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When will hydrogen become a competitive transport fuel?

by

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Abstract

When hydrogen becomes competitive to conventional fuels depends on the price of oil. Since there is no professional consensus about the oil price level that is likely to prevail when hydrogen and fuel cell (HFC) technology is ready for commercialisation in automotive use, the paper focuses on the oil price that would make HFC technology competitive at that time. This price is called the threshold oil price for hydrogen competitiveness. To arrive at this threshold price a number of simplifying assumptions are made and a competitiveness model is developed. The model is used to examine a number of scenarios characterised by different fuel taxation principles. The conclusions are that 1) If the differences in the level of fuel taxation between USA and EU continue to exist, hydrogen and fuel cells will be competitive in automotive use in Europe a long time before it will in the US. 2) At the oil price that makes natural gas based hydrogen competitive, renewable based hydrogen may very well be more competitive. 3) Changes in taxation principles from final use towards all use taxation and from differentiation according to income distribution and industrial competitiveness towards differentiation according to environmental pressure will strengthen the competitiveness of hydrogen. 4) The Hydrogen and Fuel Cell Technology Platform in Europe will not benefit from introducing a hydrogen cost target as in the US DOE approach but rather from focusing on the performance parameters of the hydrogen infrastructure.

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Academic disciplines involved:

Energy economics, environmental economics, public finance.

Keywords:

Hydrogen, fuel cells, cost, competitiveness, fuel taxes

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As fuel prices rise and still more resources are deployed in developing alternatives the question of when hydrogen becomes competitive with conventional fuels is raised more and more often.

The competitiveness of hydrogen depends of course strongly on the cost of owning a fuel cell vehicle relative to the cost of owning a car with competing technology. To answer the question, we have to reduce the number of unknowns and we will in the following assume that the fuel cell vehicles (FCVs) can be produced at a cost comparable to internal combustion engine vehicles (ICEVs) or hybrid electric vehicles (HEVs) that are fuelled by petrol or diesel. Many car manufacturers believe that they will be able to do so at a point of time in the period 2015-2025. Thus, it is the basic assumption for the considerations about hydrogen competitiveness that FCVs are introduced on the market in this period at prices that are comparable to the ICEVs and HEVs that they are competing with.

One answer to the question is given by the US Department of Energy. Its hydrogen programme announced in 2005 that the hydrogen cost target is when the cost of hydrogen is reduced to $2-3 per kg of hydrogen. This is a less ambitious goal than the goal in the preceding years where it was plainly $2 per kg H_2, but it is calculated on some very restrictive assumptions. However, it is regarded as a precondition for commercialising the HFC technology in automotive transport.

The model used for defining the hydrogen cost goal is shown below.

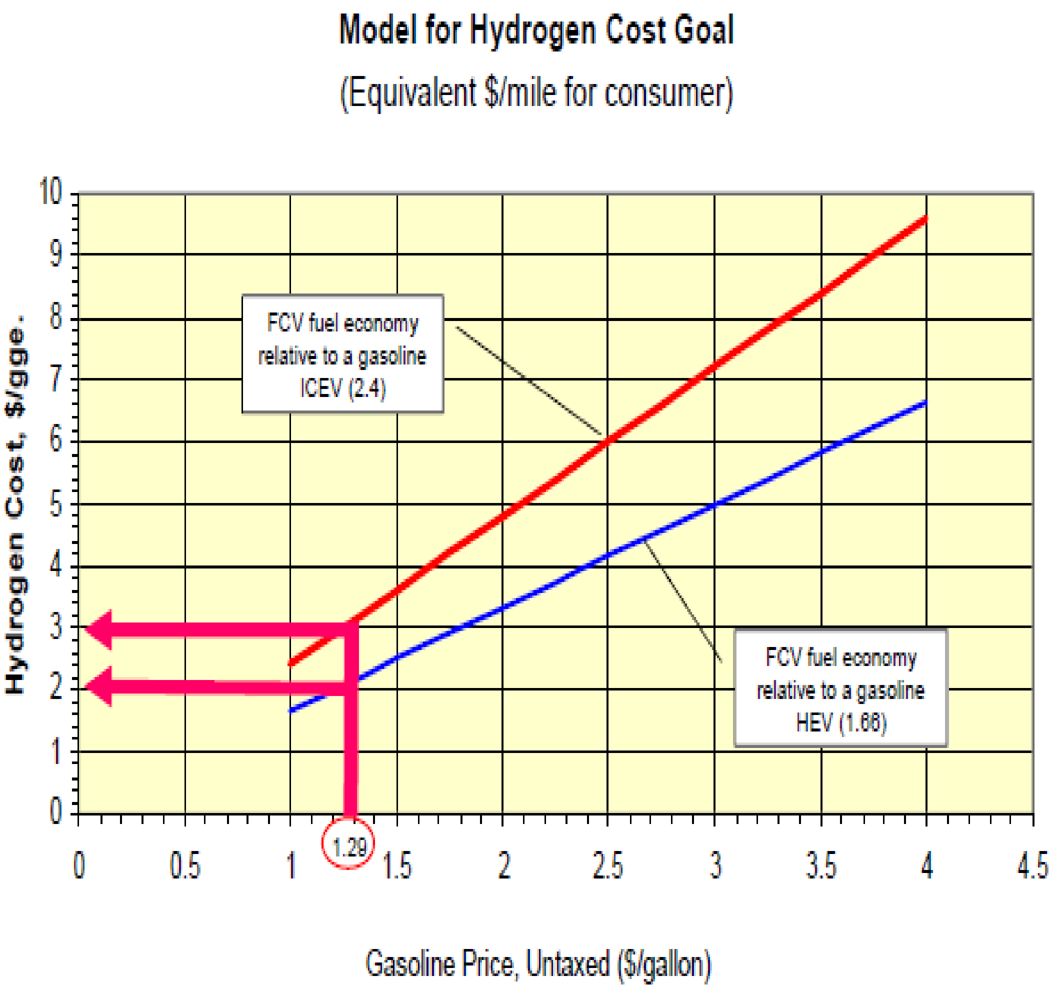


Figure 1. The US DOE approach to hydrogen competitiveness.

Source: US Department of Energy (DOE) (2005)

The DOE-model defines the goal as the cost of the hydrogen necessary to drive a given distance that will equal the cost of gasoline to drive the same distance. Whereas the gasoline is fuelling a conventional or a hybrid electric vehicle, the hydrogen is fuelling a much more fuel efficient fuel cell vehicle. Thus, the cost that hydrogen is compared to depends on the gasoline price as well as the energy efficiency of the FCV compared to the ICEV and the HEV.

There are several aspects of the model as well as its assumptions that would make a similar hydrogen cost goal misplaced in a European context.

First, it is assumed that the FCV fuel efficiency relative to ICEVs and HEV fuel efficiency is 2.4 and 1.66 respectively. In Europe, FCVs will, when they are introduced at the market be competing with much more fuel efficient petrol and diesel cars and probably more advanced HEV technology too. Relative fuel efficiency advantages of FCVs of 2 and 1.5 respectively are more likely in Europe.

Second, the ICEVs with low energy efficiency are of less interest when considering the competitiveness of FCVs in the period when they are introduced. In this period FCVs will probably be competing with HEVs and advanced ICEVs with fuel efficiencies much closer to that of the FCVs. The fuel efficient vehicles as a group will be competing with the standard vehicles, but the consumers that choose a fuel efficient car will have to choose at least between a battery electric vehicle, a HEV, an advanced diesel, and a FCV. An efficiency advantage of 100% over the competing conventionally fuelled cars may not be relevant in Europe because the conventionally fuelled cars in Europe are more fuel efficient and will be even more fuel efficient by the time when FCVs are introduced.

Third, the calculations assume a gasoline price of $1.29 per gallon based on a crude oil price assumption of $34 per barrel. Few analysts of the oil market will find that oil price realistic for the period of 2015-2025.

Fourth, the hydrogen produced now - and expectedly in 2015 too - is mainly based on natural gas as a feedstock in processes of steam reforming or catalytic partial oxidation. Thus, it is not only the gasoline price that depends on the international oil price. As shown in Hansen (2007b) the same applies to hydrogen as long as its primary energy basis is natural gas because the natural gas price depends heavily on the crude oil price.

Fifth, the European fuel taxation is much different from that in the US. In some countries taxes on some fuels constitute more than half of the consumer price and when considering the future hydrogen cost to the consumer this fact has to be taken seriously into account. In the UK and Netherlands, the total tax (including excise tax and VAT) was $33 per GJ in 2005 while it was $3 per GJ in the US or close to negligible in comparison.

The most important observation here is that the question of when hydrogen becomes competitive cannot be answered without knowing the price of oil. Although it is not the aim of this study to deliver an oil price projection for the future decades, the next section will provide some historical and conditionality framework for considerations about the future oil price. In the third section, the hydrogen competitiveness model is presented along with the core assumptions used with it. The fourth section presents results based on different scenarios about future fuel (including hydrogen) taxation. Conclusions are drawn in section five.

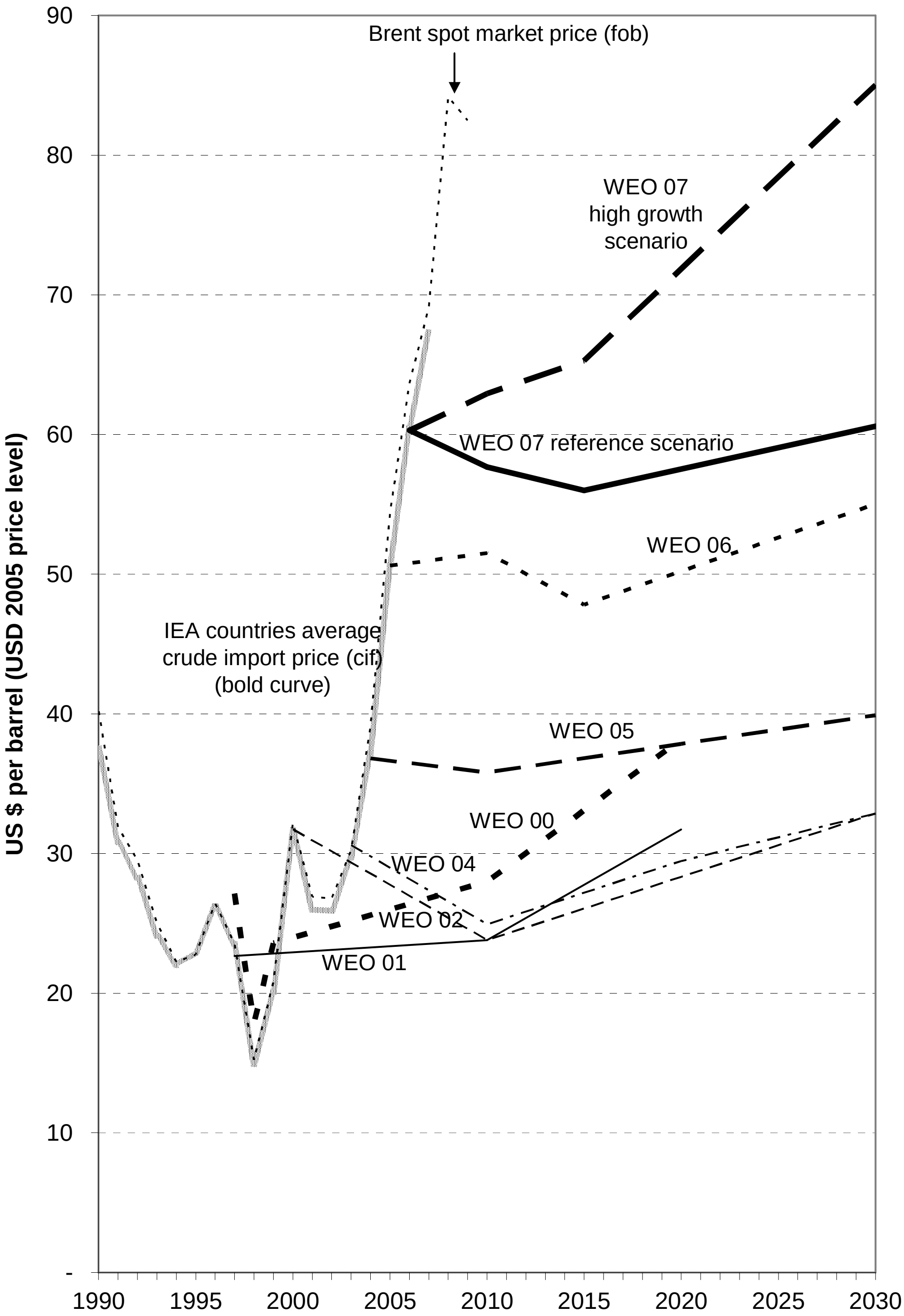
Oil prices when hydrogen as transport fuel is introduced

The difficulties of projecting future oil prices is quite clearly demonstrated by the systematic underestimation of the future oil price by one of the leading centres for oil market analysis, the International Energy Agency. The figure below shows the oil price projections from the agency in the first eight years of this century and how the oil price actually has developed.

Figure 2. Actual oil price and assumed future oil prices in the annual World Economic Outlook (WEO) from the International Energy Agency (IEA).

Source: Various issues of IEA World Energy Outlook, International Energy Agency (IEA) (2008), and Brent price and deflator data from OECD (2008) (Economic Outlook no. 82).

The figure shows the actual development of the average import price for crude oil to the IEA



countries and the Brent spot price. The average IEA crude oil import price is the price that the International Energy Agency attempts to predict in its annual World Energy Outlook (WEO). This average is published with some delay, but it appears to be close to the spot market price of Brent quality crude oil that is reported instantly in the media as "the oil price". In the figure, the price of Brent crude for 2008 and 2009 as expected by the OECD is shown as well. All figures are converted to US dollar in 2005 prices (i.e., in US dollars with 2005 purchasing power) for comparability.

As the figure above shows the oil prices in the World Energy Outlook has not been very good indicators of the future oil price in the first decade this century. This is unfortunate since they are often used as the best guess or most probable future oil price. The error is, however, mostly on the part of those who use the figures as predictions. The IEA explicitly call them "assumptions" rather than "projections". In International Energy Agency (IEA) (2007) it is stressed that "They should not be interpreted as forecasts." (p. 63).

Some patterns persist in the future prices assumed in WEO 2000 through WEO 2007. First, the oil price at the end of the period is higher than it is in the outset. Second, the already high oil prices are assumed to invoke a wave of upstream investments leading to an increased supply and temporarily lower prices before the increasing demand has lifted the price again. This temporary price drop remains a central assumption even though it has been postponed in the later reports.

The general pattern is, however, that the recent surge in the international oil price has surprised the IEA analysts every year. The price assumptions are systematically underestimating the future price increases and have been adjusted upwards year by year as the observed prices turned out to be higher than the anticipated prices.

One of the factors that has developed stronger than expected is the economic growth of China and India. The associated increase in energy demand has contributed to the considerable oil price increases and the future oil price depends very much on whether the future rate of economic growth will be high or more modest in these economies. These two scenarios are reflected in the high growth and the reference scenario.

The high growth scenario is accompanied by an oil price of $65-80 per barrel in the period considered here (2015-2025) while they in the reference scenario will not exceed $60/bbl. These assumptions should, however be compared to the Brent spot price for 2007 and the projected price for 2008 and 2009 of around $85/bbl (all expressed in US dollars with 2005 purchasing power).

The prices can, however, be much higher for other reasons. The uncertainties related to the future oil *supply* – in particular that from OPEC countries – are not considered in the price assumptions, but they are quite large. The International Energy Agency (IEA) (2007) warns: "In view of these uncertainties, a supply-side crunch in the period to 2015, involving an abrupt run-up in prices, cannot be ruled out." (p. 84).

According to an earlier report the peak of oil production in OPEC countries is not expected before after 2030, but it could appear as early as in 2013-2017 (International Energy Agency (IEA) (2004)). The future oil supply depends critically on the decline rates of the oil reserves that have reached or are about to reach their peak and on the current investments in production capacity (International Energy Agency (IEA) (2007)). However, the government controlled oil companies seem to lack willingness as well as ability to invest in new capacity beyond what is already planned. Thus, the assumptions of an accelerated growth of oil production behind the high growth as well as the reference scenario are rather optimistic.

It should also be noted that the neither of the scenarios foresee wars or internal conflict in the oil producing countries in the future decades. In the light of the experience of the recent decades, it would however be naïve to expect that the time until 2030 will pass without any conflicts involving disruptions of oil supply in the oil producing countries. This is indeed one of the main reasons for the search for alternatives to oil. War and conflict causes a war premium on the oil price via supply disruptions, higher oil demand due to warfare itself, speculative price bubbles, and war premiums on insurance of international transport including transport of energy commodities.

All of these supply side related risks that would lead to higher prices are not incorporated in either of the two scenarios. They are not sufficiently predictable and quantifiable to be incorporated into a model. Nevertheless, they represent likely future developments with major impacts on the oil price.

With the uncertainties described above and the complete absence of a professional consensus on the future oil supply, oil demand, let alone the oil price, there is not a sufficiently solid basis on which it is possible to base a European hydrogen cost target on like in the US DOE approach. Instead we will search for answers to the question of at which oil price hydrogen becomes cost competitive as a transport fuel. This oil price we may call the *threshold price* that makes hydrogen competitive.

For this end we will use a hydrogen competitiveness model comparing the fuel costs of transport services using alternative technologies.

The hydrogen competitiveness model

The question of at which oil price, hydrogen becomes competitive rests on the assumption that the first generation of hydrogen supply for transport purposes will be produced using natural gas as feedstock in a stream reforming or similar process. This process as well as the storage and transport of hydrogen is more expensive than the processing, storing, and transporting conventional fuels both in terms of energy costs and in terms of non-energy costs like infrastructure equipment and plants. Used in a fuel cell and electric drive train, however, the hydrogen is so much more efficient that the efficiency gain can overshadow the fuel transformation costs.

The price of natural gas is very closely associated to the price of oil and therefore the hydrogen costs will depend closely on the price of oil to the extent that hydrogen is based on natural gas. The cost per energy unit of hydrogen, however, depends less on oil than costs per energy unit of petrol and diesel. Thus, there is an oil price at which hydrogen becomes cost competitive and this “competitiveness threshold” is at a lower oil price the more fuel efficient the fuel cell car is compared to petrol and diesel cars.

The figure below illustrates the model developed to find this competitiveness *threshold price*.

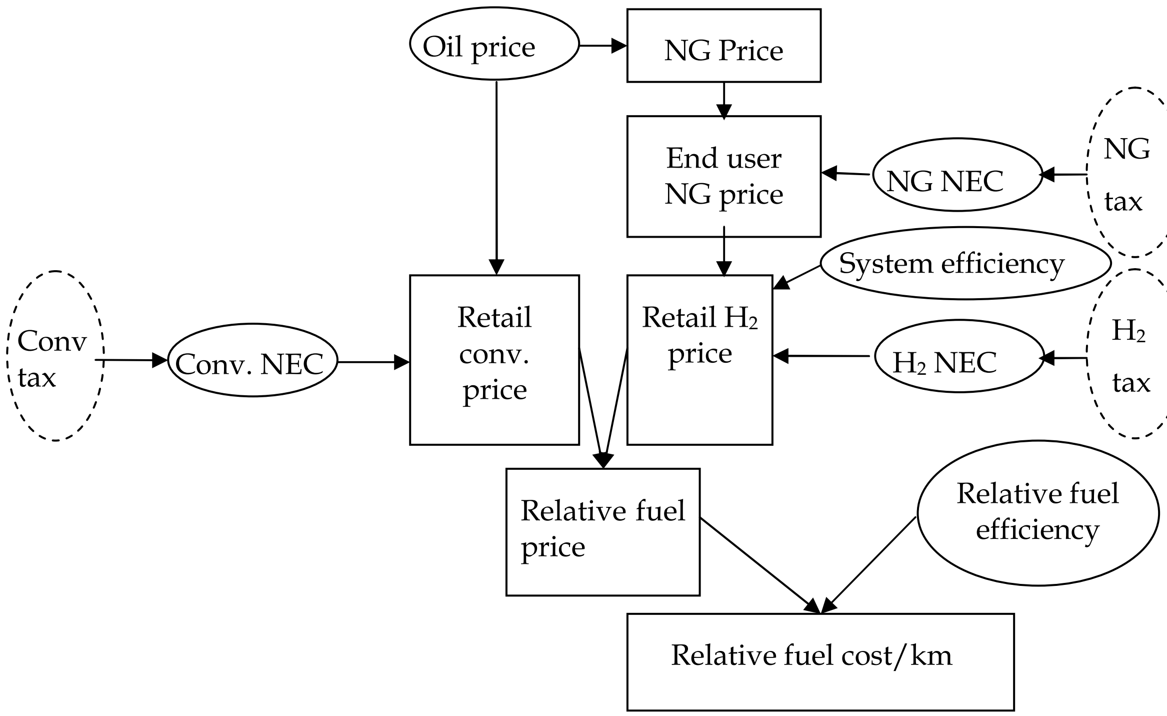


Figure 3. The hydrogen competitiveness model.

The model compares the relative fuel prices to the relative fuel efficiencies. In order to do that it is a critical assumption that the costs of owning a FCV are identical to those of owning an ICEV. There are reasons to believe that it will be possible to produce the FCVs at still lower costs in the period of 2015-2025. The cost level will be comparable first to vehicles with the more expensive technologies such as hybrid and advanced diesel and latest to conventional ICE technologies.

However, the relative fuel efficiency compared to the advanced diesel and hybrid technologies is not so high and it is a good question whether the fuel economy can be competitive when the vehicles are. Thus, we focus on the competition between FCVs and advanced ICEVs and HEVs where we assume that FCVs are only 50% more fuel efficient.

The relative fuel price is composed of the calculated petrol and diesel costs and the calculated hydrogen cost.

For simplicity, the petrol and diesel costs are weighed together in a "diesoline" cost. This cost depends on the cost of crude oil and the non energy costs of processing, transportation, and storage. The energy costs are estimated with regression analysis thus comprising the throughput of energy as well as the energy consumed in the process. The non-energy costs are estimated as the margin between crude oil and retail prices. Taxes can then be added to the non-energy costs.

The hydrogen costs are computed in the same way, but in two loops. First crude oil prices and non-energy costs in the natural gas sector are used to calculate the natural gas costs and then the natural gas costs are used as input together with non-energy costs to arrive at the hydrogen retail cost.

For the relative fuel price the critical parameter assumptions are the system efficiency and the non-energy costs. The non-energy costs and system efficiencies achievable in 2015-2025 are mostly guesswork, but based on earlier studies and enginierial calculations, some realistic ranges can be circled in. We consider non-energy costs in the range of €10-13 per GJ H_2 (for natural gas based H_2) and system efficiencies of 62-70%. To reflect the costs that would result if a breakthrough in storage technology is obtained in or before the period (such as a practicable hydrogen pill technology or similar), the calculations are also made with non-energy costs of €7 per GJ H_2.

To these calculations we have added the costs of hydrogen produced with the use of renewable electricity instead of natural gas. Here we assumed non-energy costs of €10-15 per GJ H_2 and system efficiencies of 65-70%.

The following table shows the core assumptions of non-energy costs and system efficiencies.

Table 1. Core assumptions of non-energy costs and system efficiencies in the calcualtions.

	Natural gas		Wind	
H2 production	Non-energy costs	System efficiency	Non-energy costs	System efficiency
Best case	€10/GJ	70%	€10/GJ	70%
Worst case	€13/GJ	62%	€15/GJ	65%

The model can be condensed to the following equation:

(1) P = (a + ak – c – de) / (df – b – bk)

where

P = oil price where H_2 cost/km = diesoline cost/km

a = "diesoline" NEC

b = "diesoline" oil price dependency

c = hydrogen NEC

d = hydrogen gas price dependency

e = natural gas NEC

f = natural gas oil price dependency

k = efficiency advantage: [(HFC km/GJ)/(ICEkm/GJ)]-1

More detailed background information on the model, the parameters, and the relations between the oil price and other fuel prices is available in Hansen (2007b) and Hansen (2007a).

Alternative fuel taxation scenarios

The fuel taxes play an important role in the competitiveness of hydrogen because they amplify the economic effect of fuel efficiency. The higher the fuel taxes the more economically important is the fuel efficiency advantage of FCVs. But how will hydrogen and conventional fuels be taxed in 2015-2025? There are several signs of changes in the European taxation systems in the direction of other taxation principles than those that are prevailing at present and hydrogen can be taxed in many ways depending on the taxation principles applied. Thus we consider a number of different scenarios. These calculations are presented in detail in Hansen (2007a).

The first question relates to the level of taxation. The European Union Fuel Taxation Directive prescribes minimum tax rates to be imposed on petrol and diesel close to €10 per GJ. As it appears from the figure below many member states impose much higher taxes on these fuels.

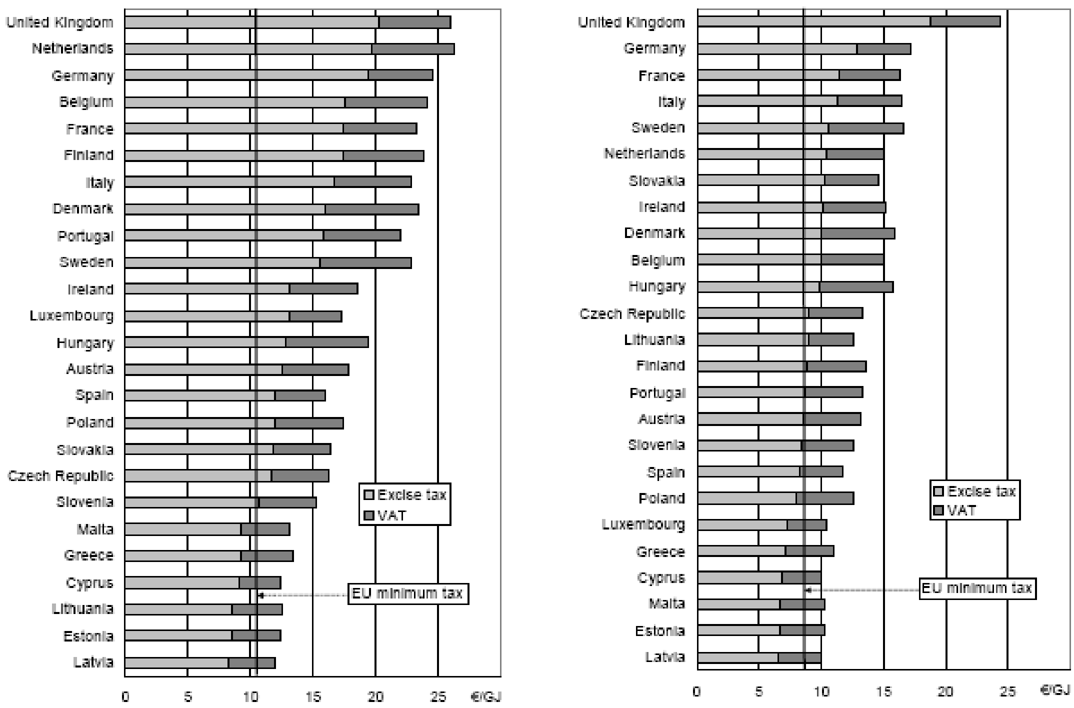


Figure 4. Petrol and diesel taxes in the European Union in 2004 (€ per GJ).

Source: Hansen (2007a).

With the currently strong focus on energy and climate issues in the European Union it can be argued that it is more likely that future tax level follows the level of UK, Germany, and the Netherlands rather than the present minimum level. Especially if the European countries want to avoid excessive fuel consumption in advance of anticipated oil price increases.

Hydrogen could, however, be taxed in several ways. In Europe fuel taxation mostly follows the principle of final use taxation. This means that there is no taxation in the transformation process (processing, transport, storage) and thus no price distortions due to different tax rules affecting fuel trade between countries. On the other hand, it also means that large energy losses in the transformation process are untaxed and as described above these losses are particularly large for hydrogen production. Thus, it is reasonable to consider scenarios where the final-use taxation principle is replaced by an *all-use taxation principle*, at least for hydrogen. Of course, this would only be possible with a very advanced international cooperation to ensure a common level of taxation of transport fuels.

Finally, the European minimum taxes are intended to tax fuels equally according to their energy contents while differentiating according to use. Fuels used for heating are typically taxed by lower rates than fuels used for other purposes and industrial use of energy is typically fully or partly exempt from energy taxes. Obviously, energy taxes are not the best instruments with which to pursue neither distributive nor competitiveness related societal goals. If the EU member states increasingly make use of more appropriate fiscal instruments for these ends fuel taxes may be more differentiated according to environmental pressure instead. An example of how hydrogen may be taxed in a scenario with environmentally differentiated taxes is presented by Chernyavs'ka and Lanfranconi (2006). The reader is referred to this report for details on environmentally adjusted fuel taxation.

On this background we consider the following scenarios:

(1) No fuel taxes

(2) End-use taxation of €10/GJ of hydrogen as well as conventional fuels

(3) Taxing conventional fuels and natural gas used as feedstock for hydrogen by €10/GJ

(4) Like 3. but differentiating to a natural gas tax of €8/GJ

(5) Like 4. but with double rates, i.e., conventional €20 and natural gas €16 per GJ.

In the alternatives (3) to (5), the electricity produced by windmills is not taxed at all or subsidised to an extent that neutralises the taxation. In all scenarios we disregard the VAT-component as it is the same for any fuel and already is applied in all links of the value added chain.

Fuel taxation scenarios and hydrogen competitiveness

With the hydrogen cost model, we calculate the oil price at which hydrogen will reach the competitiveness threshold under the core assumptions and in fuel the taxation scenarios described above. The results are shown in the table below.

Table 2. Hydrogen competitiveness threshold prices in alternative fuel taxation scenarios (€ and US$ with 2005 purchasing power and exchange rate).

Scenario	**(1)**		**(2)**		**(3)**		**(4)**		**(5)**	
Diesel and petrol tax (€/GJ)	0		10		10		10		20	
Hydrogen tax (€/GJ)	0		10		0		0		0	
Natural gas tax (€/GJ)	0		0		10		8		16	
Feedstock (natural gas/wind)	NG	Win	NG	Win	NG	Win	NG	Win	NG	Win
Best case ($/bbl)	188	105	86	85	174	45	115	45	42	-16
Worst case ($/bbl)	542	170	327	150	590	110	452	110	362	49

The results show that tax rates make a tremendous difference to the threshold price, even when hydrogen is taxed in exactly the same way (per GJ) as petrol and diesel and when only the minimum tax rates required by the fuel taxation directive are applied. In the best case (non-economic costs of €10/GJ and system efficiency of 70%) hydrogen is already competitive at $86/bbl, that is the present (winter 2007/2008) oil price. The difference between scenarios (1) and (2) is instructive for considering the difference between the US and Europe.

In the scenarios 3-5 electricity generated by wind power is not taxed. In these scenarios fuel taxation follows the principle of all use taxation, that is, all energy that is used in the process is taxed when and where it is used. Today the European Union member states typically apply the final use taxation principle supplemented with various subsidies and feed-in tariffs to accomplish an approximation to a taxation structure without taxes on renewable energy.

The difference between the parameter assumptions in the worst and the best cases are not very large, but they have a decisive effect on the competitiveness of hydrogen. The results indicate that the performance of hydrogen production, storage, and transport facilities is not allowed to be much poorer than indicated by the best case parameters before the competitiveness evaporates.

In the academic "hydrogen community" there is often a tacit understanding that even though the major societal advantage of the hydrogen and fuel cell technology is its ability to replace oil based fuels with electricity in transport the first generation of hydrogen will be based on natural gas as feedstock because natural gas based hydrogen is cheaper. These results show that it is not necessarily so. When the oil price reaches the heights of winter 2007/2008 natural gas becomes correspondingly expensive and hydrogen from electrolysis becomes a competitive option, even if the electricity is renewable. See also Hansen (2007b) for a discussion of this.

Conclusions

Several conclusions can be drawn from the competitiveness thresholds presented in table 2 above.

First, the high fuel taxes on petrol and diesel in Europe means that hydrogen will be competitive as a transport fuel in Europe a long time before it will in the US. If the present differences persist, the difference between US and the EU in 2015-2025 could be close to the difference between scenario 1 and the other scenarios.

Second, changes in taxation principles from final use towards *all-use taxation* and from differentiation according to income distribution and industrial competitiveness towards differentiation according to environmental pressure will strengthen the competitiveness of hydrogen.

Third, the standard assumption that introduction of hydrogen and fuel cell technology in transport will be based on natural gas reforming because it is cheaper than electrolysis is not at all evident at oil price around and above $80/bbl. In all of the scenarios at the oil price that would make natural gas based hydrogen competitive, renewable based hydrogen would be even more competitive.

Fourth, the implementation plan adopted by the European Hydrogen and Fuel Cell Technology Platform will not benefit from adopting a hydrogen cost target along the lines of the US DOE approach. Focusing on non-energy costs and system efficiency parameters is a much more direct and precise way to ensure competitiveness.

The parameter values used here are critical for the conclusions. Therefore, much more research in the opportunities of reaching the necessary performance is necessary. Hopefully this research can benefit from the use of the simple model with its simple parameters presented above.

Literature

Chernyavs'ka, L. and C. Lanfranconi (2006) Report on Taxation and Subsidies in Southern Europe. Deliverable from WP7 7.6

Hansen, A. C. (2007a) Hydrogen and Fuel Taxation. EECG Research Papers 05-07 Roskilde University, Department of Environmental, Social, and Spatial Change (ENSPAC) Roskilde http://hdl.handle.net/1800/2991

Hansen, A. C. (2007b) The International Oil Price and Hydrogen Competitiveness. EECG Research Papers 1/07 Roskilde University, Department of Environmental, Social, and Spatial Change (ENSPAC) Roskilde http://rudar.ruc.dk/handle/1800/2433

International Energy Agency (IEA) (2004). World Energy Outlook 2004, (ISBN: (World Energy Outlook 2004).

International Energy Agency (IEA) (2007). World Energy Outlook 2007, (ISBN: (World Energy Outlook 2007).

International Energy Agency (IEA) (2008) Energy Prices and Taxes. 2008 21.01 http://www.sourceoecd.org/

OECD (2008) Oecd.Stat. 2008 21.01 http://stats.oecd.org

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