ECO-BALANCES FOR SUPPLY PATHS OF HYDROGEN FUEL

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Abstract: Hydrogen constitutes a prime option not only as future fuel for transport but as an energy carrier in general. Its use in fuel cells is emissions-free but for the release of water vapour. Although hydrogen therefore often is labelled a “green” energy vector it cannot be regarded as environmentally benign in itself.

Its properties in this respect depend strongly on the primary energy it was derived from and on the process chain between primary source and end user. The evaluation of environmental impacts must take into account all aspects of the processes involved. We present here eco-balances of six hydrogen supply paths relying on conventional or renewable energy sources. Diesel serves as the reference case.

1. Background

Based on the decisions of the world climate protection conferences, political action has been taken to curtail emissions from vehicles. In the European Union, road traffic accounts for roughly 25% of energy used and for even higher percentages of some of the air pollutants. Hydrogen-powered fuel cell vehicles reduce harmful exhaust gases since they only emit water vapour.

Hydrogen can be produced from renewable or fossil sources alike. From a global point of view, the (local) exhaust emissions are only one element in the ecological balance. The total balance will have to take into account all steps in hydrogen production and processing from primary energy source to end user supply. This analysis “from well to wheel” will consider all resources utilised in the process chain.

Fuel cells display the highest potential for reducing traffic emissions in the near future. Prototype and small series vehicles have been presented in recent years. A major demonstration project with passenger buses operating in several European cities will start in 2001. Urban passenger and small goods transport appear as the first niche markets for hydrogen vehicles. First series of small passenger cars are expected by the year 2005.

2. Methodology

“Life Cycle Analysis” (LCA, also “eco-balance”) as defined in ISO 14040 ff. forms the basis for the following comparisons. It constitutes a method in tracing the life cycle of products (emissions and expenses in materials and energy) from raw-material and primary energy sources over the entire processing chain - including transportation and handling - to the end user, during utilisation and up to the treatment of all materials as waste. This also comprises resources required to establish the respective processing equipment itself.

Emissions, material and energy usage are gathered into a balance sheet that enables an evaluation of the overall environmental impact. The software tool GEMIS (Global Emissions Model of Integrated Systems) was used as a database and for the balance calculations [1].

Hydrogen life cycles are reviewed under the aspects of “cumulated energy usage” and “CO_2-equivalent emissions”. The former sums up all primary energy utilised in fuel processing and for establishing the necessary infrastructure whilst the latter renders the respective figure for greenhouse gases, normalised to the effects of carbon dioxide.

The analysis refers to the life cycle of hydrogen fuel for a passenger bus with a fuel cell drive. Fuel consumption data of 411 kWh/100 km were derived from information on the MAN prototype fuel cell bus operating on gaseous hydrogen at a pressure of 250 bar [2].

The supply and consumption chain of diesel serves as a reference system since this is the traditional fuel in large scale passenger and freight transport. GEMIS includes various data sets for diesel buses. Values were chosen that represent the engine standard in 2000 when the EURO 3 emission limits had taken effect [3]. The “European Transient Cycle” (ETC) comprises statistics for acceleration, deceleration and typical speeds in various traffic situations for a number of vehicle classes. It represents a standardised basis for determining emissions and fuel consumption of road traffic. A cycle depicting a passenger bus was applied. The reference system is further determined by a fuel consumption of 398 kWh/100 km [4].

Especially under part load conditions as displayed by the stop-and-go movement of public transport buses, the efficiency of fuel cells is high compared to that of internal combustion engines. It is therefore surprising that the hydrogen bus as defined above does not consume less energy than its diesel counterpart. Two facts explain this observation: First, diesel engines today constitute a well developed technology whereas the fuel cell system under consideration is only a prototype and far from being optimised. Second, the ETC includes travel on motorways which would not apply to urban transport. This has favourable effects on the diesel bus performance. Up to now, the data used could not be normalised in a better way so this unsatisfying situation remains.

3. Scenarios

Six hydrogen supply paths or “scenarios” (following GEMIS vocabulary) were investigated. They differ with regard to several aspects. Hydrogen production is either decentral (on-site the filling station) or central (in a larger plant, implying hydrogen transport to the station). Another aspect is the type of hydrogen generation. Three basic systems were chosen: electrolytic production by water electrolysis, generation from natural gas (NG) by steam reforming and by methanol reforming. All scenarios assume a standard passenger bus with fuel cell propulsion and, with one exception, rely on gaseous hydrogen.

Three scenarios are based on fossil primary energy:

1. *Central* methanol synthesis from NG with on-board hydrogen generation by methanol reforming. The rated capacity of the synthesis plant was set to 1,000 MW and the distance between plant and methanol filling station chosen to be 100 km.
2. *Decentral* natural gas steam reforming on the site of the filling station (100 m^3_N/h rated capacity at 450 kW NG including process heat). The hydrogen is compressed and stored at 300 bar.
3. *Decentral* water electrolysis (56 m^3_N/h) at the site of the filling station with German grid electricity as the (secondary) energy source (statistics from the year 2000 with 28.14% nuclear, 53.5% coal, 9.51% natural gas, 3.5% hydro, 5,35% others [5]). As in scenario 2, hydrogen is compressed to 300 bar at the site of the filling station, stored and delivered to the vehicle(s).

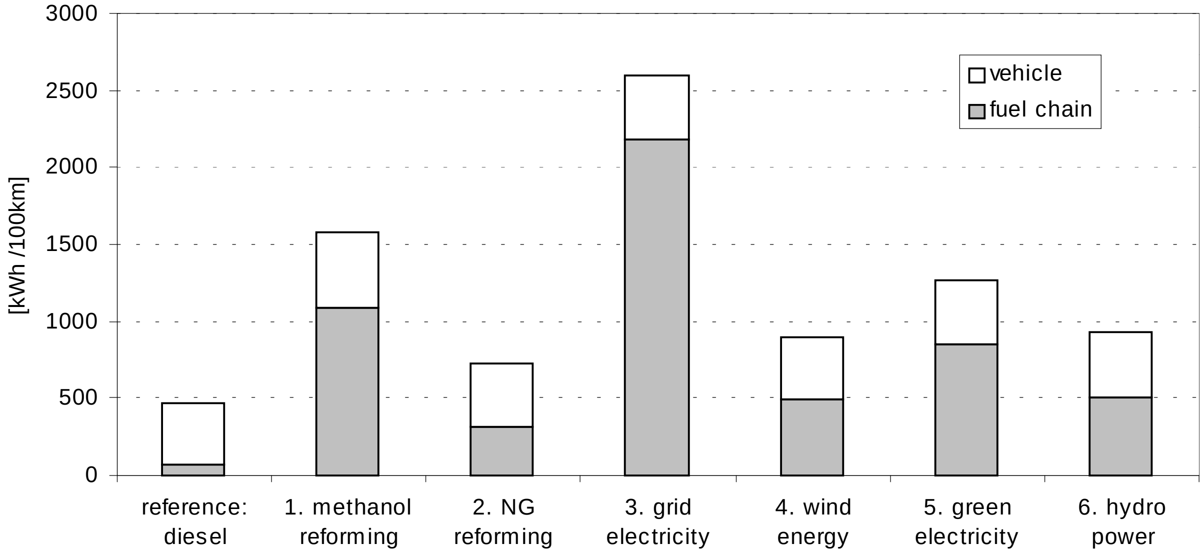

Figure 1: *Cumulated energy "from well to wheel" in kWh primary energy per 100 kilometres. The dark sections of the bars depict contributions from the fuel chain. The light parts denote fuel consumption on board of the vehicle. "NG" stands for natural gas.*

The other three scenarios are based on renewable energies:

4. *Decentral* water electrolysis (56 m^3_N/h) at the site of the filling station, electricity source 100% wind energy. All other conditions coincide with scenarios 2 and 3, respectively.
5. *Decentral* water electrolysis (56 m^3_N/h) at the site of the filling station, assuming a "green" electricity mix as offered by several German power producers in different compositions (assumed here: 49% hydro power, 45% wind energy, 5% biomass and 1% PV [5]); identical to scenarios 2 to 4 otherwise.
6. *Central* water electrolysis with hydro power. This scenario is derived from the concept of the EQHHPP project: Canadian hydro electricity is used to produce hydrogen (25,000 m^3_N/h) which is then liquefied and transported by tanker (904 t load capacity) to Europe. Hydrogen is further handled and filled into the vehicle tank in its liquid state.

4. Results

4.1 Cumulated Energy

In analysing fuel life cycles, it is informative to distinguish between shares from the fuel processing chain up to the filling post of the station and from the actual vehicle propulsion (*Figure 1*). In scenarios 2 to 5, the size of the contribution for propulsion is of course identical following the assumptions made in section 2 regarding the bus. Additional processes on board require slightly (scenario 6) or significantly (scenario 1) more energy.

In comparison to the reference system, all hydrogen paths display an increased energy consumption in the fuel chain (dark sections in *Figure 1*). This is due to the fact that hydrogen needs to be derived from other energy vectors (being primary or secondary) which induces high conversion losses. Consequently, regarding total energy consumption diesel today still is superior to its hydrogen competitor(s).

In an environmental assessment, though, the total energy consumption cannot be the key determinant. *Figure 2* shows the same data as *Figure 1* but broken down with respect to their primary fossil and renewable contributions to energy investment and scaled in relative terms.

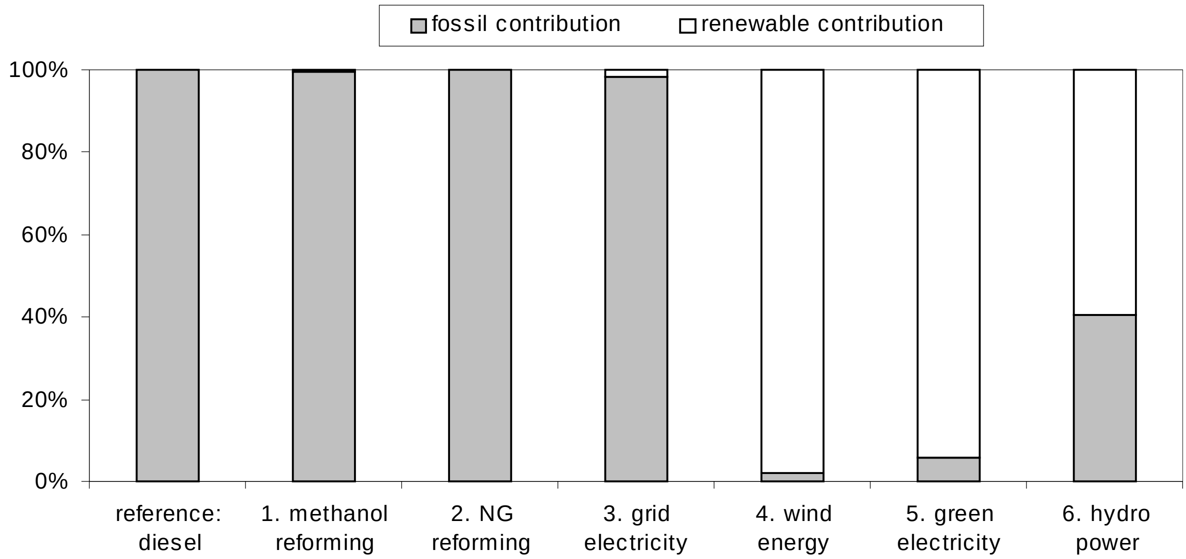

Figure 2: *Cumulated energy in kWh primary energy per 100 kilometres; same data as in Figure 1 but differentiated with regard to the sources of primary energy and displayed in relative terms. A third category of minor importance is omitted here for clarity (cf. main text).*

It is evident that in addition to the principal energy vectors being either renewable or fossil, all scenarios include contributions from both sources. The renewable share is negligible for scenarios 1 and 2, though. Scenario 3 displays a quantum of hydro power by definition (cf. section 2). In the "renewable" scenarios 4 and 5, fossil energy input results from equipment manufacture. The amazing distribution for scenario 6 with its central hydrogen generation is explained mainly by the use of electricity from combined cycle power stations for hydrogen liquefaction.

The wind energy / water electrolysis scenario 4 can be seen as the most advantageous regarding energy use as it displays the highest renewable and lowest fossil primary energy input. Although the total consumption is higher than in the reference scenario (cf. *Figure 1*), its fossil share is smaller by more than one order of magnitude.

(Note: In addition to fossil and renewable contributions, GEMIS uses a third category for "other" inputs. This is omitted in *Figure 2* for clarity. Its shares are neglectable in most scenarios except for no. 3 with 220 kWh/100 km for waste combustion and no. 5 with 316 kWh/100 km for the combustion of recycling wood).

4.2 Carbon Dioxide Equivalents

Greenhouse gas emissions are a further important aspect in today's environmental considerations. *Figure 3* shows results from the scenario analysis normalised to CO_2-equivalents (cf. section 2), again differentiating the fuel processing chain and the vehicle (local emissions) as sources. Due to the utilisation of a fuel cell, vehicle emissions are naturally "zero" in all hydrogen scenarios except for on-board reforming of methanol (scenario 1).

The wind energy scenario 4 is by far the most efficient in emission avoidance. Compared to the diesel reference the reduction amounts to more than 95%.

The fossil-based reforming process chains for methanol and natural gas (scenarios 1 and 2) display results inferior to the diesel reference. Scenario 3 using "conventional" grid electricity scores even worse although the German energy mix includes about 28% nuclear energy [5]. Compared to the wind energy scenario 4 emissions are higher by almost two orders of magnitude. For a country like Norway this would differ due to a high share of water power in its grid mix.

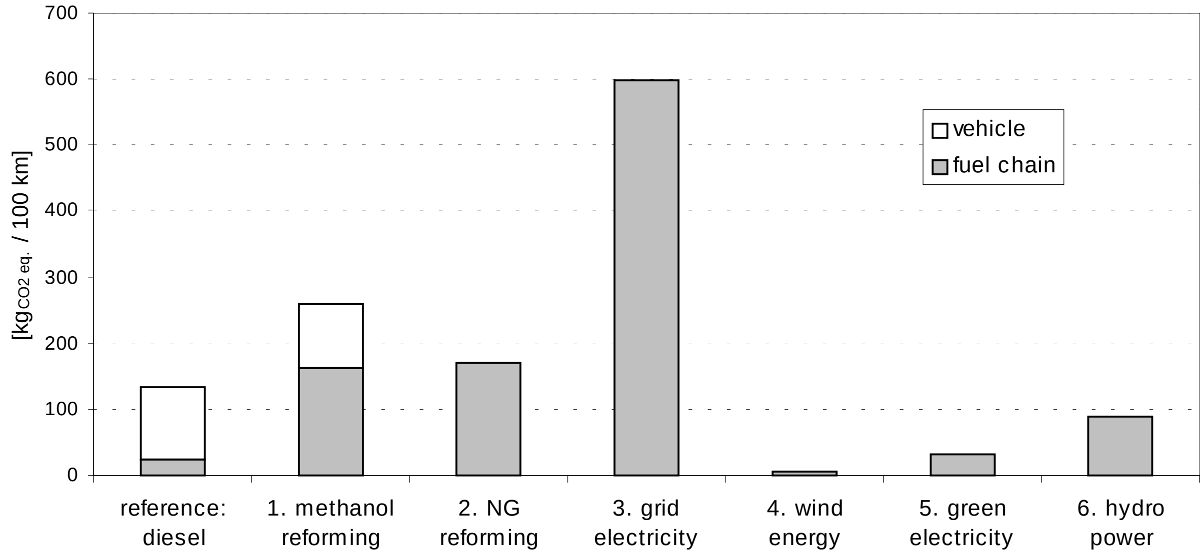

Figure 3: *Carbon dioxide equivalent emissions for the scenarios as in Figure 1. Again, the dark parts of the bars depict contributions from the fuel processing chain, the light parts stand for emissions from the vehicle itself. As fuel cells only emit water vapour, the vehicle contribution is zero in all hydrogen scenarios except for the case of on-board methanol reforming.*

5. Conclusions

The comparison of life cycle analyses for various hydrogen fuel chains renders a plain superiority of systems based on renewable energy sources. The reduction in fossil energy input and greenhouse gas emissions is pronounced. Among the "renewable" scenarios, decentral hydrogen generation is more beneficial in terms of emissions as efforts for hydrogen transport can be avoided.

The electrolytic production of hydrogen from conventional German grid electricity would even aggravate today's situation both in view of energy consumption and carbon dioxide equivalents. The benefits of cutting local emissions to zero are offset and even reversed in the global balance.

Note: The results presented here will be part of a more detailed analysis for a master thesis to be finalised in July 2001. This thesis also refers to changes in results which are expected to be induced by technological advance up to 2010.

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