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Roskilde University, Denmark

The international oil price and hydrogen competitiveness

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Research Paper no. 1/07

Research Papers from the Energy, Environment, and Climate Group (EECG) at the Department of Environmental, Social and Spatial Change (ENSPAC), Roskilde University, Denmark.

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ISBN: 978-87-7349-696-1

Abstract

Natural gas based hydrogen is expected to provide most of the hydrogen supply in the period prior to and during at least the first years of market introduction of automotive hydrogen and fuel cell technology in large scale. Due to the natural gas price dependency of the international oil price the hydrogen cost level that is required for competitiveness of hydrogen and fuel cell technology depends on the oil price. This gives rise to the question: At which oil price will natural gas based hydrogen and advanced hydrogen be competitive? The question is addressed by developing a model that links hydrogen and conventional fuels to the oil price and to related fuel efficiencies. The model results indicate that advanced hydrogen production in some respects could become competitive before natural gas based hydrogen.

Acknowledgements:

This study is carried through as a part of the Zero Regio project financed through the European Union's 6th framework programme for research and technological development. The Zero Regio project tests and demonstrates hydrogen infrastructure solutions in Frankfurt (Germany) and Mantova (Italy) and at the same time explores how the hydrogen and fuel cell solutions will work in a socioeconomic context. Valuable comments from the project partners are gratefully acknowledged.

Academic disciplines involved:

Energy economics

Keywords:

Hydrogen, fuel cell, transport fuels, competitiveness

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Introduction

Hydrogen Competitiveness Goal

In many future scenarios the "hydrogen economy" is envisaged to supersede the "oil economy" when the hydrogen and fuel cell solutions deliver services such as transport services (measured in person or ton kilometres) at a cost competitive to conventional fossil based solutions. But what cost level must be achieved to arrive at this competitiveness?

Answering this question for light duty vehicle (LDV) transport involves the cost of hydrogen fuel as well as the cost of the fuel cell vehicle. Since many of the important components of the workable solutions are still under development, it is necessary to analyse the cost of hydrogen given that the cost competitive fuel cell vehicles are available and the cost of fuel cell vehicles given that cost competitive hydrogen is available. In this paper we use the former approach and focus on the prospects for achieving hydrogen at a competitive price at a time when fuel cell cars can be bought at a reasonable price.

The US Department of Energy (DOE) has defined hydrogen competitiveness in a target of $2-3 per kg H_2 at the pump (2005 prices) (US Department of Energy (DOE) (2005)). The target translates to €2 +/- 0.40 (2005 exchange rate) but the European Hydrogen and Fuel Cell Technology Platform has been reluctant to set a similar target (Hydrogen and Fuel-Cell Technology Platform (HFP) (2006)) and as it will appear below, it is probably a good decision.

The US DOE target is set from the expectation of a crude oil price of $34 corresponding to an estimated gasoline price of $1.26 per gallon before taxes. The fuel efficiency of a hydrogen and fuel cell vehicle (HFCV) is expected to exceed the fuel efficiency of a standard gasoline and internal combustion engine (ICE) system by 140% and that of a gasoline hybrid electric vehicle (HEV) by 66%. On a per kilometre basis this requires a hydrogen price of $3 and $2 per kg H_2 respectively to be competitive with gasoline (US Department of Energy (DOE) (2005)).

There are several problems with determining such a target. First, the future oil price is neither given nor fixed and the oil price assumptions behind the calculations are unrealistically low. Second, most of the hydrogen supply prior to and during at least the first years of market introduction of fuel cell vehicles will be based on natural gas. Since natural gas prices depend on oil prices, higher oil prices will make not only conventional fuels and ICE based transport but also HFC transport more expensive (though not as much as oil based fuels). Third, at the present and at the time of market introduction of HFCVs in Europe competing standard ICEVs and HEVs will probably be more fuel efficient than indicated by the DOE assumptions referred above. Moreover the buyers will have to choose first between conventional and efficient alternatives and then between alternative efficient solutions including HFCVs, HEVs, and advanced ICEVs with flexible fuel. The HFCV solution will have to be competitive not only with the conventional solutions, but also with the other efficient solutions to be chosen.

Several reports have been made over the previous decade on the cost of hydrogen and fuel cell solutions in light duty vehicle (LDV) transport compared to conventional solutions. These studies have led to the priorities in the European hydrogen strategy as well as hydrogen strategies elsewhere. They are, however, all based on oil price expectations that today must be regarded as unrealistically low. The National Academy of Science (2004) study was based on an oil price of $30 per barrel and the Joint Research Centre of the EU Commission (2006) on oil prices of €25 and €50 per barrel (assumed to equal $25 and $50 per barrel respectively).

This gives rise to the question: At which oil price will natural gas based hydrogen and advanced hydrogen be competitive with the oil based fuels, gasoline and diesel in Europe? This paper will address the question by quantifying the balances behind the problems mentioned above.

The question is interesting for several reasons. The nature of the technology requires a simultaneous development and implementation of hydrogen production, infrastructure, and vehicles. Another reason is that if it is found socially desirable to advance the introduction of HFC in European transport, how large incentives would then be required compared to alternative technologies?

We also need to address the question in a new way where the oil price is the unknown factor rather than taking a specific oil price for given. Experience shows us that calculations based on a specific oil price very often become obsolete shortly after they have been published.

The Oil Price Dependent Hydrogen Competitiveness Model

The Approach

The competitive hydrogen price is the price that would equal the cost per km with the cost per km for competing technologies. In this analysis we are interested in the costs to society, not to the individual consumer and therefore taxes and subsidies are omitted from the analysis. That is, € per kilometre driven. These costs include fuel costs as well as vehicle ownership cost (purchase, repair, and maintenance).

The European hydrogen strategy - as well as the strategies of US and Japan - starts with developing a hydrogen supply based on natural gas as feedstock. Due to its substitutability with oil in generation of electricity and heat, natural gas is closely correlated with the oil price. Thus, the cost of hydrogen depends on the cost of natural gas, which in turn depends on the crude oil price on the international markets. We analyse the problem with a set of very simple cost relations separating the fuel cost per energy unit in a part depending on the amount of feedstock used for producing the fuel (energy costs) and a part that is independent (non-energy costs). Energy and non-energy costs will be estimated with regression analysis.

This approach allows us to include the oil price as the unknown factor and calculate the oil price that is required for HFC solutions to be cost competitive.

The Data

For simplicity, it is assumed that these ownership costs are identical for HFCVs and the competing solution. This assumption is important because, in principle, we could have a situation where the fuel costs were lower but the ownership costs higher for HFCVs and yet they would be competitive. However, in practice we are starting from much higher fuel costs as well as much higher ownership costs where both will have to get down and in the hydrogen strategies the required conditions for launching mass produced HFCVs is that they can be produced at costs comparable to the ordinary cars. The assumption should be seen in this perspective.

The energy component includes primarily the cost of the feedstock or the throughput cost, but also the auxiliary energy used for conversion, conditioning, etc. The non-energy component is the cost of owning and operating the fuel infrastructure from production to filling. This approach is used for gasoline and diesel as well as for natural gas and hydrogen.

Since the aim of the model is not to analyse the social desirability of HFC based transport solutions, but only their cost competitiveness, external costs are not included in the calculations. All the prices in the model are real factor prices per energy unit: 2005 price level, net of subsidies and taxes, and in €/GJ. 2005 prices means that the price is comparable with the prices and wages that was paid in 2005. A price of, e.g., €10 in 2005 price level is the amount of other goods you could get for €10 in 2005 even it the price concerns transactions in, say, 2015.

The Model

The model consists of five price equations and one competitiveness criterion. The price equations are:

$P_P = a + bP$

$P_H = c + dP_N$

$P_N = e + fP$

$V_H = P_H / E_H$

$V_P = P_P / E_P$,

where

a = oil price independent costs per GJ petroleum based fuel

b = fuel price dependency on crude price

c = natural gas independent costs of hydrogen

d = hydrogen cost dependency on natural gas

e = oil price independent costs of natural gas

f = natural gas dependency on oil price

P = crude price (Brent, dated)

P_P = price of conventional fuels

P_H = price of hydrogen

P_N = price of natural gas

All the above prices and cost components are in € per GJ.

V_H = hydrogen cost per kilometre driven

V_P = petroleum based fuel cost per kilometre driven

E_H = fuel efficiency of the hydrogen electric vehicle (km/GJ)

E_P = fuel efficiency of the conventional vehicle (km/GJ)

The criterion for fuel cost competitiveness can now be stated as

$V_H \leq V_P$

Inserting equations (1) to (5) into (6) and reducing yields

$(c + de + dfP) / E_H = (a + bP) / E_P$

$dfP / E_H - bP / E_P = a / E_P - (c + de)/E_H$

$P = [a(E_H / E_P) - c - de] / [df - b(E_H / E_P)]$

Defining $(E_H / E_P) = 1+k$, where k is the efficiency advantage of HFC vehicles over conventional (or other) vehicles, we can reduce further to

$P = (a + ak - c - de) / (df - b - bk)$

Equation (10) determines the oil price (Brent, dated) that will make the cost of hydrogen produced from natural gas per kilometre equal to the petroleum based fuel cost per kilometre.

In the following, we will find useful estimates for the variables in the model in Europe. The model variables are estimated on data for Germany with a view to extension to the rest of the EU later on.

Parameter Estimates

The Future Oil Price

What can we expect about the future oil price? The experience from decades of failed attempts to predict the international oil price does not encourage giving an unambiguous answer to that question. A few fundamental factors behind the future demand and supply can, however, be predicted with some degree of certainty.

In large parts of the developing world industrialisation and growth of the modern sector has now finally taken off. The mobility offered by motorised transport is a necessary prerequisite for as well as one of the main objectives of this economic growth. Transport services have for a century been fuelled almost exclusively by oil based fuels. For these reasons, it is likely to expect a high sustained growth of oil demand in the coming decades.

During a century the supply of conventional oil has been able to keep pace with the growing demand for fossil fuels, but in the next decades the world production of conventional oil is expected to peak whereas the global demand for transport services and thus eventually for transport fuels continue to grow in proportion to the economic growth. According to the International Energy Agency (IEA) (2006d) conventional oil production from OECD[1] countries has already peaked in the 1990s. For Non-OPEC countries as a whole the IEA expects the peak of conventional oil production to appear in 2012 and if natural gas liquids (NGL) is included a few years later. This leave the oil reserves from the OPEC countries to provide not only the oil supply missing from the declining non-OPEC oil production, but also the increasing oil demand. The exploitable reserves of the OPEC countries are expected to be abundant at least until 2030, but the production figures are highly unpredictable.

The International Energy Agency (IEA) (2006d) rolls out two scenarios through 2030, a reference scenario and a high price scenario. In both cases the oil price predictions are higher than in any predictions in the recent two decades.

The reference scenario projects a moderate drop in the oil price to 2015 as new capacity enters the market. Hereafter the oil price is expected to increase to about $104 per barrel Brent crude oil in nominal terms in 2030 or almost $60 per barrel in

[1] Organisation for Economic Co-operation and Development.

2005 prices (assuming Brent crude remains 7.7% more expensive than the average IEA crude import price as in 2005). This projection assumes vast investments in additional capacity in the future.

In particular the OPEC[2] countries are assumed to expand their production from 2005 to 2030 by 23 mb/d or 2.1% annually. Whether these investments actually will materialize and be successful is highly uncertain. The rate of OPEC supply growth has been 0.5% from 1980 to 2000, 1.7% from 2000 to 2005, and 0.7% from 1980 to 2005.

In the high price scenario the OPEC production capacity grows only half as much, i.e., 12 mb/d from 2005 to 2030 or 1% annually. In that case, the International Energy Agency (IEA) (2006d) predicts the nominal Brent price to increase to about $140 per barrel in 2030 corresponding to almost $80 per barrel in 2005 prices.

Less additions to OPEC supply than 12 mb/day are not considered, but other projections point to a peak in OPEC supply as well in the very near future. In that case, the oil price will be considerably higher.

It is not easy to assess which of the three scenarios are most likely since it depends on the future OPEC strategy and the cartels ability to keep itself together. However, the

[2] Organisation of the Petroleum Exporting Countries.

inevitably stronger market power of the cartel and the concentration of the remaining reserves on still fewer suppliers point towards the high and higher price scenarios.

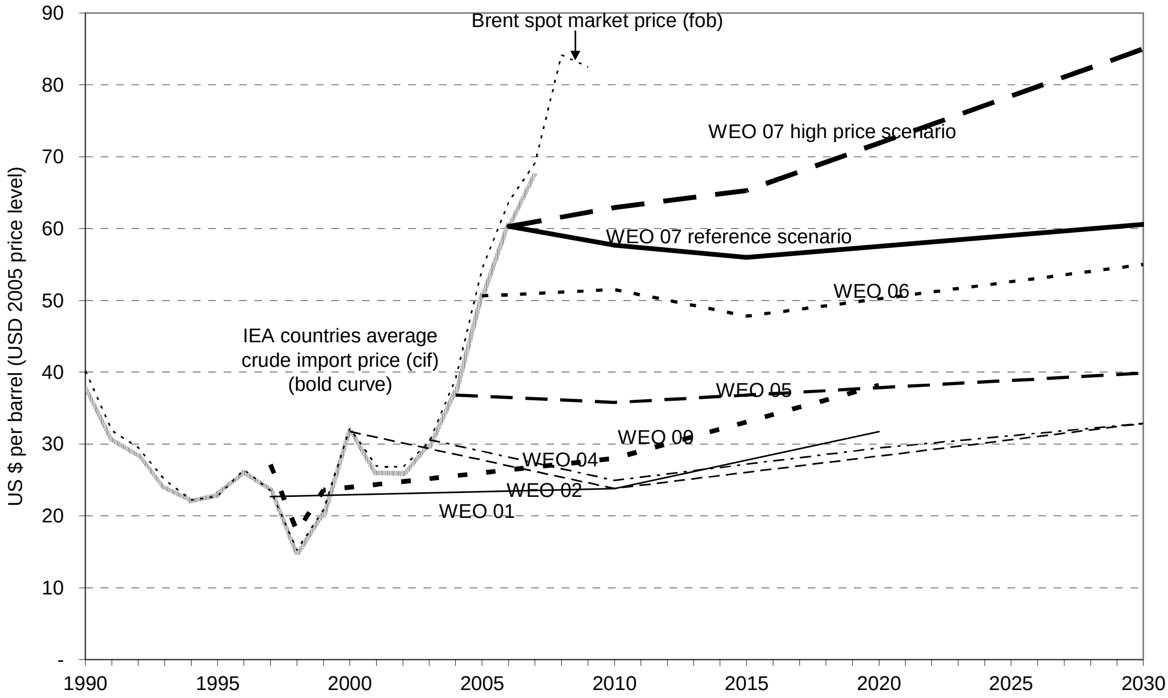

Figure 1. Actual crude oil price and oil price assumptions in IEA World Energy Outlook.

Source: Table 1 and IEA, World Economic Outlook (various issues), OECD (2007), and author's calculations.

Figure 1 illustrates the development of the international oil price from 1992 to 2005 adjusted for inflation. The surge in oil prices from 2002 and onwards was unexpected by the IEA as it was to other oil market analysts including the US DOE EIA and the European Commission. Consequently oil price projections have been adjusted upwards year by year.

The oil price projections, even those represented by straight lines in the diagram, include expectations of a temporary high growth in global oil supply probably in some period between 2010 and 2020. This is an effect of the time it takes for the investments undertaken in the recent years under impression of the persisting high oil price level to lead to additional supply. Such temporary deviations from the trend is, however, not very important for analysis of competitiveness in the long term.

The IEA assumptions are closely linked to the expected expansion of the OPEC oil supply. They can roughly be reduced to three scenario ranges:

In the OPEC accelerated expansion scenario the OPEC supply is expanded considerably and the current price level of $50-65 per barrel will be maintained.

In the OPEC modest expansion scenario OPEC supply is only expanded a little and oil prices will be in the $65-85 per barrel range.

In the OPEC peak scenario oil supply will not expand at all and we will face oil prices far above $85 per barrel.

Table 1. Oil price assumptions for 2015 - 2025.

	Accelerated expansion of OPEC oil supply	Moderate expansion of OPEC oil supply	Peak in OPEC oil supply
Annual growth 2005-2030	2.1%	1.0%	0%
Oil price (Brent)	$50-65	$65-85	$85-?

As noted above, the experts disagree as to which of these scenarios is the most likely. Assertions differ with respect to the geological opportunities for increased OPEC production as well as the likely OPEC strategy and the ability of the cartel to maintain discipline.

Oil Based Fuel Costs

Diesel and gasoline prices are mainly determined by the international oil price as shown in table below.

Table 2. Prices net of taxes of petroleum based fuels converted to €/GJ in deflated to 2005 price level 1988-2005.

	Brent Crude Dated	Exchange rate	GDP deflator Germany	Brent Crude dated	Diesel at pump Germany	Gasoline at pump Germany	Diesel share Germany	Gasoline share Germany	Diesoline Germany	Diesel trf.& distr. margin	Gasoline trf.& distr. margin	Diesoline. trf.& distr. margin
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Unit	$/bbl	$/€	2005 =1	€/GJ 2005	€/GJ 2005	€/GJ 2005	Per cent	Per cent	€/GJ 2005	€/GJ 2005	€/GJ 2005	€/GJ 2005
1988	14.9	1.12	0.76	2.7	5.7	6.6	65%	35%	6.0	3.0	3.9	3.3
1989	18.2	1.04	0.78	3.5	6.5	7.4	62%	38%	6.9	3.1	3.9	3.4
1990	23.7	1.21	0.80	3.8	7.2	7.7	62%	38%	7.4	3.4	3.9	3.6
1991	20.0	1.18	0.83	3.2	7.1	7.2	65%	35%	7.1	3.9	4.0	3.9
1992	19.3	1.25	0.87	2.8	5.9	6.2	65%	35%	6.0	3.1	3.4	3.2
1993	17.0	1.18	0.90	2.6	5.6	5.7	66%	34%	5.6	3.0	3.1	3.0
1994	15.8	1.21	0.93	2.3	5.3	5.4	67%	33%	5.3	3.0	3.0	3.0
1995	17.0	1.37	0.94	2.3	5.3	5.5	66%	34%	5.3	3.0	3.2	3.1
1996	20.7	1.30	0.95	2.8	6.5	6.3	67%	33%	6.4	3.7	3.5	3.6
1997	19.1	1.13	0.95	2.9	6.8	7.0	67%	33%	6.8	3.9	4.1	3.9
1998	12.7	1.11	0.96	1.9	5.3	5.8	66%	34%	5.5	3.4	3.9	3.6
1999	18.0	1.07	0.96	2.9	6.0	6.6	65%	35%	6.2	3.1	3.7	3.3
2000	28.5	0.92	0.95	5.3	9.0	9.0	66%	34%	9.0	3.7	3.7	3.7
2001	24.4	0.90	0.96	4.6	8.6	8.2	68%	32%	8.5	3.9	3.6	3.8
2002	25.0	0.95	0.98	4.4	8.0	7.8	67%	33%	7.9	3.6	3.4	3.5
2003	28.8	1.13	0.99	4.2	8.2	8.0	68%	32%	8.1	4.0	3.8	3.9
2004	38.3	1.24	1.00	5.0	9.3	8.9	68%	32%	9.2	4.3	3.9	4.2
2005	54.5	1.24	1.00	7.2	12.3	11.0	69%	31%	11.9	5.1	3.8	4.7
Aver.										3.6	3.7	3.6

Sources and calculations:
(1): Brent, dated (CIF) (International Energy Agency (IEA) (2006b)). P in the price model.
(2): Organisation for Economic Cooperation and Development (OECD) (2006). ECU used for pre-Euro years, adjusted for DM/ECU exchange rate.

(3): Organisation for Economic Cooperation and Development (OECD) (2006)
(4): From (1), (2), and (3). Assuming that 1 barrel of Brent contains 5803 Mbtu, which is the average of UK crude according to International Energy Agency (IEA) (2006a).
(5) and (6): Dollar figures from International Energy Agency (IEA) (2001), International Energy Agency (IEA) (2006b) converted with (2) and (3) assuming that the energy content of diesel is 0.036 GJ/l and for gasoline 0.034 GJ/l (derived from International Energy Agency (IEA) (2006b).
(7) and (8): International Energy Agency (IEA) (2006c).
(9) Average diesel and gasoline fuel weighted by (7) and (8). P_P in the price model.
(10), (11), and (12): (1)- (5), (6), and (9) respectively.

In column 9, the price of the average transport fuel, which we name "diesoline", is calculated with the shares of diesel and gasoline in total transport fuel sales as weights (shown in columns 7 and 8 respectively). Diesoline is sold with a margin of 3.6 €/GJ above the crude oil price. However, some of this margin covers own fuel consumption in transformation and distribution. The relation between crude oil and diesoline prices are therefore more precisely determined by linear regression. A simple linear regression (ordinary least squares, OLS) yielded the following results:

Table 3. Linear Regression Results of "Diesoline" Price and Brent Crude Price.

	Coeffi-cients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%		
Intercept	2.66	0.20	13.49	3.7E-10	2.25	3.08	**R-square**	97.4%
Brent price	1.26	0.05	24.32	4.6E-14	1.15	1.37	**Adj.R-sq.**	97.2%

The linear regression result indicates a pattern according to which transport fuel prices consist of a oil price independent component of €2.66 (a in the price model) and an oil price dependent component of 1.26 (b in the price model) multiplied with the Brent price.

As a rule of thumb regression models for time series such as this one should be specified in first differences or dlog. This is particularly important in the study of behavioural patterns where underlying trends due to factors not specified in the model affect the explaining as well as the explained variable in parallel. However, in this case the material basis of the causality is that the energy in the fuels physically is made of the energy in the crude oil, which weakens the reason for concerns of this kind. The model predicts the diesoline price quite well as shown in the figure below.

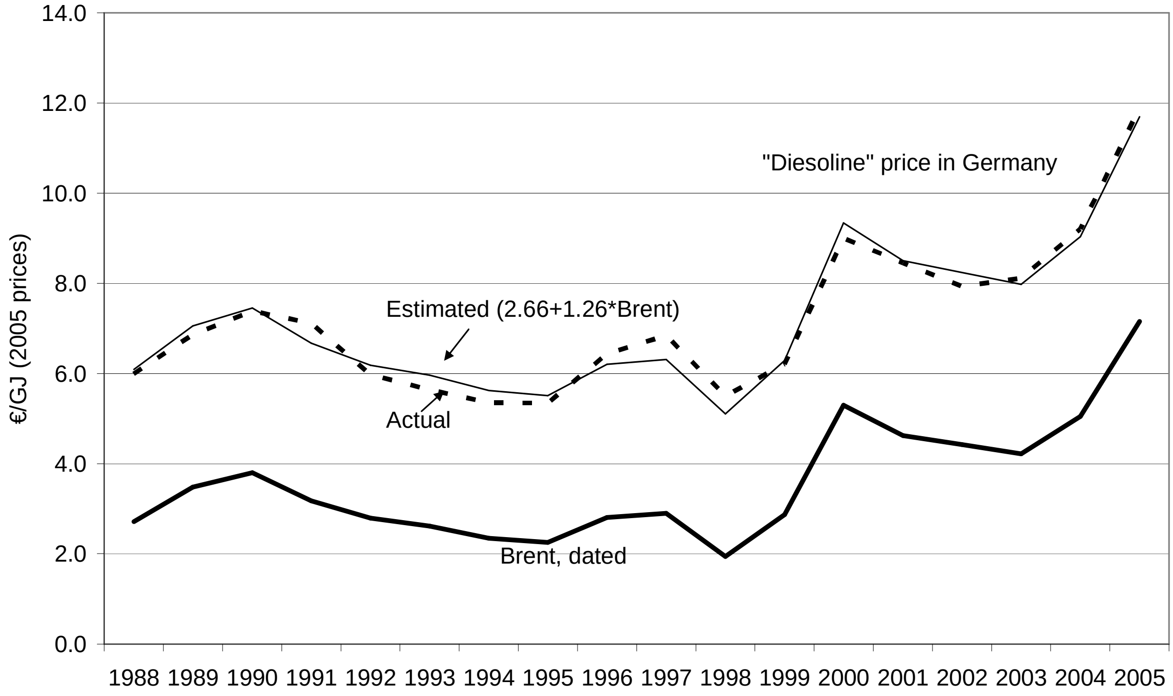

Figure 2. Diesoline and crude oil price 1988 - 2005.

Source: Table 2.

Natural Gas Costs

Natural gas prices follow oil prices very closely. The figure below compares the oil price with some indices of international natural gas prices relevant for Europe.

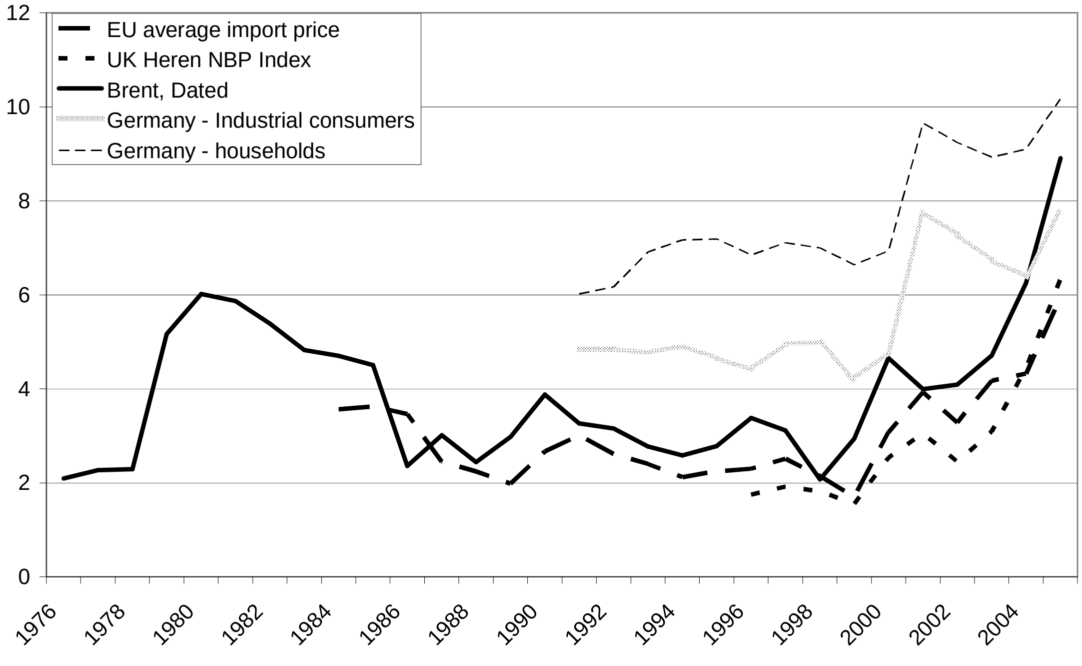

Figure 3. Oil price and Natural Gas Prices in €/GJ (deflated to 2005 price level) 1976-2005.

Source: BP (2006), EUROSTAT (2006). Conversion to 2005 €/GJ: See table 1.

The figure shows two indices of international natural gas prices relevant to the European natural gas market, the EU average import price and the UK Heren NBP Index. It also shows the natural gas prices for German consumers. First, it can be seen from the figure that the international natural gas market follows the market for crude oil rather closely. Among a series of regression trials, the best model appeared to be a model that links the European natural gas import price to the Brent crude price with a lag of one period (year) and a constant term reflecting the non-energy or infrastructure costs. The results are shown in table 4 below.

Table 4. Regression Results of Natural Gas Consumer Prices Against Crude Oil Prices.

Industrial consumers								
	Coeffi-cients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**		
Intercept	2.24	0.20	11.14	5.1E-08	1.81	2.68	**R Square**	97%
Brent price, 1 year lag	1.06	0.06	18.82	8.2E-11	0.94	1.18	**Adj. R Square**	96%
Household consumers								
	Coeffi-cients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**		
Intercept	4.36	0.53	8.26	9.4E-07	3.23	5.49	**R Square**	80%
Brent price, 1 year lag	0.92	0.12	7.38	3.4E-06	0.65	1.19	**Adj R Square**	78%

The coefficients to the Brent price show that natural gas prices for German industrial consumers are slightly more sensitive to oil prices than natural gas prices for households are. In addition to this, German natural gas consumers face oil price independent costs of €2.24 per GJ for industrial consumers and almost twice as much, €4.36 per GJ for households.

The differences in oil price independent costs underline the vast scale economies of the natural gas transformation and distribution network. The data do not allow for a more specific analysis of the costs of an expansion of the already existing network relative to the observed costs of the now established network. The oil price independent costs for industrial consumers must be seen as a high estimate of the non-oil dependent costs of expanding the capacity of the natural gas transformation and distribution network to satisfy increasing natural gas use as transport fuel.

In this study, we assume this pattern to be valid in the medium term future as well. This assumption could be challenged since strong efforts have been directed towards the creation of a natural gas market with a price formation that is more independent of the oil price. In Japan considerable progress towards this end seems to have been achieved in natural gas imports from suppliers in the region. It is, however, difficult to see the economic motivation for the natural gas suppliers relevant to Europe for favouring another pricing strategy and Russia has directly announced that it will continue to pursue the indexing of natural gas prices to oil. Moreover, increasing use of natural gas for transport will strengthen the substitutability between natural gas and oil, which is the real economic basis for price dependency.

Like in the section on oil prices above, the specification of the regression model could be a matter of concern, but since the physical and institutional background for the causality is well known (substitutability in heat and power as well as direct indexing in contrast) there is little reason to be concerned about interpreting trends that are not specified in the model as causal relations. The actual and estimated natural gas price is shown in the figure below.

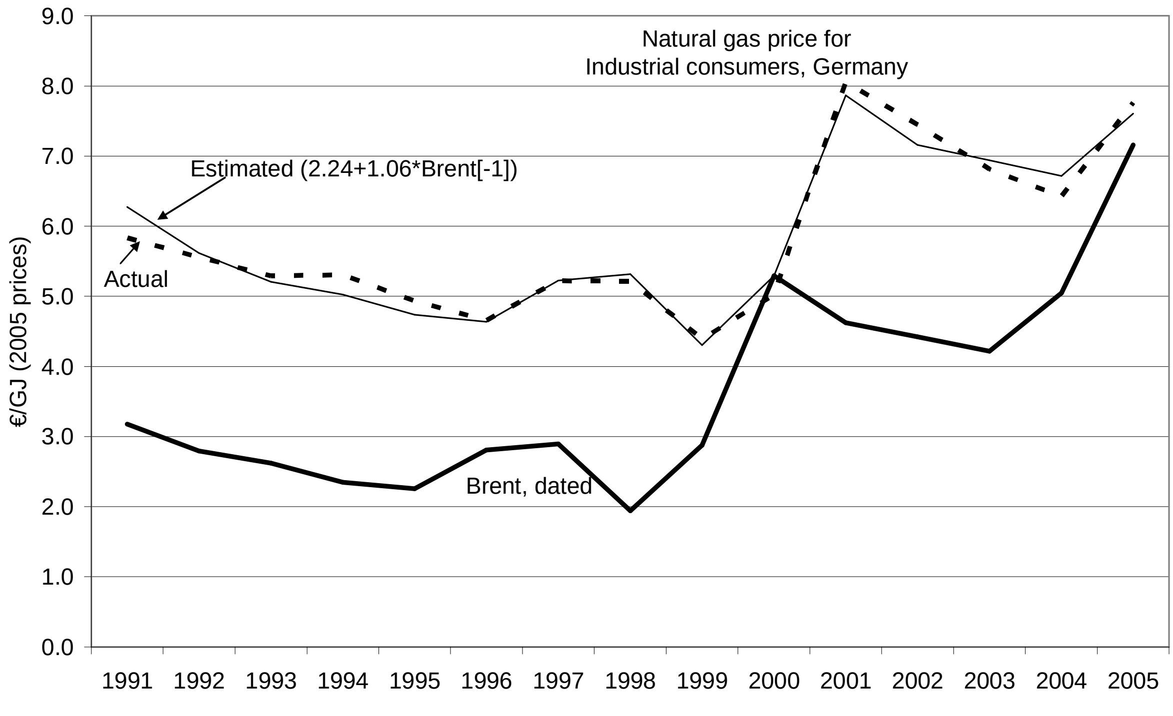

Figure 4. Crude Oil and Natural Gas Price in Germany 1991 - 2005.

Source: Table 2.

Note that the estimated natural gas price is explained by the price of Brent lagged one year.

Hydrogen Costs

The hydrogen market of the future will be totally different in size and actors from the hydrogen market today. Thus, data must come from test projects and technical experiments and converted to estimates of how the processes in question will perform in a future hydrogen market where they are optimised in a global market. The figures used in this report draws on studies that have reviewed these data and attempted to transform them into realistic estimates in the context of a future hydrogen market.

The natural gas price dependent cost component can be defined as the amount of natural gas, necessary to produce one unit of hydrogen. As we calculate in energy terms, it means GJ natural gas input per GJ hydrogen output. The natural gas input must include the indirect natural gas input. Compression and liquefaction consumes large amounts of electric power, and as noted above there are reasons to regard natural gas as the primary feedstock for this electricity. With a conversion efficiency of 60% (standard assumption for CCGT power generation) adjusted for a 10% distribution loss we get a conversion factor of $54\%^{-1}$ (=1.85) for the natural gas equivalent of one GJ of electricity.

Hydrogen production can lead to higher natural gas demand in several ways. Hydrogen can be extracted from natural gas through chemical reactions. The cost of this process, however, depends strongly on economies of scale as well as economies of scope. The scale of production can be classified in three categories: Central, distributed, and household. The hydrogen produced today, take place in central air gas industry plants and the resulting output is primarily used for the production of ammonia and for upgrading fuels of lower quality. If hydrogen is to be used in cars, the central production structure will hardly be competitive with distributed production based on the existing natural gas grid in the initial phases. As a distributed supply in a given region is built up, the economies of scale attainable by concentrating supply in a central plant will most likely make the central solution more competitive in the longer term.

However, breakthroughs in targeted development of mini-systems could lead to a different path as innovative efforts are directed towards miniaturization of natural gas steam reformers integrated in household size combined heat and power units. If sufficiently high conversion efficiency can be obtained at a reasonable cost, the hydrogen infrastructure becomes superfluous. The same could be the case with small electrolysers.

The costs of distributed natural gas based hydrogen production are only observable from experimental plants and plants supplying industrial customers. Assuming an oil price of $50 per barrel the Joint Research Centre of the EU Commission (2006) (WTW app. 2, p. 13) estimates the cost of hydrogen production on-site from natural gas at a 2MW plant as €7.1 per GJ for capital expenditure and €3.0 for operating expenditure. Of the latter, €0.43 per GJ is auxiliary energy and chemicals expenditure, the price of which depend on the oil price. This leaves a total of oil price independent costs for hydrogen production €10 per GJ.

Weinert (2005) reviews some more recent experiences with hydrogen production costs and find that the costs per GJ to vary from $42 to $260. Costs of the individual components as well as installation cost per unit of hydrogen vary by up to an order of magnitude. Some of these variations are explained by variations in capacity or capacity utilisation, but even when adjusted for such properties, the variation is considerable. The study develops a Hydrogen Station Cost Model (HSCM) to arrive at more realistic estimates of what hydrogen will cost when it will be introduced in large scale. Adjusting for capacity, capacity utilisation, learning, standardised installation, etc. the model produces a current non-energy cost estimate of $27 (2004 prices) per GJ for hydrogen produced with steam methane reforming with a capacity of 480 kg per day. With learning economies, this cost is expected to decline to $15 per GJ after cumulative production of 4000 units. With the 2004 $/€ exchange rate these figures correspond to €22 per GJ declining to €12 per GJ respectively.

National Renewable Energy Laboratory (NREL) (2006) takes this approach further attempting to estimate the costs of producing hydrogen in a market environment with a demand for 500 new 1500 kg per day forecourt units per year, a mature, licensed, certified, permitted technology, skid-mounted, sheet metal enclosed, fence protected system approach, and installation/startup time reduced from 1 year to approximately 3 months. Under these assumptions and based on detailed information from industrial actors and currently running test and demonstration facilities, the study estimates the non-energy costs to be $16 (2005 prices) per GJ corresponding to €13 per GJ hydrogen with the 2005 $/€ exchange rate.

Based on these studies, we will assume that the natural gas price independent part of the costs of transforming natural gas to hydrogen (c in the model above) is €10-13 per GJ. This assumption, of cause, is to be scrutinized in the many hydrogen infrastructure test and demonstration projects planned in Europe and elsewhere. The scale economies obtainable in a central production of hydrogen cannot be tested before a sufficient number of FCVs are available and filling stations are in place. Moreover, the scale economies are not necessarily the most important, since heat recovery could contribute considerably to the cost competitiveness as it already does in CHP production. A future cost level of €7 per GJ in central production is a very optimistic assumption.

Table 5. Core Assumptions of Future Supply of Hydrogen as Transport Fuel.

		Non-energy costs		
		High €13/GJ	**Medium €10/GJ**	**Low €7/GJ**
System efficiency (NG to CH2)	**62%**	On-site	On-site	
	70%		Central	Central

Three Fuel Efficiency Advantage Scenarios

The main desirable feature of hydrogen and fuel cell technologies is the superior fuel efficiency of the fuel cell combined with an electromotor. The efficiency advantage is, however, modified by "parasitic losses" due to other energy required for cooling, pumping, weight of system, etc. Similarly, the energy losses in conversion of primary energy to hydrogen as well as transport and storage partly outweigh the efficiency advantage.

Data for comparing the future efficiency advantage are derived from the very comprehensive and well documented studies by JRC, EUCAR, and CONCAVE in Europe (Edwards, Griesemann et al. (2004), Edwards, Griesemann et al. (2006)) and for the US the Argonne National Laboratory GREET model and its database at http://www.transportation.anl.gov/software/GREET/index.html.

The table below shows the assumed TtW efficiency advantage of HFCVs compared to competing fuel and powertrain configurations beyond 2010.

Table 6. Additional Energy Efficiency of Hydrogen and Fuel Cell Vehicles Over Most Efficient Competing Technologies in 2010

	SI	CIDI	GI SI HEV	GI CI HEV	GC CI HEV 25/75	HFC	GC CI HEV 50/50	HFC hybrid	EV
GREET (USA)	100-150%	71%	45%	36%	14%	0%	-1%		-34%
JRC (EU)	102%	88%	73%	55%		0%		-11%	

Sources: *Joint Research Centre of the EU Commission (2006)**,** Argonne National Laboratory (2006)*.

The table shows that FCVs are expected to be at least 100% more fuel efficient than conventional gasoline-ICE configurations (SI) in Europe. In the United States, the efficiency advantage can be much larger because gasoline-ICE configurations are much less efficient than they are in Europe.

The diesel engine (CIDI) is more efficient, so the efficiency of the FCV is only estimated to be 88% over this configuration in Europe and 71% in USA. Apparently diesel is assumed to be more efficient in the USA.

Grid independent hybrid electric vehicles of the gasoline type (GI SI HEV) on the other hand are assumed to be much more efficient than diesel vehicles in the United States, but only slightly more in Europe. This leads to an HFCV efficiency advantage of 45% and 73% respectively.

In the same way hybrids of the diesel type (GI CI HEV) are assumed to be more efficient in the US than in Europe with HFC efficiency advantages of 36% and 55% respectively.

Grid connected HEVs, however, can be as effective as HFCVs if they are fuelled 50/50 by the grid and by liquid fuels. The more they are fuelled by liquid fuels, of cause, the less fuel efficient they will be.

The table also shows that the HFCV with a battery (HFC hybrid) will be even more efficient than the FCV without and the electric vehicle (EV) is the most efficient of all vehicles (but unfortunately within a short range per recharging).

Based on these assumptions, we calculate efficiency advantage scenarios for Europe for 50%, 75%, and 100% HFC efficiency advantage. The 100% is relevant for standard fuel and ICE solutions, the 75% of standard fuel and advanced ICE solutions, and the 50% for grid independent HEV solutions.

If the fuel cell vehicles follow the normal cost and price path of new products, it will be priced high in the first years of market introduction and then gradually less until it becomes an option relevant to all consumer segments. It is considered realistic that such a cost level can be a fact in the period to 2030. Since the powertrain technologies are more expensive the more fuel efficient they are, the sequence of scenarios must be assumed to be first the 50% scenario where HFCV will be an alternative to HEVs, then the 75% scenario where they are alternatives to advanced ICEVs, and finally the 100% scenario where they will be alternatives to standard ICEVs. In the calculations below, we will try to investigate the oil price at which they become cost competitive in these three scenarios.

The Competitiveness of Hydrogen

Oil Dependent Cost Competitiveness in Natural Gas based Solutions

The first scenario is the 100% efficiency advantage scenario. It shows at which oil price, natural gas based HFC transport will become cost competitive to conventional fuel-ICE based transport in vehicles that are only half as fuel efficient.

Table 7. Calculation of the Oil Price (in 2005 € and $) necessary for the Competitiveness of Natural Gas based Solutions. 100% Efficiency Advantage case.

Variable name		Medium non-energy costs On-site efficiency	Medium non-energy costs Central efficiency	High non-energy costs On-site efficiency	Low non-energy costs Central efficiency
Oil independent gasoline/diesel price (€/GJ)	a	2.66	2.66	2.66	2.66
Oil to gasoline/diesel price coefficient	b	1.26	1.26	1.26	1.26
Natural gas independent hydrogen cost (€/GJ)	c	10	10	13	7
Natural gas to hydrogen system efficiency		62%	70%	62%	70%
Inverse efficiency	d	1.61	1.43	1.61	1.43
Oil independent natural gas price (€/GJ)	e	2.24	2.24	2.24	2.24
Oil to natural gas price coefficient	f	1.06	1.06	1.06	1.06
HFC efficiency advantage over gasoline and diesel cars	k	100%	100%	100%	100%
€/GJ Brent = (a+ak-c-de)/(df-b-bk)		10	8	14	5
$/bbl Brent at GJ/bbl=6.1, $/€=1.25		78	60	107	37
€/GJH2		31	25	41	18
€/kgH2		3.74	3.01	4.87	2.11
$/kgH2		4.68	3.77	6.08	2.64

The table shows the oil price that would make HFC transport competitive under varying assumptions of non-energy costs and efficiency. The non-energy costs are considered in medium, high, and low cases (€10 +/-3 per GJ) whereas two cases for conversion efficiency are considered (on-site and central production, 62% and 70% respectively). The assumptions that are identical for all four cases of hydrogen production performance are shown in italics.

The table shows that if hydrogen can be delivered with non-energy cost as low as €7 per GJ then it is actually possible for the HFC technology to compete with conventional fuel and standard ICE solutions at an oil price of $37 per barrel (Brent crude). Infrastructure costs of just €10 per GJ would only be competitive at oil price levels of $60 per barrel and if additionally the conversion efficiency is down to 62% the oil price would have to be $78 per barrel for hydrogen to be competitive.

In the 75% efficiency advantage case the cost competitiveness become more questionable. The competing solutions over which HFCVs will posses a 75% efficiency advantage could be vehicles with advanced ICE technology. The same calculations as in table 7 are shown in table 8 below, but with the assumption of 75% efficiency advantage.

Table 8. Calculation of the Oil Price (in 2005 € and $) necessary for the Competitiveness of Natural Gas based Solutions. 75% Efficiency Advantage Case.

Variable name		Medium non-energy costs On-site efficiency	Medium non-energy costs Central efficiency	High non-energy costs On-site efficiency	Low non-energy costs Central efficiency
Oil independent gasoline/diesel price (€/GJ)	a	2.66	2.66	2.66	2.66
Oil to gasoline/diesel price coefficient	b	1.26	1.26	1.26	1.26
Natural gas independent hydrogen cost (€/GJ)	c	10	10	13	7
Natural gas to hydrogen system efficiency		62%	70%	62%	70%
Inverse efficiency	d	1.61	1.43	1.61	1.43
Oil independent natural gas price (€/GJ)	e	2.24	2.24	2.24	2.24
Oil to natural gas price coefficient	f	1.06	1.06	1.06	1.06
HFC efficiency advantage over gasoline and diesel cars	k	75%	75%	75%	75%
€/GJ Brent = (a+ak-c-de)/(df-b-bk)		18	12	24	8
$/bbl Brent at GJ/bbl=6.1, $/€=1.25		139	95	185	61
€/GJH2		45	32	58	22
€/kgH2		5.37	3.84	6.98	2.69
$/kgH2		6.71	4.80	8.72	3.36

In table 8 the top 7 rows are identical to table 7. The lower 8 rows show that HFC transport in this scenario would be competitive if the oil price exceeded $61 per barrel, if non-energy costs are very low, and if conversion efficiency is high.

If non-energy costs are higher and/or conversion efficiency is lower not even an oil price of $85 per barrel will make HFC transport competitive to solutions it possesses an efficiency advantage of 75%.

Table 8 also indicates that HFC solutions hardly will be cost competitive to solutions over which the efficiency advantage is less than 75%. For completeness we show the results for the 50% efficiency advantage case.

Table 9. Calculation of the Oil Price (in 2005 € and $) necessary for the Competitiveness of Natural Gas based Solutions. 50% Efficiency Advantage Case.

Variable name		Medium non-energy costs On-site efficiency	Medium non-energy costs Central efficiency	High non-energy costs On-site efficiency	Low non-energy costs Central efficiency
Oil independent gasoline/diesel price (€/GJ)	a	2.66	2.66	2.66	2.66
Oil to gasoline/diesel price coefficient	b	1.26	1.26	1.26	1.26
Natural gas independent hydrogen cost (€/GJ)	c	10	10	13	7
Natural gas to hydrogen system efficiency		62%	70%	62%	70%
Inverse efficiency	d	1.61	1.43	1.61	1.43
Oil independent natural gas price (€/GJ)	e	2.24	2.24	2.24	2.24
Oil to natural gas price coefficient	f	1.06	1.06	1.06	1.06
HFC efficiency advantage over gasoline and diesel cars	k	50%	50%	50%	50%
€/GJ Brent = (a+ak-c-de)/(df-b-bk)		54	25	71	17
$/bbl Brent at GJ/bbl=6.1, $/€=1.25		413	188	542	127
€/GJH2		106	51	138	35
€/kgH2		12.74	6.07	16.56	4.25
$/kgH2		15.92	7.59	20.70	5.31

According to table 8, the HFC will hardly be cost competitive with the best HEV technology as long as the fuel costs of both depend on oil.

The following table summarises the oil price required for hydrogen to be competitive under the four hydrogen supply assumptions and the three efficiency advantage assumptions.

Table 10. Summary of Oil Price Requirements for Hydrogen Competitiveness under Hydrogen Supply and Fuel Cell Vehicle Efficiency Advantage Assumptions.

	Med. NEC Low eff.	Med. NEC High eff.	High NEC Low eff.	Low NEC High eff.
H2 NEC	10	10	13	7
System eff.	62%	70%	62%	70%
	($ per barrel, 2005 prices)			
100% eff.adv.	78	60	107	37
75% eff.adv.	139	95	185	61
50% eff.adv.	413	188	542	127

The fuel costs per kilometre for fuel cell vehicles and competing "diesoline" vehicles appears from the figure below.

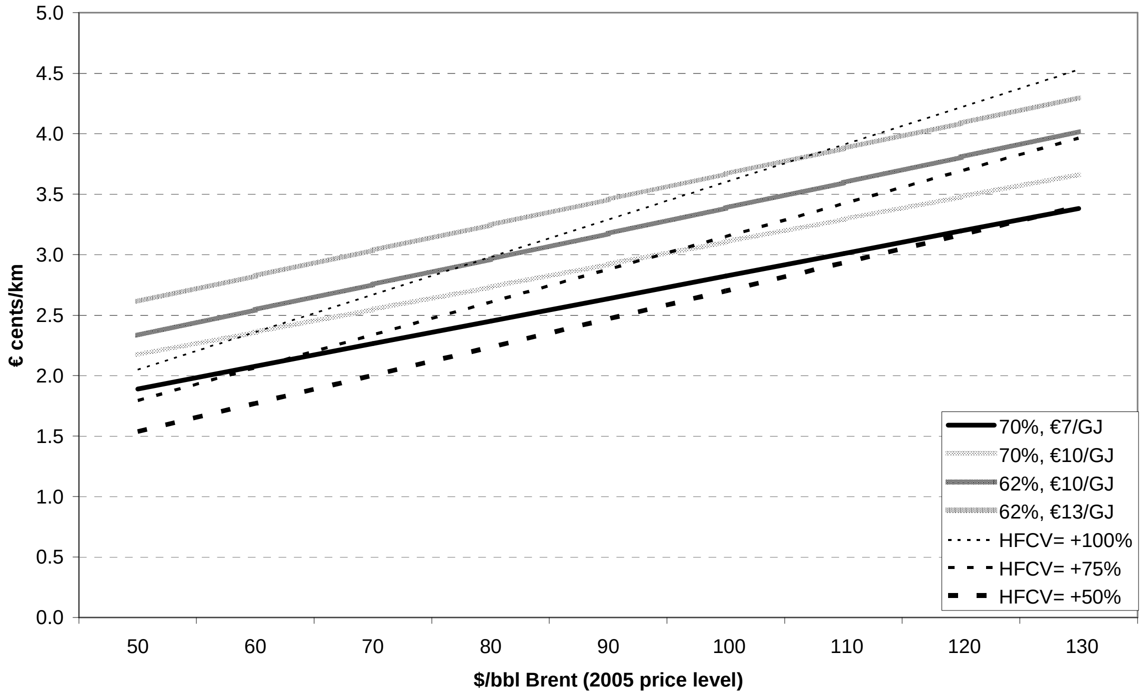

Figure 5. Fuel Cost per Kilometre for alternative Hydrogen Supplies to HFCVs (System efficiency, non-energy costs) and for competing solutions to HFCVs (+efficiency advantage of HFCVs over competing solution). €c/km.

The transport service cost results are shown in figure 5. The oil based fuel solution cost curves are steeper than the hydrogen cost curves. The oil based fuel solutions include the 3 categories over which HFCVs have a fuel efficiency of 100%, 75%, and 50% respectively.

If we assume that hydrogen is produced with 62% system efficiency and €13/GJ non-energy costs it will only make HFCVs competitive to standard ICEVs at oil prices in the OPEC peak scenario range. HFCVs will not be competitive to more fuel efficient oil based solutions such as advanced ICEVs and HEVs. If hydrogen can be produced with 70% efficiency and €10 per GJ non-energy costs, it can make HFCVs competitive to standard ICEVs even in the price range of an OPEC accelerated expansion scenario and advanced ICEVs at oil prices above $75 per bbl, i.e., in the OPEC modest expansion scenario. To be competitive with HEVs, HFCVs should be fuelled by very cheap hydrogen produced with 70% system efficiency and €7 per GJ non-energy costs.

Competitiveness of Natural Gas compared to Wind based Hydrogen

The analysis above showed that natural gas based hydrogen may only be cost competitive with oil based fuels at rather high levels of oil prices. At this price level, however, natural gas is not necessarily the most competitive basis for hydrogen production. Wind power, for instance, is now cost competitive to any other power generation technology in very many locations and the cost of electrolysers is expected to drop dramatically over the next ten years.

The hydrogen and fuel cell based transport solutions could very well become competitive at an oil price of \$65-85. But at the corresponding price of natural gas renewable hydrogen may very well be competitive to natural gas based hydrogen. At an oil price of \$65 natural gas based hydrogen will cost €3.4 (+/- 0.3) per kg with efficiencies from 62% to 70% and non-energy costs from €10 to €13 per GJ. At an oil price of \$85, natural gas based hydrogen would cost €4.0 (+/- 0.3) per kg under the same conditions. With wind power generation costs of €c4-5, transmission and distribution loss of 10%, non-energy costs of €12 per GJ, and electrolysis and compression efficiency of 75% hydrogen could be produced at €3.6 (+/- 0.3) per kg H_2. The US Department of Energy (DOE) (2006) expects even more efficient wind power based hydrogen leading to a hydrogen cost level of €2.5 per kg H_2 in 2015.

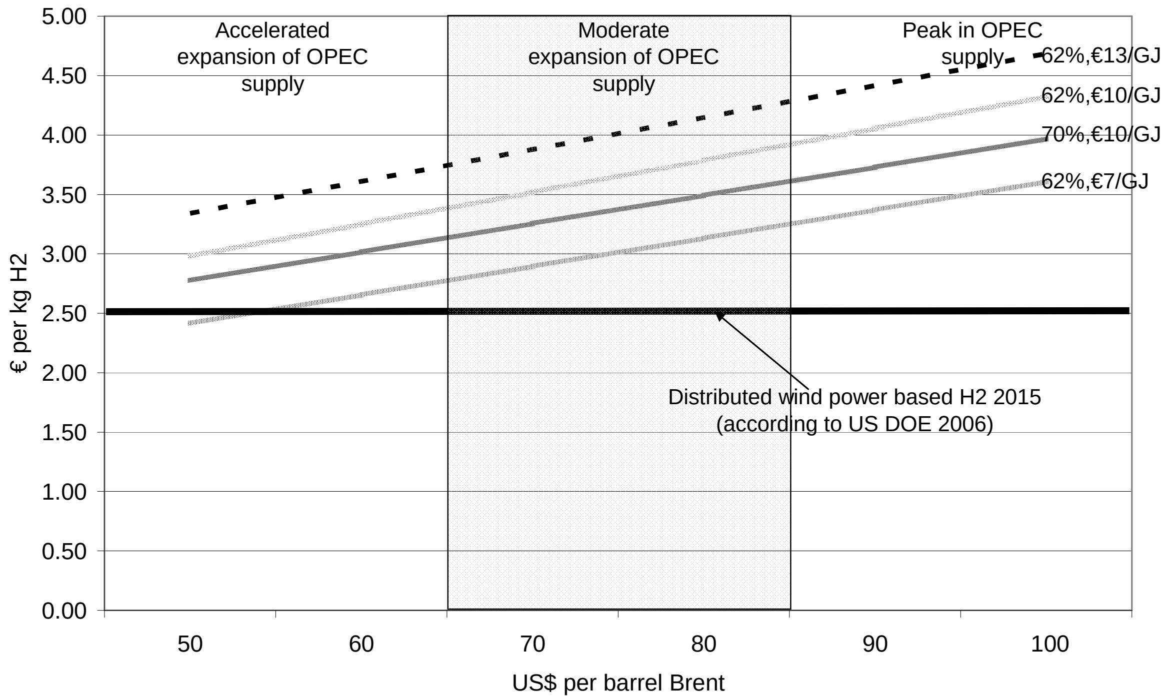

Figure 6. Hydrogen Cost at Pump for Distributed Wind Power based Electrolysis and Natural Gas based Reforming with varying Performance Parameter Values.

Source: Own calculations based on the model above and US Department of Energy (DOE) (2005).

Comparing the future cost of distributed wind power based electrolysis with natural gas based reforming indicates that only in the scenario of accelerated expansion of OPEC supply and with the very low non-energy hydrogen costs of €7 per GJ would the natural gas based solution be cost competitive.

The DOE prediction could be considered overly optimistic, but even with a hydrogen cost of €3 per GJ (the proposed 2015 target for biomass to hydrogen and for high temperature hydrogen production in Hydrogen and Fuel-Cell Technology Platform

(HFP) (2006)) natural gas based hydrogen would only be competitive in the modest expansion of OPEC supply if the very low non-energy costs were achieved.

Discussion and Conclusions

If Europe should adopt a target for hydrogen cost, it would however not be justified to adopt the US DOE target corresponding to €2 +/-0.40. A temporary drop in oil prices as expected by some analysts in the middle of the 2010-2020 period could lead to obtaining the target without having a cost competitive production technology. On the other hand a strong increase in oil prices could imply that the target is never reached although the hydrogen and fuel cell technology is competitive as is the case in the 100% efficiency advantage scenario. Targets should rather focus on non-energy costs and system efficiency.

The results in this paper indicate that HFC systems have a good chance to become competitive to oil based LDV transport solutions that are only half as fuel efficient as the HFC system. In a scenario with oil prices varying between $65 and $85 per barrel, even solutions with only 62% system efficiency can be competitive if the non-energy costs can be reduced to €10 per GJ. In other words HFC solutions will be competitive to conventional LDV solutions even at the current (2006) oil price if the vehicle costs are equal and the non-energy costs of hydrogen are €10 per GJ.

However, the competitiveness of hydrogen when compared to other efficient LDV solutions requires very low non-energy costs of hydrogen and it is highly uncertain whether such a low cost level can be obtained within this time horizon. In fact, it is very possible that natural gas based hydrogen in HFCVs will never become competitive with HEV solutions and maybe not even with advanced ICE solutions. At least within the time frame considered here.

Of cause, government taxes and subsidies can change this, but then there should be compelling reasons for governments to use the tax and subsidy instruments to make HFCVs more favourable for consumers. The absence of tail pipe emissions is definitely a major advantage, but in this case it doesn't differ much from HEVs. If there should be a case for government to favour HFCVs over HEVs, it would probably require that hydrogen was produced from renewable energy sources with their preferable environmental and supply security aspects.

As the analysis shows, hydrogen produced from wind or biomass could very well be competitive with natural gas based hydrogen in 2015-2025. Thus the partial economic analysis suggests that it would advance the competitiveness of hydrogen in 2015-2025 to aim at more than the targeted 10-20% 2nd generation hydrogen in 2015. However, 2nd generation hydrogen technologies are not much different from greenhouse gas lean electricity and heat generation technologies. If the growth potential of the European generation capacity for carbon free energy is very limited compared to the growth of the combined demand for green energy then expansion of carbon free hydrogen will be at the expense of carbon free electricity and heat. This is a very important issue for future research.

Literature

Argonne National Laboratory (2006). Greet Version 1.7, Systems Assessment Section, Centre for Transportation Research (Greet Version 1.7).

BP (2006). Statistical Review of World Energy 2006. **2006** www.bp.com (Statistical Review of World Energy 2006).

Edwards, R., J.-C. Griesemann, et al. (2004) Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context.

Edwards, R., J.-C. Griesemann, et al. (2006) Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context. Version 2b. http://ies.jrc.ec.europa.eu/wtw.html

EUROSTAT (2006). Online Database. **2006** http://europa.eu.int/comm/eurostat/ (Online Database).

Hydrogen and Fuel-Cell Technology Platform (HFP) (2006) Draft Implementation Plan – Status 2006.

International Energy Agency (IEA) (2001). Energy Prices and Taxes, Quarterly Statistics, First Quarter, 2001, (ISBN: (Energy Prices and Taxes, Quarterly Statistics, First Quarter, 2001).

International Energy Agency (IEA) (2006a). Energy Balances of Oecd Countries, 2003-2004, (ISBN: (Energy Balances of Oecd Countries, 2003-2004).

International Energy Agency (IEA) (2006b). Energy Prices and Taxes, Quarterly Statistics, Third Quarter, 2006, (ISBN: (Energy Prices and Taxes, Quarterly Statistics, Third Quarter, 2006).

International Energy Agency (IEA) (2006c). Oil Information 2006, (ISBN: (Oil Information 2006).

International Energy Agency (IEA) (2006d). World Energy Outlook 2006, (ISBN: (World Energy Outlook 2006).

Joint Research Centre of the EU Commission (2006) Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, Version 2b, May 2006.

National Academy of Science (2004). The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, National Academies Press, (ISBN: ISBN: 0-309-53068-7), http://www.nap.edu/books/0309091632/html/ (The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs).

National Renewable Energy Laboratory (NREL) (2006) Distributed Hydrogen Production from Natural Gas. Independent Review. October 2006. NREL/BK-150-40382 http://www.osti.gov/bridge

Organisation for Economic Cooperation and Development (OECD) (2006). National Accounts Statistics. **2006** www.oecd.org (National Accounts Statistics).

US Department of Energy (DOE) (2005) Hydrogen Cost Goal. Item: $2.00 -$3.00/Gge. DOE Hydrogen Program Record 5013 http://www.hydrogen.energy.gov/pdfs/5013_h2_cost_goal.pdf

US Department of Energy (DOE) (2006) Distributed Hydrogen Production from Wind. http://www.hydrogen.energy.gov//docs/cs_distr_wind.doc

Weinert, J. (2005) A near-Term Economic Analysis of Hydrogen Fueling Stations. UCD—ITS—RR—05—04 Institute of Transportation Studies, University of California, Davis