gas, biomass, and electrolysis, from the grid or from wind. Coal is also viewed as a possible option for hydrogen production, particularly through coal gasification, or in the case of Greece, lignite gasification. This holds especially for countries where coal already today plays a significant role in the electricity production.

The impact of hydrogen on the energy system

Hydrogen production

Until 2030, hydrogen production from fossil fuels with carbon capture and storage (CCS) is expected to be the most important production source in Europe, with renewable hydrogen slowly being phased in. This is explained by the maturity of fossil fuel based technologies, assumptions on the availability of feedstocks and consequently the cost of hydrogen produced, as well as uncertainty about allocation of renewables to different energy sectors. At the same time, the baseline sees a drive towards low-carbon fuels, or carbon capture technologies, due to the strong carbon policy assumed. These conclusions hold even in the most extreme sensitivity run for the crude oil price, running at 200 $/barrel in 2050, with both natural gas and coal price assumed to follow the oil price.

Although the overall trends clearly indicate a continued dominance of fossil resources in the timeframe considered, in some cases benefits from local production and use may be advantageous to the use of renewable resources. This is most apparent for the use of biomass in rather small-scale gasification units, connected to local networks. To a lesser extent this also holds for intermittent resources, like wind power. In the first phase of HyWays, the consequences on electricity prices of intermittent resources have not been taken into account. It is foreseen that further analysis will be carried out on the costs of and conditions for production of hydrogen from renewable energy sources. Some countries clearly see a window of opportunity for the production of hydrogen from such resources, due to side benefits other than simple cost-competitiveness. Moreover, in some countries there is likely to be a political will to stimulate the use of renewables in a local setting. At the European level, the result is a limited but growing contribution from renewable resources.

Benefits of the hydrogen economy

There are three potential benefits from the introduction of hydrogen in the energy system: reduced emissions (environment), reduced dependence on critical imports of fossil fuels (security of supply), and economic growth opportunities for industry (economic stability). The impacts on the emissions are rather straightforwardly evaluated, as emissions are covered by a number of the models used in HyWays. Power production with CCS plays an important role in attaining the CO_2-emission reduction target. Some important CCS technologies have hydrogen as an intermediate product, and the use of such technologies may facilitate the large-scale introduction of hydrogen as an energy vector.

The energy system analysis shows that there is no direct effect on Security of Supply (SoS) when comparing the introduction of hydrogen to the baseline projections because the baseline already assumes that more diversification of energy sources will occur due to rather strict emission targets. However, the introduction of hydrogen eases the strong dependence on biomass in the transport sector induced in the baseline due to the CO_2-target. Hence, introducing hydrogen leads to a more robust projection of an increased SoS.

Impact on Industry and Economy

Economic analysis of hydrogen fuel cell vehicles compared with conventional vehicles

Four major drivers influence the cost-competitiveness of hydrogen cars compared with conventional vehicles: the crude oil price, hydrogen price (infrastructure costs), internalisation of CO_2-emissions and hydrogen drive system costs. Figure 3 shows the influence and the range of uncertainty of different drivers on the economy of fuel cell vehicles (FCVs).

The cost assumptions for the hydrogen drive system are dominant, followed by the variation of crude oil price, hydrogen feedstock and production technology, and then the internalisation of CO_2 emissions. Whereas the infrastructure costs for a hydrogen-based energy system can be estimated on the basis of today's technologies, it is more difficult to estimate the future development of hydrogen drive system costs. The main challenge to hydrogen use in the transport sector is to reach a price level for FCVs near the prices of conventional vehicles. Dependent on the other drivers, the target is between 0 and 1500 Euro of additional cost compared to conventional vehicles. It is important to notice that the calculations are based on the assumption that FCVs are perfect substitutes for conventional cars.

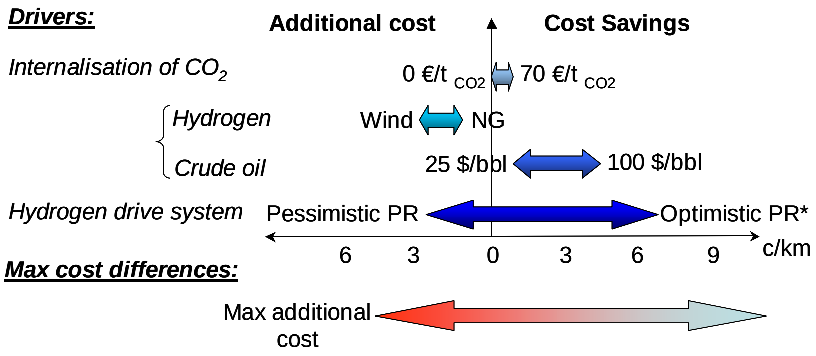

Figure 3: Specific additional cost and savings of an FCV compared with a conventional vehicle (PR: progress ratio for fuel cell cars; describes the speed of cost reduction over the cumulative output)

In order to reach cost-competitiveness of fuel cell vehicles investments in both research, demonstration and development as well as in large-scale deployment are needed. Figure 4 shows the cumulative additional investments (additional compared with conventional vehicles) required until cost-com-petitiveness of FCVs for different scenarios. All cases analysed show that FCVs will reach this cost-competitive-ness but with a wide range of cumulative cost. The important factors in reaching cost-competitiveness are the potential for cost reductions of fuel cells, given as the progress ratio (PR), and the oil price. For low oil prices around 30 $/barrel the break-even point depends strongly on the value of the progress ratio, and the investments show variations by a factor six. For high oil prices of 50 $/barrel or higher, the impact of the magnitude of the progress ratio is substantially smaller[3], varying only by a factor two. The uncertainty in cumulative costs between positive and unfavourable circumstances for hydrogen-fuelled vehicles can be as big as a factor ten.

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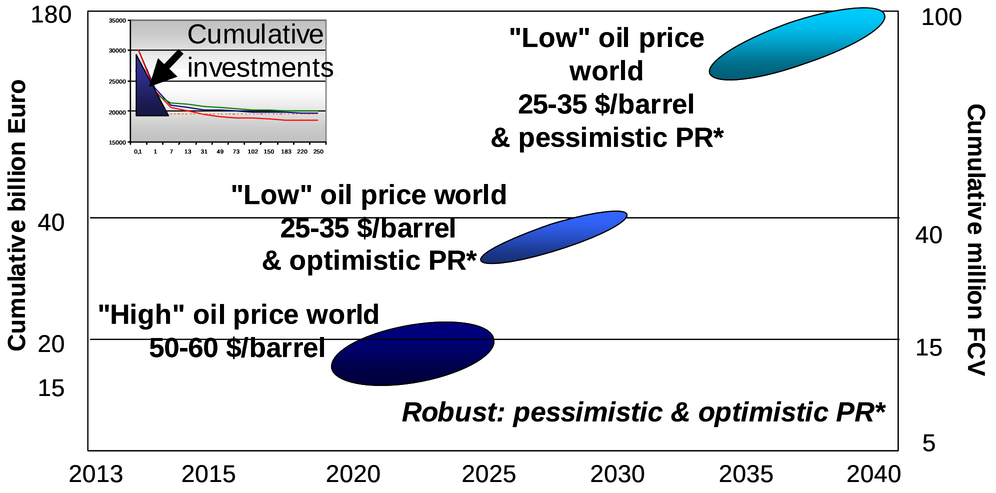
[3] Conclusions hold for similar variations in progress ratio for the two oil price ranges. The potential for cost reduction is essential, in that with cost reductions the oil price should be considerably higher than 50 $/barrel to reach cost-competitiveness.



* **PR** = **P**rogress **R**atio describes the speed of cost reduction over the cumulative output

Figure 4: Accumulated additional investments in hydrogen vehicles and number of cars until cost-competitiveness of FCVs is reached (without externalities and interest rate, from the beginning of mass production (€ 10,000 more for a fuel cell car), worldwide)

To put the investment costs required to reach cost-competitiveness for FCV into perspective, a comparison can be made with the global investment of 16 trillion USD that would be required for the overall energy supply system until 2030 according to the IEA World Energy Outlook Reference Scenario (IEA, 2004). Alternatively, the number can be compared to the 1 billion US$ which is typically necessary to bring one new car type into the market, and which besides R&D expenditures includes costs for marketing, construction of plants, etcetera.

From the economic viewpoint, CO_2 reduction is not a major driver for the introduction of hydrogen. As compared to for example the price of hydrogen production and transport, the impact of carbon prices is relatively small. They could play a relevant role in decision-making of consumers only if FCVs are nearly cost-competitive. Having said this, if hydrogen fuel cell cars enter the market due to their competitiveness, this would lead to a significant CO_2 reduction (up to a factor of 10 for every vehicle substituted). In this case, it is a win-win situation for the economy and environment. The benefits are even higher as not only CO_2 emissions but also other local air emissions and noise will be reduced by the introduction of hydrogen vehicles.

Impacts of a hydrogen economy on employment

The structure of the investments necessary for a transition to a hydrogen economy is clearly dominated by the expenditures for hydrogen vehicles (see Figure 5). If a hydrogen vehicle is imported in a country, not only the hydrogen drive system will be imported, but the whole vehicle. Therefore the structure of the domestic vehicle industry sector turns out to be one of the key factors for the employment analysis, but also for GDP and welfare development.

Four import/export scenarios have been analysed so far (Figure 6). Every scenario tells a story of a possible future for the competitiveness of the hydrogen technologies produced within the EU. The "Structural identity" scenario is based on today's technology imports and exports, in which the EU and the six countries have a good market position. A lead market analysis shows that other regions of the world, namely USA and Japan, are also in a very strong position to become a lead market for hydrogen. This is expressed by the "Today's potential" scenario where the EU export falls back compared to the structural identity scenario. The "Pessimistic" scenario shows what would happen if other regions of the world take over the leading position and Europe has to import hydrogen vehicles. In the "Optimistic" scenario, great efforts will be undertaken which result in increased EU exports of hydrogen vehicle and technologies.

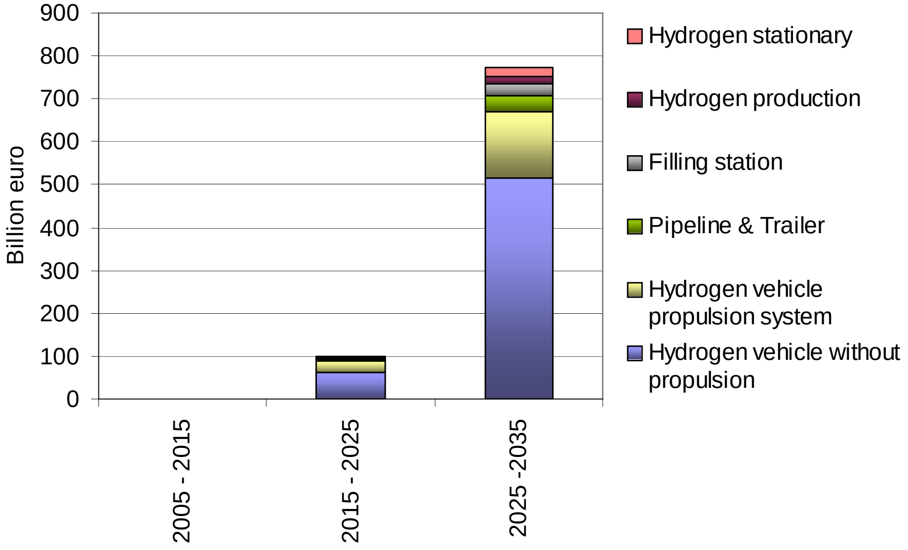


Figure 5: Structure of the investments in a hydrogen economy of the six HyWays countries (cumulative investments for a ten-year period, hydrogen high penetration scenario)

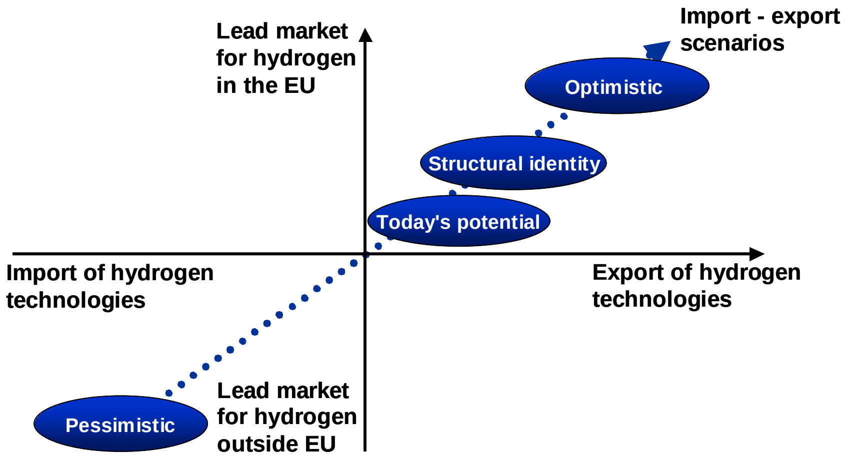


Figure 6: The classification of the four hydrogen import/export scenarios for the economic analysis

The analysis shows that the transition to a hydrogen based energy system has the largest employment effects on the automotive industry and to a lesser extent on the plant and equipment sector. Whether the impact is negative or positive depends strongly on Europe's efforts to consolidate or improve its current position in the car market. This holds even stronger for the current car manufacturing countries, which therefore face the dilemma: should they invest in a risky new technology, losing possibly many billions of R&D investments, or not, at the possible expense of even higher losses in GDP and jobs.

The replacement of conventional vehicles by FCVs induces a sectoral employment shift away from the traditional car manufacturing. This shift requires considerable training of the workforce. Because of the required gradual build-up of manufacturing capacity and hence skilled labour force, preparing for expected mass production by 2015 necessitates political early action.

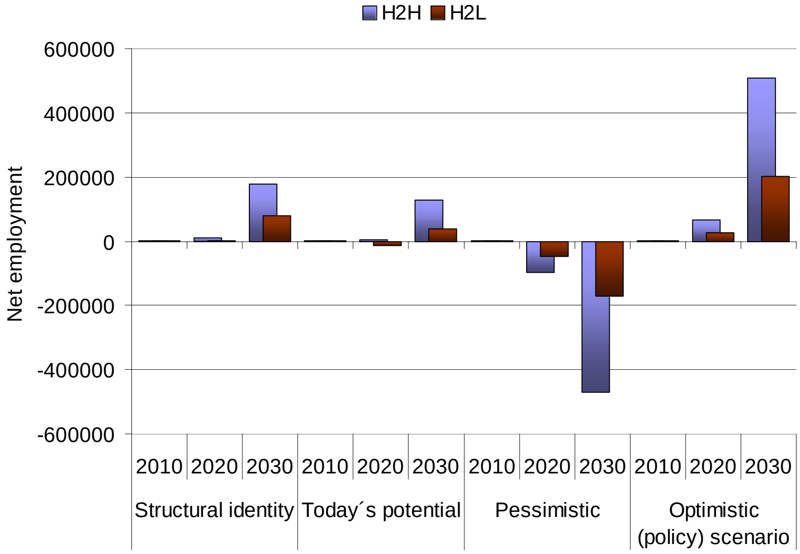


Figure 7: Net employment effects for the "hydrogen high penetration (H2H)" and "hydrogen low penetration (H2L)" scenarios with high learning rates for hydrogen passenger cars for the years 2010-2030. Shown are the net employment effects for the six HyWays Phase I countries in four import/export scenarios

The production and maintenance of hydrogen and fuel cell technologies and related services offer economic growth opportunities for industry. It is important to develop a strong position for European industry compared to U.S. and Japanese competition among others to maximise the economic benefits for Europe.

Impacts of a hydrogen economy on welfare and GDP development

The impact of the transition to a hydrogen based energy system on overall welfare is quite small, as the change in GDP. Figure 8 shows the impact of the high-penetration scenario on GDP in the HyWays Phase I countries (again given as percentage deviations from the baseline scenario). The difference between countries is mainly due to differences in H2 production costs and car-class dependent penetration rates. Whether the impact on welfare is positive or negative depends strongly on the cost reduction potential of FCVs. GDP changes take place in those periods where actual resources from the transport sector (lower overall costs of hydrogen cars) are released for use in other sectors. This means that GDP increases are broadly proportional to the car cost differences and to the penetration rates (which are both rising over time).

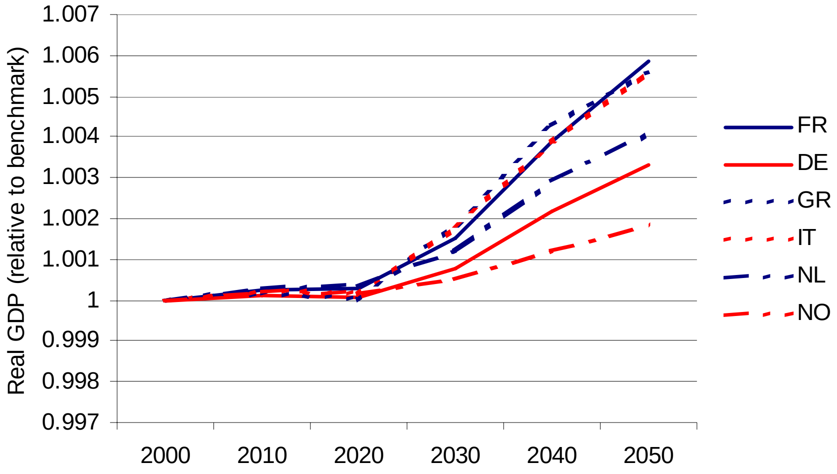


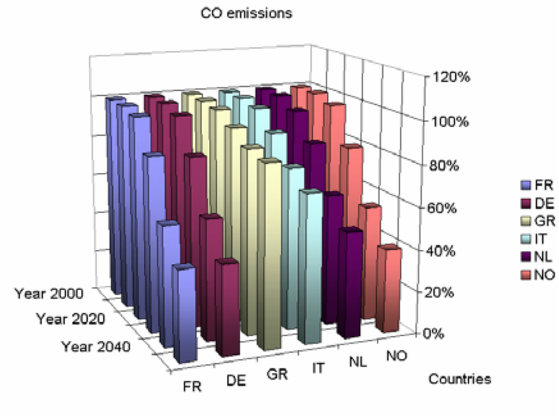
Figure 8: Real GDP (structural identity scenario)

Impact on emissions

The introduction of hydrogen technologies for mobile and stationary applications has the obvious advantage of reducing end-of-pipe emissions. Particularly for fuel cell technologies in the transport sector, emissions can be substantially reduced. At local level the benefits are very relevant for the air quality, especially in urban areas, as combustion of hydrogen results in no exhaust emission of pollutants when used in a fuel cell, and only few when used in an internal combustion engine (ICE). Therefore the emissions of local pollutants are considerably lower in the hydrogen penetration scenarios than in the baseline. The emissions have been calculated using the COPERT III model (Ntziachristos, 2000), as the road transport sector is the one where hydrogen has the largest deployment, using furthermore the TREMOVE database (EC, 2005) for projections of the fleet composition to 2050.

For hydrogen vehicles zero emission of pollutants from the tailpipe has been assumed. The assumption is mainly based on the predominant share in the long term of fuel cell vehicles, and the fact that these have zero pollutant emissions from the tailpipe. Lack of information was an additional reason to ignore specific emissions from hydrogen ICE such as NO_x-emissions. While future additional information on such emissions may render a more complete analysis feasible, this would not change the results much.

Calculated emission levels for CO, NO_x and Particulate Matter (PM) in the high hydrogen penetration scenario are shown in Figure 9ff, for all six countries, and for the periods from 2000 to 2050. As the figures illustrate, there are important positive environmental effects for



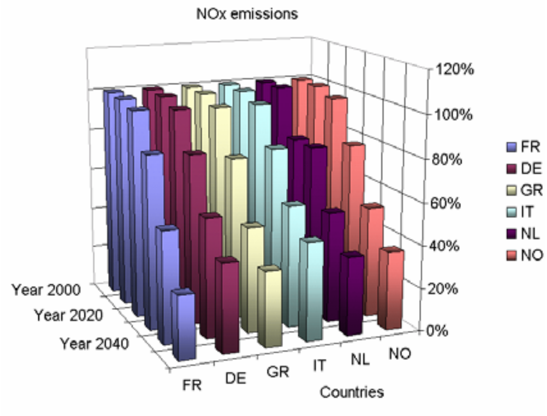


Figure 9: Development of CO emissions normalised to reference scenario for the period 2000 – 2050

Figure 10: Development of NOx emissions normalised to reference scenario for the period 2000 - 2050

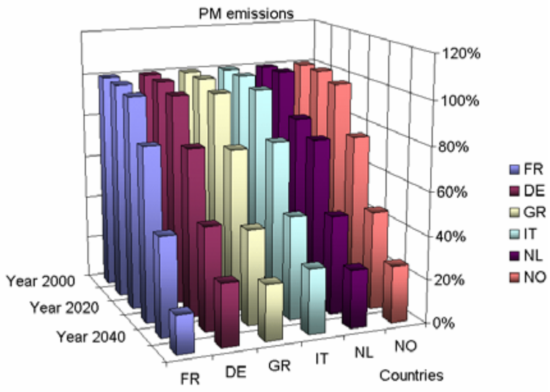


Figure 11: Development of the PM emissions normalised to reference scenario for the period 2000-2050

all of these pollutants, when compared to the reference scenario. In most of the cases the reductions are higher than 50%, except for CO-emissions in Italy and Greece due to a relatively high share of two-wheelers. For PM the reduction is even higher due to the large share of diesel cars in the reference scenario, which amplifies the positive effects of hydrogen.

A major advantage of hydrogen use is the impact on local emissions, particularly due to the assumed high penetration of FCV. Aside from the reduction of conventional fuel consumption and CO_2 emissions, which are in line with the MARKAL results, emissions in urban areas with large population density are substantially reduced, indicating possible benefits on health.

The above results include also emissions from trucks and two-wheelers, where it is currently assumed that hydrogen will not contribute. The effects could be more substantial if further analysis would show that such vehicles actually do show potential for update of hydrogen technologies.

Development of MS-specific end-visions

The development of member state specific end-visions on the development of the energy system as well as the future role of hydrogen is an important step in the HyWays process. By means of these end-visions, stakeholder preferences with respect to e.g. the source for hydrogen production as well as views on the development of hydrogen demand can be taken into account. These end-visions for example set the boundary conditions for the analysis on infrastructure build-up and are also of key relevance in the discussion of the selection of MS-specific energy chains. In this chapter, a brief overview of the most important elements of these end-visions is given for the countries assessed in Phase I of HyWays.

Example: German Vision of Hydrogen Chains

The German HyWays stakeholders have developed a national vision of the deployment of hydrogen energy for the next decades. This national vision takes into account: a wide variety of relevant H_2 sources from fossil to renewable feedstocks, as well as the different scales of production from onsite to centralised production. In this vision CO_2-reducing or CO_2-free sources should play an important role especially in a long-term view.

The most promising application sector for hydrogen is seen in transport with a focus on cars and regional vehicle fleets using hydrogen in fuel cells, and in the transition phase also in internal combustion engines. For stationary applications the potential to use hydrogen is also envisioned, but to a lower extent. The key drivers for a hydrogen economy – energy supply security and international competitiveness – put less pressure on industry and politics than the transport sector. In the transition phase to a wider use of hydrogen energy starting after 2010, industrial by-product hydrogen can significantly contribute. Additionally hydrogen will be produced by on-site steam methane reforming (SMR) and electrolysis. Demand centres in densely populated areas will arise and for hydrogen transport liquid or compressed hydrogen trucks will play a relevant role.

After 2020 the growth in hydrogen demand is expected to broaden the range of options for local and central hydrogen production. Another H_2 supply option with growing importance is electrolysis from renewables and grid mix electricity. Depending on the hydrogen penetration rate and the feasibility of CCS (economy, security) natural gas (NG) and coal can contribute to secure higher amounts of GHG emission free hydrogen (centralized). For hydrogen transportation pipelines will play a relevant role at this stage. But also on-site steam methane reforming (SMR) and electrolysis production will be important, especially for the supply in rural areas with warranted demand profiles.

After 2030, hydrogen already plays a major role in supplying vehicles and a remarkable role for stationary applications. Provided, CCS is already established at industrial scale, central hydrogen production schemes based on fossil fuels could dominate in Germany either from SMR, or coal gasification - depending on long-term price developments of the energy carriers. Although the end-use competition for the merits of renewable resources between different sectors (transport, electricity, heat) will grow, the share of renewable hydrogen will increase. Main renewable H_2 supply chains are wind (on- and off-shore) via grid electricity and central or de-central electrolysis as well de-central biomass gasification. New renewable resources (geothermal) might fit the growing hydrogen demand with the help of new storage systems. The import of hydrogen (e.g. from Norway via a European pipeline network) may become another option. The transport of hydrogen will be by pipeline or liquid hydrogen truck depending on the hydrogen demand and location of the end use.

Current state of affairs and next steps in Phase II

In the first phase of HyWays, the emphasis was on the development and validation of the assessment framework. For each of these member states participating in Phase I, a number of preferred hydrogen pathways have been selected and analysed on various aspects such as costs and benefits, impacts on emissions, energy consumption and impact on fossil and renewable resources. By means of a series of workshops, the results of analyses were discussed within a broad group of stakeholders in order to take into account the stakeholder views as well as to validate the first results.

The following steps are foreseen in Phase II of HyWays:

- Finalisation of the actor analysis. The actor analysis aims to identify critical actors that are involved in the key changes in the energy system resulting from the introduction of hydrogen.

- Identification of open issues not yet covered. The internal and external workshops have revealed a number of issues that have to be tackled in Phase II of the project. Some of these issues defined up until now are:

    1. The price gap between hydrogen produced from fossil and renewable resources. A number of factors have to be considered such as the learning curves of renewable resources as well as the efficiency and cost development of electrolysers.
    2. The development of the demand of goods transported with light, medium and heavy trucks, possibly deviating from the Energy Trends 2030 scenarios.
    3. Constraints imposed on the energy system such as the (local and regional) availability of biomass as well as possible limitations of CCS technology, e.g. due to a lack of (local) storage capacity or related to public acceptance.
    4. Analysis of the infrastructure build-up. For several reasons, it has not been possible to carry out an assessment of infrastructure build-up and have this validated by the various stakeholders.

- Evaluation of the process as well as contents produced in Phase I of the HyWays project. In Phase II, the assessment framework as developed and applied in Phase I will be used again. It is however critical to check if key research questions can be answered and the objectives of the project are met. Possible gaps need to be identified and actions to overcome these flaws have to be taken.

- The development of a common framework to derive a general EU-wide roadmap based on MS-specific analyses, e.g. by identification of the drivers and policy aspects that surpass the developments within the individual MS.

- For six member states, a country specific analysis has been performed in HyWays Phase I. In the second phase of HyWays, the process will be repeated for another four member states. The member states to enter into the second phase of HyWays (Finland, Poland, Spain, and United Kingdom) have been selected through a public call for tenders. This call was issued on 6th of August 2005, see http://www.hyways.de/call. For these additional MS, also a number of workshops will be held where stakeholders are encouraged to deliver input to the process. Also in Phase II, the MS partners from Phase I will participate in 2 out of a row of 3 workshops to update their assumptions, carry out the analysis which had to be omitted in Phase I and harmonise their results with the new member state partners.

References

J.M. Agator, S. His, and J. Schindler, (2003). Decision Aiding Tool E3Database for Energy, Emission-related and Economic Regional Evaluation of Hydrogen Fuel Chains. Paper presented at the 1st European Hydrogen Energy Conference 2003, September 2-5, 2003, Grenoble, France.

EC, (2005). TREMOVE 2.30 Model and Baseline Description; Final report. EC DG Environment, Service Contract B4-3040/2003/366851/MAR/C.1, 18 February 2005. http://www.tremove.org/download/TREMOVE%202.30%20v18feb05.pdf

HyWays website: http://www.hyways.de

IEA, (2004). World Energy Outlook 2004. International Energy Agency, Paris, France.

L. Ntziachristos and Z. Samaras, (2000): COPERT III Computer programme to calculate emissions from road transport Methodology and emission factors (Version 2.1). ETC/AEM, http://vergina.eng.auth.gr/mech/lat/copert/copert.htm

Session 3: Atmospheric Chemistry-Climate Interactions in Relation to Potential Future Emission Changes in a Hydrogen Economy

Comparative Effects on Air Pollution, Health, and Climate of Converting U.S. Vehicles to Hydrogen Fuel Cell or Hybrid Vehicles

Mark Z. Jacobson, Whitney G. Colella, and David M. Golden, Department of Civil and Environmental Engineering, Stanford University, Stanford, California, USA

Converting all onroad vehicles in the United States to hydrogen fuel-cell vehicles (HFCV) may improve air quality, health, and climate significantly, whether the hydrogen is produced by steam-reforming of natural gas, wind-electrolysis, or coal gasification. Most benefits would accrue from eliminating current motor vehicle exhaust. Wind- and natural-gas-HFCV offer the greatest potential health benefits and could save 3700-6400 lives and decrease respiratory illness and asthma by millions of cases in the U.S. each year. Wind-HFCV should benefit climate the most. Conversion to coal-HFCV may improve health but would damage climate more than fossil/electric hybrids. An all-HFCV fleet, compared with the current fossil-fuel fleet, would hardly affect tropospheric water vapor. The real cost of hydrogen from wind-electrolysis may be below that of U.S. gasoline.

Reference

Jacobson, M.Z., W.G. Colella, D.M. Golden (2005), Cleaning the air and improving health with hydrogen fuel-cell vehicles, Science 308 (5370), 1901-1905.

CTM Studies of Tropospheric Chemistry and Implications for Atmospheric Hydrogen

S. A. Isaksen, F. Stordal, S. Dalsøren, and T. F. Berglen, Department of Geosciences, University of Oslo, Norway

A 3D Chemical Transport Model (CTM) OsloCTM2 has been used to estimate the atmospheric chemical production of hydrogen from biomass burning. The formation occurs via formaldehyde, and results for various parts of the year are investigated. Further, we have studied the evolution of the hydroxyl radical by using the emission inventory for ozone precursor gases for the period 1990-2001 available from the EU-funded project POET. This database contains emissions of NO_x, CO and NMVOCs as well as methane concentration fields based on surface observations. The CTM was run for the 12 years with constant meteorology to isolate the effects of emission changes on tropospheric chemistry. Large regional variations are found in hydroxyl (OH) distributions and changes as a result of variations in regional emissions and their trends. The evolution of global OH is highly dependent on the ratio of CO to NO_x in the emissions, and a simple statistically significant linear relation between this ratio and the OH trend is found. Implications of the trends in OH for trends in tropospheric hydrogen is discussed.

The Impact of a Hydrogen Increase on Stratospheric Ozone Loss - An ERA 40 Reanalysis Study

Th. Feck, J.-U. Grooß, M. Kaufmann, M. Riese, Forschungszentrum Jülich, Institute of Chemistry and Dynamics of the Geosphere, Stratospheric Research (ICG I), Jülich, Germany

Although the usage of hydrogen (H_2) in fuel cells produces only water vapour (H_2O) as exhaust, the impact of direct H_2 emission to the atmosphere e.g. by pipeline leakage could be a source for the formation of polar stratospheric clouds (PSC). Our box model simulations show that all H_2 that enters the stratosphere from below is oxidized to form H_2O which leads to a cooling of the stratosphere and to larger PSC formation areas. The chemical reactions that occur on the surface of PSCs lead to the "ozone hole" in the Polar Regions. To analyse the potential impact of a future anthropogenic H_2 increase we investigated different H_2 scenarios and their impact on the formation of PSC by using meteorological data (ERA 40) of the European Centre for Medium Range Weather Forecast (ECMWF) for the years 1958 – 2001. The corresponding ozone depletion is determined by using the empirical relation between the average PSC volume (V_{PSC}) and the ozone change (ΔO_3). This relation was derived from ozone sonde observations and ECMWF meteorological analysis by Rex et al. in 2004. With this method we are able to make first estimates of the ozone loss that a future hydrogen prioritised energy supply chain could cause.

Session 4: Costs and Benefits of Hydrogen Energy in Relation to Alternative Energy Scenarios

The Role of Hydrogen in Emissions Scenarios

Nebojsa Nakicenovic, IIASA, Laxenburg, Austria

There are numerous scenarios in the literature that describe a wide range of future outcomes including energy choices and the consequent emissions. One common trait is that the scenarios that describe more "business-like-usual" developments tend to rely quite heavily on fossil energy sources also in the very long term. These are often the scenarios with very high future greenhouse gas emissions. Carbon dioxide emissions alone would increase many fold and in some extreme case grow by an order of magnitude during this century. To a large extend this is related to humble degree of technological progress assumed in such futures. In contrast, scenarios that deploy a wider-range of energy options usually tend to gravitate toward median emissions outcomes, say in the range of a three-fold increase. The scenarios with lowest emissions are often also the ones with relatively more humble energy needs in the first place and higher degrees of decarbonization. Thus, decarbonization of the future energy system plays a central role across a wide range of future developments. This is especially the case in the futures that are characterized by a transition away from the current dependence on fossil energy sources.

Decarbonization basically implies that an increasing share of energy services have to be provided by carbon-free energy carriers. This means a much larger role of hydrogen and electricity (hydricity) as energy carriers of choice. The resulting greenhouse gas emissions in such scenarios depend very much how these clean and zero-carbon carriers are produced. Emissions would be relatively low in scenarios with very large shares of renewables and/or nuclear. In contrast, fossil-intensive scenarios can achieve low emissions only in conjunction with carbon capture and disposal. In most of the scenarios, both decarbonization and zero-carbon sources of energy are required to achieve the deep emissions reductions that would eventually lead to the stabilization of the atmospheric concentrations of greenhouse gases in accordance to the Article 2 of the UN Framework Convention on Climate Change.

This all indicates that hydrogen plays a potentially important role in low emissions futures. The potential advantages range from many synergies and complementarities with electricity. Both can be generated from virtually all energy sources, both are emissions free as carriers of energy and both can be converted into each other. They are complementary because hydrogen can be converted into electricity and vice versa. Electricity has advantages in stationary uses while hydrogen has advantages in mobile ones. But here they are also complementary. For example, zero-emissions cars would most likely convert hydrogen into electricity and would thus be literarily electric cars as well.

This will be illustrated on the basis of single scenarios and on the basis of statistical assessment of scenarios in the literature. Furthermore, the emerging studies of very low greenhouse gas stabilization levels require extremely deep emissions reductions, amplifying the need for a larger role of hydrogen and electricity. For example, the idea of capturing carbon from biomass and thereby effectively removing carbon from the atmosphere is being studied as a potential, albeit very challenging, strategy of compensating for a possible future "overshoot" of emissions or alternatively as a strategy of reaching in the future stabilization levels comparable to the present concentrations. In either case, carbon removal from biomass implies hydricity as the main energy carrier.

Achieving any of the transitions toward low emissions futures is a major planetary challenge. Hydricity will no doubt have an important role to play in delivering the required, emissions-free energy services. There are many modeling and other challenges to be resolved before a better understanding can be achieved both about these transitions and conditions that could make hydricity carriers more economically viable and more technically attractive.

Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context - Pathways to Hydrogen and Comparison with Other Alternatives

Jean-François Larivé, CONCAWE, Brussels, Belgium

EUCAR, CONCAWE and JRC (the Joint Research Centre of the EU Commission) have updated their joint evaluation of the Well-to-Wheels energy use and greenhouse gas (GHG) emissions for a wide range of potential future fuel and powertrain options, first published in December 2003. The specific objectives of the study were to establish the energy and GHG balances of a wide range of pathways while also considering the viability and costs of all alternatives.

The scope of the study is summarised in the WTT and TTW matrices

Fuel / Resource		Gasoline, Diesel, Naphtha (2010 quality)	CNG	LPG	Hydrogen (comp., liquid)	Synthetic diesel (Fischer-Tropsch)	DME	Ethanol	MT/ETBE	FAME/FAEE	Methanol	Electricity
Crude oil		X										
Coal					X$^{(1)}$	X$^{(1)}$	X				X	X
Natural gas	Piped		X		X$^{(1)}$	X	X				X	X
	Remote		X$^{(1)}$		X	X$^{(1)}$	X$^{(1)}$		X		X	X
LPG	Remote			X					X			
Biomass	Sugar beet							X	⇳			
	Wheat							X	X			
	Wheat straw							X				
	Sugar cane							X				
	Rapeseed									X		
	Sunflower									X		
	Woody waste				X	X	X	X			X	
	Farmed wood				X	X	X	X			X	X
	Organic waste		X$^{(2)}$									X
	Black liquor				X	X	X				X	X
Wind												X
Nuclear												X
Electricity					X							

(1) with/without CO_2 capture and sequestration

(2) Biogas

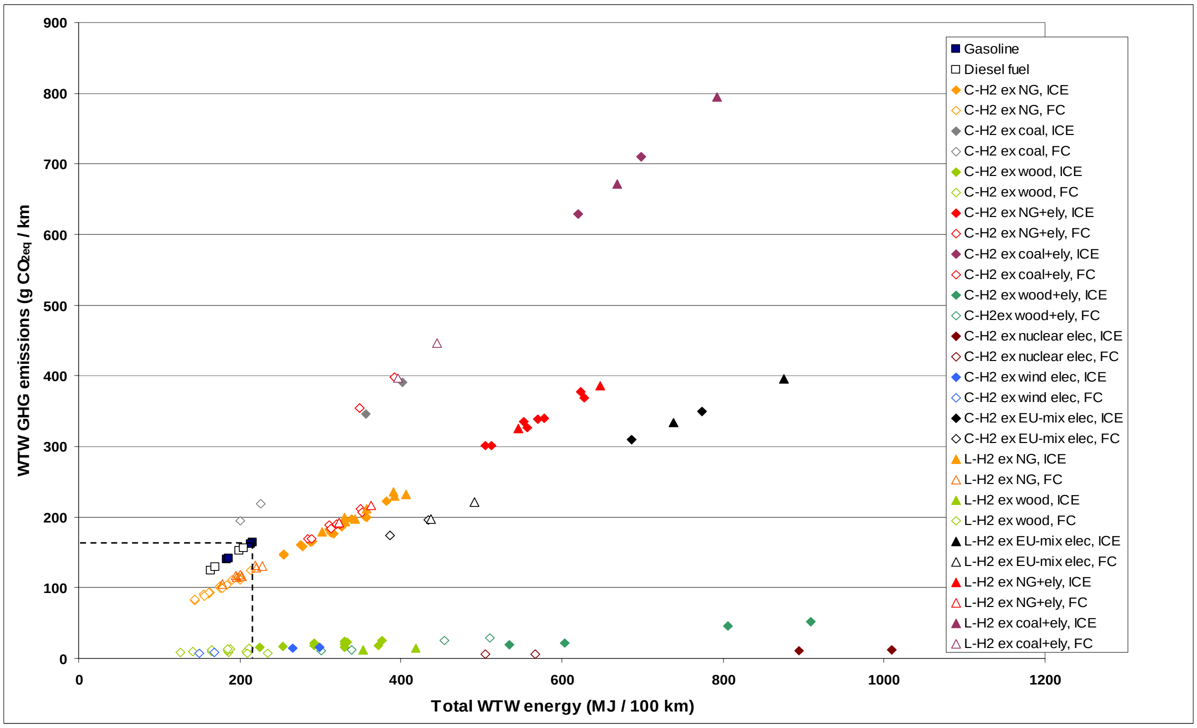
Powertrains	PISI	DISI	DICI	Hybrid PISI	Hybrid DISI	Hybrid DICI	FC	Hybrid FC	Ref. + hyb. FC
Fuels									
Gasoline	2002 2010+	2002 2010+		2010+	2010+				2010+
Diesel fuel			2002 2010+			2010+			2010+
LPG	2002 2010+								
CNG Bi-Fuel	2002 2010+								
CNG (dedicated)	2002 2010+			2010+					
Diesel/Bio-diesel blend 95/5			2002 2010+			2010+			
Gasoline/Ethanol blend 95/5	2002 2010+	2002 2010+			2010+				
Bio-diesel			2002 2010+			2002 2010+			
MTBE/ETBE	2002 2010+	2002 2010+		2002 2010+	2002 2010+				
DME			2002 2010+			2010+			
Synthetic diesel fuel			2002 2010+			2010+			
Methanol									2010+
Naphtha									2010+
Compressed hydrogen	2010+			2010+			2010+	2010+	
Liquid hydrogen	2010+			2010+			2010+	2010+	

The Tank-to-Wheels evaluation was carried out on the basis of a common vehicle platform, representative of a medium sized passenger car. A set of minimum performance parameters covering, acceleration, maximum speed and range was imposed on all configurations.

Hydrogen vehicle configurations included a 1.3 l turbo charged ICE (Internal Combustion Engine) both conventional and hybrid as well as fuel cell with an optional hybrid configuration (larger battery).

Hydrogen pathways

The following figure summarises the WTW energy and GHG balance of all hydrogen pathways considered. The points for fossil fuels and conventional vehicle pathways are shown for reference. Note that the energy figures plotted here refer to the total energy involved in the pathway, regardless of is origin. In particular it includes "bio" energy contained when biomass is used. This metric is therefore a measure of efficient use of energy resources.



Ely=electrolysis

Most pathways to hydrogen are more energy-intensive than conventional pathways. A number of options result in a reduction of GHG emissions required for meeting a certain transport demand, but many result in an overall increase in GHG emissions.

Looking in more details one can make the following observations:

- Fuel cells have the potential to deliver a large efficiency gain compared to ICEs. If it can be realised, this will be a major advantage of hydrogen over all other fuels.
- Using hydrogen in Liquid rather than compressed form carries an energy and GHG penalty.
- When hydrogen is obtained from renewable sources GHG emissions are low. Inasmuch as renewable resources have, in practice, a limited availability the real issue here is whether using them through hydrogen is the most appropriate route.
- Electrolysis is less energy-efficient than direct hydrogen production via thermal routes.

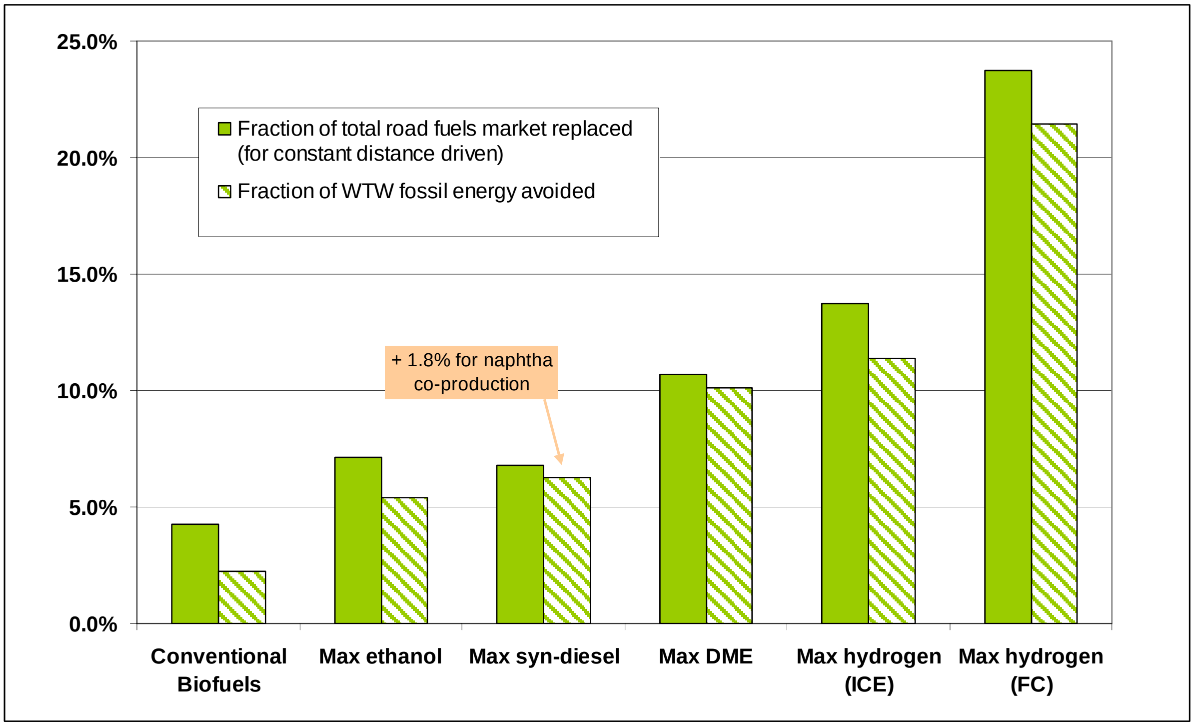
- The combination of on-board reformer (using gasoline or naphtha) and fuel cell may offer marginal benefits compared to direct use of hydrogen (from similar sources) in an ICE but would not be as efficient as direct use in a fuel cell.
- CO_2 capture and storage has the potential to provide a low CO_2 emissions route to hydrogen from fossil fuels. Much development still remains to be done both from a technical and legislative point of view before this can become a reality.

Comparison with other alternatives

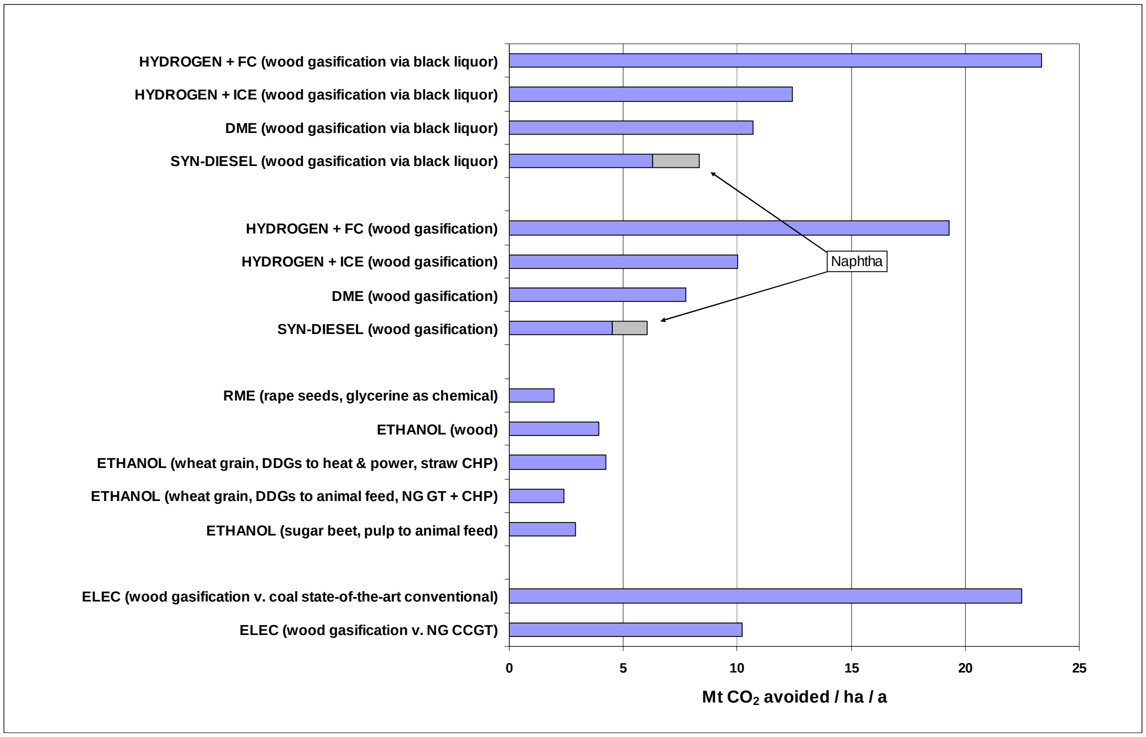
Conventional fuels and powertrains including hybrid configurations still have a significant potential for improvement which must be taken into account when evaluating alternatives including hydrogen pathways.

Unless hydrogen is used in a fuel cell vehicle, it is more efficient to use natural gas as such (as CNG in an ICE) than as hydrogen.

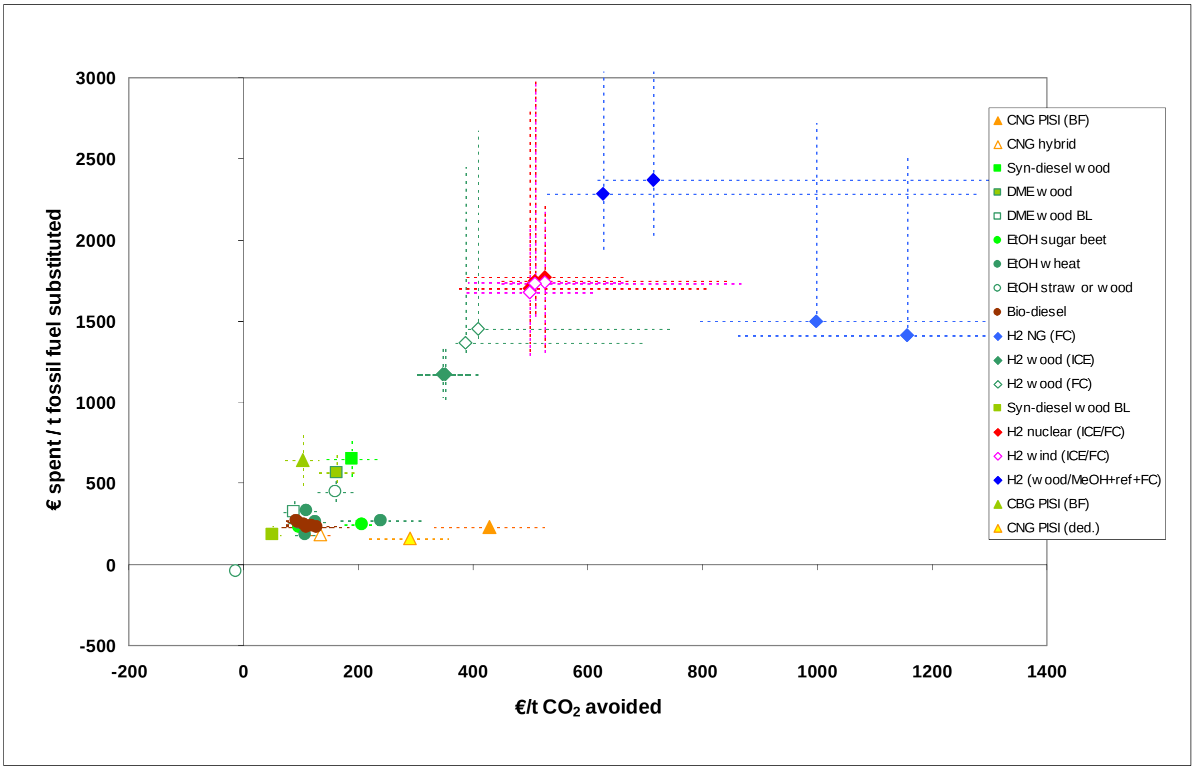
The hydrogen route can be an efficient way of turning biomass into road fuels. Advanced processes such as biomass gasification tend to be more efficient when geared to hydrogen than to other fuels such as FT-diesel, methanol or DME. The possibility of using hydrogen in efficient fuel cells is another big advantage. As a result a larger proportion of road fuel transport demand could be met by turning biomass to hydrogen rather than to other fuels.



Another way of looking at this issue is to consider the efficiency with which available land can be used to reduce overall GHG emissions. Hydrogen pathways, particularly in association with fuel cells are amongst the most promising from this point of view, on a par with electricity generation.



Hydrogen routes remain, however, considerably more expensive than other routes in terms of both cost of CO_2 avoided and overall cost of substitution. The main reason for this is the high cost of distribution and refuelling infrastructure and the significant extra cost of the vehicles, particularly fuel cells.



Oil price scenario: 50 €/bbl

Conclusions

Hydrogen may provide a credible and efficient low carbon alternative for road transport. There are, however, three main issues that need to be successfully resolved:

- High volume, low carbon routes for hydrogen production must be identified, developed and commercially proven while not having any significant effect on other environmental or societal aspects.
- Fuel cell vehicles must be developed that achieve the high energy efficiency figures in real life, the same or better performance than advanced conventional vehicles and are as durable and reliable.
- All costs, particularly those related to vehicles and refuelling infrastructure must be brought to commercially acceptable level.

The full report of the Joint JEC WTW study can be downloaded at
http://ies.jrc.cec.eu.int/WTW

Recent Literature

This list contains references to journal articles, reports, or book chapters on the topic of hydrogen and the environment and on the potential developments of hydrogen energy. The collection may be incomplete and is limited to articles, which appeared after the year 2000. A more complete and up-to-date list is maintained on the HyCARE web pages http://www.fz-juelich.de/hycare/.

2005

Colella, W.G., M.Z. Jacobson, D.M. Golden (2005), Switching to a US hydrogen fuel cell vehicle fleet: The resultant change in emissions, energy use, and greenhouse gases, J. of Power Sources, 150, 150-181.

Hart, D., (2005). The Economics of a European Hydrogen Automotive Infrastructure - A study for Linde AG, E4tech study, http://www.hydrogenday.com/WGAP/hydrogen/file/rwar-69wdr8.en.1/e4tech%20hydrogen%20study.pdf.

Jacobson, M.Z., W.G. Colella, D.M. Golden (2005), Cleaning the air and improving health with hydrogen fuel-cell vehicles, Science 308 (5370), 1901-1905.

2004

McCarthy, M.C., K.A. Boering, T. Rahn, J.M. Eiler, A.L. Rice, D.C. Tyler, S. Schauffler, E. Atlas, D.G. Johnson (2004), The hydrogen isotopic composition of water vapor entering the stratosphere inferred from high-precision measurements of delta D-CH_4 and delta D-H_2, J. Geophys. Res. 109 (D7),doi: 10.1029/2003JD004003.

Oi, T. and Wada, K. (2004). Feasibility study on hydrogen refueling infrastructure for fuel cell vehicles using the off-peak power in Japan. International Journal of Hydrogen Energy, 29, 347-354.

Schneider, M.T., Schade, B., and Grupp, H., (2004). Innovation Process 'Fuel Cell Vehicle': What Strategy Promises to be Most Succesful? Technology Analysis & Strategic Management, 16 (2) 147-172.

Sørensen, B., Petersen, A.H., Juhl, C., Ravn, H., Sondergren, C., Simonsen, P., Jorgensen, K., Nielsen, L.H., Larsen, H.V., Morthorst, P.E., Schleisner, L., Sørensen, F., and Pedersen, T.E., (2004). Hydrogen as an energy carrier: scenarios for future use of hydrogen in the Danish energy system. International Journal of Hydrogen Energy, 29, 23-32.

Stephan C., and Sullivan, J., (2004). An Agent-Based Hydrogen Vehicle/Infrastructure Model. IEEE Proceedings of the 2004 Congress on Evolutionary Computation (vol. 2), Portland, USA.

Warwick N. J., S. Bekki, E. G. Nisbet, and J. A. Pyle (2004). Impact of a hydrogen economy on the stratosphere and troposphere studied in a 2-D model, Geophys. Res. Lett., 31, L05107, doi:10.1029/2003GL019224.

Winter, C.J. (2004), On the path towards the hydrogen energy economy, BWK 56 (1-2), Springer VDI Verlag, Düsseldorf, Germany, ISSN 1618-193X.

2003

Barnes, D.H., S.C. Wofsy, B.P. Fehlau, E.W. Gottlieb, J.W. Elkins, G.S. Dutton, and P.C. Novelli, (2003). Hydrogen In The Atmosphere: Observations Above A Forest Canopy In A Polluted Environment Journal Of Geophysical Research-Atmospheres, 108/D6.

Barreto, L., A. Makihira, and K. Riahi, (2003): The hydrogen economy in the 21st century: a sustainable development scenario. International Journal of Hydrogen Energy, 28 (3), 267-284.

Dong, Z., L. Wu, B. Kettlewell, C.D. Caldwell, and D.B. Layzell, (2003). Hydrogen Fertilization Of Soils - Is This A Benefit Of Legumes In Rotation?, Plant Cell And Environment, 26/11, 1875-1879.

King, G. M. (2003). Contributions of atmospheric CO and hydrogen uptake to microbial dynamics on recent Hawaiian volcanic deposits. Appl. Environ. Microbiol. 69: 4067-4075.

Prather, M.J., (2003). An Environmental Experiment with H_2?, Science, 302, 624-627.

Röckmann T., T. S. Rhee, A. Engel, (2003). Heavy hydrogen in the stratosphere. Atmospheric Chemistry and Physics, 3, 2015-2023.

Sanderson, M.G., W.J. Collins, R.G. Derwent, and C.E. Johnson, (2003). Simulation Of Global Hydrogen Levels Using A Lagrangian Three-Dimensional Model, Journal Of Atmospheric Chemistry, 46/1, 15-28.

Schultz, M. G., T. Diehl, G. P. Brasseur, and W. Zittel, (2003). Air pollution and climate-forcing impacts of a global hydrogen economy. Science, 302, 624-627.

Sonnemann, G.R., and U. Korner, (2003). Total Hydrogen Mixing Ratio Anomaly Around The Mesopause Region, Journal Of Geophysical Research-Atmospheres, 108/D22.

Stromberger, R., (2003). Building up a gas station infrastructure to supply vehicles with hydrogen as an alternative fuel, taking technical, economic and ecological aspects into consideration. Abridged version of dissertation, Vienna University of Technology http://www.hydrogenhighway.ca.gov/tt/economy/stromberger.pdf.

Tromp, T. K., R.-L. Shia, M. Allen, J. M. Eiler, and Y. L. Yung, (2003). Potential environmental impact of a hydrogen economy on the stratosphere. Science, 300, 1740-1742.

Venetsanos A.G., T. Huld, P. Adams, and J.G. Bartzis, (2003). Source, dispersion and combustion modeling of an accidental release of hydrogen in an urban environment, Journal of Hazardous Materials, A105, 1-25.

2002

Hauglustaine D. A., and D.H. Ehhalt, (2002). A three-dimensional model of molecular hydrogen in the troposphere, J. Geophys. Res. 107, 4330, doi:10.1029/2001JD001156.

Mercuri, R., Bauen, A., and Hart, D., (2002). Options for refuelling hydrogen fuel cell vehicles in Italy. Journal of Power Sources, 106, 353-363.

Ogden, J.M., (2002). Modeling Infrastructure for a Fossil Hydrogen Energy System with CO2 Sequestration. Paper prepared for the Sixth Greenhouse Gas Control Technologies Conference, Kyoto, Japan.

Schmidt, U., and T. Wetter, (2002). Tropospheric chemistry and composition: H_2, in: Encyclopedia of Atmospheric Sciences, (J. Holton, J. Pyle, and J.A. Curry, eds.), Vol. 6, pp. 2397-2402, Academic Press.

2001

Gerst, S., and P. Quay, (2001). Deuterium Component Of The Global Molecular Hydrogen Cycle, Journal Of Geophysical Research-Atmospheres, 106/D5, 5021-5031.

Marquart, S., R. Sausen, M. Ponater, and V. Grewe, (2001). Estimate Of The Climate Impact Of Cryoplanes, Aerospace Science And Technology, 5/1, 73-84.

2000

Gerst, S., and P. Quay, (2000). The Deuterium Content Of Atmospheric Molecular Hydrogen: Method And Initial Measurements, Journal Of Geophysical Research-Atmospheres, 105/D21, 26433-26445.

Gödde, R., K. Meuser, and R. Conrad, (2000). Hydrogen Consumption And Carbon Monoxide Production In Soils With Different Properties, Biology And Fertility Of Soils, 32/2, 129-134.

Madamwar, D., N. Garg, and V. Shah, (2000). Cyanobacterial Hydrogen Production, World Journal Of Microbiology & Biotechnology, 16/8-9, 757-767.

Momoshima, N., H. Kakiuchi, T. Okai, S. Hisamatsu, and Y. Maeda, (2000). Tritium In A Pine Forest Ecosystem: Relation Between Fresh Pine Needles, Organic Materials On A Forest Floor And Atmosphere, Journal Of Radioanalytical And Nuclear Chemistry, 243/2, 479-482.

Simmonds, P.G., R.G. Derwent, S. O'Doherty, D.B. Ryall, L.P. Steele, R.L. Langenfelds, P. Salameh, H.J. Wang, C.H. Dimmer, and L.E. Hudson, (2000). Continuous High-Frequency Observations Of Hydrogen At The Mace Head Baseline Atmospheric Monitoring Station Over The 1994-1998 Period, Journal Of Geophysical Research-Atmospheres, 105/D10, 12105-12121.

Yonemura, S., S. Kawashima, and H. Tsuruta, (2000a). Carbon monoxide, hydrogen, and methane uptake by soils in a temperate arable field and a forest, J. Geophys. Res. 105: 14347-14362.

Yonemura, S., M. Yokozawa, S. Kawashima, and H. Tsuruta, (2000b). Model analysis of the influence of gas diffusivity in soil on CO and H_2 uptake, Tellus 52B: 919-933.

Annex A: Meeting Agenda

2nd HyCARE symposium

Meeting venue: International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Monday, Dec 19, 2005

12:00 Lunch and registration
13:20 Welcome (Markus Amman and Martin Schultz)

Session 1: Atmospheric chemistry, the global budget of hydrogen and its past and possible future trends – oral presentations
13:40 *Thomas Röckmann (Utrecht)*: Open questions about the atmospheric hydrogen cycle (invited)
14:20 *Armin Jordan (Jena)*: Calibration of atmospheric hydrogen measurements
14:40 *Samuel Hammer (Heidelberg)*: Regional sources and sinks of H_2 derived from continuous atmospheric observations in Heidelberg
15:00 coffee break
15:20 Ib Troen (EC): The EU framework programme 7
15:40 *Martin K. Vollmer (EMPA)*: Road traffic hydrogen emissions from a tunnel study
16:00 *Nicola Warwick (Cambridge)*: Global modelling of the atmospheric hydrogen budget

16:20 coffee break, poster session, and open discussion:

POSTERS	
Tuula Aalto	Measurements of H2 deposition to forest soil in southern Finland
Yingshi Li	Modeling of hydrogen in the troposphere by LMDz-INCA and the hints on sources and sinks of hydrogen
Martin Schultz	A global modelling study of atmospheric hydrogen in the 1960's and 1990's
Andreas Engel	EUROHYDROS: A proposal for a European monitoring network and budget studies of atmospheric hydrogen
Christos Zerefos	Updated results on the effects of conventional fuelled aircraft on cirrus and contrail cirrus

17:45 Bus transfer to social event (Heurigen)

Tuesday, Dec 20, 2005

Session 2: Pathways into a hydrogen economy and their possible consequences for greenhouse gas and air pollutant emissions

09:30 *Jean-François Larivé (CONCAWE)*: The CONCAWE/EUCAR/JRC well-to-wheels analysis – main findings, cost estimates, and availability of key resources (invited)

10:15 coffee break

10:40 *Malte Schwoon (Hamburg)*: Optimal initial distribution of hydrogen filling stations

11:00 *Stefan Berger (Opel)*: European hydrogen energy roadmap (HyWays) – First results from simulation, energy stakeholder discussion, and evaluation

11:30 HyCARE business meeting: - report on activities in 2005- plans for 2006- election of steering committee

12:30 Lunch and meeting of the steering committee

Session 3: Atmospheric chemistry-climate interactions in relation to potential future emission changes in a hydrogen economy

13:30 *Mark Jacobsen (Stanford)*: Comparative effects on air pollution, health, and climate of converting US vehicles to hydrogen fuel cell or hybrid vehicles (invited)

14:20 *Ivar Isaksen/Frode Stordal (Oslo)*: CTM studies of tropospheric chemistry and implications for atmospheric hydrogen

14:40 *Thomas Feck (Jülich)*: Impact of a hydrogen increase on stratospheric ozone loss – an ERA-40 reanalysis study

15:00 coffee break

Session 4: Costs and benefits of hydrogen energy in relation to alternative energy scenarios

15:30 *Nebosja Nakicenovic (Wien)*: The role of hydrogen in emission scenarios (invited)

16:15 *Heinz Hass (Ford)*: The CONCAWE/EUCAR/JRC well-to-wheels analysis – hydrogen pathways versus alternative fuels

17:00 Panel discussion: Chances and risks of the hydrogen economypanelists (subject to possible modification): *Jean-François Larivé, Nebojsa Nakicenovic, Mark Jacobson, Ivar Isaksen; moderator: Martin Schultz*

18:00 Adjourn bus transfer to airport

Annex B: List of Participants

Aalto, Tuula, Finnish Meteorological Institute, Helsinki, Finland
Ajanovic, Amela, Technical University, Vienna, Austria
Amann, Markus, International Institute for Applied Systems Analysis, Laxenburg, Austria
Ambus, Per, Risø National Laboratory, Roskilde, Denmark
Berger, Stefan, Adam Opel AG, Rüsselsheim, Germany
Eleftheratos, Kostas, National Kapodistrian University, Athens, Greece
Engel, Andreas, J. W. Goethe Universität, Frankfurt/Main, Germany
Feck, Thomas, Institute of Chemistry and Dynamics of the Geosphere – Stratosphere (ICG-I), Research Center Jülich, Germany
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Hammer, Samuel, Ruprecht Karls University, Heidelberg, Germany
Jacobson, Mark, Stanford University, Stanford, USA
Jordan, Armin, Max Planck Institute for Biogeochemistry, Jena, Germany
Larivé, Jean-François, CONCAWE, Brussels, Belgium
Maione, Michela, University of Urbino Carlo Bo, Urbino, Italy
Müller, Andreas, Technical University, Vienna, Austria
Nakicenovic, Nebosja, International Institute for Applied Systems Analysis, Laxenburg, Austria[1]
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Radunsky, Klaus, Umweltbundesamt, Vienna, Austria
Riahi, Keywan, International Institute for Applied Systems Analysis, Laxenburg, Austria
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Schmidt, Ulrich, J. W. Goethe Universität, Frankfurt/Main, Germany
Schultz, Martin, Max Planck Institute for Meteorology, Hamburg, Germany[2]
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Stordal, Frode, University of Oslo, Oslo, Norway
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